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Experimental Plan for Investigating Water Movement Through Fractures

E. A. Klavetter, R. R. Peters, B. M. Schwartz

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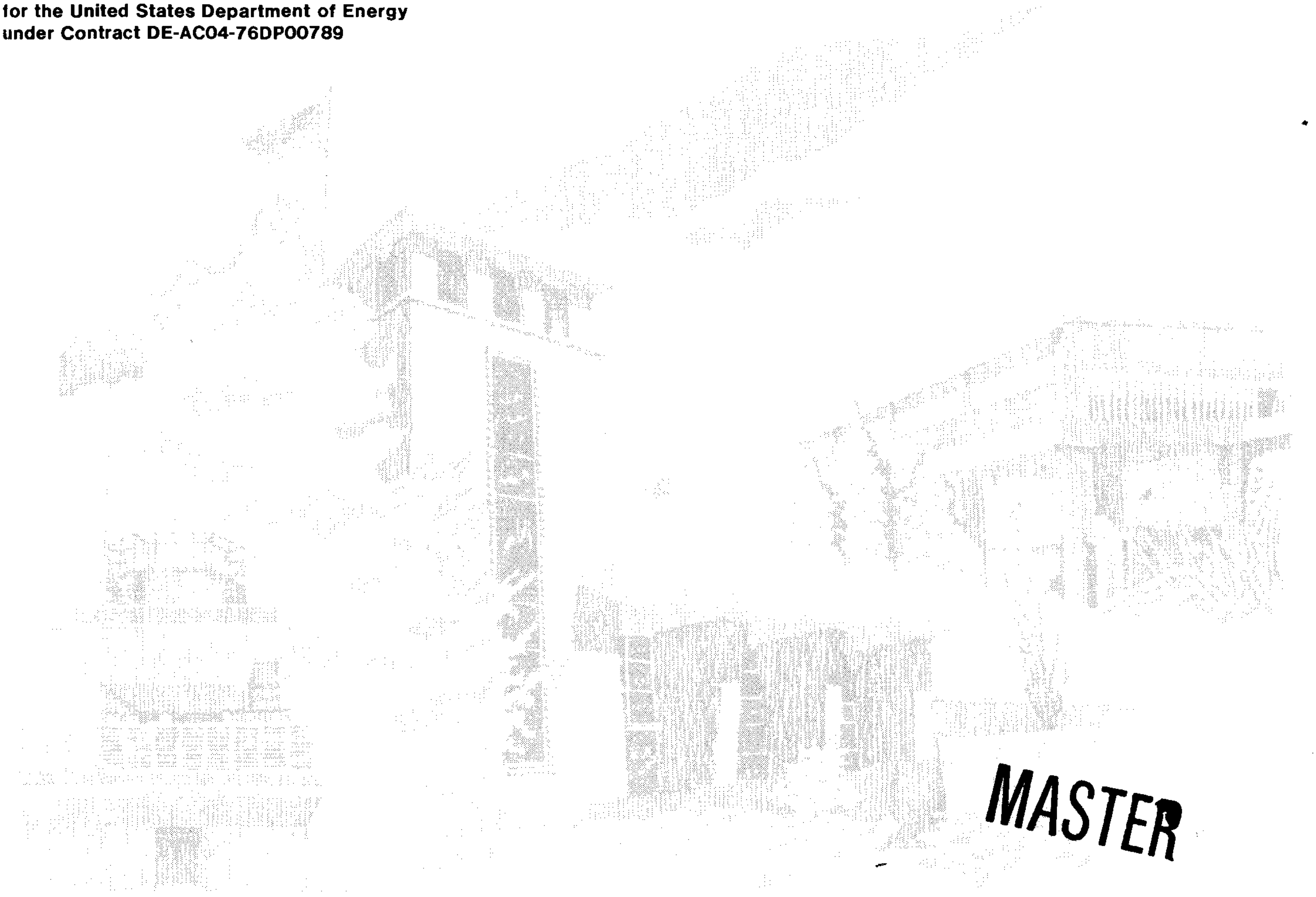

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EXPERIMENTAL PLAN FOR INVESTIGATING WATER MOVEMENT THROUGH FRACTURES

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ABSTRACT

The Yucca Mountain site in southern Nevada is being investigated by the Nevada Nuclear Waste Storage Investigations (NNWSI) project* as a possible site for a nuclear waste repository. The manner in which the water flows downward from the repository through the unsaturated zone to the water table can affect the transport of radionuclides. The travel time of water across a rock unit is considerably shorter if the flow is predominantly through fractures than if it is predominantly through the rock matrix. Current data and postulated physical models indicate that there is little or no significant flow through fractures in the unsaturated zone at Yucca Mountain. Fracture data are required to increase confidence in this conclusion and would be used qualitatively to increase understanding and quantitatively in modeling. The evaluation of water flow in fractures is also necessary for abnormal scenarios where significant fracture flow may occur because of future climatic conditions. An experimental system is described for the purpose of investigating the movement of water through fractures. The system will be used to perform the tests described in this report.

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* The name of the NNWSI Project was changed to Yucca Mountain Project (YMP) on November 9, 1988.

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INTRODUCTION

The Nevada Nuclear Waste Storage Investigations (NNWSI) project is characterizing the unsaturated geologic formations at Yucca Mountain, on and adjacent to the Nevada Test Site, as a possible site for a high-level nuclear waste repository. Flow through fractures is considered in the NNWSI project to be a potential mechanism for major water movement in certain units of Yucca Mountain. The travel time of water across a rock unit is considerably shorter if the flow is predominantly through fractures than if it is predominantly through the rock matrix. Therefore, the time for radionuclides to travel from the repository to the accessible environment is affected by the manner in which the water moves through the rock units. Current data and postulated physical models indicate that there is little or no significant flow through fractures in the unsaturated geologic formations at Yucca Mountain. Fracture data are required to increase confidence in this conclusion and would be used qualitatively to increase understanding and quantitatively in modeling. The evaluation of water flow in fractures is also necessary for abnormal scenarios where significant fracture flow may occur because of future climatic conditions.

In order to model the possible transport of radionuclides through the rock mass, it is necessary to characterize the movement of water, both through the fractures and the porous matrix. In some geologic units, such as the densely welded and highly fractured Topopah Spring Member, the fracture conductivity may be many orders of magnitude larger than the conductivity of the matrix itself, with the bulk saturated conductivity of the rock mass therefore approaching the value of the fracture-saturated conductivity. From available data, the matrix conductivity of the Topopah Spring Member is on the order of 4×10^{-9} cm/s or less, with the matrix conductivity of the non-welded tuffs generally on the order of 1×10^{-6} cm/s or less (1). Although there are few bulk permeability data for tuff available to date, field measurements in G-Tunnel on the

Nevada Test Site (2) show fracture permeabilities of 10 - 1000 darcies (1 darcy = 10^{-3} cm/s), which are much higher than the rock matrix permeabilities (10^{-1} - 10^{-8} darcies), indicating that fractures have the potential to carry a large fraction of water flux when flow occurs. Because little information is available about fracture flow in tuffaceous rocks, or any other type of rock, new investigations are needed to characterize the behavior of water flow through natural fractures. Of major interest is the determination of whether Richard's equation (3), which predicts transient, saturated/unsaturated flow in porous media, is a valid description of fracture flow, and whether the "cubic law" can be used for estimating the fracture's saturated permeability from an estimated average fracture aperture. (In the "cubic law" formulation, the fluid flow rate is proportional to the cube of the fracture aperture, b, and the fracture saturated permeability equal to $b^2/12$.) Of interest also are the changes in the fracture permeabilities (and aperture widths) due to changes in temperature and confining pressure; the degree of water migration, through capillary forces and diffusion, between the fracture and the matrix; and the possibility of channeling in a fracture as a dominant water movement phenomenon.

It is essential that the constitutive equations used to predict the water flux be valid for the conditions encountered so that the calculated water velocities and thus radionuclide transport through the rock mass be accurate. A "cubic law" model, in conjunction with Richard's equation, is in common use for predicting liquid fluxes through fractures, but it is necessary to determine whether that formulation is valid for both the saturated and the unsaturated conditions that might be encountered at a repository site. Barton et al.(4) have shown that a measured, geometric-fracture aperture (a real quantity) may be significantly larger than the equivalent smooth-wall, hydraulic aperture that is determined from flow measurements and the "cubic law" model. This indicates that predictions of water fluxes using the "cubic law" model, with measured, geometric fracture aperture values for the fractured rock mass under study, could be significantly in error. Both geometric and equivalent, smooth-wall hydraulic apertures will be determined in the experimental test series described in Section 4 to investigate the difference between the two apertures.

Knowledge of the fracture permeability response to increasing temperature is also necessary for modeling the environment near the nuclear waste canisters. Because fracture apertures, and thus fracture permeabilities, decrease with increasing stress, measurements of the response of fracture permeability to confining pressure are needed to indicate the relative importance of fracture flow as depth, and thus in situ stress, in a unit increase. Results from testing samples obtained from different units will show the variation in flow response between different tuffs and aid in the determination of the modeling approach to be used in describing the water movement in the geologic units above the water table.

It is not known whether flow can occur in an unsaturated fracture or whether a saturated, or nearly saturated, condition must be present in the fracture for the fracture permeability to be significantly greater than the surrounding matrix permeability. For an unsaturated flow condition, if it can occur, no information is available about the curves describing moisture content and conductivity as a function of pressure head. These two curves are referred to as "the characteristic curves for unsaturated flow," or simply as the "characteristic curves." Information is required about the nature of flow behavior through a fracture at fluid velocities less than the saturated fracture conductivity to determine the nature of these characteristic curves for the fracture.

If the flow mechanism appears to be Darcian and follows Richard's equation, it may also be possible to determine experimentally the characteristic curves (e.g. see Ref 5) for the fracture. These characteristic curves would make it possible to model the flow characteristics in a macroscopic sense (without accounting for flow irregularities caused by fracture surface topography) using current code capabilities. Some preliminary modeling of flow in a discrete fracture has been done by Martinez (6) using the Sandia National Laboratories (SNL)-developed code SAGUARO (7) to predict fluid penetration through the fracture and into the matrix. Characteristic curves for the fracture were not measured but postulated to resemble the curves measured for sand. The results of these calculations would be much more useful if measured rather than postulated fracture characteristic curves were used.

OBJECTIVES

The objectives for these experiments are both qualitative and quantitative. Because there is at this time a severe deficiency in the understanding of the physics of fluid movement in fractures, especially when the fractures are not completely saturated, a major qualitative goal is to increase the understanding of the mechanisms involved in the movement of water through natural fractures and to evaluate the usefulness of the "cubic law" constitutive formulation currently used to predict the saturated flow rate in a fracture. Data are desired on samples representative of the rockmass under study. It is important to note that each fractured-tuff core sample (obtained from boreholes in and around Yucca Mountain) to be tested contains a single, natural, open fracture; i.e., the fracture in each core sample was not man-made or judged to be induced by drilling and was thus assumed to have been present in the core sample's in situ state. Unlike tests on prepared samples where the fractures resemble parallel plates and flow must inherently be closely predicted by the "cubic law" model, the naturally fractured samples have fracture surfaces that may induce different flow mechanisms (e.g., channeling for unsaturated flow or transitional flow behavior between Darcian and wholly turbulent flow). Strong capillary forces present in the matrix may also alter the water movement through the fracture, depending on the matrix saturation and water flow rate, causing water to move from the fracture into the matrix. These different flow mechanisms may require that a different constitutive equation, or modification of the currently used formulation, be used to successfully model the water movement through fractures. The methods used to acquire the information concerning the mechanisms of water movement through a fracture are described later in this document.

The quantitative objectives will be the determination of the response of fracture aperture and saturated permeability to changes in the effective confining pressure on the sample and to changes in temperature. Information about the variation of fracture aperture and permeability with stress will indicate the variation of in-situ permeability of the fractures with depth. This variation is necessary for modeling the hydrologic system in Yucca Mountain. Data on the temperature dependence of fracture permeability are necessary for modeling the repository environment near the waste canisters.

All experiments described in this document employ the same basic fracture-flow apparatus, with modifications made to conduct the individual tests. A major task is the development of an experimental system that can be used to

- Observe the fundamental behavior of water movement through a discrete natural, open fracture and the water movement from the fracture to the matrix,
- Determine the validity of applying Richard's equation with a "cubic law" model assumed to predict the saturated permeability of a natural fracture,
- Determine the response of fracture aperture and permeability to changes in applied confining pressure that simulate in-situ pressures, and
- Determine the response of fracture aperture and permeability to changes in temperature.

To accomplish the objectives for this experimental series, it will be necessary to measure not only the macroscopic flow parameters through the fractured samples, such as the overall flow rate and pressure drop, but also to be able to monitor the flow behavior of the fluid as it moves through the fracture and cross the fracture surface. To monitor the water movement within the unsaturated fracture, an instrumentation technique for making laboratory electrical impedance (capacitance and resistance) measurements of fracture flow will be employed. As a fluid moves across the fracture surface, the electrical impedance will vary between locations along the surface in direct relation to the saturation. The variation of the impedance on the fracture surface will indicate the passage of fluid and the nature of the flow paths. Therefore, the electrical impedance technique provides the means to determine the volume of water (and thus the saturation) within the fracture between any two designated locations and the flow rate of water between the locations. This information is needed for determining fracture apertures, evaluating the "cubic law" model, and determining fracture hydraulic conductivity as a function of saturation. This impedance technique is described in the following section.

