**A Coupled Mechanical-Hydrological
Investigation of Crystalline Rocks:**

**Annual Technical Progress Report,
Proposed Test Matrix, and
Preliminary Results**

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A COUPLED MECHANICAL-HYDROLOGICAL
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SUMMARY

This report reviews the Fracture Flow Behavior in Rock Study being performed at the Pacific Northwest Laboratory and sponsored by the U.S. Department of Energy Office of Civilian Radioactive Waste Management. The study's objective is to determine the feasibility of predicting mechanical-hydrological behavior of natural rock fractures by accurately characterizing fracture surface topography and mineralization.

A laboratory-scale facility is currently being used to ensure optimum control of variables. Devising a technique to study small-scale samples is the first step to understanding the complex coupled processes encountered in geomechanics and hydrology. The major accomplishments during fiscal year 1987 were:

- initial development of the innovative testing method
- identification of appropriate specimens
- substantial renovation to the facility
- completion of several sets of experiments
- procurement of hardware components for a laser-imaging device used to characterize fracture surfaces.

A complete set of preliminary results and findings is presented in this report. These results, gathered from a basalt core with a natural fracture, have demonstrated that the methodology is valid, and definite trends in the data are readily apparent. In addition:

- Phase I testing, which examined matched joints, produced results suggesting linear mechanical properties at low stresses but strong hysteresis in hydrological behavior.
- Phase II test results suggested that offset joints exhibit a radically different mechanical-hydrological response relative to matched joints, including increased hysteresis in all results and nonlinear stiffness.
- Phase III test results suggested that a transition zone for mechanical properties exists, above which the mechanical properties of joints may become strongly nonlinear.

Follow-on testing during FY 1988 will emphasize the transition to granite rock core samples. Detailed testing is planned to evaluate the mechanical and hydrological response of these naturally fractured granite cores from the Atomic Energy of Canada Ltd. Underground Research Laboratory site. A parallel task will focus on code development and hardware refinement for the advanced laser-imaging device.

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1.0 INTRODUCTION

The Pacific Northwest Laboratory (PNL)^(a) currently performs research for the U.S. Department of Energy (DOE) Office of Civilian Radioactive Waste Management (OCRWM). A significant effort by PNL focuses on developing and evaluating analytical methods used by OCRWM to assess the suitability of sites for geologic disposal of high-level radioactive waste. Research includes consideration of hydrological, geomechanical, geochemical, and thermal processes, as well as coupled interaction with waste package components.

This report, prepared for the Repository Technology Program (RTP), DOE Chicago Operations Office, summarizes the ongoing geomechanics research at PNL involving flow through discontinuous rock. Discontinuities include natural breaks in rock such as fissures, fractures, joints, faults, or cracks. However, the flow paths discussed in this report would most accurately be described as joints or fractures. Although the terms joint and fracture may imply breaks of different areal extent, the terms will be used interchangeably for this laboratory-scale investigation.

The objective of the fracture flow research is to propose a constitutive flow model based on laboratory testing results combined with extensive fracture surface characterization. This model will describe the mechanical (stress) and hydrological (flow) behavior of natural fractures. Validation of the model will be done by predicting the coupled mechanical-hydrological behavior of a fracture and then performing small-scale laboratory tests to determine whether the approach has merit.

Section 2.0 discusses the background of the PNL research effort in fracture flow, fracture flow research performed by other laboratories, and the numerical technique proposed for modeling fracture flow in jointed rock masses. Section 3.0 discusses samples used during the FY 1987 research effort, the prototype and proposed sample characterization methodology, and the sample preparation techniques. The Fracture Flow Laboratory equipment,

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including instrumentation and data handling, is illustrated and described in Section 4.0. The test matrix used to evaluate core samples during FY 1987 is outlined in Section 5.0. It is proposed that this test matrix be used on core tested during FY 1988. Results of the laboratory studies that highlight the various data representation techniques for the coupled mechanical-hydrological processes are provided in Section 6.0. Suggestions for future work are given in Section 7.0. Detailed matrices for the three testing phases are included in Appendixes A through C.

2.0 BACKGROUND

The purpose of the Fracture Flow Behavior in Rock Study (Fracture Flow Study) conducted by PNL is to develop a better understanding of the coupled mechanical-hydrological processes that affect the travel of groundwater through natural fractures in the near- and far-field of a nuclear waste repository. This study complements PNL's Fluid Flow Investigation Program, which studies the coupled chemical-thermal-hydrological properties of crushed rocks. Together, these studies will provide a comprehensive coupled process constitutive relationship that could significantly benefit the nuclear waste repository siting process.

Groundwater travel time is a critical hydrological parameter used to determine the suitability of a nuclear waste repository site. Understanding the flow of groundwater in a repository's geologic formation is of utmost importance because groundwater will be the most likely transport mechanism of radionuclides to the accessible environment. Water travels through rocks primarily in two ways. The easiest flow path for water is along natural breaks or fractures in a rock formation. The second is usually slower and occurs when water moves through connected pores of the intact rock material. A subset of the second travel path occurs when groundwater travels through a permeable infilling material which commonly lines a fracture. The PNL study seeks to develop a method that will estimate the movement of water through natural rock fractures under expected repository conditions.

Figure 2.1, an idealized view of the plane of partial contact between two rock faces, illustrates the concept of flow or channeling along a fracture. The percentage of the rock face's surface area in contact is a function of normal stress across the fracture; hence, as normal stress is increased, void volume between the rock faces (the mechanical response) decreases, and the volumetric flow rate (hydrologic response) is likely to decrease. The excavation of a nuclear waste repository and emplacement of the waste will increase the mechanical and thermomechanical stresses around the repository. Stress levels across natural fractures surrounding the repository could change dramatically. Zones of in situ compressive stress

Low Normal Stress

Channels with
Mobile Water

Moderate Normal Stress

Areas with Stagnant Water
Access by Diffusion Only

High Normal Stress

Fracture Surfaces in
Contact with Each Other

FIGURE 2.1 Variation of Flow Paths Within a Fracture
as a Function of Normal Stress
Source: Rasmuson and Neretnieks (1985,
Vol. 50, pp. 641-653).

could become regions of tensile stress, shear forces could develop, and the magnitude of in situ compressive stress could increase by several hundred percent. For a saturated, discontinuous (fractured) rock mass, these changes will alter the hydrologic behavior of the rock relative to that which existed in situ before repository development.

Although numerical modeling will be used to predict the large-scale, regional flow through complexly fractured host rocks, mathematical relationships describing the coupled mechanical-hydrological-chemical-thermal properties must be developed and validated in smaller-scale laboratory and field experiments before full-scale computer models can produce reliable results. This is the basis for PNL's approach to the coupled process investigation. The approach is to carefully study the mechanical-hydrological response using laboratory experiments and then to use this data

to develop a code capable of evaluating rock formations under various loading scenarios that are expensive and difficult to evaluate experimentally.

