Yucca Mountain Site Characterization Project

G-Tunnel Pressurized Slot-Testing Preparations

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G-TUNNEL PRESSURIZED SLOT-TESTING PREPARATIONS

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ABSTRACT

Designers and analysts of radioactive waste repositories must be able to predict the mechanical behavior of the host rock. Sandia National Laboratories elected to conduct a development program on pressurized slot testing and featured (1) development of an improved method to cut slots using a chain saw with diamond-tipped cutters, (2) measurements useful for determining in situ stresses normal to slots, (3) measurements applicable for determining the in situ modulus of deformation parallel to a drift surface, and (4) evaluations of the potentials of pressurized slot strength testing. This report describes the preparations leading to the measurements and evaluations.
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CONTENTS

1.0 INTRODUCTION

2.0 BACKGROUND

3.0 OBJECTIVES

4.0 SLOT-CUTTING DEVELOPMENTS

4.1 Chain-Saw Development

4.1.1 Chain-Saw Development Stages

4.1.2 Chain-Saw Equipment

4.1.3 Chain-Saw Cutting Discussions

4.2 Wire Saw

4.2.1 Wire-Saw Applications

4.2.2 Wire-Saw Equipment

4.2.3 Wire-Saw Cutting

4.3 Summary of Slots Cut

4.3.1 Slots Cut with the 1.1-m Chain Saw

4.3.2 Slots Cut with the 2.1-m Chain Saw

5.0 PHYSICAL COMPONENTS FOR TESTING

5.1 Slot-Normal Stress and Pressure-Deformation Testing

5.1.1 Layouts

5.1.2 Equipment

5.1.3 Instrumented Flatjack Details

5.1.4 Calibrations

5.1.4.1 Instrumented Flatjacks

5.1.4.2 Borehole Stressmeters

5.1.5 Measurement Procedures

5.1.5.1 Normal-Stress Measurements

5.1.5.2 Pressure-Deformation Measurements

5.2 High-Pressure Testing

5.2.1 Layouts

5.2.2 Equipment
## CONTENTS (concluded)

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.2.3 Calibrations</td>
<td>5-23</td>
</tr>
<tr>
<td>5.2.4 Measurement Procedures</td>
<td>5-23</td>
</tr>
<tr>
<td>5.3 Slot Impressions</td>
<td>5-24</td>
</tr>
<tr>
<td>5.3.1 Layout</td>
<td>5-24</td>
</tr>
<tr>
<td>5.3.2 Equipment</td>
<td>5-25</td>
</tr>
<tr>
<td>5.3.3 Procedures</td>
<td>5-25</td>
</tr>
<tr>
<td>6.0 SUMMARY</td>
<td>6-1</td>
</tr>
<tr>
<td>7.0 REFERENCES</td>
<td>7-1</td>
</tr>
<tr>
<td>APPENDIX A</td>
<td>A-1</td>
</tr>
<tr>
<td>APPENDIX B</td>
<td>B-1</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>--------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>2-1</td>
<td>Schematics Showing PS Testing Concepts</td>
</tr>
<tr>
<td>2-2</td>
<td>Schematics Showing Rocha and da Silva's Testing Equipment and Techniques</td>
</tr>
<tr>
<td>4-1</td>
<td>1.1-m Chain Saw in Cutting Position in a Rib</td>
</tr>
<tr>
<td>4-2</td>
<td>2.1-m Chain Saw in Cutting Position in the Floor</td>
</tr>
<tr>
<td>4-3</td>
<td>Diamond-Tipped Chain Links from the 2.1-m Chain Saw Before and After Cutting</td>
</tr>
<tr>
<td>4-4</td>
<td>Wire Saw in Cutting Position for Slot in Floor</td>
</tr>
<tr>
<td>4-5</td>
<td>Take-up Sled and Track for Wire Saw</td>
</tr>
<tr>
<td>4-6</td>
<td>Plan View Showing Locations of Slots</td>
</tr>
<tr>
<td>5-1</td>
<td>Layout Showing Principal Features for Cycles C1, C2, C3, D1, and D2</td>
</tr>
<tr>
<td>5-2</td>
<td>Schematic Showing Location of Flatjack for Cycles D3 and D4</td>
</tr>
<tr>
<td>5-3</td>
<td>Schematic of Pressure/Measurement System</td>
</tr>
<tr>
<td>5-4</td>
<td>Components of the Instrumented Flatjack</td>
</tr>
<tr>
<td>5-5</td>
<td>Flatjack Deformation Sensor Details</td>
</tr>
<tr>
<td>5-6</td>
<td>Elevation View of SDH Slots Used for High-Pressure Testing</td>
</tr>
<tr>
<td>5-7</td>
<td>Schematic of Pressure/Measurement System Used for High-Pressure Testing</td>
</tr>
<tr>
<td>5-8</td>
<td>Sample of AE Records With Reference Signals</td>
</tr>
</tbody>
</table>
# LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4-1</td>
<td>Summary of Slots Cut By Chain Saws and Wire Saw</td>
<td>4-13</td>
</tr>
<tr>
<td>5-1</td>
<td>Descriptions of Pressure-Deformation Testing Cycles</td>
<td>5-1</td>
</tr>
<tr>
<td>5-2</td>
<td>Flatjack Details</td>
<td>5-8</td>
</tr>
<tr>
<td>5-3</td>
<td>Calibration Factors for Instrumented Flatjacks</td>
<td>5-14</td>
</tr>
<tr>
<td>5-4</td>
<td>Summary of High-Pressure Testing Activities</td>
<td>5-18</td>
</tr>
<tr>
<td>5-5</td>
<td>Summary of Impression Flatjack Testing Activities</td>
<td>5-24</td>
</tr>
</tbody>
</table>
1.0 INTRODUCTION

Yucca Mountain on the Nevada Test Site (NTS) is composed of a thick sequence of volcanic ash-fall and ash-flow tuffs. This mountain is being considered as a site for a potential nuclear waste repository, and feasibility studies for this purpose are being conducted by the Yucca Mountain Project (YMP) (DOE, 1980). G-Tunnel, located in Rainier Mesa on the NTS, intersects layers of welded and nonwelded tuffs that have thermal and mechanical properties and stress states similar to the tuffs in Yucca Mountain (Zimmerman and Finley, 1987). The availability of this tunnel for immediate field experimentation allows Sandia National Laboratories (SNL), a YMP participant, to conduct field characterizations of tuffs without high excavation and facility development costs.

SNL is responsible for assessing the potential repository design and performance as well as characterizing the geomechanical behavior of the rock. Some of the major factors in repository designs are the stress state, the deformability of the rock (described by the modulus of deformation), and the strength of the rock.

The stress state can affect the rock mass deformability and strength. The underground state of stress results primarily from (1) lithostatic pressures caused by the weight of the rock; (2) tectonic stresses, which are caused by deformations of the earth's crust; (3) structural stress concentrations, which may be caused by rock mass inhomogeneities or excavations; (4) historical loadings, which may result from previous rock mass loadings and resulting rheological behavior; and (5) thermal loadings, which may be caused by geothermal conditions or induced by a nuclear waste repository.

Deformability is the relationship between stress and deformation in a rock mass; knowledge of the deformability properties is necessary for the safe and economical design of underground openings. Important properties are the modulus of deformation for the rock mass, Young's modulus for intact rock, and Poisson's ratio for both.
Rock mass strength is the load-carrying capacity that develops as a combination of the strength of intact rock and the strength of complex interactions of intact rock segments separated by fractures or joints. Determination of rock mass strength is an important consideration in making stability predictions. Design of underground openings incorporates factors for stress, deformability, and strength. Field measurements and tests provide information to assess the impacts of these factors. Stability predictions affect decisions regarding sizes and shapes of underground drifts and ground support requirements.

Stress, deformability, and strength can be assessed through the use of pressurized flatjacks inserted in the rock. The overall testing program described here is called pressurized slot (PS) testing. This testing is a developmental effort designed to (1) improve the technology of field measurements of the mechanical properties of welded tuff and (2) obtain field data for welded tuff to support YMP repository conceptual design efforts. The primary thrust of the development effort has been to upgrade and improve technologies that have been in use since the 1950s.

PS testing is potentially useful for measuring (1) in situ stresses normal to slots, (2) rock mass moduli of deformations, and (3) rock mass strengths near a drift surface at a scale large enough so that the measurements are more applicable to a jointed rock mass. Features in the development are

- improving slot-cutting methods using chain saws with diamond-tipped cutters,
- cutting slots with fewer stress concentrations,
- using analytical techniques to guide data interpretations,
- using impression flatjacks to characterize slot surfaces,
testing at a scale large enough to include effects of fractures and inhomogeneities in the rock mass, and

- evaluating new measurement techniques to enhance deformability and strength investigations.