DESCRIPTION OF LABORATORY IMPEDANCE MEASUREMENTS OF FRACTURE FLOW (LIMFF)

Description of Technique

There is an electrical impedance associated with any pair of points on a fracture surface. The value of this impedance will depend on the electrical properties of the fluid in the fracture, the fluid volume, and the electrical properties of the surrounding media. As a fluid (e.g., water) moves across the fracture surface, displacing another fluid (e.g., air), the electrical impedance between the pair of points, or electrodes, on the fracture surface will change. These changes in electrical impedance along the fracture surface will provide information about the characteristics of fluid movement through the fracture.

The LIMFF technique will aid in the understanding of how fluid moves through an open fracture. A similar impedance technique has been used previously by Wayland and Lee (8) to investigate the movement of oil and brine through sand, but monitoring fluid movement in rock fractures on a laboratory scale has not been attempted using this technique. The measurement system consists of parallel, open grid lines electroplated onto the rock surface forming one side of the fracture, where the signature of the changing capacitance/conductance will identify the fluid front and its instabilities (if any) as the fluid moves perpendicularly past the emplaced electrode grid. A core sample, containing the fracture with the emplaced electrode grid, is confined within a pressure vessel that allows simulation of in situ stresses and movement of fluid through the fractured core sample. A brief description of the mechanics of the technique and how the responses are interpreted is given below.

To derive an idealized description of the type of response to be expected, consider a fracture filled with a fluid. For a set of electrodes (wires or an electroplated grid), there will be some capacitance, C, between any two electrodes given by

$$\underset{A}{C} = \frac{\varepsilon_{l} A}{4\pi\ell} \tag{1}$$

where A is the area of the electrodes (perpendicular to the fracture surface), ℓ is the spacing, and ε_l is the dielectric constant of the conducting fluid. Now a fluid solution or some solution with electrical properties (e.g., the dielectric constant, ε, and electrical permeability, K) contrasting those of the original fluid is injected into the fracture and begins to move toward the electrodes. As shown in Figure 1, a bank or front will form that will displace some or most of the non-conducting fluid. For the tests in this experimental series, water is the conducting fluid.

Assume that this is an inherently stable displacement, but with small-scale turbulence that creates "fingers" (small extensions or fringes) that will move in advance of the general front. Given the asperities and roughness on the fracture surface, this is a likely assumption. Let us restrict attention to the case where the electrode spacing is smaller than the length of the fingers. Before the fingers reach the first electrode, the capacitance is C_{init} (A in Figure 1), but begins to decrease (B in Figure 1) as the fingers occupy some fraction, Δ, of the area. The capacitance will decrease until the fingers pass through both electrodes (C) where a constant reading will continue until the front is at the first electrode (D). Then, as the front moves through the spaces between the electrodes, the capacitance will again decrease until the front is completely pushed

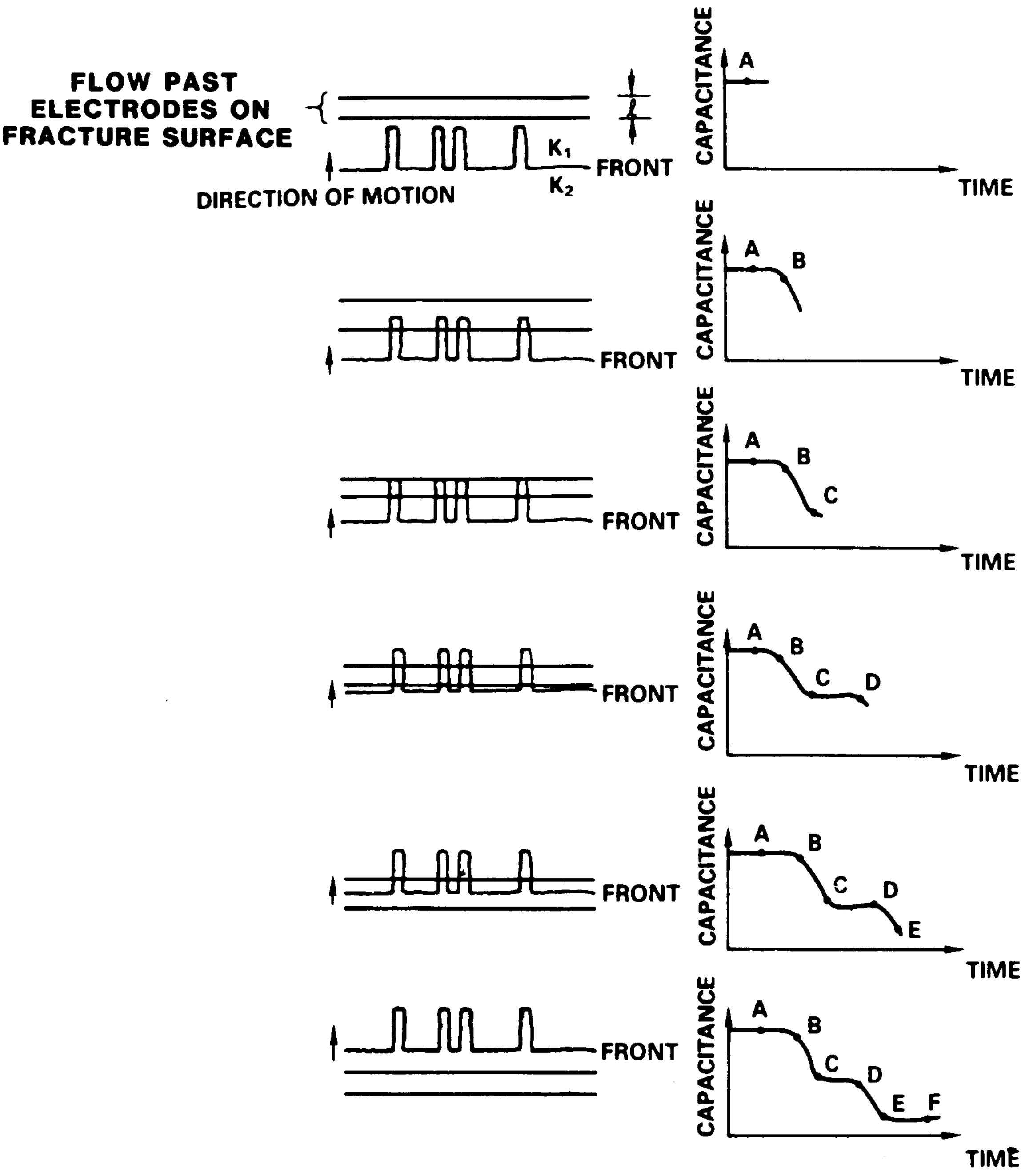


Figure 1. Schematic of the Effects on Measured Capacitance When a Conductive Fluid is Displaced by an Insulating Fluid in a Fracture

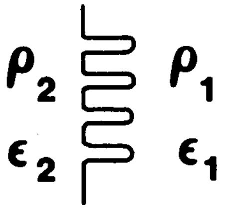
through the second grid (E), after which the capacitance remains constant (F). The response curve will, of course, change with electrical properties of the fluids. These properties can be measured easily for the fluids of interest for all expected conditions (e.g., temperature, pressure, fluid pH).

The magnitude and shape of the response curve will depend on the resistivity and dielectric constants of the fluids. If the ratio of the resistivity of the displaced medium, ρ_1, to the resistivity of the displacing media, ρ_2, is greater than one, i.e., $\rho_1/\rho_2 > 1$, a stairstep curve similar to that shown in Figure 2 will result. For water displacing air in the fracture, this ratio is much greater than one, and the change in signal response as the water moves across the electrode grid is very distinct. The general trend will be a decreasing resistivity. This same case, i.e., water flowing into a dry fracture, will have a ratio of dielectric constant less than one, and the capacitance curve will be an increasing stairstep as shown in Figure 2. The results considered are at a fixed frequency. There are very definite frequency effects. By careful experimentation during the calibration procedure, the frequency that will give the most distinct signature will be found. The expected frequency range is 5-1000 Hz (7).

If all the fingers are of equal length and greater than the grid separation, then one should obtain a characteristic curve that will predict the velocity of the fingers and of the front the length of the fingers, and the areal fraction occupied by the fingers. In Figure 3, an idealized response curve is shown. Here, Δt_1 is the time taken by the fingers to go from the first grid to the second grid, Δt_f is the time taken for just passage of the fingers until the main body of fluid, (fluid bank), encounters the first grid, and Δt_2 is the time required for the bank to pass through the grids. Then, if ℓ is the separation of

RESPONSE

$$\frac{\rho_1}{\rho_2} > 1 \text{ and } \frac{\epsilon_1}{\epsilon_2} < 1$$



EX: WATER FLOWING INTO A DRY FRACTURE

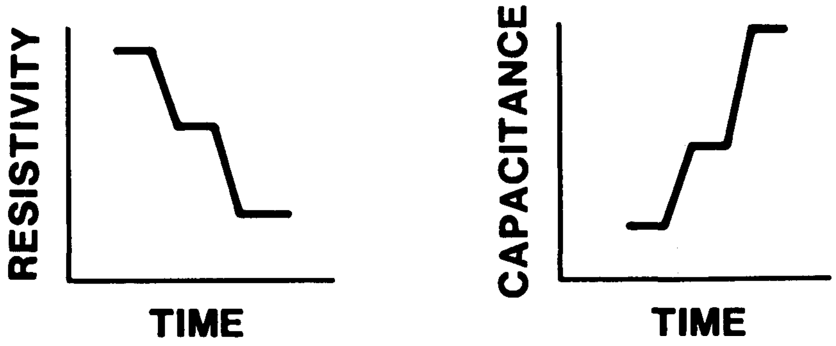
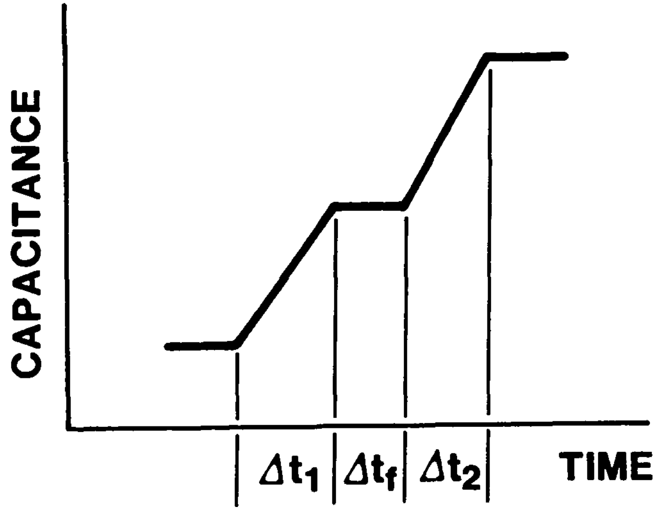


Figure 2. Response to be Expected for Idealized Frontal Instabilities



$$V_f = \frac{\ell}{\Delta t_1}$$

$$V_b = \frac{\ell}{\Delta t_2}$$

$$\ell_f = \ell + V_f \Delta t_f$$

Figure 3. Definition of Times Associated with Frontal Instability Measurements

the grids,

$$
\begin{aligned}
&\text{velocity of fingers} = V_f = \ell/\Delta t_1, \\
&\text{velocity of bank} = V_b = \ell/\Delta t_2, \text{ and} \\
&\text{length of fingers} = \ell_f = \ell + V_f \Delta t_f.
\end{aligned}
\tag{2}
$$

In the simplest case the areal fraction, Δ, occupied by the fingers can be obtained under the condition of fingers long enough to extend through both grids as shown in Figure 4. For measurements between the electrodes, the equivalent circuits are parallel capacitors and resistors. Thus, the equivalent or effective capacitance, C_e, is given by

$$C_e = C_1 + C_2 = \frac{A}{4\pi\ell}\left[(1-\Delta)\varepsilon_1 + \Delta\varepsilon_2\right] \tag{3}$$

or

$$\Delta = \frac{C_e \frac{4\pi\ell}{A} - \varepsilon_1}{\varepsilon_2 - \varepsilon_1} = \frac{C_e - C_b}{C_a - C_b} \tag{4}$$

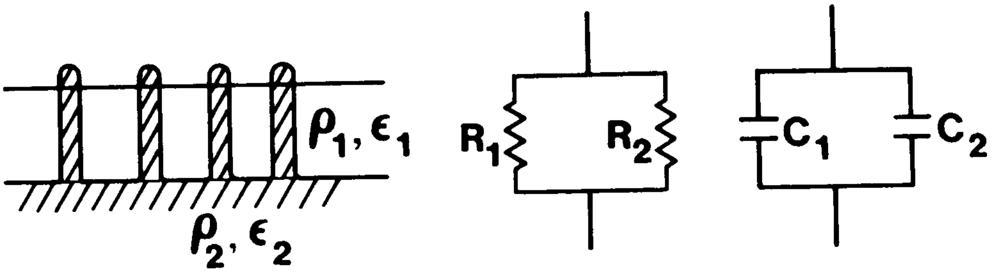
where

$$C_b = \frac{\varepsilon_1 A}{4\pi\ell}, \quad C_a = \frac{\varepsilon_2 A}{4\pi\ell} \tag{5}$$