Previous laboratory research efforts have investigated the effect of several variables on the hydraulic conductivity of rock joints. These variables include normal stress across the joint, dislocation (shear) of the joint surfaces, scale effects, surface expression or roughness, and rock type. Normal stress-conductivity experiments have been performed using a number of different rock types (Gale 1982; Raven and Gale 1985; Kranz et al. 1979). Other studies have considered the scale effect on fluid flow properties of joints (Raven and Gale 1985) and the effect of fracture roughness (Tsang and Witherspoon 1983). Makurat (1985) investigated the effect of shear displacement on joint conductivity characteristics. In laboratory tests using rock samples containing rough natural joints, Makurat found that 1 to 2 mm of shear displacement was sufficient to cause nearly a two-order-of-magnitude increase in joint conductivity.

Experiments at PNL differ from previous studies in several ways. Although other researchers have studied isolated individual factors that affect the conductivity of rock joints, the PNL facility allows several of the factors to be studied concurrently. The effects of joint normal stress, joint dislocation, temperature, and geochemistry can be evaluated individually or in various combinations (i.e., coupled). Temperature and geochemistry effects are not being studied at this time, but are mentioned to emphasize the comprehensive capabilities of the equipment now being used. The capabilities will be added to the scope of the research efforts according to planned increases in experiment complexity as the data base is developed.

The ability to better define and control the rock conditions in the laboratory during early stages of model development presents certain advantages compared to expensive field studies, where the rock is more difficult to characterize and the control of test conditions is more uncertain. Small-scale core samples were used in the Fracture Flow Study for several reasons:

- Coupled mechanical-hydrological modeling of a jointed rock is a complex task. The small-scale tests contain fewer variables, and these are easier to identify and control. More realistic and necessarily complex large-scale tests will be pursued after the capability to validate simpler small-scale models is demonstrated.
- Existing facilities were available for studying flow through jointed core samples.
- Core samples containing natural joints were already available.

The tests conducted to date by PNL have used basalt core samples containing single natural fractures running subparallel to the long axis of the sample. Core diameter is approximately 6.5 cm and the length of each specimen is 11 cm. Basalt samples were obtained from the Basalt Waste Isolation Project (BWIP) core library and were chosen because of the large number and availability of jointed core.

Future tests will use granite specimens containing natural fractures in the core. These samples will be supplied by the Atomic Energy of Canada Ltd. Underground Research Laboratory (URL) and the NAGRA research facility at Grimsel, Switzerland.

Laboratory tests at PNL are designed to determine 1) the normal stress-conductivity characteristics for undisturbed or interlocked joints, and 2) the normal stress-conductivity behavior for dislocated or sheared joints. Hence, the mechanical-hydrological behavior of both matched and offset joints is being investigated.

Initially, several fracture-flow models will be developed. These models will use information about the structure of the joint surface (characterization) to predict volumetric flow rate for a fracture, given various stress levels and hydraulic gradients. The relationships will be incorporated into the two-dimensional flow subroutine of the Universal Distinct Element Code (UDEC). The UDEC is based on the distinct element method (Cundall 1971, 1974) that represents jointed rock masses as an assemblage of blocks or a discontinuum. The distinct element method directly models individual

fractures, unlike the boundary element or finite element methods, both of which are continuum methods.

After several flow models have been proposed, continued testing will evaluate the validity of these UDEC fracture flow models. A fracture will be characterized, and the mechanical-hydrological behavior of the specimen will be predicted based on the UDEC models. Ensuing laboratory tests of the core specimen will be used to determine the precision with which the various UDEC models can predict the flow of water along the natural fracture, at various normal stress levels and hydraulic gradients.

...the boundary element method, which are continuous methods.

After several flow models have been proposed, continued efforts will evaluate the validity of these models. Future flow models will be characterized, and the mechanical behavior of the specimen will be predicted based on the model. Existing laboratory tests of the core specimen will be used to determine the precision with which the model can predict the flow of water along the natural fracture, and for normal stress levels and hydraulic gradient.

3.0 CORE SAMPLES

Basalt core samples were tested during FY 1987. Under the U.S. DOE-Atomic Energy of Canada Limited (AECL) cooperative agreement, negotiations were conducted in July 1987 to obtain granite core specimens from the AECL's Underground Research Laboratory (URL) near Pinawa, Manitoba, Canada. The selection, characterization, and preparation processes discussed in this section concern basalt core samples but are expected to require only minor modifications to accomodate URL granite. The URL has committed to provide a minimum of six granite specimens to PNL during FY 1988.

3.1 SELECTION

Colonnade and entablature basalt core samples from the Pomona flow near Richland, Washington were used for the FY 1987 tests (DOE 1986). During the selection of samples, intervals were chosen such that two or more specimens could be tested from the same 6-m interval. Samples were collected from a depth of 275 to 335 m below the Hanford site surface.

The samples are fine-grained basalt from the dense interior portion of the flow. They contain natural joints running subparallel to the long axis of the core. Joints in most core samples contain a thin layer of secondary minerals. Montmorillonite clay is thought to be the most abundant of the secondary minerals, with some fractions of zeolite, silica, and pyrite (DOE 1986).

Core samples 6.4 cm in diameter were cut to a final length of 10.8 cm with the ends ground to parallelism suitable for testing. Very few samples longer than 10.8 cm are available with a single natural fracture running subparallel to the long axis of the core; therefore, this length was chosen to maximize both the number of available samples and the length of the flow path.

The triaxial flow facility is not capable of testing samples greater than 12 cm in length or 8 cm in diameter. This is due to the physical size of the pressure vessel, required space for instrumentation, and the need to have a long platen for proper sealing.

For standard triaxial compression strength testing, a length-to-diameter ratio of 2:1 is recommended to minimize the end effects of platens on the failure plane of the intact rock core specimen. Because the fracture flow tests are not intended to evaluate the uniaxial or triaxial compressive strength of intact rock, it was not necessary to maintain the 2:1 ratio. Thus, the length-to-diameter ratio was determined instead by the factors outlined in the previous paragraphs.

3.2 CHARACTERIZATION

The objective of characterization is to identify and quantify all physical properties of the core and its fracture surfaces. Only when this process is completed can a statement be made regarding the variation in mechanical-hydrological behavior observed among two or more fractured cores. Sample characteristics of interest include joint wall roughness profiles, joint shear strength, joint stiffness, infilling material thickness, and the connectivity of voids within the fracture plane.

Properties indirectly related to fracture surface topography have been used to back-calculate an empirical descriptor of fracture surfaces. For example, the aperture of a joint can be back-calculated using the cubic flow law and the measured flow rate. However, the cubic flow rule has been shown by Tsang (1984) to not hold for joints to which high normal stresses are applied and for joints that have partial contact of opposing sides.

Several methods are currently available for directly characterizing the surface topography of rough surfaces such as rock fractures. One method used at the University of Pennsylvania Skin Research Institute is based on a technique that casts light at an angle to a rough surface and then optically surveys the extent and frequency of the shadows. The resulting statistical evaluation of the surface roughness can be expressed as a relative number and can be used to compare other rough surfaces and to determine similarities and differences. A second method currently being investigated by researchers at Lawrence Berkeley Laboratory involves injecting molten material, like Wood's metal, along fractures and then allowing it to solidify and form a mold of

the fracture contact surface. A third surface-topography recording device consists of a laser beam cast directly on a rough surface while the image of the beam is then digitized by a camera. The digitized image is used purely for creating a three-dimensional image of the fracture surface.