The preparations for, results of, and evaluations of the PS testing activities are presented in three reports. This first report emphasizes the preparations, contains background information, and defines the objectives. Preparations include discussions of the slot-cutting developments and descriptions of the physical components for testing including equipment, calibration activities, and measurement procedures.

The second report (Zimmerman et al., 1992a) provides a data summary; the data are organized into the three main topics of (1) normal stress measurements, (2) pressure-deformation measurements, and (3) high-pressure testing results. Emphasis is placed on providing appropriate pressure histories.

The third report (Zimmerman et al., 1992b) involves interpretations of the data and applications for determining the stress-strain response of the rock mass. Analytical techniques are emphasized. A summary of pertinent findings and recommendations for future development efforts are presented.
2.0 BACKGROUND

Background for the PS testing is provided by discussing the basic methodology that has been developed. Development periods are discussed here in terms of stages. Stage 1 consisted of early developments where slots were cut with drilling processes and measurements were taken on the rock surrounding the slot. Stage 2 brought about improved slot cutting techniques and additional rock deformation measurements taken within the slot. Stage 3 was initiated by this effort and consisted of improved rapid slot cutting developments and formulations of additional analytical techniques.

The first stage was initiated in France (Mayer et al., 1951, and Tincelin, 1951). Schematics illustrating the concepts used in Stage 1 applications of flatjacks to measure in situ stresses and modulus of deformations in a rock mass are shown in Figure 2-1. In this testing, metal pins were located on both sides of the slots before the slot was cut, and distances between the pins were measured. The slot was cut using a line drilling method and the flatjack was grouted in. The flatjack was then pressurized to restore the pins to their original positions. The flatjack pressure to restore the pins to their original positions was taken as the measure of the in situ stress normal to the slot and is called the flatjack cancellation (FC) pressure. The pins were located in nonlinear strain gradients, and approximations were required to extract single values of the modulus of deformation, which is a value describing the general deformability of a rock mass.

Several investigators made important contributions to the evolution of the Stage 1 PS testing. Alexander (1960) improved the process somewhat by taking measurements between reference pins located across the slot. The application was similar to the one defined by Kruse (1963), which is shown in Figure 2-1b. Kruse changed the process used by Mayer et al. and Alexander by deepening the location of the flatjack and the measuring pins. Measurements were taken over periods of days and potential effects of creep were considered in the results. Hoskins (1966) conducted a series of laboratory tests to evaluate the normal stress-measuring technique and
Figure 2-1. Schematics Showing PS Testing Concepts
found that the FC method proved to be excellent in sound rock, but that the effectiveness of the measurement diminished as the creep became important. He suggested that flatjacks should not be used as stress monitors if rock mass creep is a significant problem in the desired measurement period.

Rocha (1966) initiated Stage 2 by proposing the use of an instrumented flatjack containing deformation sensors. The emphasis was on obtaining the displacement measurements in the slot rather than using the surface pins. This meant that depth of measurement and location of the flatjack in the slot became a factor. In a follow-up effort, Rocha and da Silva (1970) performed measurements using instrumented flatjacks. Their equipment and test setup are shown in Figure 2-2. A feature in the Stage 2 development was that the slot was essentially machined into the rock; that process allowed both more refined testing on a larger scale and the use of removable flatjacks.

Deklotz and Boisen (1970) developed equipment and procedures to determine the modulus of deformation and in situ stress in rock masses using concepts pioneered by Rocha, but they presented no data or test results. They reported on three serious problems that appeared to detract from the usefulness of PS testing at that stage of development. These problems were (1) stress concentration effects of guide holes required to cut the slots, (2) rock mass creep, as reported previously by Hoskins (1966), and (3) accuracy of converting field measurements to in situ stresses and moduli of deformation. The problem associated with the stress concentration was that the large guide hole caused a significant rearrangements of stresses near the hole and subsequent measurements with the instrumented flatjack were difficult to interpret. In another effort, Vogler et al. (1976) fabricated large flatjack testing equipment and applied the Rocha method. They found that the equipment worked well but they acknowledged the difficulties in converting the measured data to modulus of deformation values.

In a later study, Bieniawski (1979) reported on the results of investigations involving measurements of the normal stress and modulus of deformation by three methods: the petite sismique, the Goodman jack, and
Figure 2-2. Schematics Showing Rocha and da Silva's (1970) Testing Equipment and Techniques
the FC technique. In this case, the term flatjack applies to the use of a flatjack similar to that used in PS testing. Bieniawski separated his analyses into discussions of small and large flatjacks. He discussed only small flatjack measurements, however, because he felt that the Rocha and da Silva large flatjack applications suffered from technical uncertainties. He indicated that major problems in determining rock mass deformabilities were evaluating the shape of the loaded area and the positions where displacements were measured. The technical uncertainties of the large-scale measurements were significant to the extent that he presented flatjack data from surface pin measurements only.

Researchers in Portugal have continued with the Stage 2 applications. The instrumented flatjack method, initiated by Rocha (1966), was developed further and has been proposed to the International Society for Rock Mechanics as a "Suggested Method for Deformability Determination Using a Large Flatjack Technique" (Loureiro-Pinto, 1986). In considering the three problems outlined by Deklotz and Boisen, the suggested method does not address problems of the guide holes. Creep evaluation techniques are suggested but not defined. Finally, the analytical methods to determine the modulus of deformation are an extension of the Rocha method. The analytical techniques emphasize effects of crack growth in the plane of the slot. The suggested method is limited to Rocha-type flatjacks having a partially rounded surface or rectangular flatjacks and to slots located near the surface. Application to other configurations need additional numerical modeling.

This third stage of PS development was initiated by SNL in the G-Tunnel Underground Facility (GTUF) primarily to restructure PS applications and address the three problems listed by Deklotz and Boisen. First, the guide-hole problem was addressed by improving slot-cutting methods so that guide-hole effects are eliminated. This problem led to the development of the chain saws with diamond-tipped cutters that are discussed in this document. Second, time-dependent behavioral effects were reduced with the relatively rapid chain-saw cutting method. These time effects were monitored as part of the measurement process. Finally,
Improved analytical techniques that addressed the measurement interpretation problems were applied. The results provided in these three reports provide the documentation for this third stage. High-pressure flatjack testing with potential applications to rock mass strength measurements, an addition in this third stage of development, has been made possible because of the smooth slots that can be cut in the rock mass.
3.0 OBJECTIVES

In this document, PS testing involves using thin slots that have a surface area of at least 1 m². This size was selected (1) to ensure that the effects of joints, whose frequencies in G-Tunnel have been reported to vary from 3-4.5 joints/m (Langkopf and Gnikr, 1986), are factored into the measurements taken from the slots and (2) to be achievable with proposed slot-cutting methods and flatjack fabrication techniques. This scale of testing is an enlargement over normal borehole methods and larger than plate-loading tests (Loureiro-Pinto, 1986). A feature of this testing is that each slot can be cut into the rock so that flatjacks can be inserted without the use of a coupling medium.

Specific program objectives were to

1. develop slot-cutting methods that would provide a smooth slot surface and minimize stress concentrations at the rock mass/flatjack interface;*

2. use surface pin measurements to determine in situ surface stresses normal to slots;

3. perform pressure-deformation measurements with instrumented flatjacks in thin slots to determine the modulus of deformation of jointed, welded tuff;

4. use uninstrumented flatjacks to develop high pressures for evaluating in situ strengths; and

5. use analytical techniques for interpretation and conversion of data.

*Underlined items are not addressed in this text.
Achieving Objective 1 allows the other objectives to be accomplished. One of the contributions of developing the slot-cutting methods is achieving the ability to cut the slots quickly, thereby decreasing potential time-dependent effects as was seen by Hoskins (1966). Achieving this objective also opens up opportunities for other rock mechanics applications, such as defining blocks for heated block experiments or developing thermal stress measurements using flatjacks.

A smooth slot also allows the measurement pins to be placed closer to the slot. Sensitivities are improved so that Objective 2 can be achieved.

Achieving Objective 3 enhances measurements of the rock mass modulus and can provide an alternative to plate-loading testing, which is used as a proposed standard in international rock mechanics testing (Brown, 1981). Plate-loading tests are laborious, expensive, time consuming, and have two major limitations: the stress is applied in a direction normal to a recently disturbed surface and the volume of rock affected is somewhat small. As a comparison, PS testing equipment is relatively expensive, some time consuming, but effective testing volumes can be greater and testing times are greatly reduced. Also, the direction of the measurement is parallel to the surface in potentially less disturbed rock.