Note that (Figure 4) the values of C_a, C_b, and C_e can be read directly from the measured capacitance response curves. Because the displaced fluid, with an areal fraction of $(1-\Delta)$, acts like a resistor in parallel with the fingers of the displacing fluid, with an areal fraction of Δ, it can be shown that

$$\Delta = \frac{\rho_a(\rho_b - \rho_e)}{\rho_e(\rho_b - \rho_a)} \tag{6}$$

AREAL FRACTION MODELS



$$\Delta = \frac{C_e - C_b}{C_a - C_b}$$

$$\Delta = \frac{\rho_a\left[\rho_b - \rho_e\right]}{\rho_e\left[\rho_b - \rho_a\right]}$$

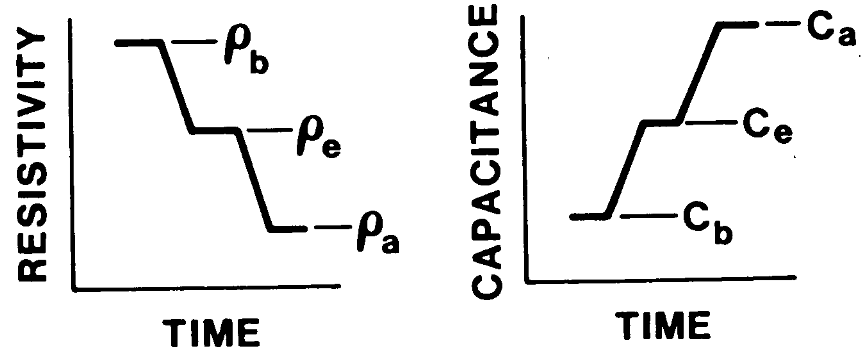


Figure 4. Computation of the Areal Fraction, W, Occupied by Fingers in an Advancing Front

where ρ_a, ρ_b, and ρ_e are as defined in Figure 4, and the resistivity, ρ, is given by

$$\rho_i = \frac{R_i A_i}{\ell} \tag{7}$$

The reciprocal of the effective resistance, R_e, is thus equal to the sum of the reciprocals of the individual resistances of the fingers and the displaced fluid.

If the fingers are not of uniform length, or if they are not longer than the electrode separation, the response curve will not show the sharp discontinuities and flat plateaus that are depicted in Figure 2. The sharp corners will become more rounded, and the discontinuities may become inflection points on the curves. For these cases, establishing relationships between the impedance response curves and water movement and water volume will provide information on the characteristics of the shape of the water front.

Establishment of Relationship between Impedance Response and Water Volume and Movement

As mentioned in the above description of the LIMFF technique, the impedance measurements will change as one fluid displaces another fluid with different electric properties. The magnitude of the change will depend upon the relative magnitude of the electrical properties (resistivity and dielectric constants). When water completely displaces air, the impedance response can change by more than four orders of magnitude, since the ratio of the resistivity of water to air is generally in the range of $10^2 - 10^5$ (depending upon the electrolyte concentrations in the water). The impedance response will indicate the passage of the conducting fluid past the electrodes and indicate the shape of the fluid front. To provide more detail about the front and the amount of water moving past the electrodes, it is necessary to establish a relationship between the magnitude of the impedance response and the water volume associated with it.

To establish this relationship in a controlled manner, a fracture will be simulated by constructing two flat plates in a parallel arrangement with a spacing, or aperture, that can be regulated and defined (see Figure 5). An electrode grid will be emplaced on the interior surface of one plate using the same technique (see Appendix B) used on the fractured tuff core samples to be used in the experimental tests described later in this document. One plate will be made of glass to allow visual observation of fluid moving through the simulated fracture, or crack. The sides of the flat-plate arrangement will be sealed to allow fluid to run only through the ends. With water moving through the crack and past the electrodes, a frequency-dependent map of ϵ and ρ can be made along the length of the crack. The water moving through this simulated fracture will be at temperatures and pH values similar to those of the water used in the experimental tests that will be carried out using fractured tuff core samples. Both temperature and pH of the fluid will affect the electrical-property readings. Pressures used in the experimental testing will not be high enough to significantly affect the electrical-property readings.

The first test will be to check whether the electrode grid size has a surable effect upon the flow behavior of water through a crack. With the aperture of the crack set to a definable value of 20-100 µm (characteristic of the size of a closed fracture), water will be allowed to flow through the crack, and impedance measurements will be made. The electrode grid will then be removed from the flat plate and another grid emplaced, decreasing the size and areal extent of the electrode grid. The plates will be reassembled with the aperture set to the previous value, and impedance measurements will again be

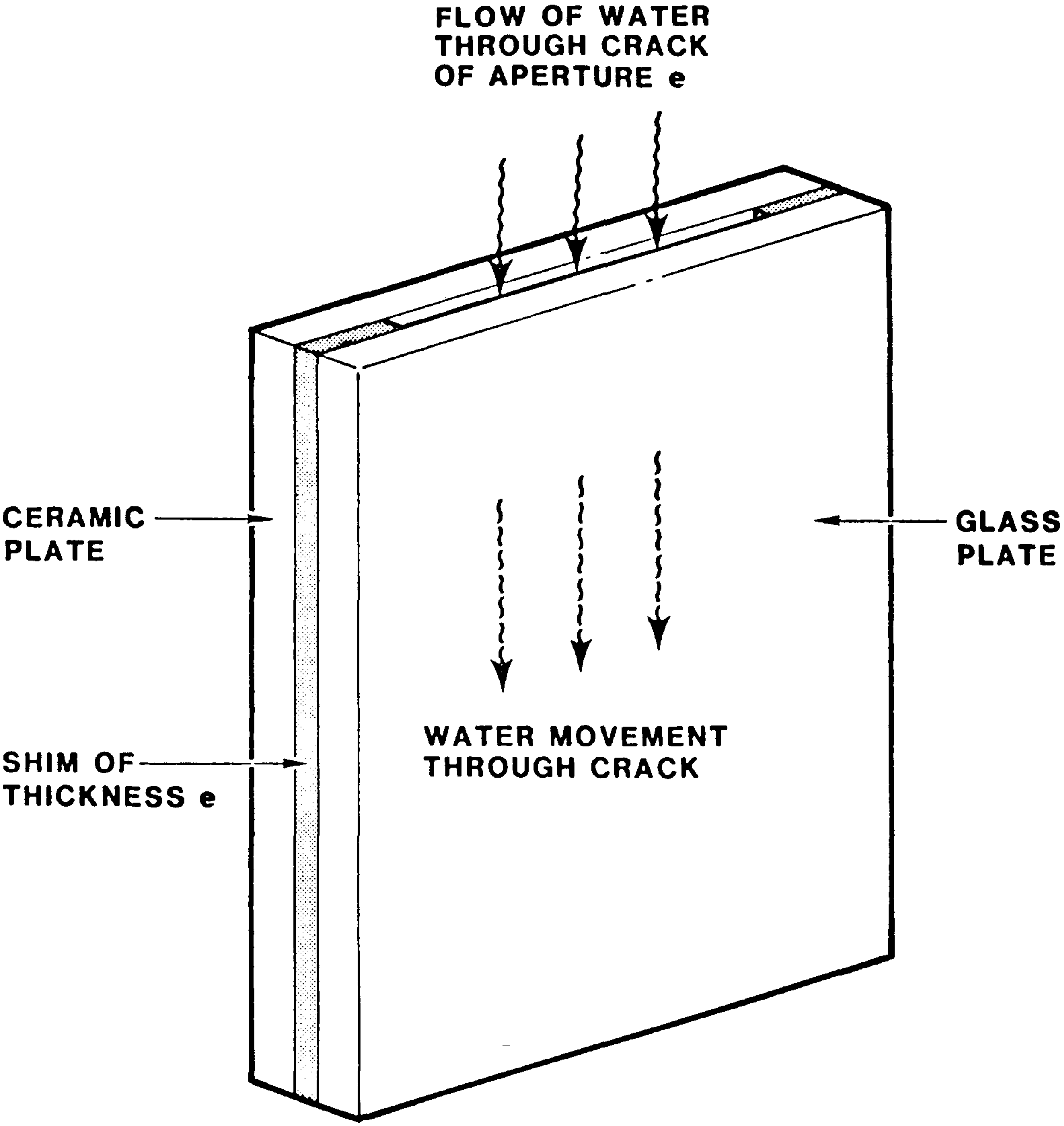


Figure 5. Simulated Fracture

made. The electrode grid size will be decreased until no significant change in the impedance measurements, and thus in the fluid flow behavior, is detected. This grid size will be assumed to be suitable for emplacing on the fractured samples.

To provide a relationship between impedance measurements and water volume, the aperture of the crack will be varied and impedance measurements taken as water flows past the electrodes. A certain volume of fluid between two electrodes will yield a certain electrical impedance value. Since the dimensions of the crack aperture will be known, the volume of water will be known and can be correlated with the impedance response. Therefore, during experimental tests on fractured core samples, the volume of water between two electrodes on the fracture surface can be determined from the value of the impedance response.

If the shape of the water front, as it passes through the discrete fractures in the tuff core samples, cannot be approximated by the idealized case discussed previously, it will be necessary to develop a correlation between the impedance responses and the fluid front development. The need for this will not be known until after testing the core samples and evaluating the impedance responses. To provide this relationship, the parallel plates can be set at various orientations to induce different patterns of fluid flow. For example, when the plates are set in a vertically upright position, with flow perpendicular to the grid, the fluid front will have a symmetric, parabolic velocity distribution moving past the electrodes. With the plates set at an angle, the shape of the front that moves past the electrodes will change, with a corresponding change in the impedance response. The surface of the plates can also be physically altered by adding obstructions to flow to induce various fingering effects. A visual (photographic) record of the fluid movement can be made through the glass plate, and the shape of the fluid front can be correlated to the impedance response. These correlations can then be used to infer the shape of the fluid front in the core samples from the impedance measurements. The extent of the procedure to correlate fluid-front development with impedance response will depend upon the experimentally determined impedance responses obtained as fluid moves through the fractured tuff core samples, the variation in the correlation between fluid front development and impedance response, and the resolution that is deemed necessary.

TEST DESCRIPTION

Tuff core samples from various depths of USW G-4, containing a single, discrete fracture, will be tested (see Table 1 for sample depth and unit description). The fracture in each sample generally runs approximately axially through the middle of each core. Some or all of these samples will be tested, with the possibility of adding other samples, based upon experimental results and data needs. A series of experimental tests will be run consecutively on the core samples selected for testing.

The core samples will be enclosed in a pressure vessel capable of providing confining pressures up to 3000 psi (200 bars) and temperatures up to 225°C, with the pore fluid able to enter either the top or bottom of the sample as desired. As shown in Figure 6a, the test specimen will sit on a metal cylindrical platen and be constrained inside the pressure vessel by a core holder assembly that will allow the pore fluid to move in and out of the sample and that will allow for electrical wire leads to be attached to the copper electrode grid emplaced on the fracture surface. An illustration of the core holder assembly and the electrode grid on the fracture surface is shown in Figure 6. The end platens and porous stones will allow the pore fluid to enter and leave the core sample, and the fluorosilicone sealant will insure that no fluid leaks down the side of the sample or leaves through the sides of the core. The sealant will also keep the confining fluid from entering the sample. The wire leads will be attached to each electrode in the grid pattern to allow monitoring of the impedance measurements as water moves past the electrodes.

TABLE 1

Sample Specification

USW G-4 Depth of Sample (ft)	Unit	Unit Description
1114	II-L	Moderately to densely welded, devitrified zone of the Topopah Spring Member of the Paintbrush Tuff that contains more than approximately 10%, by volume, of vugs (voids in rock.)
1215	II-NL	Moderately to densely welded, devitrified zone of the Topopah Spring Member of the Paintbrush Tuff that contains less than approximately 10%, by volume, of vugs. This is the proposed repository unit.
1278	II-NL	(See above)
1360	III	Nonwelded ashflows, bedded and reworked tuffs, vitric and primarily nonzeolitized, from the Topopah Spring Member and/or the Calico Hills.
1551	IV-A	Nonwelded ashflows, bedded and reworked tuffs, primarily zeolitized, from the Topopah Spring Member and/or the Calico Hills.
1778	IV-C	Upper zeolitized zone of the Prow Pass Member of the Crater Flat Tuff.