The inability to precisely compare several different fracture surfaces is acknowledged as a major problem by the staff conducting the Fracture Flow Study and by other geomechanics researchers studying fracture flow (Raven and Gale 1985). Rarely do two cores of similar appearance behave in a similar manner. Evaluating pre-test fracture surface conditions and the changes to the fracture surface resulting from stressing the joint is nearly impossible on a qualitative scale. The PNL Fracture Flow Study staff decided that the laser imaging device possessed great potential for supplying the accuracy necessary to evaluate fracture conductivity behavior.

As part of the geomechanics research conducted under the Performance Assessment Scientific Support (PASS) Program, PNL developed a prototype laser optic device to measure the actual surface topography of a joint plane. The prototype's success led to the conclusion that the laser approach had strong potential. The costs of further refining the prototype to achieve commercially available levels of accuracy and sophistication outweighed the benefits. Consequently, PNL procured a laser imaging system during FY 1987.

The laser imaging device comprises five major components:

- laser light source
- oscillating scanning mirror
- sample transport table
- video camera with a position-sensitive detector
- microcomputer data acquisition and controller system.

The relationships of the various components are illustrated in Figure 3.1.

The laser beam is focused on the oscillating mirror, which reflects the beam to the sample where it passes over the sample surface at some variable scanning rate. At high oscillating rates, the laser appears to form a

FIGURE 3.1. Fracture Surface Characterization Device

continuous scan line across the sample, as shown in Figure 3.2. The video camera is mounted at an angle normal to the beam scan direction and "sees" the topography of the joint surface. A cylindrical lens is used to focus the laser line onto the position-sensitive detector. The analog output of the detector, beam spot position, and stepper motors is stored on magnetic media on the microcomputer and provides the necessary data to reproduce the entire three-dimensional surface profile. The microcomputer is also used to move the sample under the scanning beam by controlling a series of stepper motors attached to the sample bed.

When the relative position of the sample is known, the digitized information can be used to generate statistical distributions of the joint

FIGURE 3.2. Fracture Plane and Laser Scanning Beam

surface characteristics, such as asperity height and spacing. The distribution of aperture and the apparent flow paths could also be estimated by scanning the surfaces of opposite sides of the joint surface and then overlaying the fracture surfaces in three dimensions. These processes could be fully automated, and field applications are feasible.

A turnkey laser system, estimated to cost approximately \$100K, includes the manpower costs for assembling the various components, equipment, and software. The basic components of the laser system were ordered during FY 1987 at a cost of approximately \$60K and are expected to be delivered to PNL near the first week of FY 1988. A limitation of the system will be a 30-cm by 30-cm sample size with a sensitivity of approximately 5μ (0.0005 cm). The sample size is limited by sophistication of the sample transport system.

A two-dimensional system with a higher translation and weight capacity could accommodate much larger sample sizes. However, the sensitivity depends on the width of the camera's field of view. Therefore, larger specimens would require more scan paths. Maximum resolution is achieved with a 1-cm field of view. The 6.4-cm by 10.8-cm specimens used in the Fracture Flow Study will require approximately 60 Mbytes of memory for both halves of the fracture plane to be recorded.

It is anticipated that, by January 1988, the laser system will be functional and the programming effort will begin. The resulting codes will facilitate reducing, to a comprehensible result, the large data bases containing surface coordinates of fracture planes to a comprehensible result. This will likely be a combination of statistical evaluations of the surface roughness and the fit of the two fracture surfaces. Evaluation of void volume and channeling paths will also be attempted.

3.3 PREPARATION

The sample must be prepared with parallel ends, and each half of the fractured specimen must be of precisely equal length. The fracture plane must be in its natural "matched" position when the top and bottom of each half are aligned. Figure 3.3 shows the fractured core specimen after the ends have been finished and the "stack" has been assembled. During the following discussion of sample preparation and assembly, refer to Figure 3.3.

Stainless-steel platens are positioned at the top and bottom of the specimen. The platens are designed to serve two functions: 1) the platens must transfer all axial load uniformly to the specimen, and 2) they must permit water to be pumped from outside the triaxial chamber, to be induced to flow along the fracture path, and to exit freely from the triaxial chamber. Channels are machined into the contact surface of the platen to encourage uniform fluid pressure on the ends of the core. The diameter of the platen is matched to the specimen, and the axial length of the platen has been experimentally determined to ensure proper sealing of the assembly. If the

FIGURE 3.3. Sample Assembly for Testing

seal between the water flowing along the fracture and the confining oil is lost, oil will enter the fracture plane, contact surface, and permeability loop.

After the platens are positioned on opposing ends of the specimen, the perimeter of the contact surface is coated with a high-strength, high-pressure, room-temperature-vulcanizing silicone rubber (RTV). The RTV has been proven successful in sealing the small contact gap. A positive seal must also be constructed where the fracture plane intersects the perimeter of the specimen. Sealing all gaps is necessary to prevent confining oil from entering the permeability loop and also to prevent permeability fluid from exiting the fracture and traveling between the outside of the core and the inside of the protective membrane.

If confining pressures are to exceed 68 MPa (10,000 psi), it has been experimentally determined that brass shim stock must be placed over the fracture before RTV is applied, to prevent the penetration of the fracture by confining fluid. Historically, the fracture plane has proven more difficult

to seal than the contact gap between the specimen and the platens because the fracture plane near the perimeter of the core has often suffered slight damage during coring. This slight damage can create relatively large spans (1 to 2 mm) that must be sealed.

Shrink tubing is used to completely cover the sample and platen assembly to prevent oil from entering the basalt sample pores. The shrink tubing also complements the sealing performed by the RTV and ensures a competent seal against confining fluid contamination of the permeability loop.

The completed sample assembly is then placed in the triaxial chamber of the Fracture Flow Laboratory, and the chamber is flooded with confining oil. Stress is exerted on the specimen through combinations of confining pressure and axial load. The permeability fluid (demineralized water) is injected at the top of the specimen and removed after flowing from the bottom of the fracture. The inset in Figure 3.3 displays the loading conditions on the core specimen.

4.0 FRACTURE FLOW LABORATORY EQUIPMENT

The Fracture Flow Laboratory equipment is an assemblage of components supplied from different manufacturers. Most of the system was designed and built by Terra Tek, Inc. in the late 1970s to support PNL in the geomechanics testing needs of the Compressed Air Energy Storage (CAES) Program.

Because the Fracture Flow Study evaluates loading scenarios dissimilar to those examined in the CAES Program, several modifications were completed on the facility during FY 1987 to enable it to accurately apply and measure stresses and hydraulic gradients expected in a nuclear waste repository environment. Also, because the state of the art in instrumentation and data acquisition has improved dramatically in the last decade, changes were made in these areas to upgrade the facility.