Achieving Objective 4 allows flatjack technology to be further developed. The cutting of a slot with a smooth surface allows high-pressure flatjack testing that can be used to evaluate rock mass strengths near the surface of underground openings.

Achieving Objective 5 is essential to accomplishing Objective 3 because data interpretation for PS measurements is a known problem (Deklotz and Boisen, 1970). The goal here is to try to use analytical techniques and numerical modeling to minimize costly laboratory measurements to establish the reasonable conversion factors for converting mechanical, sometimes nonlinear, measurements to desired rock properties.
The data obtained from testing of this type, in particular those data obtained with Objectives 2, 3, and 4, can be used in repository conceptual designs. Field data of this type are needed to evaluate assumptions required in current conceptual design efforts and to provide data that can be compared with results from other testing activities (Zimmerman and Finley, 1987).

This text addresses Objectives 1, 2, and precursive investigations to Objective 3 and possibly Objective 4. Objective 5 is not discussed in this text.
4.0 SLOT-CUTTING DEVELOPMENTS

The slot-cutting method developed by Rocha and da Silva (1970) had limitations that were discussed by Deklotz and Boisen (1970). The main problem associated with the slot-cutting method was the presence of a guide hole to hold the drive apparatus for the diamond-disk saw. One of the first technical problems addressed by SNL was to determine if the slot-cutting technique could be improved. The goal was to develop a new method to cut slots that would eliminate the effects of the internal guide hole required by the Rocha method. In effect, machined slots, without major discontinuities, would be available in a jointed rock for flatjack testing without the use of a coupling medium. Two methods were investigated: chain-saw cutting and wire-saw cutting.

Chain-saw-type cutters have been used with coal and soft limestone. They are primarily large ripping devices that are used as undercutters in coal mines and provide neither minimal damage to the surrounding rock nor thin slots. In an early experimental effort, Comeau (Zimmerman et al., 1987) used a small (bar < 0.5 m) chain saw with diamond tips to cut blocks of granite and quartzite; this encouraged our efforts and led to the development of the chain saws with diamond-tipped cutters.

Wire saws are known to be effective in granite quarries. The potential for using the wire-saw cutting method in an underground application was reviewed because of potential cost advantages over the chain saws.

4.1 Chain-Saw Developments

4.1.1 Chain-Saw Development Stages

A set of general requirements was established for the demonstration of the slot-cutting processes. These were that the slot width should be capable of receiving a planar flatjack approximately 7 mm thick and that minimum slot planar dimensions should be 1 x 1 m.
A phased development effort was initiated (Zimmerman et al., 1987). North Pacific Research (NPR) was placed under contract to pursue a three-step development and demonstration approach. The first step was to modify an existing wood-cutting chain to incorporate diamond-impregnated tips and demonstrate the cutting effectiveness on a 15-cm-dia welded tuff core that was readily available. The next step was to fabricate a large chain saw such that a slot 1-m deep could be cut for a proof-of-concept demonstration to satisfy the general requirements discussed earlier. A slot was cut and a 1 x 1-m flatjack was successfully inserted. Based on the success of cutting the 1-m-deep slot, a third step consisted of designing and fabricating a chain saw that could cut a slot 2 m deep.

4.1.2 Chain-Saw Equipment

Figure 4-1 shows the 1.1-m chain saw in place. The 1.1-m chain saw is a hybrid unit consisting of a 1.1-m-long bar made by Homelite and a 14-HP Stanley heavy duty hydraulic chain saw drive unit. Mountings for the chain saw were adapted so that the saw could be attached to a sliding sleeve, which in turn was attached to a column that could be mounted underground. The ends of the column were butted against the roof and floor with wedges to provide stability.

The slot-cutting technique involved cutting along a circular arc, as shown in the configuration in Figure 4-1, until the bar reached the horizontal position. Next, the saw was translated downward along the column with the bar held in a horizontal position so that a rectangular slot was formed. The slot was slightly longer than it was deep because of the geometry of the saw. The actual rock-cutting process was abrasion of a harder diamond tip on the slot surface under normal pressure from the bar. Water was applied to facilitate cooling and to remove cuttings.

Figure 4-2 shows the larger 2.1-m chain saw in place for a cut in the floor. The 2.1-m saw was mounted on a ring so that the bearing (orientation) of the cut could be easily set. The ring was designed so that it could be mounted either on the floor or on the side of a drift. The ring
was held in place with rock bolts and kept in position with wood wedges as shown in the figure. Within the ring was a hydraulically driven screw-feed mechanism that was used to translate the drive unit along the column located within the ring. The mechanism that controlled the angle of the cutting bar and the drive mechanism for the chain was also hydraulically driven. The hydraulic pump was operated by a 100-HP motor, shown in the background in Figure 4-2. The controls for the saw were mounted in the panel. The saw was operated from a control panel not shown in the figure.

All chains incorporated diamond-impregnated tips, designed and manufactured by Christensen Diamond Products. The tips were impregnated with medium-grade diamonds to a concentration of about 70%. The tips were fitted to a chain link prepared by NPR. Figure 4-3 shows new and used links for the 2.1-m chain saw.

4.1.3 Chain-Saw Cutting Discussions

The chain-saw method proved effective for the use intended and was selected for cutting slots for flatjack testing. An evaluation of the chain-saw cutting is presented in Zimmerman et al. (1987), and the details are not repeated here. The paper concluded "that (1) inhomogeneities in some welded tuffs present the most problems in cutting and (2) the cutting bars and links have to be designed properly for effective use. Preliminary investigations have been made and results suggest that (1) cutting can be improved with different cutting fluids and (2) cutting processes can be improved through further considerations of cutting speeds and pressures." The cutting rates reported were 0.73 m²/hr for the 1.1-m saw and 2.80 m²/hr for the 2.1-m saw.

The chain saws are expensive to fabricate. Most of the expense is in the cost of the chain. Estimated equipment costs were $4,000 for the 1.1-m saw and $30,000 for the 2.1-m saw as used. In the early development period, the completed chain links cost as much as $160 each. There were 50 links for the 1.1-m saw and 64 for the 2.1-m saw; thus, chain costs were in the $8,000-10,000 range. Experience in G-Tunnel shows that a chain can
Figure 4-3. Diamond-Tipped Chain Links from the 2.1-m Chain Saw Before and After Cutting
be used for cutting a minimum of two slots in welded tuff. More could be cut in nonwelded tuff. After cutting two slots, the tips can be worn to the point that dimensional tolerances may not be met. It is apparent that efforts are needed to develop extended lives for chains. Also, it is suggested that the general cutting process could be improved with "better mechanization" for the two saws. Better mechanization in this context is the design, fabrication, and installation of feedback-based control systems for operating the saws.

4.2 Wire Saw

4.2.1 Wire-Saw Applications

Wire saws are commonly used in quarries. Slots over 300 m² have been cut, and it was assumed that the method could be adopted for underground applications. Two cutting stages were required in the G-Tunnel Underground Facility (GTUF). First, large diameter (0.5-m) holes were diamond drilled so that the sheaves that guide the wire could be lowered into the rock. These sheaves were attached to a guide apparatus that was mounted on the rock surface. When the holes were in place, the wire-saw apparatus was set up as shown in Figure 4-4. The continuous tensioned wire was lowered against the rock surface, abrasives were added, and the slot cutting commenced. The abrasives, in combination with the tensioned wire, cut the slot, and the sheaves advanced with the cutting. The wire was tensioned to maintain alignment.

A major advantage of the wire saw is that it is relatively inexpensive to fabricate, install, and repair. In addition, the technology has been proven in surface applications. The wire-saw method was considered for this testing because equipment could be set up in a selected region for a slot, and the guide holes could be located outside the flatjack pressurization area. Thus, the guide holes would not be located in the region of testing as was the case for Rocha and da Silva (1970).
4.2.2 Wire-Saw Equipment

Figure 4-4 shows the operating (slot) end of the wire saw. Figure 4-5 shows the take-up end. The wire saw was fabricated and installed by J. Peters of the Jema Corp., Cold Spring, Minnesota. The continuous wire extended from the cutting area up over the upper sheaves, back to another set of sheaves, and on to the take-up sled. The sled provided tension to the wire and advanced as the wire translated into the rock. A slurry consisting of water and silica-carbide was added as an abrasive. The relative proportions were selected by the contractor. Lead weights were placed in the vertical assemblies that translated down the guide holes to provide wire pressure on the rock. The nominal wire speed range was 1,100-1,300 m/min. Wire diameters ranging from 4.7-6.4 mm were tried. Wire diameters were necessarily small so that wires would not be strained excessively on the sheaves. The size of the guide hole (0.5-m dia) established turning radius limitations that determined the maximum diameter of wire that could be used on the wire saw.