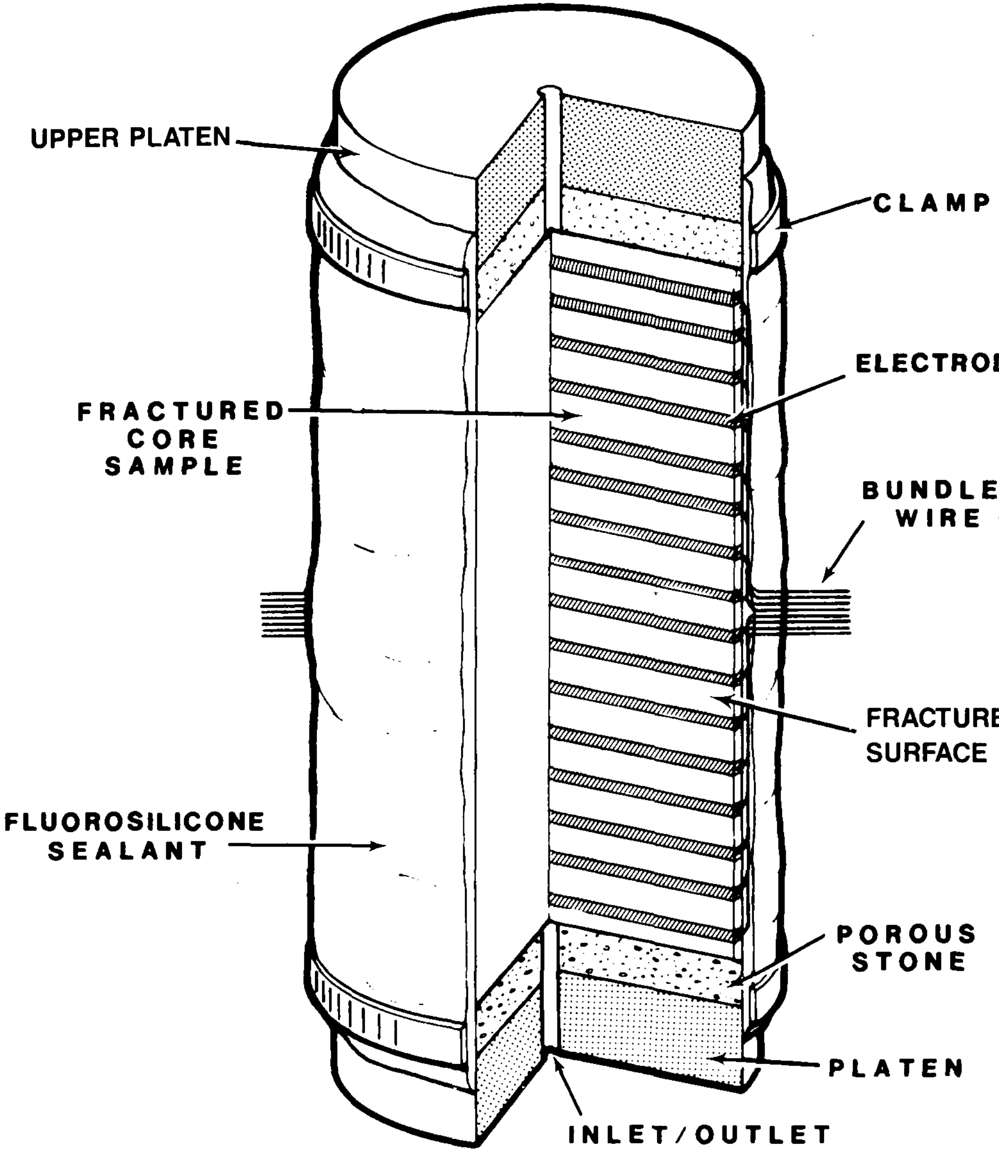


Figure 6a. Core Sample Encased in Core Holder Assembly with Cutaway View of the Fracture Surface

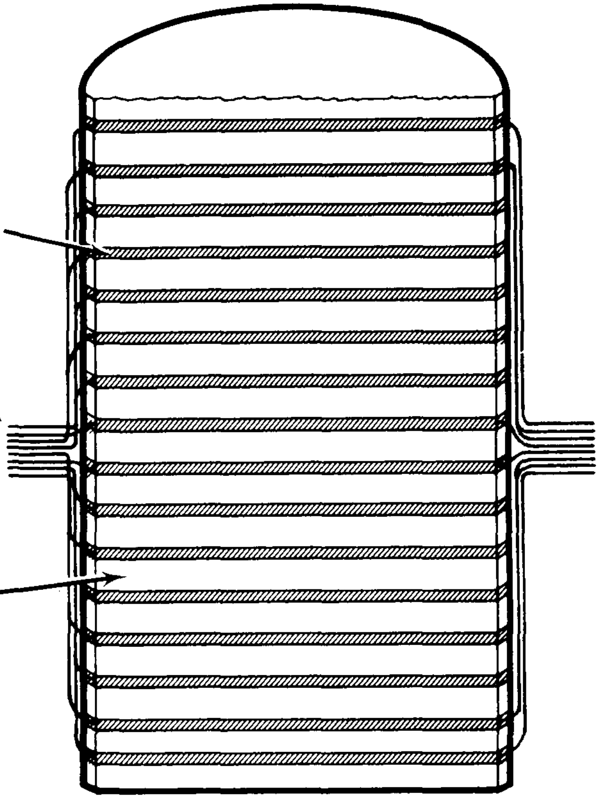


Figure 6b. Electrode Grid Pattern on the Fracture Surface

For the first test, water will be input slowly from the bottom of the saturated sample. The sample will have been saturated (see Appendix A) prior to placement in the pressure vessel to prevent any water from moving from the fracture into the matrix because of capillary forces during testing. By utilizing the impedance measurements, to monitor the water movement up the fracture utilizing the impedance measurements, the flow rate, and thus the volume of water in the fracture, can be determined between electrode pairs. The total fracture volume can also be determined by monitoring the input flow rate and the total time required to reach the top of the fracture. From the length and width of the fracture, an average fracture aperture (geometrical) can be determined as well as an estimate of the geometrical aperture change along the core length. The test will be run at approximately 6-10 effective confining pressures in the range of 15-2250 psi (1-150 bars). The fracture will be cleared of excess water after each test by blowing saturated air through the fracture. This test should give the fracture aperture as a function of the applied confining pressure along the fracture length, as well as give a more complete characterization of the fracture geometry.

The second test series will be a conventional permeability test with the water inlet flow rate at the top of the sample at a velocity greater than the expected saturated conductivity. The flow rate and pressure drop across the sample will be measured when steady state is achieved. Using a similar experimental configuration, Pacific Northwest Laboratories (9) has measured saturated fracture permeabilities as a function of effective confining pressure for five fractured tuff core samples and shown that the fluid flow rates vary more than three orders of magnitude among the core samples tested. In this test series, the confining pressure will be varied as in the first test to produce changes in the fracture aperture. These permeability data, with the aperture known as a function of the confining pressure, will indicate the validity of the "cubic law" model for fracture permeability by comparing the average aperture determined by the previous test with that calculated using the model. Barton et al. (4) have shown that the measured geometric aperture may be significantly different from the smooth-wall, hydraulic aperture predicted by the "cubic law" model. At each effective confining pressure, the pressure drop across the sample will be varied to give the flow rate as a function of pressure drop. The range of the pressure drop and the number of values tested will depend on a particular sample and its fracture permeability and will be determined during the test. Knowledge of the relationship between pressure and flow rate will indicate the validity of assuming Darcian flow for water movement in fractured tuff samples. Tests recently performed by Evans (10) on a sample of granodiorite containing a single natural fracture indicated that the flow was generally transitional between Darcian and wholly turbulent flow. These tests will also be run with the water velocity at various fractions of the measured saturated conductivity value and the moisture history monitored along the fracture. The moisture history, as determined by the impedance measurements, will indicate the nature of flow and the effects on flow of channeling or fingering, if they occur.

The sample will then be dehydrated using a vacuum drying process (see Appendix A). With the sample matrix dry, the open fracture will be filled with water and no water allowed to leave or enter the fracture through the end platens. Impedance measurements will monitor the movement of water from the fracture into the matrix as capillary forces draw water into the dry matrix. After all, or a significant portion, of the water has moved into the matrix, leaving a relatively dry, drained fracture, the fracture can again be filled and the water movement into the matrix monitored. As the matrix saturation increases, this rate of transport should decrease. A rate of water transport between the fracture and the matrix can be determined as a function of the saturation of the matrix. This will indicate the natural saturation condition of fractures underground at various matrix saturations.

Saturated permeability tests will also be performed to determine the permeability (and fracture aperture) response to temperature. These tests will generally be done last, because the sample must be heated through the use of a heating jacket that can be attached to the pressure vessel and there is an increased possibility of leaks around the sample at increased temperatures due to increased stresses on the sealant encapsulating the sample. With the confining pressure set initially at the desired constant value (the simulated in-situ pressure is 0.97 psi/ft x sample depth), the temperature will be gradually stepped up, the sample allowed to reach steady state, and the permeability determined. The test will be repeated at higher temperatures, up to a maximum of 225°C. This information will yield the fracture's permeability response to a temperature change, which is needed for near-field calculations.

When a test series has been completed on a core sample, the surface roughness characteristics of the discrete fracture can be determined using a profilemeter to show the deviation of the fracture's surface from a planar crack. The need for this information will depend on the nature of the flow behavior and the moisture history in the fracture as determined by the impedance measurements during the various tests. This surface topography information may be necessary to understand channeling, if it occurs.

EXPECTED RESULTS

With the theoretical development of flow in natural fractures in its initial stages and the sparsity of data concerning the flow of water in fractured rock masses, there is an essential need for hydrological measurements on fractured rock samples. The experimental series planned is an initial laboratory effort to provide qualitative and some quantitative information on the characterization of fluid flow in discrete fractures. While specific results of the experiments cannot be defined a priori for a general set of tuff core samples, some general expected results, as well as some of the data analysis methods to be used, are presented here. The type of response expected from the impedance measurements as water flows past the electrode grid on the fracture surface, as well as methods for interpreting the data, are presented in Section 3 and are not repeated here.

The fracture aperture, and thus the saturated conductivity, are expected to change with the applied stress (effective confining pressure), decreasing asymptotically as the pressure increases. The rate of decrease will depend on the characteristics of a particular fracture, but experimental data for other rock types indicate that the following functional forms may be useful in describing the change of the aperture and saturated conductivity as a function of the effective confining pressure (see, e.g., Figures 7 and 8, and 9):