Information provided in this section describes the testing equipment used in the Fracture Flow Study. Section 4.1 is an overview of the entire facility, while Sections 4.2 and 4.3 focus on the more critical components of the laboratory, including instrumentation and data acquisition.

4.1 FACILITY

The Fracture Flow Laboratory is a triaxial loading apparatus with additional capabilities of simultaneous thermal loading and hydraulic gradient applications. Facility hydraulics are complemented with electronic controllers, signal conditioners, and servo mechanisms. Instrumentation is entirely electronic, and is monitored and recorded by an intelligent data acquisition system. All data stored on the data acquisition system is reduced further and processed on a personal computer. Figure 4.1 diagrams the basic components of the Fracture Flow Laboratory.

By applying a wide range of structural, thermal, and fluid loads to rock core specimens, the thermal, mechanical, and hydrological responses to many possible loading scenarios may be established. Coupled loading can be used to simultaneously evaluate the changes in stress, strain, or fluid flow that

FIGURE 4.1. Components of the Fracture Flow Laboratory

result from a combination (coupling) of two or more of these loading conditions. This capability allows an assessment of the correlation between stress and volumetric flow or temperature and volumetric flow, for example. The test facility permits axial loads of up to 45,500 kg, confining pressures up to 100 MPa, hydraulic gradient differential pressures up to 100 MPa, and temperatures up to 260°C. The maximum specimen diameter is approximately 8 cm, and the maximum specimen length is approximately 12 cm.

The Fracture Flow Laboratory permeability loop is used to apply a hydraulic gradient or differential pressure accross the sample ends. It is composed entirely of stainless steel, which prevents reaction with the demineralized water initially used in fracture flow tests. Stainless-steel lines also permit geochemical analysis of fractures via analytical tests of the fluid collected at the downstream end of the permeability loop. Titanium

lines may need to be added, depending on the type of fluid and temperature chosen in future geochemistry applications. In addition, temperatures significantly above room temperature may necessitate the use of different sealing materials to prevent chemical breakdown and contamination of the permeability fluid.

4.2 INSTRUMENTATION

The Fracture Flow Laboratory is equipped with electronic instrumentation for instantaneous and precise monitoring of all stress conditions, displacements, and flow rates. Precision instruments calibrated by Hanford Engineering Development Laboratory (HEDL) standards are used to calibrate laboratory transducers.

Differential pressure in the permeability loop is measured to within ± 0.009 MPa above and below the specimen. This provides precise pressure drop information that is completely independent of any head losses that may occur in the flow loop. In addition to upstream and downstream pressure transducers, a differential pressure transducer designed to monitor the head loss across the sample, not the absolute magnitude of either the upstream or downstream pressure, confirms the pressure drop across the sample to within ± 0.009 MPa. A unique valving configuration in the Fracture Flow Laboratory permits reversal of the flow direction, thereby enabling assessment of the directional dependence of a gradient and detection of the possibility of infilling material plugging the flow paths.

The volumetric flow rate of water along the fracture path varies widely from specimen to specimen. Because the range of the volumetric flow rate may not always be determined in the initial stages of experimentation, several methods for measuring volumetric flow per unit of time were built into the system, ensuring that one or more instruments will obtain flow measurements in any possible range. The primary device used to measure flow is an analog-output scale capable of accuracy to ± 0.001 g. The scale continuously monitors the permeability fluid as it collects at the exit point. The change in the scale reading is assessed for a known time range, permitting

calculation of volumetric flow rate. The second method for measuring flow monitors the displacement of the cylinder supplying the permeability fluid. Permeability fluid is pumped into the permeability loop using an oil/water fluid intensifier. Because the volume of the water-filled cylinder is known, a linear variable-differential transformer (LVDT) was used to monitor the position of the cylinder. Total displacement of the cylinder over time is used to compute total volumetric flow rate. The third flow measuring device is an in-line, paddle-wheel flow meter.

An oil bath exerts confining pressure on the specimen. The triaxial cell is completely flooded with synthetic oil, and the oil is pressurized to create the desired stress state simulation and exert a normal force across the fracture plane. The confining pressure is monitored by using a manifold and several pressure transducers that permit the appropriate transducer to be selected for optimal precision ($\pm 0.5\%$ of full scale) in each confining pressure range. Flow tests often prescribe confining pressures ranging from 1.8 MPa to 80 MPa, which demands that more than one transducer be used to ensure that accurate pressure readings are recorded for all data points.

Temperature effects are not currently being addressed in the Fracture Flow Study, although the facility is designed and equipped to heat the specimen up to 260°C. The oil bath medium is heated via an immersion heater mounted at the bottom of the triaxial cell. Temperature is monitored ($\pm 2.5^\circ\text{C}$) at the top of the cell near the upper plug seals, primarily to ensure seal integrity. Two thermocouples are routed through the bottom of the triaxial cell and monitor the fluid temperature inside the vessel. One thermocouple is dedicated to monitor the heater temperature and provide feedback to the servo controller.

The axial load applied to the specimen is monitored with a custom-made load cell. The load cell is a 10.2-cm-long hollow cylinder with outside and inside diameters of 5.1 cm and 4.6 cm, respectively. Four square holes are cut from the cylindrical surface of the cylinder midway between the flat ends of the cylinder. These four holes serve to form four pillars to maximize the strain in a localized area. Strain gages are attached to the pillars and

used to monitor the deformation of the load cell. A wall thickness of 0.25 cm ensures structural integrity within the axial load ranges applied in the laboratory and also permits sufficient elastic deformation, to allow precise axial load measurements in the lower ranges of load application. Axial load is commonly held at approximately 90 kg above hydrostatic force, primarily to rigidly fix the sample position.

The axial deformation of the specimen may result from hydrostatic confining pressure, direct axial load, shear displacement of the fracture plane if the specimen were intentionally offset initially, or a combination of any of these. Axial deformation is measured by two LVDTs attached to the platens. The LVDTs are positioned 180° apart such that a line connecting them is approximately normal to the fracture plane. An LVDT is also mounted to the load ram used to exert axial forces on the specimen. The load ram LVDT is used as a backup to the axial LVDTs attached adjacent to the specimen.

The change in the fracture aperture and specimen diameter is monitored by two clamps, each equipped with four strain gages wired in a Wheatstone bridge configuration. The Wheatstone bridge eliminates any effect from the strain resulting from hydrostatic loading of the gage while it is submerged in the oil medium and maximizes the voltage drop induced by small strains. The clamping device was designed with rigid arms and a very flexible center portion, to concentrate the strain in a limited area and also to comply with physical space requirements imposed by the dimensions of the triaxial cell.

4.3 DATA ACQUISITION, DATA PROCESSING, AND STORAGE

The analog signals from each of the transducers are directed to a central data acquisition system. The system, manufactured by Daytronics, digitizes each incoming channel, converts the digital representation of the signal to engineering units, and stores information from the experiment in a data base. The data acquisition system is also capable of acting as a controller.