4.2.3 Wire-Saw Cutting

Evaluations of wire-saw cutting are discussed in terms of operational and process aspects. Wire-saw cutting was attempted on one slot.

Operational problems were associated with the operation of the equipment in the underground environment. Parts broke, feed systems failed, and take-up systems had some problems in this initial demonstration. These problems could be solved by engineering design and fabrication; solutions are not emphasized here. The process problems are more pertinent to these discussions.

The cutting process consisted of the tensioned wire sliding over the rock in the presence of the abrasive. The wire saw was used to cut a slot in the rock with dimensions of 1.9 m long and 0.81 m deep near the guide holes and 0.74 m deep at the center. The slot was slightly less deep than desired, but of sufficient depth to evaluate the cutting process. The most persistent problem involved wire breakage during the cutting. Breakage was
Figure 4-5. Take-up Sled and Track for Wire Saw
probably caused by strain hardening resulting from the passage of the wire over the short radius of curvature for the guide hole sheaves (< 0.1 m). Another problem was the presence of rock particles in the tuff. The wire-saw was located in a moderately welded tuff that contained pockets of loose rubble. Because of the presence of fractures and these rubble zones, small particles of rock could be dislocated and wedged against the wire, causing it to break. As a result of these problems, the longest continuous-cutting period was 50 min. When a break occurred, the wire was joined and repaired with silver solder, a process taking from 0.5 to 2.5 hr. A nominal cutting rate under operation was 0.8 m²/hr.

The slot surface was visually not as smooth as the surface produced by the chain saw. The wire appeared to form small grooves that were not totally planar. This among other factors led to the eventual abandonment of the wire saw from further considerations.

4.3 Summary of Slots Cut

Slots were cut in two drifts of the GTUF. Figure 4-6 shows a plan view of that portion of the GTUF containing these drifts. The slots in the Small Diameter Heater Alcove were located in a densely welded tuff, which was part of the Grouse Canyon Member, Belted Range Tuff (Langkopf and Eshom, 1982). This unit was reasonably uniform in texture. The slots in the Experiment Drift were in a moderately welded tuff that contained pockets of hard lithics that were easily dislodged from the rock formation by the chain.

4.3.1 Slots Cut with the 1.1-m Chain Saw

The 1.1-m chain saw was used to establish the applicability of this method for cutting slots in welded tuff (Zimmerman et al., 1987). A total of six slots were cut with this saw, all in ribs of Small Diameter Heater Alcove #1. The locations of the slots are shown in Figure 4-6. Table 4-1 summarizes the details of the slots. The slots are identified by the drift followed by a two-character alphanumeric that identifies the individual slot.
### TABLE 4-1
SUMMARY OF SLOTS CUT BY CHAIN SAWs AND WIRE SAW

<table>
<thead>
<tr>
<th>Cutting Methods</th>
<th>Slot Identification</th>
<th>Location</th>
<th>Nominal Dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1-m Chain Saw</td>
<td>SDH-S1</td>
<td>Small Diameter Heater Alcove #1--South Side</td>
<td>Length (m)</td>
</tr>
<tr>
<td></td>
<td>SDH-S2</td>
<td>&quot;</td>
<td>1.02</td>
</tr>
<tr>
<td></td>
<td>SDH-S3</td>
<td>&quot;</td>
<td>0.53</td>
</tr>
<tr>
<td></td>
<td>SDH-S4</td>
<td>&quot;</td>
<td>1.09</td>
</tr>
<tr>
<td></td>
<td>SDH-S5</td>
<td>&quot;</td>
<td>0.53</td>
</tr>
<tr>
<td></td>
<td>SDH-N1</td>
<td>Small Diameter Heater Alcove #1--North Side</td>
<td>1.10</td>
</tr>
<tr>
<td>2.1-m Chain Saw</td>
<td>EXP-EW</td>
<td>Experiment Drift--East-West Direction</td>
<td>2.74</td>
</tr>
<tr>
<td></td>
<td>EXP-NS</td>
<td>Experiment Drift--North-South Direction</td>
<td>-—*</td>
</tr>
<tr>
<td>Wire Saw</td>
<td>EXP-WS</td>
<td>Experiment Drift--Wire Saw Area</td>
<td>1.90</td>
</tr>
</tbody>
</table>

* Not cut to full rectangular shape.

Slots SDH-S1 and S2 were the first two cut with the 1.1-m saw. Slot SDH-S1 was successfully cut, proving the method to be feasible. These first slots were demonstration slots that were to be capable of accepting a 1-m square flatjack. Unfortunately, the chain saw bar wore unevenly, and the slot was not planar. Thus, the first slot could not be used for large flatjack testing. A second slot, SDH-S2, was cut, but some of the rock near the surface broke away, and the slot could not accept a 1-m square flatjack. A new bar and chain were used for subsequent 1-m slots because of problems encountered in the first two (Zimmerman et al., 1987). Table 4-1 shows that the widths of the first two slots were 9.5 mm. After
increasing the size of the bar and chain, subsequent cuts had a width of 12.7 mm. SDH-S3 was cut with the new bar and chain, but could not be completed because of rock failure problems which consisted of spalling of pieces of rock near the surface. These pieces were formed by the surface and intersecting fractures. Slot SDH-S4 was successfully cut, and the 1-m square flatjack was inserted, thus completing this phase of the chain-saw cutting demonstration. Slots SDH-S1 and S4 were later used for the high-pressure flatjack testing (S Cycles). Slot SDH-N1 was cut so that the normal stresses (Cycles C1 - C3) and deformation properties (Cycles D1 and D2) could be measured.

4.3.2 Slots Cut With the 2.1-m Chain Saw

The 2.1-m chain saw was used to cut two slots, EXP-EW and EXP-NS. These slots were located in the floor of the experiment drift, which was formed by a moderately welded portion of the Grouse Canyon Member. One slot, EXP-NS, was not completed to the full rectangular shape because of cutting problems. The two slots were used for deformability testing, Cycles D3 and D4.
5.0 PHYSICAL COMPONENTS FOR TESTING

Three major phases of testing make up the PS efforts: (1) slot normal stress, (2) pressure-deformation, and (3) high pressure rock failure evaluations. The physical components for the first two measurements are the same, and they are presented in Section 5.1. Physical components for high-pressure measurements are covered in Section 5.2. A nonmeasurement topic involves investigations with impression flatjacks. Details of these are covered in Section 5.3.

5.1 Slot-Normal Stress and Pressure-Deformation Testing

Slot-normal stress and pressure-deformation testing consisted of deformation measurements taken while a flatjack was being pressurized and depressurized. The FC measurements to determine the slot normal stress, identified as Cycles C1, C2, and C3, were taken in Slot SDH-N1. Pressure-deformation measurements to estimate an average modulus of deformation were taken in the same slot for Cycles D1 and D2. Pressure-deformation measurements for Cycle D3 were taken in Slot EXP-NS, and measurements for Cycle D4 were taken in EXP-EW. Table 5-1 summarizes the C- and D-type tests that were conducted. Each inflation and deflation is considered to be a test cycle.

<table>
<thead>
<tr>
<th>Cycle</th>
<th>Slot</th>
<th>Date Tested</th>
<th>Flatjack</th>
<th>Maximum Pressure (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>SDH-N1</td>
<td>06/03/86</td>
<td>FJ30-1</td>
<td>3.6</td>
</tr>
<tr>
<td>C2</td>
<td>SDH-N1</td>
<td>06/03/86</td>
<td>FJ30-1</td>
<td>3.7</td>
</tr>
<tr>
<td>C3</td>
<td>SDH-N1</td>
<td>06/04/86</td>
<td>FJ30-1</td>
<td>3.8</td>
</tr>
<tr>
<td>D1</td>
<td>SDH-N1</td>
<td>10/29/86</td>
<td>FJ30-1</td>
<td>8.9</td>
</tr>
<tr>
<td>D2</td>
<td>SDH-N1</td>
<td>01/09/87</td>
<td>FJ30-2</td>
<td>13.3</td>
</tr>
<tr>
<td>D3</td>
<td>EXP-NS</td>
<td>10/21/87</td>
<td>FJ30-3</td>
<td>10.3</td>
</tr>
<tr>
<td>D4</td>
<td>EXP-EW</td>
<td>10/22/87</td>
<td>FJ30-3</td>
<td>9.0</td>
</tr>
</tbody>
</table>
C-cycle testing consisted of flatjack pressure, borehole stressmeter (BSM), and cross-pin measurements on the surface. BSMs were not used in the D-cycle measurements, but instrumented flatjacks were added.