$$b = [c_1 - c_2 * \ln(p_e)]^n \qquad \text{(Ref 14)} \qquad (8)$$

$$k/k^* = A + B * p_e^{(-n)} \qquad \text{(Ref 11)} \qquad (9)$$

$$(k/k^*)^{1/3} = D - E * \ln(p_e) \qquad \text{(Ref 14)} \qquad (10)$$

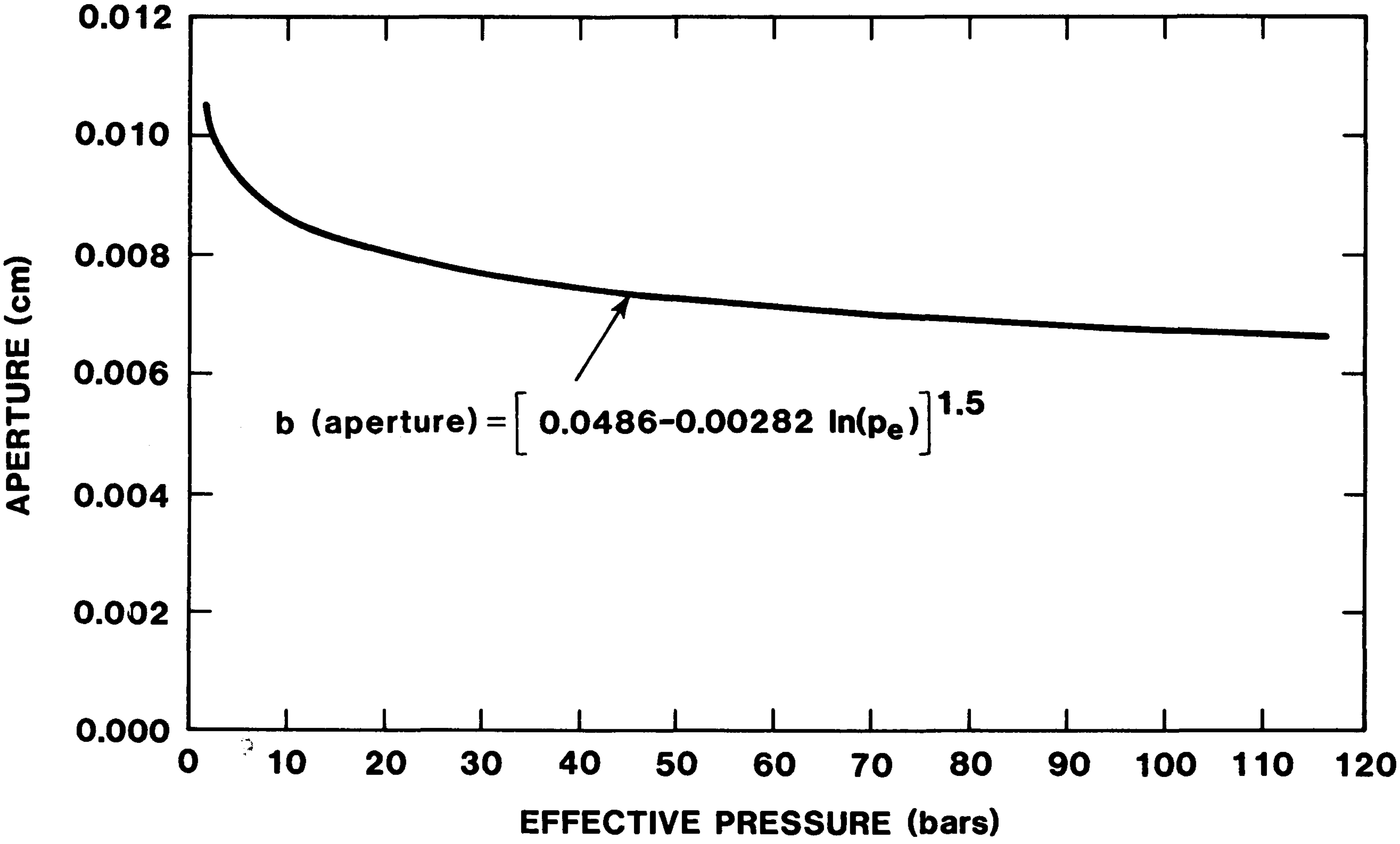


Figure 7. Fracture Aperture Versus the Effective Confining Pressure

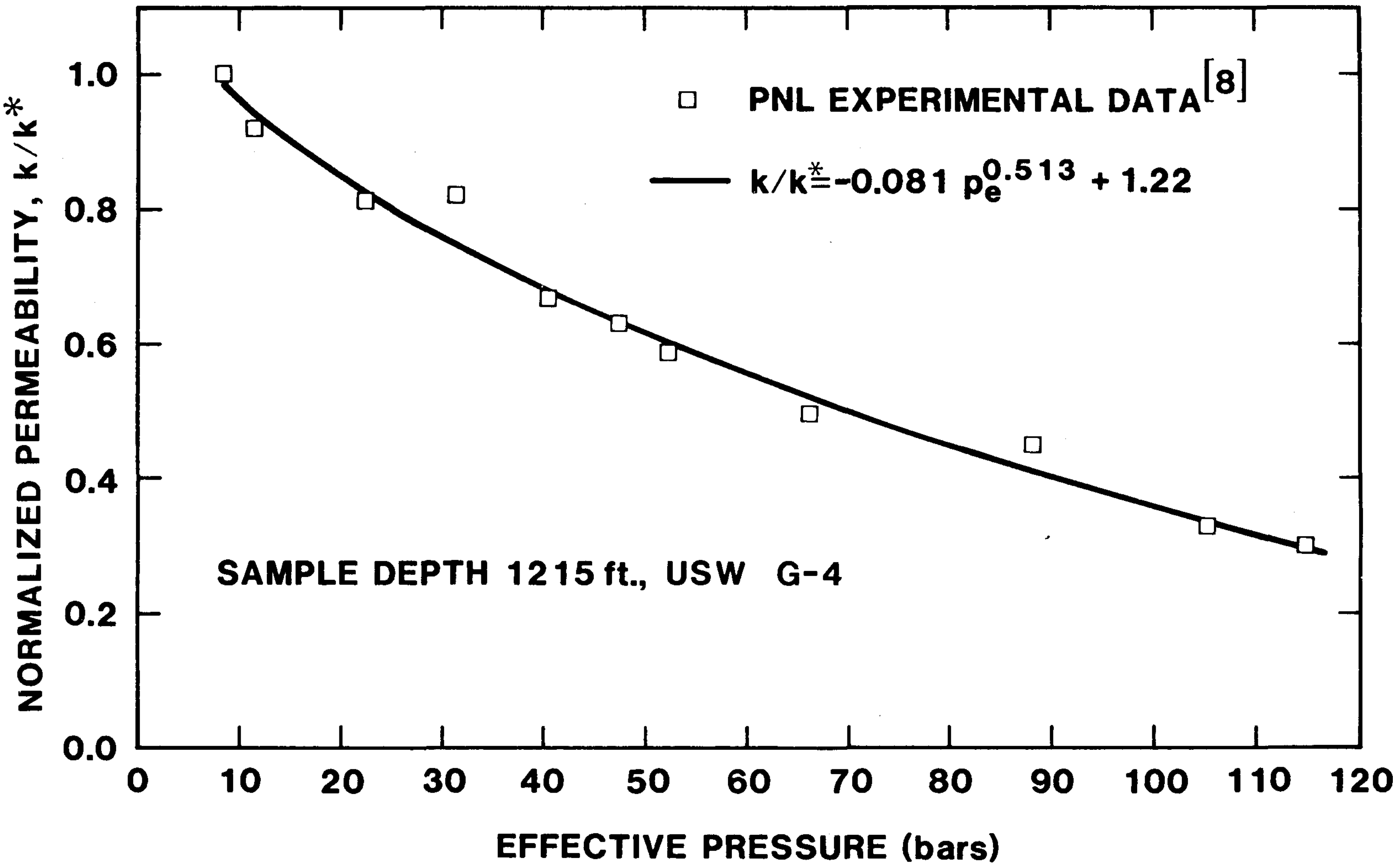


Figure 8. Normalized Fracture Permeability Versus the Effective Confining Pressure

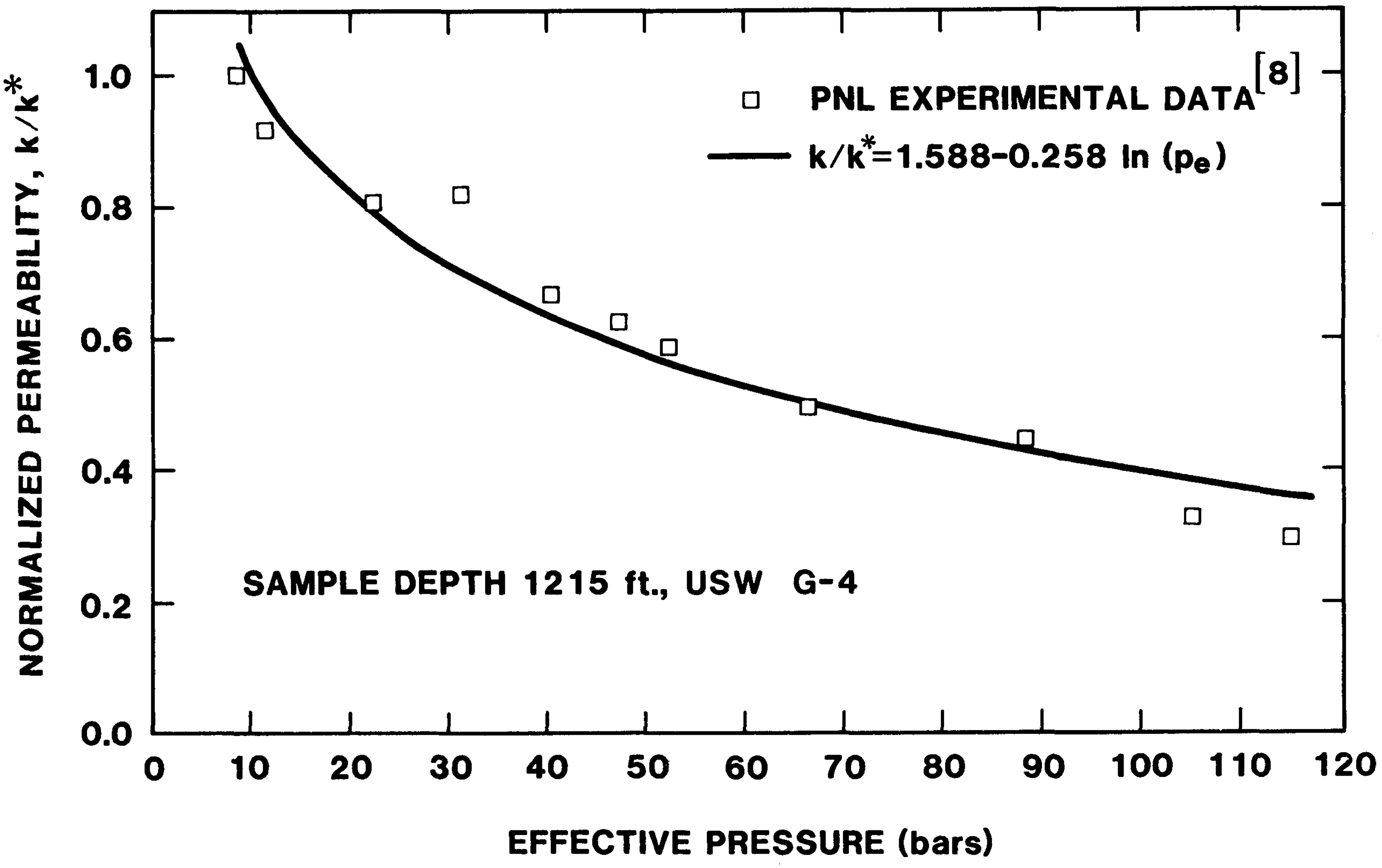


Figure 9. Normalized Fracture Permeability Versus the Effective Confining Pressure

where:

b = fracture aperture

k = saturated fracture permeability

k^* = an arbitrary reference permeability

p_e = effective confining pressure

$= p_{(\text{confining fluid})} - p_{(\text{pore fluid})}$

c_1, c_2, A, B, D, E, n = constants

With the fracture aperture measured or estimated as a function of the effective confining pressure, these equations can be used to determine the permeability as a function of the aperture. These experimental results will be used to determine the error involved in using the "cubic law" model with assumed Darcian flow for determining the fracture conductivity and thus the flow in a fracture. The "cubic law" model for a single fracture gives:

$$q = \frac{-b^3 \rho g W}{12\mu} I \tag{11}$$

where:

q = water flow rate

μ = viscosity

ρ = density

g = gravitational constant

W = fracture width

I = hydraulic gradient

The assumption of Darcian flow can be checked by plotting flow rate versus the hydraulic gradient. If the plot is linear, Darcian flow is a valid assumption; if non-linear, it indicates that the flow regime is between Darcian and turbulent flow.

Data on the fracture saturated conductivity and aperture response to temperature are scarce, with the phenomena involved not well understood. Experiments done to date by other researchers have been done almost exclusively using sandstone at low pressures, which gives little information on the expected response of tuff. For a discrete fracture in a tuff core sample of essentially constant volume, it is expected that the permeability will decrease because of thermal expansion but increase because of the changes in the viscosity of water. Which effect will dominate is not apparent. There does not appear to be any functional relationship for fracture-conductivity response to temperature, largely because of the lack of data on any rock type and the subsequent lack of analysis.

With no previous laboratory evidence to suggest the nature of the moisture content and fracture conductivity as a function of suction head, there have been no postulated functional forms to describe these curves. It is not even known if an unsaturated flow condition can exist in a fracture (other than film flow), with some researchers suggesting an "on-off" mechanism where flow can occur when the fracture is fully saturated and no continuous flow occurs at all other levels of saturation. If information about these curves can be deduced from observing the water movement in the unsaturated fractures, it is expected that the data will yield a characteristic curve resembling a step function.

The general lack of data and understanding of the phenomena involved in fracture hydrology makes the results difficult to anticipate. General results that can be expected and some methods for data analysis have been presented, with the information from the experiments serving to direct further analysis.

EXPERIMENTAL APPARATUS CONFIGURATION

General Description

The experimental apparatus is designed to measure water movement through core samples at above-ambient pressures to monitor the flow characteristics of water through a fractured rock. The individual components are, in general, off-the-shelf equipment with modifications specified to suit experimental needs. The electrode grid applied to the fracture surface and the core holder were designed in-house. The basic experimental apparatus and configuration are similar to pressurized permeability apparatus used by other investigators (9,11,12), with modifications made to support the operating conditions and instrumentation needs for the planned fracture flow experiments. The core sample to be tested will be placed in a pressure vessel capable of providing for a confining pressure of up to 3000 psi (200 bars) to be applied to the sample. This will be adequate to simulate the in-situ pressure condition of the samples to be tested. The core samples will be physically isolated from the confining fluid by coating the samples with a fluorosilicone sealant. The core holder assembly that supports the core sample is shown in Figure 6a. The pore fluid, water, will be able to enter through either end of the sample in the pressure vessel and can be pressurized to give pore pressures up to 750 psi, which is greater than the anticipated in situ pore pressures of the rocks to be tested. A schematic diagram of the experimental apparatus and configuration to be used is shown in Figure 10. The specifications of the major equipment and instrumentation components are listed in Table 2.