The data bases are processed using an IBM PC/XT-compatible machine. The raw data is subjected to a series of computations in a spreadsheet supported by graphics software. Magnetic tape and hardcopy of the resulting processed information is created and stored in a data base and processed in graphic form for engineering and statistical evaluation.

5.0 TEST MATRIX

The test matrix described in this section was developed during the FY 1987 experimentation. Naturally-fractured basalt specimens were used to develop the test matrix; however, granite core samples, which are planned to be tested next year (FY 1988), are expected to behave in a manner similar to basalt samples. Hence, the test matrix described in this section was developed and used on basalt samples and will also be used to evaluate granite samples from the Atomic Energy of Canada Ltd. URL.

The test matrix used in the Fracture Flow Study is intended to optimize data supporting the project objective, i.e., to evaluate the coupled mechanical-hydrological behavior of rock mass fractures. Stress, strain, and flow data are gathered during testing and then used as input into equations to produce 1) joint closure - joint normal stress relationships, 2) conductivity - joint normal stress relationships, 3) conductivity - joint closure relationships, and 4) joint normal stiffness versus stress relationships.

The incremental changes of the confining pressure, the number and duration of differential pressure (hydraulic gradient) applications, and the number of cycles applied to each basalt specimen were determined experimentally. For example, initial shakedown tests provided graphic results that were used to assess the number of data points necessary to closely approximate the normal stiffness curve. This information indicated that confining pressure increments of approximately 1.7 MPa would provide enough data to adequately define the stiffness relationships, and this incremental pressure increase would also minimize the time necessary to complete an individual test. Tests were performed twice on each specimen because it was discovered that the behavior of the joint is often highly path-dependent. There were no recorded instances of a second load cycle providing exactly the same results as an initial load cycle.

When developing and evaluating a test matrix for geologic specimens, several general guidelines of variability must be considered. First,

specimens from different formations, even if the rock type is similar, cannot be expected to behave identically. Spatial variability within a formation will often result in significant mechanical-hydrological property variation observed in two or more samples from the same formation. Also, a specimen may produce different results on consecutive tests. For these reasons, it is difficult to assess the causes of variability that can be observed from specimen to specimen, and hysteresis is often observed in repeated tests on the same specimen. The order in which tests are performed on each specimen may also bias results because each additional test may continue to change the fracture surface. Investigation into each of these problems is ongoing and may continue to refine the test matrix.

A test procedure and equipment to investigate the shear stiffness of joints are considered necessary additions to the current matrix, but have been delayed because of difficulties encountered with maintaining the hydraulic seal around the specimen as the fracture is displaced. High confining pressure in the triaxial cell can rupture the seal membrane if any gaps develop in the contact between opposing halves of the fractured specimen. The current strategy for simulating a sheared fracture is to assemble the fracture in the stack in an offset position using 0.1-cm shim stock. Shear loads and normal loads are therefore not applied during shear displacement of the fracture plane.

5.1 PHASE I: FLOW TEST ON MATCHED FRACTURE WITH MODERATE NORMAL STRESS APPLIED TO FRACTURE

In the first phase of the test plan, the specimen is subjected to confining pressure in eight equal increments of 1.75 MPa until a maximum confining pressure of 14 MPa is reached. Confining pressure is then decreased in eight equal increments to complete one cycle. A maximum confining pressure of 14 MPa was selected to minimize the damage to asperities during each loading cycle. Several combinations of upstream and downstream fluid pressures (creating various differential pressure) are applied to the specimen for each increment of confining pressure. Downstream pressure is applied to enable observation of the variation of effective

normal stress on the fracture and the effect of this variation on fracture flow. Effective normal stress is the difference between confining pressure (which tends to close the fracture) and the average differential fluid pressure (which tends to force the fracture open). Table 5.1, an abbreviated example of the test plan, illustrates steps 1 and 2 of the 16-step Phase I test. Appendix A contains the complete test matrix for Phase I testing. When referring to Appendix A, note that this matrix is repeated to determine the significance of hysteresis effects.

TABLE 5.1. Abbreviated Example of the Phase I Test Matrix

Confining Pressure, MPa	Upstream Hydraulic Pressure, MPa	Downstream Hydraulic Pressure, MPa
1.75	0.2	0
	0.4	0
	0.6	0
	0.8	0
	1.0	0
	0.5	0.3
	0.8	0.3
	1.0	0.3
	1.2	0.3
	1.4	0.3
3.5	0.2	0
	0.4	0
	0.6	0
	0.8	0
	1.0	0
	0.5	0.3
	0.8	0.3
	1.0	0.3
	1.2	0.3
	1.4	0.3

By following the same loading path back down from a maximum confining pressure of 14 MPa, path dependency of the experimental results can be evaluated. Upstream and downstream hydraulic pressures are varied to produce net differential pressure (downstream hydraulic pressure subtracted from upstream hydraulic pressure) across the sample. Differential pressures (10 increments varying from 0.2 to 1.0 MPa) are used at each of the confining pressure levels. The same set of hydraulic pressures (10 combinations) is applied to the water-conducting fracture plane regardless of the confining pressure.

5.2 PHASE II: FLOW TEST ON OFFSET FRACTURE WITH MODERATE NORMAL STRESS APPLIED TO FRACTURE

The second phase of the test plan begins by offsetting the fracture plane approximately 0.1 cm (0.038 in.). This is accomplished by placing 0.1 cm of shim stock between one-half of the fractured specimen and the top platen. Another piece of shim stock is placed between the opposing half of the specimen and the bottom platen.

The confining pressures and permeability pressures are applied to the offset sample in a manner similar to Phase I (see Section 5.1), thereby enabling a direct comparison of the behavior of matched joint surfaces to that of offset joint surfaces. Appendix B contains the complete test matrix for Phase II testing; this matrix is repeated to evaluate the significance of hysteresis.

5.3 PHASE III: NORMAL STIFFNESS TEST ON MATCHED FRACTURE WITH HIGH NORMAL STRESS APPLIED TO FRACTURE

The third phase of the test plan does not subject the fracture to hydraulic gradients, but applies very high normal stresses to it. The relationship of the joint's normal stiffness to various applied normal stresses can then be studied for the widest possible ranges of stress expected near a nuclear waste repository. Previous observations of zero flow, when normal stresses applied to fractures reached high levels, prompted the decision to drop the hydrologic parameter from this phase of testing.

This behavior is thought to result largely from the clay layer in the basalt sample tested. Therefore, in future studies using granite samples containing relatively clean fractures, hydraulic gradients may be added to this phase.

The confining pressure is increased from an initial point of 3.5 MPa in increments of 3.5 MPa until a maximum pressure of approximately 83 MPa is reached. Pressure is then decreased in increments of 3.5 MPa until the confining pressure reaches 3.5 MPa. See Appendix C for a complete listing of the pressure applications used in Phase III tests. The Phase III test matrix is performed a second time to assess cyclic loading effects and experiment repeatability.

6.0 PRELIMINARY RESULTS

This section provides the format for representing data from the Fracture Flow Study. This data, collected from basalt core, is presented in a manner that is planned to be used to display data collected in FY 1988 and beyond on crystalline rock samples. Graphs display primary relationships gathered during laboratory testing, and the essential terms and parameters are discussed.