5.1.1 Layouts

Two layout configurations were used in this phase of testing. First, testing for Cycles C1, C2, C3, D1, and D2 was conducted in a vertical slot (SDH-N1) in the north side of Small Diameter Heater Alcove #1. In this phase of testing, the flatjack was located near the surface. Figure 5-1 shows the layout details of the measurements for these cycles. The major features are the measurement lines, numbered 1 through 4, which were established between reference pins bonded to the surface. BSMs were installed in holes positioned near the center of the expected loading region for the instrumented flatjack.

In the second configuration, Cycles D3 and D4 were conducted in the floor of the experiment drift in Slots EXP-EW and EXP-NS. Flatjacks were located deeper in the slots in these measurements. Slot EXP-EW was cut perpendicular to the major joint set, and Slot EXP-NS was cut parallel to this set. These slots were cut with the 2.1-m chain saw, and testing was performed at depths between 0.5 and 1.3 m to decrease the influence of the drift surface on the measurements. Figure 5-2 shows a schematic for the testing. The figure also shows that Slot EXP-NS was not rectangular.

Difficulties were encountered in cutting the slot with the 2-m saw, and a decision was made to conduct Test D3 in the slot configuration shown. It was assumed that there was sufficient slot area with the configuration shown.

5.1.2 Equipment

Equipment required for the testing is shown in Figure 5-3. The components necessary to pressurize the slot included a Haskel pump (Model MS 110), pressurized nitrogen gas, pressure gages, 3.2-mm-dia stainless steel tubing, and appropriate fittings and valves. The Haskel pump is an
NOTE: DIMENSIONS
A = 25.40 cm
B = 25.40 cm
C = 16.51 cm
D = 24.31 cm
E = 19.68 cm

F = 1.27 - 10.16 cm (Range)
G = 6.98 - 12.70 cm (Range)
H = 12.70 - 22.86 cm (Range)
I = 53.24 cm for 9N
   53.08 cm for 10N

A. FRONT VIEW

B. TOP VIEW

Figure 5-1. Layout Showing Principal Features for Cycles C1, C2, C3, D1, and D2
Figure 5-2. Schematic Showing Location of Flatjack for Cycles D3 and D4
Figure 5-3. Schematic of Pressure/Measurement System
automatic cycling, simple ratio pump, which was connected to the nitrogen supply, and used a relatively large piston area to drive a small-diameter hydraulic plunger. The hydraulic plunger increased the hydraulic pressure in the system.

Pressure gages were placed in the system to monitor pressure at the nitrogen bottle, between the Haskel pump and the flatjack (hydraulic pressure line), and on a line connected to the flatjack. Two Bourdon-type pressure gages were used to monitor hydraulic pressure. One had an upper limit of 34 MPa and the other 6.9 MPa. Relief valves were also placed at critical locations to prevent overpressurization of the system.

The switch and balance unit was connected to the strain indicator to allow balancing and monitoring of the multiple sensors for instrumented flatjack testing, which is described later. Data recording instrumentation included a strain indicator (Vishay-Micromeasurements, Model P-3500) and a switch and balance unit (Vishay-Micromeasurements, Model SB-1). Balancing was necessary so that the range of the transducer input was not surpassed during the test. During testing, microstrain was read directly from the strain indicator at specified pressures and manually recorded. Measurements from the different sensors were read by changing the channel assignments at the switch and balance unit.

The two BSMs used in the measurements were manufactured by Specialty Engineering Associates based on a design by Cook and Ames (1979). A BSM forms a rigid inclusion in the rock mass when wedged in a borehole. The wedging action keeps the stressmeter in place during monitoring. Changes in the stress field normal to the borehole are reflected in changes in the dimensions of the stressmeter. BSM signal output can be experimentally related to stress changes in the rock through special calibrations (Hawkes and Bailey, 1973).

The BSM consists of a stainless steel outer body, which is wedged in the borehole. Within the body is a sensing element that consists of a brass plug containing four alloy grid strain gages. Two of the strain gages read the compression of the plug, and the others provide temperature
compensation in a Wheatstone bridge configuration. The two BSMs were identified as 9N and 10N.

A Whittemore Strain Gage, manufactured by Weidmann Machine Co., provided a direct mechanical readout in inches across a gage length of 25.4 cm (10 in.). The resolution of the gage is ±0.0025 mm (±0.0001 in.), but the actual accuracy is approximately ±0.025 mm (±0.001 in.) because the gage is operated manually and is subject to visual interpretations.

Table 5-2 provides physical details regarding all the flatjacks. The table lists pertinent dimensions and design and manufacturer information for flatjacks indentified as instrumented, high pressure, and impression.

5.1.3 Instrumented Flatjack Details

A nonstandard measurement device in this testing is the instrumented flatjack. Instrumented flatjacks were used as pressure devices in the FC measurements without formal recording of sensor displacements. The sensors were monitored to ensure that they were functioning. The sensors were formally activated for the pressure-deformation testing. The instrumented flatjack is discussed here so that it can be easily referenced in later discussions.

Instrumented flatjacks consist of four components (Figure 5-4):

- stainless-steel loading sheets,
- a stainless-steel perimeter frame with electrical and hydraulic access ports,
- individual deformation sensors, and
- an inner template to locate sensors and prevent flatjack collapse.

Design, selection, experience, etc., of each of these four main components are discussed subsequently.


<table>
<thead>
<tr>
<th>Flatjack (Instrumented)</th>
<th>Overall Dimensions (cm)</th>
<th>Total Thickness (cm)</th>
<th>Sheet Thickness</th>
<th>Designer</th>
<th>Manufacturer</th>
</tr>
</thead>
<tbody>
<tr>
<td>FJ30-1&lt;sup&gt;a&lt;/sup&gt;</td>
<td>76.2 x 76.2</td>
<td>0.74</td>
<td>18 ga</td>
<td>NPR/SAICb</td>
<td>SNL</td>
</tr>
<tr>
<td>FJ30-2&lt;sup&gt;c&lt;/sup&gt;</td>
<td>76.2 x 76.2</td>
<td>0.74</td>
<td>18 ga</td>
<td>NPR/SAIC</td>
<td>SNL</td>
</tr>
<tr>
<td>FJ30-3&lt;sup&gt;d&lt;/sup&gt;</td>
<td>76.2 x 76.2</td>
<td>0.74</td>
<td>18 ga</td>
<td>NPR/SAIC</td>
<td>SNL</td>
</tr>
<tr>
<td>FJ39-1</td>
<td>99.1 x 99.1</td>
<td>0.75</td>
<td>18 ga</td>
<td>NPR</td>
<td>NPR</td>
</tr>
<tr>
<td>FJ39-2</td>
<td>99.1 x 99.1</td>
<td>0.75</td>
<td>18 ga</td>
<td>NPR</td>
<td>NPR</td>
</tr>
<tr>
<td>FJ39-3&lt;sup&gt;e&lt;/sup&gt;</td>
<td>99.1 x 99.1</td>
<td>0.75</td>
<td>18 ga</td>
<td>NPR</td>
<td>NPR</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Flatjack (High Pressure)</th>
<th>Overall Dimensions (cm)</th>
<th>Total Thickness (cm)</th>
<th>Sheet Thickness</th>
<th>Designer</th>
<th>Manufacturer</th>
</tr>
</thead>
<tbody>
<tr>
<td>FJ20-1</td>
<td>50.8 x 50.8</td>
<td>0.79</td>
<td>13 ga</td>
<td>SNL</td>
<td>RE/SPEC</td>
</tr>
<tr>
<td>FJ20-2</td>
<td>50.8 x 50.8</td>
<td>0.79</td>
<td>13 ga</td>
<td>SNL</td>
<td>RE/SPEC</td>
</tr>
<tr>
<td>FJ20-3</td>
<td>50.8 x 50.8</td>
<td>0.74</td>
<td>18 ga</td>
<td>SNL</td>
<td>SNL/SAIC</td>
</tr>
<tr>
<td>FJ20-4</td>
<td>50.8 x 50.8</td>
<td>0.74</td>
<td>18 ga</td>
<td>SNL</td>
<td>SNL/SAIC</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Flatjack (Impression)</th>
<th>Overall Dimensions (cm)</th>
<th>Total Thickness (cm)</th>
<th>Sheet Thickness</th>
<th>Designer</th>
<th>Manufacturer</th>
</tr>
</thead>
<tbody>
<tr>
<td>IFJ1</td>
<td>61.0 x 61.0</td>
<td>0.72</td>
<td>16 mil</td>
<td>SNL</td>
<td>SNL</td>
</tr>
<tr>
<td>IFJ2</td>
<td>61.0 x 61.0</td>
<td>0.72</td>
<td>16 mil</td>
<td>SNL</td>
<td>SNL</td>
</tr>
<tr>
<td>IFJ3</td>
<td>61.0 x 91.4</td>
<td>0.70</td>
<td>13.5 mil</td>
<td>SNL</td>
<td>SNL</td>
</tr>
<tr>
<td>IFJ4</td>
<td>61.0 x 91.4</td>
<td>0.70</td>
<td>13.5 mil</td>
<td>SNL</td>
<td>SNL</td>
</tr>
<tr>
<td>IFJ5</td>
<td>91.4 x 91.4</td>
<td>0.72</td>
<td>16 mil</td>
<td>SNL</td>
<td>SNL</td>
</tr>
<tr>
<td>IFJ6</td>
<td>91.4 x 91.4</td>
<td>0.72</td>
<td>16 mil</td>
<td>SNL</td>
<td>SNL</td>
</tr>
</tbody>
</table>