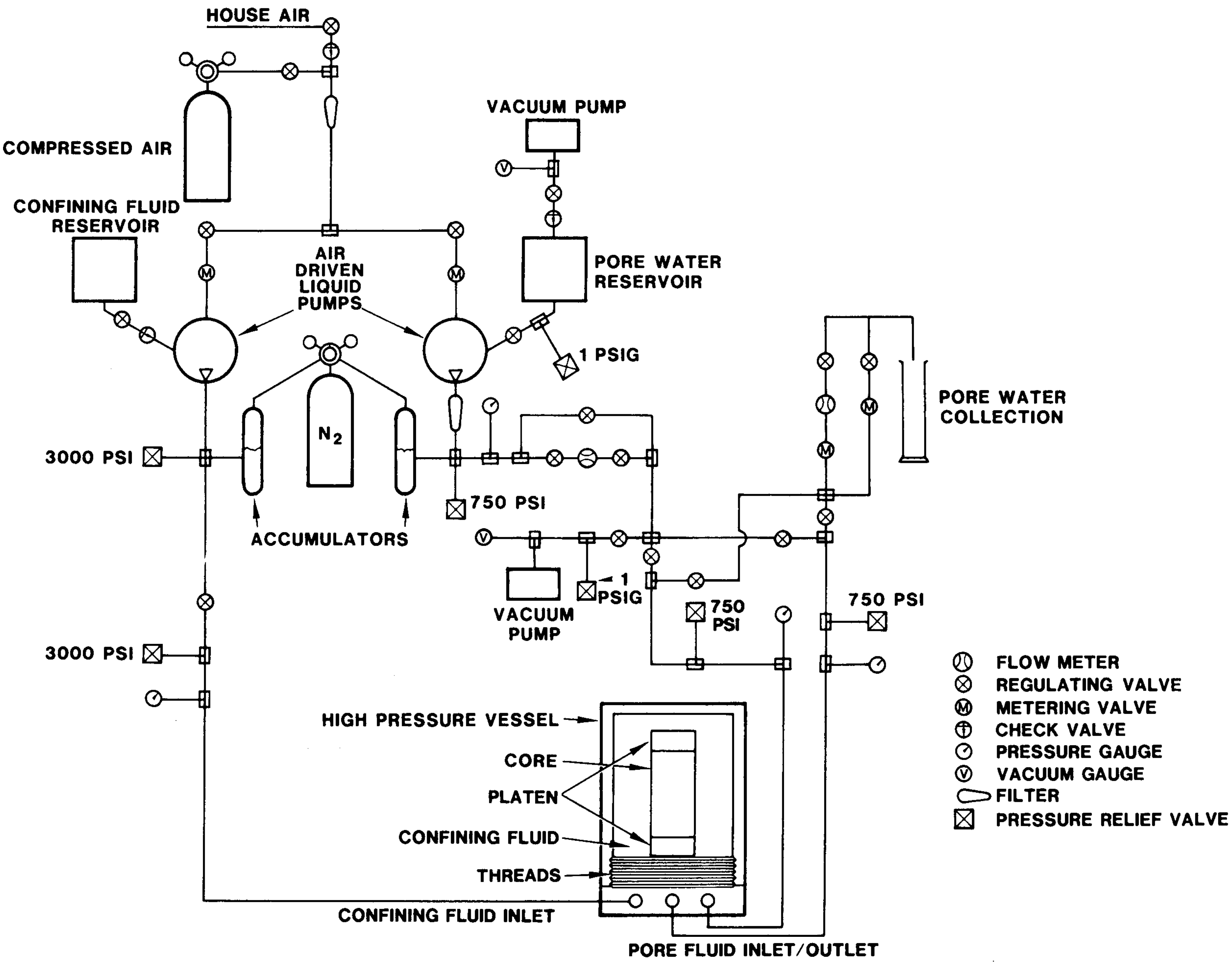


Figure 10. Fracture Flow Experimental Apparatus Schematic

Table 2

Equipment and Instrumentation Specification

Description	Specifications
Structural Behavior Engineering Labs Corp., modified Rockwell model 10 pressure vessel.	Max. Working Pressure: 3000 psi Proof tested to 10,000 psi Heating Jacket Assembly to control temperature to 425°C 14 fusite feed thrus and 2 25-pin connections for instrumentation.
Haskel Inc., air-driven liquid pump, model DSF-25 (confining fluid pump).	Max. outlet pressure: 4000 psi Max. flow rate @2000 psi: 400 cubic inches/min
Haskel Inc., air-driven liquid pump, model DSF-B22 (pore fluid pump).	Max. outlet pressure: 3200 psi Max. flow rate @1000 psi: 775 cubic inches/min
Hydrodyne Corp., bladder accumulators (water or oil) model BR30-60WS.	Max. working pressure: 3000 psi Capacity: 1 quart
Flow Measurement Systems, Inc., (2) fluid flow meters, model FMT-N.01-L410 and Indicator/ Totalizer, model PC402AA1L.	Flow rate range: 4-60 cm^3/min Operating temperature: 60-400°F Max. working pressure: 2500 psi
Precise Sensors Inc., (2) sealed pressure transducers, model 6540 (for differential pressure measurement across sample).	Operating pressure: 0-750 psi Combined non-linearity and hysteresis: <0.5% FSO Operating temperature: 60-350°F
Precise Sensors Inc., (2) sealed pressure transducers, model 6540 and indicating system, model 455-FR-3000-01-S-BD10-BC0-Q.	Operating pressure: 0-3000 psi Combined non-linearity and hysteresis: <0.25% FSO Operating temperature: 60-350°F
(2) vacuum pumps.	Max. vacuum: 0.01 Torr
Omega Corp., digital temperature indicator for type K thermocouples, 400 series.	Operating temperature range: -133°C - >1000°C Accuracy: 1°C
Hewlett Packard Impedance Analyzer Model II HP4192ALF.	Frequency Range: 5 Hz-13 MHz.

Table 2 (cont'd.)

Equipment and Instrumentation Specification

Hewlett Packard HP85B computer.	Enhanced basic language Dual disk drives, 500K byte capacity/disk 62650 bytes read/write memory
Hewlett Packard Digital Voltmeter, Model 3456A.	100 nanovolt sensitivity at 48 readings/sec with 6.5 digit resolution; HP-IB compatible
Hewlett Packard data acquisition/ control unit (scanner) Model 3497A.	Digital or analog control, includes real-time clock, 1 micro-volt sensitivity with reading rates to 300/sec

System Components

Pore-Fluid Loop

Water will be used as the pore fluid and will be deaerated using a vacuum pump to reduce errors in instrumentation responses due to trapped gases in the fluid. The water can be pressurized up to 750 psi by an air-driven liquid pump manufactured by the Haskel Corp. The pump is driven by gas pressure up to 150 psi to be provided by a combination of house air pressure and bottles of compressed air or nitrogen. The pump automatically ceases pumping (stalls) at the pressure preset by adjustment of the air-drive pressure control. A bladder-type accumulator manufactured by the Hydrodyne Corp. will help maintain pressure and damp any pressure surges in the pore-fluid system. The pore fluid then passes through a 65/35-micron, dual-disk filter. Flow meters, capable of measuring fluid flow as low as 4 cm^3 per minute will monitor the inlet fluid flow rate upstream from the pressure vessel and the effluent flow rate after the fluid leaves the pressure vessel. Valving will allow the pore fluid to bypass the upstream flow metering system, manufactured by Flow Measurement Systems Inc., when the flow rate exceeds 60 cm^3 per minute. This is the maximum flow rate the flow meters can measure without the possibility of damage to the instrumentation. The system is valved to allow the inlet pore fluid to be directed to either the top or the bottom of the test specimen and the outlet pore fluid to leave from the remaining end. The tests to be performed require the option of having the pore-fluid inlet at either the top or bottom of the sample. Just before the pore fluid collection system, the pore water will be valved to allow the bypass of the outlet flow metering system, also manufactured by Flow Measurement Systems, Inc. Fine metering valves will be used to control backpressures at the pore-fluid exit. The pore-water collection system will consist of either a volumetric or gravimetric system, depending on the experimental requirements. A vacuum pump incorporated into the pore-fluid loop will aid in the drying of the test specimen without removing it from the pressure vessel. Pressures will be monitored at the inlet and outlet of the pressure vessel with differential pressure transducers manufactured by the Precise Sensor Corp.

Confining-Fluid Loop

The confining fluid will be silicone-based and will be pressurized to the desired confining pressure (up to 2500 psi) by an air-driven liquid pump manufactured by Haskel Corp. The pump is driven by gas pressure up to 150 psi to be provided by a combination of house air pressure and bottles of compressed air or nitrogen. The pump automatically ceases pumping (stalls) at the pressure preset by adjustment of the pre-set air drive pressure. A bladder-type accumulator manufactured by the Hydrodyne Corp. will help maintain the confining pressure and will assist in damping pressure surges in the confining fluid caused by the pumping action of the air driven pumps. The pressure of the confining fluid will be monitored using a pressure transducer manufactured by the Precise Sensor Corp. and the temperature monitored using a thermocouple.

Pressure Vessel

The pressure vessel, manufactured by Structural Behavior Engineering Labs, Inc. (SBEL), is capable of withstanding confining pressures of 3000 psi. A heating jacket attached externally to the pressure vessel has a capability to heat the core to 225°C. The core samples to be tested, with dimensions of 5-7 cm in diameter and 5-15 cm in length, will sit on a platen in the interior of the pressure vessel. To accommodate the instrumentation to be attached to the sample, 14, 4-pole fusite pins internal to the pressure vessel will be connected to two, 25-pin connectors incorporated into the design of the pressure vessel. A port has also been added to accommodate a thermocouple to monitor the confining-fluid temperature.

Instrumentation

A schematic diagram of the instrumentation system to be used is shown in Figure 11. The specifications of the major instrumentation components are shown in Table 2. The data acquisition/control unit (scanner) will be used to multiplex the signals from the pressure, temperature, and fluid-flow instrumentation components to the digital voltmeter. It will also multiplex the impedance measurements from the electrode grid on the fracture surface to the impedance analyzer. The scanner provides control functions through a real-time clock.

The digital voltmeter is needed to achieve high precision and accuracy in these low-voltage-level measurements. Analog scanning rates of 330 channels/second can be obtained between the scanner and the voltmeter. The voltmeter built-in memory allows storage of up to 350 readings with a programmed time delay from 0 to 1000. This feature allows efficient use of computer time for long measurement operations. Before the signal enters the digital voltmeter, analog outputs will be made to a strip chart recorder and indicators as visual aids to the operator.

Output signals from both the digital voltmeter and impedance analyzer will be transmitted to a Hewlett Packard HP-85B computer which contains 64K bytes of memory, of which 32K bytes are directly accessible as read/write memory. The other 32K bytes are electronic disk memory with print specifications 15 times faster than the flexible disk. The response signals from the flow meters, pressure transducers, thermocouples,

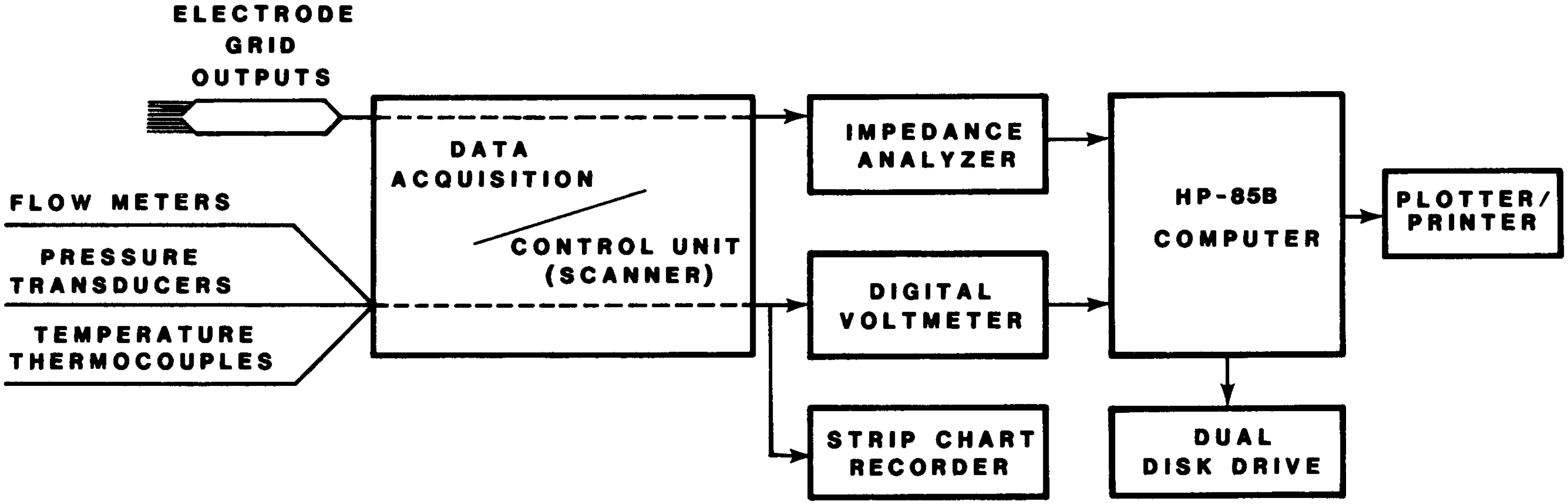


Figure 11. Instrumentation/Data Acquisition System

and impedance analyzer will all be monitored by the HP-85B computer and stored on flexible disk using the dual disk drive.

The signals monitored will include signals from the pressure transducers measuring the confining pressure, the upstream pore-fluid pressure, the differential pressure across the sample, the confining-fluid temperature, the pore-fluid temperature, the upstream and downstream fluid flow rates, and the electrical impedance measurements from the electrode pairs on the fracture surface.

QUALITY ASSURANCE

The following measures are being instituted in an attempt to comply with the spirit of the Organization 6310 Quality Assurance Program Plan (QAPP) dated 2/6/84. The QA Chief has designated this work as Minor Level III.

Quality Assurance Procedure (QAP)

A QAP was written to define quality assurance procedures for operation of the experimental apparatus described in this document. A copy of the QAP is included in Appendix C.

Safe Operating Procedure (SOP)

An SOP was written prior to the start of the experimental testing procedures. The SOP provides procedures that facilitate safe operation. It also provides for test procedures that can be repeated and referenced and can aid in achieving accurate and precise data. A copy of the SOP is included in Appendix D

Identification and Control of Samples

Test samples will be controlled and documented before, during, and after the completion of testing. All test samples will be stored in containers marked with their hole identification and depth interval (feet) before and after testing. A sample identification may be added to the hole and depth interval at the discretion of the operator.

When the test sample arrives at SNL by direct shipment from the U.S. Geological Survey core library, QAP XI-11 will be followed (13). For test samples received by means other than direct shipment from the USGS, depth interval, hole identification, and a sample identification designation (optional) will be maintained in an SNL-issued engineering notebook.