All data in this section is considered preliminary. A DOE Quality Assurance Plan was not approved by the sponsor for this project during FY 1987. Therefore, the absolute value of data presented in this report must not be used in any license-related decision. Instead, this information should be studied, to evaluate trends that resulted from laboratory tests, to assess the general manner in which data is reduced and presented, and to evaluate the capabilities of the Fracture Flow Laboratory. The data must not and cannot be used to determine the suitability of basalt for long-term storage of nuclear waste. A DOE Quality Assurance Plan has been submitted for DOE approval and will be used for work conducted during FY 1988.

The preliminary results presented here are for a series of tests performed on a 6.4-cm-diameter basalt core specimen, identified as 5L08B. It is approximately 10.8 cm long and contains a single natural fracture oriented subparallel to the long axis of the core. The fracture plane is lined by 0.5-mm-thick silica and clay infilling material.

The relationships expressed in this section deal with four parameters: flow per unit head, joint closure, effective normal stress, and joint normal stiffness. Permeability is not discussed because the basic premise of this work is that Darcy's Law may not apply to flow through fractures having very small apertures. Instead, an empirical relationship is being pursued that will be based on the fracture surface characterization and the observed mechanical-hydrological behavior.

Flow per unit head is derived from the volumetric flow rate and the differential pressure across the specimen. Equation (1) gives the formula for computing flow per unit head. Flow rate is expressed in cubic centimeters of water per minute, and the pressure drop across the specimen is expressed in centimeters of water head. Thus, the units for flow per unit head are $(\text{cm}^3/\text{min})/\text{cm}$ or cm^2/min .

$$\text{Flow per unit head} = Q/H \quad (1)$$

where Q = fluid flow rate

H = head loss along fracture path (differential pressure).

Joint closure is expressed as the absolute value of the change in joint aperture from an initial stress state of about 1.8 MPa. For example, if joint closure is stated to be 0.0009 cm, then the joint aperture has closed 0.0009 cm from the initial aperture measured at a confining pressure of 1.8 MPa. This relationship is shown by

$$\text{Joint closure} = \text{abs}[\Delta_{Ai} - \Delta_{Af}] \quad (2)$$

where abs = absolute value function

Δ_{Ai} = initial aperture

Δ_{Af} = final aperture.

A zero stress position is usually defined as 1.8 MPa to ensure that the fracture is not partially open because of assembly of the core in the test stack. The low initial confining pressure causes the fracture surfaces to be in contact for the initial aperture reading. If the initial aperture width were taken at a confining pressure of 0 MPa, the comparison between specimens would be very difficult because there would be no certainty of fracture plane contact.

Effective normal stress is expressed in Equation (3) as the difference between confining pressure (acting to compress the fracture plane) and hydraulic pressure (acting to separate the fracture plane).

$$\text{Effective normal stress} = (P_c) - [((P_{p1}) + (P_{p2}))/2] \quad (3)$$

where P_c = confining pressure
 P_{p1} = upstream hydraulic pressure
 P_{p2} = downstream hydraulic pressure.

Because the hydraulic pressure drop across the sample produces an upstream and a downstream pressure, the upstream and downstream pressures are added and divided by two, thereby producing an average pressure acting within the fracture plane. This average pressure is subtracted from the confining pressure to yield the effective normal stress that is acting to close the fracture. As is common practice in geomechanics, compressive stress is taken as positive; therefore, effective normal stress is positive on all graphs in this section.

Joint normal stiffness is the effective normal stress divided by the joint aperture closure. Joint normal stiffness is somewhat analogous to the "modulus of elasticity" of the joint, although joint normal stiffness was not always found to be a constant in any reasonable range and the joints tested did not always behave elastically. Therefore, the joint stiffness is better expressed as a function of normal stress, as shown in Equation (4). Commonly, joint stiffness may be plotted against stress to observe the change in stiffness as stress is varied.

$$\text{Joint normal stiffness} = \sigma_{\text{eff}} / [\text{abs}(\Delta_{Af} - \Delta_{Ai})] \quad (4)$$

where σ_{eff} = effective normal stress
 Δ_{Af} = final aperture
 Δ_{Ai} = initial aperture
abs = absolute value function.

Figures 6.1, 6.2, and 6.3 illustrate experimentally-derived normal stiffness results for a natural joint in basalt. Figure 6.1 was derived from Phase I testing, which specifies a maximum effective normal stress of 14 MPa exerted on a carefully matched fracture (the fracture was tested in its

FIGURE 6.1. Matched Joint: Stress Versus Closure

FIGURE 6.2. Offset Joint: Stress Versus Closure

FIGURE 6.3. Matched Joint: High Pressure Normal Stiffness Test

"natural" position). As seen in Figure 6.1, a good linear relationship is observed, with little path dependency and no permanent deformation.

To enable direct comparison between the physical behavior of a matched joint and an unmatched joint, Figure 6.2 was placed directly below Figure 6.1. Figure 6.2 is the normal stiffness relationship for a fracture surface offset approximately 1 mm from the natural matched position (Phase II testing). Note on Figure 6.2 that offset joints behave very differently from matched joints. The offset joint produces a slope about one-third as steep as the matched joint for the initial stiffness curve. (Note that Figures 6.1 and 6.2 use the same scales on each axis for ease of comparison.) The offset joint in Figure 6.2 also shows substantial permanent deformation on the first load/unload cycle. On the second loading cycle, permanent deformation is still evident in the offset joint, although it is nearly 50% less than the permanent deformation that resulted from the first loading cycle.

Figure 6.3 shows the experimental results of a matched joint normal stiffness test. The difference between Figure 6.3 and Figures 6.1 and 6.2 is the maximum confining pressure reached in the test. Figure 6.3 displays

results from Phase III testing. Phase III requires confining pressures that are six times greater than those on which Figures 6.1 and 6.2 are based. Although results in Figure 6.3 are from a matched joint surface, permanent deformation becomes apparent. Plastic deformation is observed in each of two recorded cycles. The second loading cycle produces half as much plastic deformation as the first. This raises the issue of how many loading cycles may be applied to a joint before plastic deformation is no longer detected. Note that the second loading cycle produces a higher slope, indicating that the fracture becomes stiffer on the second loading cycle. The stress-dependent fracture contact area and asperity damage are thought to account for most of the nonlinearity in Figure 6.3.

Figures 6.4 and 6.5 present the flow-versus-closure results for a matched joint and an offset joint, respectively. Figure 6.4 results from Phase I testing, and Figure 6.5 results from Phase II testing. The same scale is used for each plot to enable direct comparison of the flow versus closure characteristics of matched and offset joints. Figures 6.4 and 6.5 are the results of the same maximum confining pressure stress state of 14 MPa and the same permeability pressures. Because consistency in flow rates cannot be achieved for a completely relaxed joint, the initial stress state shown is 1.75 MPa. The initial flow rates are measured upward from this point, and the joint position is assigned zero at the stress state of 1.75 MPa for computing total joint closure at higher normal stresses. Total joint closure in Figure 6.4 is nearly one-fourth of the total joint closure in Figure 6.5. Closure is thought to be less for the matched joint because the matched joint will not exhibit asperity damage to the extent of that in the unmatched joint. The matched joint is also likely to have a greater percentage of surface area initially in contact than does the offset joint.