---

- <sup>a</sup> Contains template from older instrumented flatjack, FJ39-3.
- <sup>b</sup> SAIC: Science Applications International Corporation.
- <sup>c</sup> Contains FJ30-1 template.
- <sup>d</sup> Contains sensors from template FJ39-1.
- <sup>e</sup> Exact specifications are questionable.
Figure 5-4. Components of the Instrumented Flatjack
As a load source, the flatjack must supply a uniform pressure across the entire surface of the rock. This can best be accomplished if the flatjack surface is completely compliant. Because the flatjack transfers almost all of its pressure to the surrounding rock, it needs very little strength, except on the edges. In a thin flatjack, the unrestrained edges have little area exposed to the internal pressure, but they must be capable of undergoing large strains as the flatjack conforms to the slot. As a result of these special conditions, the flatjack edge assembly is the most difficult design problem. The outside sheets must be bonded (usually welded) to the perimeter frame, and the sheet requires modest strength and maximum flexibility. Slot smoothness and sheet thickness are other considerations. If the slot surface is not smooth and the sheet is too thin, the flatjack molds itself to the slot along the discontinuities making retrieval difficult.

Design criteria for flatjacks included a maximum pressure of 14 MPa (2,000 psi) and a minimum extension of 6.4 mm (0.25 in.) in the center. This means that the edges of the sheets must be able to deform to allow the flatjack to conform to the slot surface and accommodate this magnitude of deformation. Experiences with 18-gage 301 stainless-steel sheets in previous efforts by one of the authors suggested that this thickness might be adequate. This size was tried in preliminary effective-area testing (Section 5.1.4.1) and proved to be satisfactory.

The second component, the perimeter frame, is a structural unit that serves as a filler in the slot and as a feedthrough device for the hydraulic lines and electrical leads. The thickness of the frame is selected to achieve the desired thickness of the flatjack. One edge of the frame is wider in the plane of the flatjack to facilitate the electrical connections. The design and fabrication of this thickened section proved to be challenging. Welding of the outside sheets to the frame proved to be difficult. When the outside sheets were welded, the temperatures rose sufficiently at the electrical feedthroughs to melt the insulation and cause the internal sensors to short. The flatjack was disassembled and a
new feedthrough system designed. After many trials, a welding technique was devised whereby the outer sheets could be welded to preserve the insulation for the electrical leads.

An important consideration of the welding process was that the flatjacks should be planar when cool. Early flatjacks were warped and were difficult if not impossible to insert in the slots. Planar flatjacks require less tolerance between the flatjack and the slot, and deformations of outer sheets can be reduced.

The third component is the sensor. The sensor is designed as a spring device so that the outer edges rest against the inside surfaces of the sheets. Different types of sensors were considered in the developmental part of the testing (circa 1982) including (1) solid state strain gages, (2) linear variable displacement transformers (LVDTs), (3) capacitor gages, and (4) strain-gaged arches. These are briefly discussed.

The solid state strain gage is very rugged and is the most sensitive of the systems reviewed. The solid state gage has extreme temperature instability, a condition that might be difficult to control or compensate for in planned testing, and it was removed from further consideration.

Direct current LVDTs were too large to mount inside the flatjack and operate in the desired direction. The smaller alternating current LVDTs would have required special mounting linkages. Also, the problems of using alternating current in a sealed flatjack in field testing caused this type of device to be removed from further consideration.

A concept using the entire jack with its metal plates in a capacitor arrangement seemed attractive, and a preliminary study was made. In order to meet anticipated stability and sensitivity requirements, the simple capacitor rapidly became a complex multimaterial sandwich, and the signal conditioning requirements became expensive. Thus, capacitor concepts were removed from consideration.
Strain gages have been used with variable success in rock mechanics testing and would not have been the first choice for this type of sensor if viable alternatives existed. Strain gages must be properly bonded, and wires must be protected from moisture intrusion for successful use. The final approach was to attach strain gages to stainless-steel arches as shown in Figure 5-5. The arch was pinned to the template so it could rotate freely. The inherent spring action of the arch kept the edges in contact with the flatjack sheets.

The internal template serves two purposes. First, it locates the sensors at specified places within the flatjack. Also, the template serves as a frame for pin connectors to the sensors so that they are free to rotate about an axis parallel to the plane of the flatjack. The second purpose of the template is to serve as a clearance protector for the sensors. The sensors were designed with a minimum displacement range, and the sensors can be damaged if they are closed too tightly. Spacer blocks on the template prevent the flatjack surfaces from overcompressing the sensors.

5.1.4 Calibrations

Calibration requirements for slot-normal stress and pressure-deformation testing were related to the instrumentation used. Pressure gages were calibrated in the SNL Calibration Laboratory. The Whittemore Strain Gage has a calibration standard that was used in the measurements to ensure repeatability. Instrumented flatjacks and BSMs are nonstandard and required additional calibration efforts. Details for instrumented flatjack calibrations are provided in the Appendix.

5.1.4.1 Instrumented Flatjacks

Measurements described in the Appendix have shown that the effective area for the 0.8-m flatjacks was 0.93 times the product of outside dimensions. The calibration factors for the internal sensors are expressed in terms of με/mm. Results are summarized in Table 5-3.
Figure 5-5. Flatjack Deformation Sensor Details
**TABLE 5-3**

CALIBRATION FACTORS FOR INSTRUMENTED FLATJACKS*

<table>
<thead>
<tr>
<th>Flatjack ID</th>
<th>Cycle</th>
<th>Sensor 1 (με/mm)</th>
<th>±με</th>
<th>Sensor 2 (με/mm)</th>
<th>±με</th>
<th>Sensor 3 (με/mm)</th>
<th>±με</th>
<th>Sensor 4 (με/mm)</th>
<th>±με</th>
<th>Sensor 5 (με/mm)</th>
<th>±με</th>
<th>Calib Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>FJ30-1</td>
<td>C1, C2, C3, D1</td>
<td>192.9</td>
<td>±0.7**</td>
<td>188.6</td>
<td>±0.8</td>
<td>197.4</td>
<td>±1.8</td>
<td>185.2</td>
<td>±0.9</td>
<td>186.8</td>
<td>±0.6</td>
<td>3/6/86</td>
</tr>
<tr>
<td>FJ30-2</td>
<td>D2</td>
<td>191.4</td>
<td>±3.9</td>
<td>190.2</td>
<td>±6.6</td>
<td>198.7</td>
<td>±13.2</td>
<td>186.4</td>
<td>±4.6</td>
<td>186.9</td>
<td>±4.3</td>
<td>12/2/86</td>
</tr>
<tr>
<td>FJ30-3</td>
<td>D3, D4</td>
<td>179.0</td>
<td>±3.4</td>
<td>178.1</td>
<td>±3.4</td>
<td>178.0</td>
<td>±3.9</td>
<td>177.9</td>
<td>±4.9</td>
<td>178.2</td>
<td>±5.7</td>
<td>6/2/87</td>
</tr>
</tbody>
</table>

*Linear regression slopes by method of least squares; "microstrain" is synonymous with "counts" in this context.

**Numbers with ± refer to Y Standard Error and are in units of με (Appendix A).**

5.1.4.2 **Borehole Stressmeters**

The BSMs were calibrated by directly loading the units in a load frame. The BSM was incrementally loaded with uniaxial force parallel to the diametral sensing element while monitoring and recording the output. The results were nonlinear, but linear equations were fit to data applicable to the expected range of operation for the BSMs. The results are

<table>
<thead>
<tr>
<th>BSM</th>
<th>Calibration Constant (με/N)</th>
<th>Standard Error (με)</th>
<th>Range (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9N</td>
<td>0.6945</td>
<td>± 7.90</td>
<td>9.8-24.6</td>
</tr>
<tr>
<td>10N</td>
<td>0.6908</td>
<td>± 6.15</td>
<td>7.4-24.6</td>
</tr>
</tbody>
</table>
5.1.5 Measurement Procedures

5.1.5.1 Normal-Stress Measurements

Measurement procedures for the FC process included:

1. installing pins and BSMs at proper positions in the rock before cutting the slot;
2. measuring distances between pins and BSMs;
3. cutting the slot;
4. preparing the pressurization and instrumentation system;
5. remeasuring distances between pins and reading BSM outputs;
6. installing the flatjack in the slot in the designated position, initializing measurements for the flatjack pressure, BSMs, and distance between surface pins, and establishing FC pressure criteria;
7. seating the flatjack and reinitializing the surface pins and BSMs;
8. increasing the pressure of the flatjack in specified increments (nominally 0.35 MPa) and measuring and recording surface pin distances and BSM outputs; and
9. terminating pressurization when cancellation pressure is established and acquiring data during the depressurization.