Control of Measuring and Test Equipment

Whenever possible, the SNL Measurements Standards Laboratory will calibrate and recall for calibration the measuring and test equipment used in this system. If the SNL Measurements Standards Laboratory does not possess the capability to calibrate a device, the manufacturer's certificate of calibration, if referencable to a known standard, will be acceptable. If this occurs, it will be the responsibility of the personnel operating the system (as defined in the SOP) to have the equipment calibrated on an appropriate recall basis. Calibration guidelines that will be followed on the measuring and test equipment are listed in Table 3.

Table 3

Calibration Guidelines

Instrument	Manufacturer	Model Number	Calibration Location	Frequency of Calibration
Data acquisition/ control unit	Hewlett Packard	3497A	SNL Div. 7243	6-month intervals
Digital voltmeter	Hewlett Packard	3456A	SNL Div. 7243	6-month intervals
Impedance analyzer	Hewlett Packard	4192A	SNL Div. 7243	6-month intervals
Calibrator	Soltec	6141	SNL Div. 7243	6-month intervals
Strip chart recorder	Houston Instrument	4990	SNL Div. 3425	12-month intervals
Pressure transducer indicating system	Precise Sensors		SNL Div. 7546	6-month intervals
Thermocouples	Autoclave	TP4401-K TP4400-K	SNL Div. 7243	12-month intervals
Temperature indicator	Omega	400-A	SNL Div. 7243	6-month intervals
Analytical balance	Mettler	PC4400	SNL Div. 3425	12-month intervals
Flow meter/ flow meter indicating system	Flow Measurements Systems	FMT-N.01-L410/ PC402AA1L	Flow Measurement System*	6-month intervals

* Not capable of being calibrated at SNL and will be calibrated by the manufacturer, with documentation as to this referencable calibration using Nationl Bureau of Standards Procedures.

Sample Preparation

Any physical treatment that the test sample is exposed to will be documented in an SNL-issued engineering notebook. Procedures designed to obtain the desired moisture content of the test samples and processes used in preparing the sample and core holder are documented in Appendix A.

Quality Assurance Records

At the end of each quarter in which testing has occurred, all test data are to be copied and sent to the Org. 6000 QA Chief. A cover letter verifying that the contents have been furnished will be sent with the data. The Org. 6310 Department Manager and Org. 6313 Division Supervisor will be on distribution of the cover letter (without attachments). At the end of each month, copies of the data stored on floppy disks will be duplicated and kept in a separate location from the original test data.

System Function Verification

Before testing of a sample, there will be a two-part system function verification to check the electrical characteristics of the electrode grid pattern on the fracture face and to check the instrumentation/computer system electronics.

After the core holder has been assembled and electrically connected to the fusite connectors in the pressure vessel, the electrical characteristics of the electrode grid pattern will be checked using the system digital voltmeter and the results recorded in an

SNL-issued engineering notebook. To verify that the instrumentation/computer system is functioning properly, the Soltec Calibrator will be used to input a known voltage to the scanner. The voltage will be fed through the entire instrumentation system and be recorded by the computer. Any voltage drop or other electrical problems in the system should be exposed during this procedure. The results will be recorded in an SNL engineering notebook.

SAFETY

A Pressure Safety Analysis Report (PSAR) on the Division 6313 fracture flow apparatus has been written to meet the SNL Pressure Safety requirements and has met the necessary approvals. A copy of this report is included in the SOP in Appendix D.

The SNL Division 6313 Pressure Safety Advisor and Division 3441 Safety Engineering consultant will personally inspect the system prior to its operation.

SUMMARY

In a fractured rock formation, such as the Topopah Spring member of Yucca Mountain, much of the information necessary to model the water movement using computer codes must be obtained through small-scale or laboratory experimental measurements; little of this information is available for the fractured tuff of interest to the NNWSI project. The purpose of this work is to develop an experimental apparatus that will enable us to increase our understanding of flow characteristics in a natural, discrete fracture and, through this knowledge, to increase our ability to estimate the water movement through a fractured tuff unit. The experiments described in this document are an initial laboratory effort intended to ascertain the important parameters needed for modeling. In addition to qualitative information, the experiments can provide needed quantitative hydrological data: the determination of the fracture permeability at various confining pressures is needed for estimating the saturated conductivity of a volume of rock mass at various depths, and information on the fracture permeability response to temperature is needed for modeling the repository near waste canisters. The results of these experiments will also provide direction for future efforts to obtain the information needed for modeling.

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APPENDIX A

Sample Preparation

Sample Preparation

A. Log In/Log Out

1. If the core sample arrives by direct shipment from the U. S. Geologic Survey at Mercury, Nevada, log in/log out procedures per SNL QAP XI-11 (13) will be followed.

2. Samples arriving by other means will be logged in and out through entries in an SNL Patent Notebook.

3. The sample history of the core samples prior to testing will be documented in an SNL Patent Notebook. This includes the mechanical, pressure/vacuum and thermal history of the sample as well as its exposure to solvents.

B. Machining of Samples

1. All machining of core samples will follow the requirements stated in Section 5.4 of QAP XI-11.

2. Posttest samples and scrap will be handled per the requirements stated in Section 5.6 of QAP XI-11.

C. Placement of the Copper Electrodes on the Fracture Surface

A vacuum evaporation process will be used to emplace copper electrodes on one fracture surface of the test sample. The procedure is documented in Appendix B. The electrode thickness will be approximately 0.00025-0.00050 inches and the width approximately 0.1-0.2 inches. The spacing between the electrodes will range from 0.1-0.5 inches, as desired.

D. Soldering of the Instrumentation Wires to the Electrodes

To attach wires to the electrodes emplaced upon the fracture surface, a soldering iron heated to between 500 - 600°F will be used to solder insulated copper wire to the copper electrodes. The solder to be used is a resin-core solder, containing a non-corrosive and electrically non-conductive flux residue. Gloves will be used at all times to reduce the chance of contaminating the sample. The use of degreasing solvents will be avoided whenever possible to reduce any possible damage to the electrodes.

E. Moisture Content of the Test Sample

1. Vacuum Saturation of Test Specimens

Vacuum saturation has proved to be a time effective method of saturating natural (geologic) materials and will be used on test samples which need to be saturated prior to testing. The vacuum saturation process for test samples will be performed external to the pressure vessel after attaching the electrical leads to the electrode grid. The procedure empirically derived by Schwartz (15) will be followed and has been written to meet or exceed ASTM requirements (16) for obtaining constant weight values during a saturation process. After vacuum saturation has been completed, the surface of the test sample will be allowed to dry and the adhesive sealant will be placed on the sample. The adhesive will be cured in high humidity conditions, an electrical check made on the electrical connections, and the sample then submerged in water. Final preparations prior to loading in the pressure vessel include sealing the porous stone end caps and platens to each end of the test sample using an adhesive sealant.

2. Vacuum Dehydration of the Test Specimens

Vacuum dehydration is used as a means of drying the test sample without heating the test sample above ambient temperatures. The test sample will be vacuum dehydrated either before the attachment of electrical wires and adhesive sealant using a vacuum apparatus external to the experimental apparatus or after the prepared test sample is placed in the pressure vessel. Vacuum capability incorporated into the pore-fluid loop will be used in the case of the latter. In either case, a vacuum of less than 0.1 Torr will be used to dry the sample.

When a test sample is evacuated external to the experimental apparatus, it will be weighed using an analytical balance until it is determined that it has been dried to constant weight. Care will be taken to maintain sample dryness using a dessicator when possible until the test sample is loaded into the pressure vessel.

When a sample is vacuum dried while still within the pressure vessel, it is not possible to determine its dryness by gravimetric analysis. Therefore, samples of similar physical properties (bulk density and porosity) and dimensions will be used to optimize the vacuum drying procedure within the pressure vessel. The actual test sample will then meet or exceed the vacuum drying regime determined to obtain constant weight on the samples.

APPENDIX B

Procedure for Placement of an Electrode Grid on Rock Samples

Procedure for Placement of an Electrode Grid on Rock Samples

1. Wash off excess dust and loose dirt from the fracture surface with water, using a soft brass brush.

2. Dry using soft paper towels and then using air.

3. Degrease (using Chloroethane Nu).

4. Wrap wire around sample for handling during electro-less copper process and during electroplating, making sure the wire does not touch the fractured surface of the core samples.

5. Degrease again.

6. Electro-less copper deposition.
   - 6.0 Immerse core into heated (130°F) Conditioner 1175 (a slight etchant) for 5 minutes.
   - 6.1 Rinse thoroughly with water.
   - 6.2 Immerse core sample into ammonium persulfate for 1 minute.
   - 6.3 Rinse with deionized water.
   - 6.4 Immerse into 10% sulfuric acid for 1 minute.
   - 6.5 Rinse with deionized water.
   - 6.6 Place core sample in a 1000 ml beaker and fill with Cataprep 404 (a catalytic preparation) and soak for 10 minutes.
   - 6.7 Remove Cataprep 404 from beaker and fill with Cataposit 44, (a deposition solution) leaving rock core immersed for 15 minutes.
   - 6.8 Remove rock core from beaker and rinse.
   - 6.9 Immerse core into electro-less copper solution for 15 minutes and rinse.

7. Electroplate copper at 20 amps per sq.ft. for 15 minutes. Copper thickness should be around 0.00025 inches.

8. Rinse.

9. Dry with air.

10. Draw line across fracture surface using "Pilot SC-UF" permanent ink.

11. Immerse plated core sample with inked lines in ammonium persulfate solution to etch excess copper off.

12. Remove residue ink with acetone.

APPENDIX C

Quality Assurance Procedure

Quality Assurance Procedure for Operation of the SNL Division 6313 Fracture Flow Apparatus

Page	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Rev	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A

Approved by:

Barry Schwartz
Investigator and Author
B. M. Schwartz, 6313

8/27/84
Date

Elmer A. Klavetter
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E. A. Klavetter, 6313

8/28/84
Date

Division Supervisor
J. R. Tillerson, 6313

10/13/84
Date

D. C. Reda
Independent Reviewer
D. C. Reda, 1512

7/24/84
Date

Gary R. Romero for
Organization 6300 QA Chief

10-22-84
Date

1.0 Purpose and Content of Document

1.1 Purpose

The purpose of this document is to define quality assurance procedures for operation of an experimental system investigating the movement of water through fractured rock samples. The work is being performed in support of the Nevada Nuclear Waste Storage Investigation Program (NNWSI).

1.2 Content

The document will describe:

- Quality Classification Level (2.0)
- Approval Requirements (3.0)
- Personnel Qualifications (4.0)
- Sample Handling (5.0)
  - a. Log In/Log Out of Samples (5.1)
  - b. Machining of Samples (5.2)
  - c. Sample Encapsulation (5.3)
  - d. Moisture Content (5.4)
  - e. Placement of Electrodes on Samples (5.5)
  - f. Signal Output from Electrodes to Instrumentation (5.6)
- Equipment Specifications (6.0)
- Calibration Guidelines for Instrumentation (7.0)
  - a. Calibration Checks Performed by the Experimenter (7.1)
- Posttest Sample Storage (8.0)
- Documentation Requirements (9.0)
- Deviations from this QAP (10.0)
- Experimental Apparatus Schematic (11.0)
- References

2.0 Quality Classification Level

The level is minor (Level III) at the time of this writing.

3.0 Approval Requirements

The persons listed below shall review and approve this document.

(1) The author and investigator
(2) The principal investigator
(3) An additional reviewer with "hands-on" experience from outside the department of the investigators
(4) The division supervisor of the investigators
(5) The QA chief of the investigators

4.0 Personnel Qualifications and Requirements

4.1 Qualifications

Persons engaged in these activities shall have demonstrated capability in laboratory and documentary skills by previous training and experience.

5.0 Sample Handling

The information in this section shall be entered into an experimental logbook unless specified otherwise.

5.1 Log In/Log Out of Samples

- If the sample arrives by direct shipment from the US Geological Survey at Mercury, Nevada, Log In/Log Out procedures per QAP XI-11 will be followed.
- Samples arriving by other means will be logged in and out using hole and depth interval identifications and/or outcrop/sample identification system.
- The history of samples prior to testing will be documented. This includes mechanical, saturation and thermal history as well as exposure to solvents.

5.2 Machining of Samples

- All machining of samples shall follow the requirements stated in Section 5.4 of QAP XI-11.
- Posttest samples and scrap shall be handled per the requirements of Section 5.6 of QAP XI-11.

5.3 Sample Encapsulation

- The methods and materials used to encapsulate the samples (ie, adhesives and tubing) shall be documented in a thorough manner.

5.4 Moisture Content

- The methods used to saturate and/or dry the samples, both prior to and after entry into the pressure cell, shall be documented in an experimental logbook.

5.5 Placement of Electrodes on Samples

- The processes and materials used to emplace electrodes on the fracture surfaces shall be documented in a thorough manner for each sample tested.

5.6 Signal Output From the Electrodes to Instrumentation

- The methods and materials used in signal output from the fracture face to instrumentation shall be documented in a thorough manner.

Note: Subsections 5.5 and 5.6 pertain only to test samples which will be used in tests where impedance measurements will be made. It shall be noted in the experimental logbook which test samples impedance measurements will be made.