A substantial amount of path dependency is observed in Figures 6.4 and 6.5. Each case initially provides much higher flow, while the flow rate does not recover after the loading cycle is complete and the joint is relaxed. This is thought to be due to asperity damage. The offset joint in Figure 6.5 displays much higher flow initially than the matched joint. However, the

FIGURE 6.4. Matched Joint: Flow Versus Closure

FIGURE 6.5. Offset Joint: Flow Versus Closure

offset joint produces much lower flow as the total closure surpasses the matched joint closure. Also, the flow rate for the offset joint does not recover as the confining pressure is relaxed. Joint closure does not recover in the offset joint, but it does in the matched joint. The second load/unload cycle duplicates the first unload cycle in Figure 6.5, implying that the path dependency for the offset joint may diminish greatly after the first loading cycle. A second load/unload cycle is not available for the matched joint because of a transducer failure. Because conductivity of the offset joint becomes much less than the matched joint as loading conditions are increased on the first loading cycle, it is thought that asperity damage in the offset joint is much greater than that in the matched joint and that this high degree of asperity damage results in significant flow path restriction and plugging in the offset joint.

Figures 6.6 and 6.7 portray the flow versus stress results for a matched and unmatched joint, respectively. Identical scales are presented for the vertical and horizontal axes on each graph. Phase I testing results are represented in Figure 6.6; Phase II results are shown in Figure 6.7. Figure 6.7 shows the offset joint to permit a volumetric flow rate nearly twice as high as the matched joint for the initial effective normal stress of 1 MPa. After each joint is stressed to 3 MPa on the initial loading path, the offset joint begins to show lower flows and never recovers to initial levels. The offset joint exhibits lower conductivities than the matched joint for all remaining loading cycles. Lower conductivity characteristics of the offset joint are thought to be due to more severe asperity damage resulting in flow path restrictions.

The apparent nonlinearity of joint normal stiffness is displayed in Figures 6.8 (from Phase I) and 6.9 (from Phase II). These graphs are thought to be nonlinear because of the stress dependency of the contact area of fractures. Asperity damage and asperity contact area changes induced by Poisson's effects may also play an important role. The surface scanning device discussed in Section 3.0 may eventually isolate the cause of the nonlinear joint stiffness behavior.

FIGURE 6.6. Matched Joint: Flow Versus Stress

FIGURE 6.7. Offset Joint: Flow Versus Stress

FIGURE 6.8. Matched Joint: Stiffness Versus Stress

FIGURE 6.9. Offset Joint: Stiffness Versus Stress

7.0 FUTURE WORK

The results from research performed during FY 1987 are encouraging. Definite trends have been observed in the relationships between crucial parameters, and it has been demonstrated that the laboratory facility is capable of extracting accurate mechanical-hydrological data from fractured basalt core specimens. No complications are anticipated for the transition to granite core samples.

The laser-based scanning system described in Section 3.2 will arrive near the beginning of FY 1988. Surface topography analysis will require extensive software development to process and manipulate the large data bases of coordinates that will result from high-resolution scans of the core specimens. Software development and hardware refinement for the prototype system are complex tasks that will probably require a large effort in FY 1988. A continued effort over several years will be necessary to refine the system into a sophisticated characterization tool.

Upgrades to the Fracture Flow Laboratory equipment will continue during FY 1988. This will enable more accurate data acquisition in the gradient and stress ranges anticipated in repository host rock. Major remodeling has been completed during FY 1987. However, upgrading the facility is a continual requirement to keep all equipment state-of-the-art.

A top priority will be to complete a substantially higher quantity of tests. Further results are needed to assess the variability among samples from the same geologic formation and of similar characterization. Also, the variability induced by the order in which tests are performed on a given specimen must be determined. Finally, the differences in all aspects between clean joints and those possessing infilling material must be measured.

Most of the testing during FY 1988 will be concentrated on granitic samples from the Atomic Energy of Canada Ltd. Underground Research Laboratory. A large water-bearing fracture intersects the URL in room 209 (at the 200-m level), and the hydraulic behavior of this fracture is being

extensively studied in a number of field experiments. The PNL Fracture Flow Study will evaluate core from this granite fracture and determine the ability of the Fracture Flow Laboratory facility to predict the known behavior of a field-scale fracture. Results of the PNL study will then be used to assess the suitability of a laboratory method for characterizing in situ conditions.

After additional tests are performed, the data base should be available to generate a flow law for computer code application. The ultimate goal of the Fracture Flow Study is to develop the capability to model complex flow patterns in fractured rock masses. The computer code will be used to model excavation- and thermally-induced changes in stress and displacement occurring across and along fractures while also computing the resulting change in joint flow and aperture.

Development of a flow law based on a substantial data base and supported with surface characterization data and infilling material classification must be validated. The code will be verified to ensure that it is mathematically correct, but validation must be used to ensure that it is capable of predicting reality. Small-scale laboratory experiments will be conducted on samples containing two or more fractures, and the results will be compared to those obtained from the computer code UDEC.

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APPENDIX A

PHASE I TESTING MATRIX

Confining Pressure, MPa	Upstream Hydraulic Pressure, MPa	Downstream Hydraulic Pressure, MPa
1.8	0.2	0
	0.4	0
	0.6	0
	0.8	0
	1.0	0
	0.5	0.3
	0.8	0.3
	1.0	0.3
	1.2	0.3
	1.4	0.3
3.5	0.2	0
	0.4	0
	0.6	0
	0.8	0
	1.0	0
	0.5	0.3
	0.8	0.3
	1.0	0.3
	1.2	0.3
	1.4	0.3
5.2	0.2	0
	0.4	0
	0.6	0
	0.8	0
	1.0	0
	0.5	0.3
	0.8	0.3
	1.0	0.3
	1.2	0.3
	1.4	0.3
6.9	0.2	0
	0.4	0
	0.6	0
	0.8	0
	1.0	0
	0.5	0.3
	0.8	0.3
	1.0	0.3
	1.2	0.3
	1.4	0.3

Confining Pressure, MPa	Upstream Hydraulic Pressure, MPa	Downstream Hydraulic Pressure, MPa
8.6	0.2	0
	0.4	0
	0.6	0
	0.8	0
	1.0	0
	0.5	0.3
	0.8	0.3
	1.0	0.3
	1.2	0.3
	1.4	0.3
10.3	0.2	0
	0.4	0
	0.6	0
	0.8	0
	1.0	0
	0.5	0.3
	0.8	0.3
	1.0	0.3
	1.2	0.3
	1.4	0.3
12.0	0.2	0
	0.4	0
	0.6	0
	0.8	0
	1.0	0
	0.5	0.3
	0.8	0.3
	1.0	0.3
	1.2	0.3
	1.4	0.3
13.8	0.2	0
	0.4	0
	0.6	0
	0.8	0
	1.0	0
	0.5	0.3
	0.8	0.3
	1.0	0.3
	1.2	0.3
	1.4	0.3