5.1.5.2 Pressure-Deformation Measurements

Measurement procedures included the same initial procedures as the normal stress measurements for Steps 1-5 with the exception that BSMs were not used. The remainder of the procedure included the following:
1. Installing the flatjack at the proper position in the slot.

2. Initializing measurements for the flatjack pressure, surface pin (if applicable), and deformation sensors.

3. Seating the flatjack in the slot by increasing the pressure to 1 MPa (150 psi) and then releasing the pressure.

4. Reinitializing measurements for the flatjack pressure, surface pin (when applicable), and deformation sensors.

5. Increasing the flatjack pressures in specified increments, normally 1/10 the maximum pressure planned, and recording surface pin (when applicable) and displacement sensor changes until the desired maximum is reached. A pressure of 14 MPa (2,000 psi) was the maximum pressure to be reached for Cycles D1 and D2 and a pressure of 10.3 MPa (1,500 psi) for Cycles D3 and D4. Data were acquired during the flatjack depressurization in the same increments.

6. Decreasing the flatjack pressures in the same increments and continuing to monitor the surface pin and deformation sensor changes until zero pressure is reached.

5.2 High-Pressure Testing

High-pressure flatjack testing involves inserting a flatjack in a slot and monitoring hydraulic pressure and acoustic emissions (AEs) during the loading process. The purpose of this development testing was to explore possibilities for making rock mass strength interpretations. These measurements are identified by the letter S, for stress, and a cycle number.

Acoustic emissions are microlevel bursts of acoustic energy that are generated in mechanically loaded materials. The bursts are radiated from
some source, which may be a point, surface, or volume, in the form of elastic waves that travel at the speed of sound in that material. The AE can be caused by crack growth or unsteady crack slip in a material. Bursts from unique waveforms can be detected, possibly counted, and recorded. In many AE activities, bursts are described by counts, which are the cumulative number of threshold crossings of a signal magnitude. Signals that cross a specified threshold are counted over a specific period of time without any further waveform analyses. The cumulative number of crossings indicates the intensity of the AE. Commercial equipment is available to provide this information. If velocity profiles and sensor locations are known, counts can be used in source location analyses (Koerner and Leaird, 1982). Most equipment related to these types of activities has storage limitations that restrict uses for the high-pressure measurements planned in this testing. Thus, a different system was developed, which is discussed in the next paragraph.

The system configured for this testing consisted of simulations recording of AE waveforms. Data from eight AE sensors were stored for later data processing. The goal of this measurement system was to compare AE information from individual sensors as a function of flatjack pressure increases for the different S cycles. A form of the count system was used to indicate the frequency of acoustic activity as a function of flatjack pressure and loading cycle for each sensor. The focus here is to describe the equipment used in this testing.

5.2.1 Layouts

Table 5-6 summarizes the high-pressure testing that was conducted. Figure 5-6 shows the typical layouts for the slots used in the high-pressure measurements. Slot SDH-51 was used for the initial testing. The slot was selected because it was furthest from other slots. The slot was not truly planar and uniform in cross section, and flatjacks failed at lower pressures than desired. The failures appeared at the portion of the slot that was the widest. Several passes with the chain saw had widened the slot at the bottom. Slot SDH-54 was selected for the remainder of the testing it was uniform in cross section.
### TABLE 5-4
SUMMARY OF HIGH-PRESSURE TESTING ACTIVITIES

<table>
<thead>
<tr>
<th>Cycle</th>
<th>Slot</th>
<th>Flatjack</th>
<th>Maximum Pressure (MPa)</th>
<th>Date</th>
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<tr>
<td>S1</td>
<td>SDH-S1</td>
<td>FJ20-1</td>
<td>6.89</td>
<td>6/12/86</td>
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<td>S2</td>
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<td>FJ20-1</td>
<td>6.89</td>
<td>6/12/86</td>
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<td>9/25/86</td>
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<td>S4</td>
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<td>FJ20-1</td>
<td>13.79</td>
<td>9/25/86</td>
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<tr>
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<td>SDH-S1</td>
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<td>9/25/86</td>
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<td>S6</td>
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<td>11/20/86</td>
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<td>S14</td>
<td>SDH-S4</td>
<td>FJ20-4</td>
<td>28.34</td>
<td>6/15/87</td>
</tr>
</tbody>
</table>

*Repaired flatjacks.

Note: FJ20-3 was not used in high-pressure testing.

### 5.2.2 Equipment

Figure 5-7 shows a schematic for the equipment that was used in the high-pressure testing. The hydraulic-pressure equipment was the same as for the pressure-deformation testing. The main difference was the addition of the AE equipment, which is described in this section. Table 5-2 provides flatjack details.
Figure 5-6. Elevation View of SDH Slots Used for High-Pressure Testing
The AE equipment consisted of

1 8-channel Amplifier-Signal Conditioner, manufactured by Acoustic Emission Technology, Model 140-8;

8 Acoustic Emission Technology Accelerometer Sensors, Model C 30-L (Resonant Frequency 30 kHz, Sensitivity of -75dB);

1 Tape Recorder, Ampex, Model 2230;

1 Time Mark Generator, Tektronix, Model 2901;

1 Signal Generator, Hewlett-Packard, Model 654A; and

1 Oscilloscope, Tektronix, Model 454.

The equipment was set up so that acoustic emissions were to be received by each of the eight sensors. It was planned that each of the eight sensors would have the essentially the same sensitivity so the magnitudes and frequencies of the emissions could be related to sensor locations. At the recommendation of Acoustic Emission Technology, a 1 V sine wave with a frequency of 30 kHz was substituted for the sensors and input into the amplifier and oscilloscope. The gain of the amplifier was set such that each input signal had the same amplitude on the oscilloscope. The lead to the oscilloscope was then connected to the tape recorder and the 1 V signal was input as a reference signal for each of the channels. A time mark generator was set for 0.05 ms increments and recorded on another channel. This provided a time reference for evaluating the emissions.

Tapes were processed in the SNL Data Processing Center and results were printed on a strip chart. Figure 5-8 shows a representative output of the acoustic emissions signals. The 1 V reference is shown on each of the channels. The relatively short time base (430 ms) for the figure was set to illustrate emissions that were recorded. The reference signal at a
Figure 5-8. Sample of AE Records With Reference Signals
frequency of 30 kHz has a single cycle period of 0.033 ms, thus it is shown compressed in the figure.

The tape recorder had a separate channel for voice input. Pressure magnitudes were recorded on the tape during testing so that the pressure record would be available for later data processing.

The sensors were attached to steel pins with C-clamps. The pins were 12 mm in diameter and 15 cm long. They contained a steel plate at the sensor end, which had dimensions of 50 x 50 x 3 mm. The pins were epoxied to the holes with a Devcon rapid setting epoxy. The holes were hand drilled and were approximately 7 cm deep.

5.2.3 Calibrations

The AE sensor outputs were referenced to the signal generated by the signal generator. The signal generator produced a reference signal of 2 V, peak to peak at a frequency of 30 kHz. The signal generator was calibrated in the SNL Calibration Laboratory.

5.2.4 Measurement Procedures

The measurement procedures included the following:

1. Inserting the flatjack in slot at the specified position and seated to a pressure no greater than 1 MPa.

2. Connecting all recording systems, initializing the time mark reference, and calibrating the sensor channels.

3. Increasing pressures in specified increments while recording AEs, pressure, and time.

4. Terminating pressure increases at maximum pressure specified or at failure of the flatjack.
5. Recording AEs on incremental pressure decreases of the same magnitude if maximum pressure is reached and continuing to record AEs.

5.3 Slot Impressions

The development of the flatjack testing brought out the need to better characterize the surfaces of the slots. The impression flatjacks were developed primarily as a safety inspection device in the high-pressure testing to ensure that there were no voids or unwanted discontinuities in the slot surface that could cause the flatjack sheet to fail. The approach was to insert a flatjack containing copper sheets in the slot and pressurize it to less than 3.5 MPa. The soft sheets permanently conformed to the slot surface and could be studied and photographed upon removal from the slot. Pertinent flatjack details are contained in Table 5-2 and test details are provided in Table 5-5.

<table>
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<tr>
<th>Cycle</th>
<th>Flatjack</th>
<th>Slot</th>
<th>Date</th>
<th>Maximum Pressure (MPa)</th>
<th>Failed*</th>
<th>Usable Impression</th>
</tr>
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<tbody>
<tr>
<td>IS1</td>
<td>IFJ1</td>
<td>SDH-S4</td>
<td>06/03/87</td>
<td>0.138</td>
<td>Yes</td>
<td>No</td>
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<tr>
<td>IS2</td>
<td>IFJ2</td>
<td>SDH-S4</td>
<td>06/11/87</td>
<td>1.620</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>ID3</td>
<td>IFJ3</td>
<td>EXP-EW</td>
<td>07/31/87</td>
<td>0.276</td>
<td>Yes</td>
<td>No</td>
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<td>ID4</td>
<td>IFJ4**</td>
<td>EXP-NS</td>
<td>09/02/87</td>
<td>1.344</td>
<td>Yes</td>
<td>Yes</td>
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<tr>
<td>ID2</td>
<td>IFJ5**</td>
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*All flatjacks failed at weld contacts.  
**Flatjack contained "soft copper."  

5.3.1 Layout

Slot impressions were taken in three slots. The impressions were taken in Slot SDH-S4 primarily for a safety inspection. Impressions were
taken in Drifts EXP-EW and NS primarily for slot inspection in the deep slots and secondarily for safety reasons.

5.3.2 Equipment

The equipment used for slot inspections was essentially the same as that used for the hydraulic pressurizations. Slot inspections involved a pneumatic system and copper flatjacks. For slot impressions, nitrogen gas was used to pressurize the impression flatjack directly using the pressure regulator on the nitrogen bottle. A pressure relief valve was included in the connecting tubing to prevent overpressurization.

All impression flatjacks were manufactured from copper. The thin sheets, either C110 "half hard" or C110 "soft," were brazed to the copper perimeter frames; Table 5-2 gives details. The thermal conductivity of the copper was high and the brazing process was difficult because heat was easily distributed into the sheets. Upon cooling, the sheets sometimes buckled.

5.3.3 Procedures

The slot inspection includes the following major steps:

1. Set up pneumatic pressurization system.

2. Install impression flatjack in the specified position.

3. Inflate the flatjack to no more than 3.5 MPa and slowly deflate to zero.

4. Remove flatjack, sketch a detailed schematic, and photograph it if appropriate.

All of the impression flatjacks leaked. Most leaks occurred at the seam between the perimeter frame and the sheets. When a leak developed during a test, the flatjack was removed and attempts were made to close the
leaks with solder or epoxy. These underground repairs were not very successful. When a leak was evident from pressure gage readings on both sides of the flatjack, the volume of nitrogen was increased until the pressure in the closed end of the flatjack was at least 0.3 MPa. Pressure of this magnitude was adequate to provide a limited impression with either the half-hard or soft sheets. It appears that the arbitrary upper limit of 3.5 MPa could be reduced in future efforts. A value of 1.4 MPa appears reasonable.

These problems point to the need for flatjack leakage inspections before use. This could be performed by the manufacturer. Attempts were made in the field to detect leaks with a soap solution while the flatjack was pressurized to approximately 7 kPa (1 psi). Small leaks in the peripheral welds were not detected by this method. Also, such attempts expanded the flatjack permanently, making installation more difficult.
6.0 SUMMARY

The material in this report describes the preparations leading to the fielding of the PS testing. The report provides documentation on the experiment layout, the pertinent equipment, and the instrumentation. Instrumentation details include calibration procedures and results and measurement procedures. This report is followed by a data summary report (Zimmerman et al., 1992a) and an evaluation report (Zimmerman et al., 1992b).
7.0 REFERENCES


Langkopf, B. S., and E. Eshom, "Site Exploration for Rock Mechanics Field Tests in the Crouse Canyon Member, Belted Range Tuff, Ul2g Tunnel Complex, Nevada Test Site," SAND81-1897, Sandia National Laboratories, Albuquerque, NM, 1982. (NNA.900403.0379)


APPENDIX A

**Calibrations of Instrumented Flatjack**

There are two calibration processes necessary for instrumented flatjack testing: (1) determining the effective area and (2) determining the conversion factors for the displacement sensors.

The flatjack is assumed to act as a membrane acting over its fall area, but the fabrication process dictates that the enclosing sheets of stainless steel be connected so that their contact area is less than the perimeter dimensions. A desirable objective is to relate the flatjack pressure to the actual stress being applied to the rock, and this is accomplished using an effective area. The effective area is the total surface area of the flatjack that is applying a uniform pressure to the rock. The effective area is determined by inserting a flatjack into a special fixture that can be placed in a large compression testing machine. The test fixture should be designed so that the dimensions of the slot are represented, that is, the total loading area and the slot width in the machine fixture should be representative of the in situ conditions. Once this has been established, the flatjack is pressurized, and the total force recorded on the testing machine. The effective area is equal to the force measured by the testing machine divided by the flatjack pressure. Effective areas greater than 90% of the gross flatjack areas are desirable.

The process for measuring the effective area consisted of placing a 1-m square flatjack (7.4 mm thick) in a loading frame. The flatjack was sandwiched between 12-mm-thick loading plates to provide smooth surfaces. The flatjack was inflated to a maximum deformation of 12 mm and then the pressure in the flatjack was increased in 1-MPa increments, while the deformation was held as constant as possible. The load was increased in 10 1-MPa increments to 10.3 MPa in three separate cycles. In separate calibration activities, the load cell or pressure cell was found to have a maximum error of approximately 0.5%. The average effective area was 9,570 \( \pm 52 \) cm\(^2\). This means that the effective area was 96% of the outer
dimensions. In another calibration performed in a similar manner, an effective flatjack area of 88% was determined for a 0.3-m square flatjack. Using a linear interpolation, the effective area factor for the 0.8-m square flatjack is estimated to be 0.93. After field installation and testing, a visual inspection of one of the 0.8-m flatjacks showed that the expanded edge of the flatjack, which had clear rock markings, was approximately 1.2 cm from the outside edge of the flatjack. The visually loaded area would correspond to an effective area factor of 0.93, and this confirmed the calibration-based estimate.

The deformation sensor is assumed to represent the relative displacements of opposing surfaces of the flatjack, which are also assumed to represent the deformations of the opposing surfaces of the slot. The thin V-shaped arch bears against both surfaces; as the surfaces move, the arch deforms elastically, and the strain-gage-based sensing elements produce electrical outputs. The output of the strain gage assembly is displayed in a typical field strain gage display unit. The essential calibration consists of correlating displacements at the ends of the arches with the output from the strain gauges.

Because this was a development effort, one of the precalibration investigations was to determine if the deformation sensor was sensitive to hydrostatic pressure. The instrumented arch was placed in a pressure chamber and pressurized to 14 MPa. The measurements showed that the readings (R) could be linearly related to pressure (P). The following relationship was established based on 36 measurements on one gage:

\[ R = a + bP, \]  
\[ (A-1) \]

where

- \( R \) = reading on strain indicator
- \( a \) = slope intercept based on linear-least-squares regression 
\( (a = 188.6\) readout units)
b - slope based on linear-least-squares regression
(b = 0.8914 readout units/MPa)

P - hydrostatic pressure on gage.

A useful quantity in evaluating calibration accuracies is the standard error. The Y standard error can be expressed as

\[
YSE = \left( \frac{\sum (y_i - b x_i - a)^2}{(n - 1)} \right)^{1/2},
\]

(A-2)

where

\[ y_i \] dependent variable at i in the sequence

\[ x_i \] independent variable at i in the sequence

\[ n \] number of data points.

The standard error for the measurements related to Equation A-1 was 0.91 readout units. For the readings taken, the error was less than 0.5%.

The primary calibration of the deformation sensors consisted of placing the hard steel contacts between the extensions of a hand-held caliper. The caliper's resolution was at least 0.025 mm (0.001 in.). The caliper was initialized with the sensor in the closed position and then increased in at least 10 uniform increments until a maximum displacement of 10 mm was reached. The data acquisition process was then repeated in the same increments as the caliper was being closed. The data were plotted as microstrain versus caliper displacement. The slope and YSE for the measurements were determined and are given in the text in Table 5-3, page 5-14.
APPENDIX B

Candidate Data for RIB

This report contains no data from, or for inclusion in, the RIB.

Candidate Data for SEPDB

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