Confining Pressure, MPa	Upstream Hydraulic Pressure, MPa	Downstream Hydraulic Pressure, MPa
13.8	0.2	0
	0.4	0
	0.6	0
	0.8	0
	1.0	0
	0.5	0.3
	0.8	0.3
	1.0	0.3
	1.2	0.3
	1.4	0.3
12.0	0.2	0
	0.4	0
	0.6	0
	0.8	0
	1.0	0
	0.5	0.3
	0.8	0.3
	1.0	0.3
	1.2	0.3
	1.4	0.3
10.3	0.2	0
	0.4	0
	0.6	0
	0.8	0
	1.0	0
	0.5	0.3
	0.8	0.3
	1.0	0.3
	1.2	0.3
	1.4	0.3
8.6	0.2	0
	0.4	0
	0.6	0
	0.8	0
	1.0	0
	0.5	0.3
	0.8	0.3
	1.0	0.3
	1.2	0.3
	1.4	0.3

Confining Pressure, MPa	Upstream Hydraulic Pressure, MPa	Downstream Hydraulic Pressure, MPa
6.9	0.2	0
	0.4	0
	0.6	0
	0.8	0
	1.0	0
	0.5	0.3
	0.8	0.3
	1.0	0.3
	1.2	0.3
	1.4	0.3
5.2	0.2	0
	0.4	0
	0.6	0
	0.8	0
	1.0	0
	0.5	0.3
	0.8	0.3
	1.0	0.3
	1.2	0.3
	1.4	0.3
3.5	0.2	0
	0.4	0
	0.6	0
	0.8	0
	1.0	0
	0.5	0.3
	0.8	0.3
	1.0	0.3
	1.2	0.3
	1.4	0.3
1.8	0.2	0
	0.4	0
	0.6	0
	0.8	0
	1.0	0
	0.5	0.3
	0.8	0.3
	1.0	0.3
	1.2	0.3
	1.4	0.3

APPENDIX B

PHASE II TESTING

Confining Pressure, MPa	Upstream Hydraulic Pressure, MPa	Downstream Hydraulic Pressure, MPa
1.8	0.2	0
	0.4	0
	0.6	0
	0.8	0
	1.0	0
	0.5	0.3
	0.8	0.3
	1.0	0.3
	1.2	0.3
	1.4	0.3
3.5	0.2	0
	0.4	0
	0.6	0
	0.8	0
	1.0	0
	0.5	0.3
	0.8	0.3
	1.0	0.3
	1.2	0.3
	1.4	0.3
5.2	0.2	0
	0.4	0
	0.6	0
	0.8	0
	1.0	0
	0.5	0.3
	0.8	0.3
	1.0	0.3
	1.2	0.3
	1.4	0.3
6.9	0.2	0
	0.4	0
	0.6	0
	0.8	0
	1.0	0
	0.5	0.3
	0.8	0.3
	1.0	0.3
	1.2	0.3
	1.4	0.3

Confining Pressure, MPa	Upstream Hydraulic Pressure, MPa	Downstream Hydraulic Pressure, MPa
8.6	0.2	0
	0.4	0
	0.6	0
	0.8	0
	1.0	0
	0.5	0.3
	0.8	0.3
	1.0	0.3
	1.2	0.3
	1.4	0.3
10.3	0.2	0
	0.4	0
	0.6	0
	0.8	0
	1.0	0
	0.5	0.3
	0.8	0.3
	1.0	0.3
	1.2	0.3
	1.4	0.3
12.0	0.2	0
	0.4	0
	0.6	0
	0.8	0
	1.0	0
	0.5	0.3
	0.8	0.3
	1.0	0.3
	1.2	0.3
	1.4	0.3
13.8	0.2	0
	0.4	0
	0.6	0
	0.8	0
	1.0	0
	0.5	0.3
	0.8	0.3
	1.0	0.3
	1.2	0.3
	1.4	0.3

Confining Pressure, MPa	Upstream Hydraulic Pressure, MPa	Downstream Hydraulic Pressure, MPa
13.8	0.2	0
	0.4	0
	0.6	0
	0.8	0
	1.0	0
	0.5	0.3
	0.8	0.3
	1.0	0.3
	1.2	0.3
	1.4	0.3
12.0	0.2	0
	0.4	0
	0.6	0
	0.8	0
	1.0	0
	0.5	0.3
	0.8	0.3
	1.0	0.3
	1.2	0.3
	1.4	0.3
10.3	0.2	0
	0.4	0
	0.6	0
	0.8	0
	1.0	0
	0.5	0.3
	0.8	0.3
	1.0	0.3
	1.2	0.3
	1.4	0.3
8.6	0.2	0
	0.4	0
	0.6	0
	0.8	0
	1.0	0
	0.5	0.3
	0.8	0.3
	1.0	0.3
	1.2	0.3
	1.4	0.3

Confining Pressure, MPa	Upstream Hydraulic Pressure, MPa	Downstream Hydraulic Pressure, MPa
6.9	0.2	0
	0.4	0
	0.6	0
	0.8	0
	1.0	0
	0.5	0.3
	0.8	0.3
	1.0	0.3
	1.2	0.3
	1.4	0.3
5.2	0.2	0
	0.4	0
	0.6	0
	0.8	0
	1.0	0
	0.5	0.3
	0.8	0.3
	1.0	0.3
	1.2	0.3
	1.4	0.3
3.5	0.2	0
	0.4	0
	0.6	0
	0.8	0
	1.0	0
	0.5	0.3
	0.8	0.3
	1.0	0.3
	1.2	0.3
	1.4	0.3
1.8	0.2	0
	0.4	0
	0.6	0
	0.8	0
	1.0	0
	0.5	0.3
	0.8	0.3
	1.0	0.3
	1.2	0.3
	1.4	0.3

APPENDIX C

PHASE III TESTING MATRIX

Confining Pressure, MPa	Upstream Hydraulic Pressure, MPa	Downstream Hydraulic Pressure, MPa
3.4	0	0
6.9	0	0
10.3	0	0
13.8	0	0
17.2	0	0
20.7	0	0
24.1	0	0
27.6	0	0
31.0	0	0
34.5	0	0
37.9	0	0
41.4	0	0
44.8	0	0
48.3	0	0
51.7	0	0
55.2	0	0
58.6	0	0
62.0	0	0
65.5	0	0
69.0	0	0
72.4	0	0
75.8	0	0
79.3	0	0
82.7	0	0
82.7	0	0
79.3	0	0
75.8	0	0
72.4	0	0
69.0	0	0
65.5	0	0
62.0	0	0
58.6	0	0
55.2	0	0
51.7	0	0
48.3	0	0
44.8	0	0
41.4	0	0
37.9	0	0
34.5	0	0
31.0	0	0
27.6	0	0
24.1	0	0
20.7	0	0
17.2	0	0
13.8	0	0
10.3	0	0
6.9	0	0
3.4	0	0

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