6.0 Instrumentation and Data Acquisition Specifications (See also Figure, Page 7 and Schematic, Page 15)

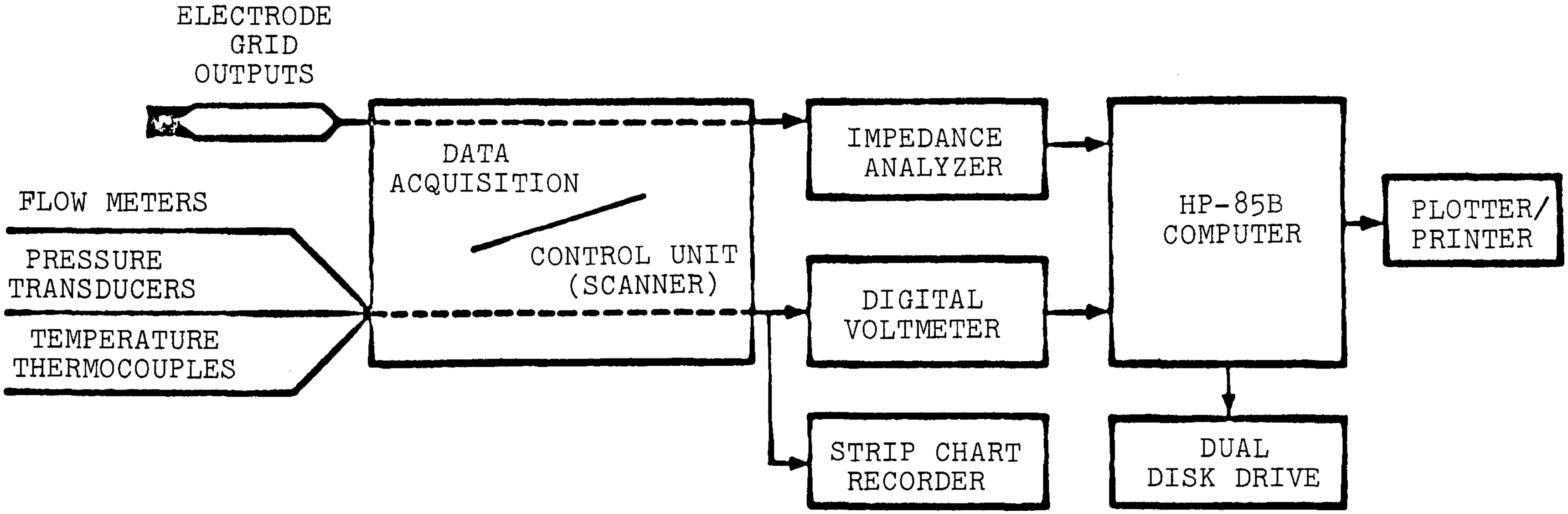
This table documents the specifications of instruments and the data acquisition system used in these experiments.

Description	Specifications
Pressure Vessel	
Structural Behavior Engineering Labs Corp., Modified Rockwell Model 10 Pressure Vessel	Max Working Pressure: 3000 psi Proof tested to 10000 psi Heating Jacket Assembly to control temperature to 425°C 14 fusite feed thrus and 2 25-pin connections for instrumentation
Liquid Pumps	
Haskel, Inc., Air-Driven Liquid Pump, Model DSF-25 (confining fluid pump)	Max outlet pressure: 4000 psi Max flow rate @2000 psi: 400 cubic inches/min.
Haskel, Inc., Air-Driven Liquid Pump, Model DSF-B22 (pore fluid pump) 775 cubic inches/min.	Max outlet pressure: 3200 psi Max flow rate @1000 psi:
Fluid Dampeners	
Hydrodyne Corp., Bladder Accumulators (water or oil) Model BR30-60WS	Max working pressure: 3000 psi Capacity: 1 quart
Flow Meters	
Flow Measurement Systems, Inc., (2) Fluid Flow Meters, Model FMT-N.01-L410 and Indicator/Totalizer, Model PC402AAIL	Flow rate range: 4-60 cm^3/min Operating temperature: 60°-400°F Max working pressure: 2500 psi
Pressure Indicating System	
Precise Sensors, Inc., (2) Sealed Pressure Transducers, Model 6540 (for differential pressure measurement across sample)	Operating pressure: 0-750 psi Combined nonlinearity and hysteresis: <0.5% FSO Operating temperature: 60°-350°F
Precise Sensors, Inc., (2) Sealed Pressure Transducers, Model 6540, and Indicating System, Model 455-FR-3000-01-S-BD10-BCD-Q	Operating pressure: 0-3000 psi Combined nonlinearity and hysteresis: <0.25% FSO Operating temperature: 60°-350°F
Precise Sensors, Inc., (2) Sealed Pressure Transducers, Model 6540 (for differential pressure measurement across sample)	Operating pressure: 0-125 psi combined nonlinearity and hysteresis: <0.5% FSO Operating temperature: 60°-350°F

Description	Specifications
Vacuum Pump	Max vacuum: 0.01 Torr.
Thermocouple Omega Corp., Digital Temperature Indicator for Type K Thermocouples, 400 series	Operating temperature range: -133°C - >1000° C Accuracy: 1°C
Data Acquisition Device for Electrode Grid Impedance Measurements Hewlett Packard Impedance Analyzer, Model II HP4192ALF	Frequency range: 5 Hz-13 MHz
Data Acquisition Devices Hewlett Packard HP85B Computer	Enhanced basic language dual disk drives, 500 K byte capacity/disk 62,650 bytes, read/write memory
Hewlett Packard Digital Voltmeter, Model 3456A	100 nanovolt sensitivity at 48 readings/sec with 6.5 digit resolution; HP-IB compatible
Hewlett Packard Data Acquisition/Control Unit (Scanner), Model 3497A	Digital or analog control, includes real-time clock, 1 microvolt sensitivity with reading rates to 300/sec.
Analytical Balance Accessories O Haus Calibrated Metric Weight Set, Sandia Calibration, SNLA-390	30 gram - 1 kg
Gravimetric Measurements Mettler Analytical Balance, Model PC4400	Toploading, 0.01 gram resolution
Satorius Analytical Balance, Model 1020	Toploading, 1.0 gram resolution
Digital Multimeter (General Usage) Keithley Digital Multimeter Model 177	4 1/2 Digit display 1uV/Digit and 1mΩ Digit resolution

Note: All electronic devices should be turned on (warmed up) for 30 minutes prior to usage.

Instrumentation/Data Acquisition System.



7.0 Calibration Guidelines: This table documents the required calibrations for instrumentation and data acquisition devices used in these experiments.

Instrument	Manufacturer	Model Number	Calibration Location	Frequency of Calibration
Data Acquisition/ Control Unit	Hewlett Packard	3497A	SNL Div 7243	6-month intervals
Digital Voltmeter	Hewlett Packard	3456A	SNL Div 7243	6-month intervals
Impedance Analyzer	Hewlett Packard	4192A	SNL Div 7243	6-month intervals
Calibrator	Soltec	6141	SNL Div 7243	6-month intervals
Strip Chart Recorder	Houston Instrument	4990	SNL Div 3425	12-month intervals
Pressure Transducer Indicating System	Precise Sensors		SNL Div 7546	6-month intervals
Thermocouples	Autoclave	TP4401-K TP4400-K	SNL Div 7243	12-month intervals
Temperature Indicator	Omega	400-A	SNL Div 7243	6-month intervals
Analytical Balance	Mettler	PC4400	SNL Div 3425	12-month intervals
Flow Meter/ Flow Meter Indicating System	Flow Measurements Systems	FMT-N.01-L410/ PC402AAIL	Flow Measurement System*	6-month intervals
Digital Multimeter	Keithley	177	SNL Div 7243	6-month intervals

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Documentation of these calibrations will be maintained in a notebook by the experimenter and recordkeeping requirements defined in Section 10.0 of this QAP will be fulfilled.

*Not capable of being calibrated at SNL and will be calibrated by the manufacturer, with documentation as to this referencable calibration using National Bureau of Standards Procedures.

7.1 Calibration Checks Performed by the Experimenter

7.1.1 Flow Meters

Once per week on weeks that the flow meters are utilized, the flow meters will have their total flow and flow rates checked. This calibration check, as described below, will be performed gravimetrically using an SNL calibrated balance, time source, and weights. The calibration check data will be entered into an experimental logbook.

7.1.1.1 Procedure for Flow Meter Calibration Check:

1. Turn the flow meter on and allow to warm up for at least 30 minutes prior to usage.

2. Connect the analog outputs of the flow meter to a strip chart recorder or another recording device listed in Section 6.0.

3. Have water flowing through the flow meter at a rate anticipated to be approximately that of the next rock sample run.

4. Have tubing attached from the downstream end of the downstream flow meter to a container located on a calibrated balance (listed in Section 6.0).

5. With the water flowing at a steady rate into the container, note the weight of the container simultaneously with the start of the strip chart recorder and the taring of the flow meter. Record the weight.

6. After an amount of water similar to that planned for the test has flowed through the meter, note the weight of the container and the flow value simultaneously with stopping the strip chart recorder. Record the weight.

7. Calculate the rates and totalized flow from the analog outputs and digital indicator.

8. Repeat steps 1-7 for all flow meters to be used.

7.1.1.2 Acceptance/Rejection Criteria

A flow meter is "in-specification" when the total flow and the flow rate values are in error less than or equal to 2.5 percent from the gravimetric measured value. If the calibration check shows that the flow meter is "out-of-specification," then tests on a rock sample are not to be done until the problem is corrected and verified by subsequent calibration checks.

7.1.1.3 Nonconformance Documentation

Any tests performed during the period that the flow meter(s) may have been out of specification shall be flagged accordingly using notations on all records where data are stored, including laboratory notebooks, strip charts, computer print-outs, and disks. The flow meters shall be identified by their model and serial numbers.

7.1.2 Pressure Transducers

The pressure transducers are part of the pressure indicating system defined in Section 6. There are 6 transducer channels which are defined in Section 7.1.2.2 and two "Delta P" channels defined in Section 7.1.2.3. The calibration check data and any adjustments made to the electronics will be entered into an experimental logbook along with reference to the procedures used in performing the calibration check.

7.1.2.1 Procedures for Checking the Zero Readout and the Calibration Bridge (R Factor) (To be performed once per month in months that the pressure transducers are utilized.)

Note: This procedure applies to pressure transducer Channels 1-6.

1. Apply a vacuum of approximately 1 torr to the pressure transducers which are to be utilized during the course of the month.

2. Move the "channel selector" button to the desired pressure transducer channel. (Located on the front panel of the Precise Sensor, Inc.'s pressure indicating system)

3. The digital indicator should read zero. If it does not, then turn the "zero/fine zero" adjustment until it reads zero.

4. Depress the "calibration" button located on the front of the Precise Sensor, Inc.'s pressure indicating system)

5. The readout on the digital indicator should match the "R factor" within 0.25% of the value for the respective channel printed on the SNL calibration sticker. If it does not, turn the "span" adjustment until the "R factor" displayed on the digital indicator falls within this range.

6. The signal from the analog outputs of the pressure transducers should match the "R factor" value for the respective channel printed on the SNL calibration sticker when read from a digital multimeter or voltmeter listed in Section 6.0.

7. Repeat steps 1-6 until the zero values and "R factors" are displayed as they should be for two consecutive cycles.

7.1.2.2 Procedure for checking the Ambient Pressure Readout (To be performed once per week in weeks that the pressure transducers are utilized). The ambient pressure will be determined just prior to this calibration check using a mercury barometer.

Note: This procedure applies for Channels 1-6.

8. Slowly release the vacuum from the pressure transducers and allow the pressure to equilibrate at the ambient level for at least 5 minutes.

9. Check each digital indicator channel according to the table below which gives the acceptable variation from nominal (ambient) for each channel.

Channel No.	Operating Range (psi)	Acceptable Variation (psi)
1	0-3000	± 1
2	0-3000	± 1
3	0-200	± 0.3
4	0-200	± 0.3
5	0-20	± 0.3
6	0-20	± 0.3

7.1.2.3 Procedure for Checking the "Delta P" Readout (To be performed once per week in weeks that the pressure transducers are utilized)

Note: This procedure applies to Channels 7 and 8. Channel 7 is the "delta P" for Channels 3 and 4. Channel 8 is the delta P" for Channels 5 and 6. (The procedure is followed after pressure transducer gauges 3 - 6 are under a vacuum of approximately 1 Torr)

10. Move the pressure indicating device "channel selector" button to Channel 7. The digital indicator should read zero ± 0.1 psi. The analog Output from Channel 7 should read O ± 0.5 millivolts when read from a Digital multimeter or voltmeter listed in Section 6.0.

11. Move the "channel selector" button to Channel 8. The digital indicator should read zero ± 0.1 psi. The analog output from Channel 8 should read O ± 0.5 millivolts when read from a digital multimeter or voltmeter listed in Section 6.0.

7.1.2.4 Acceptance/Rejection Criteria

A pressure transducer is in-specification when Steps 7 and 9 of Sections 7.1.2.1 and 7.2.2.2, respectively, have been successfully completed.

A "Delta P" channel is in-specification when Steps 10 and 11 of Section 7.1.2.3. have been successfully completed.

7.1.2.5 Nonconformance Documentation

Any tests performed during the period that the pressure transducers may have been out of specification shall be flagged accordingly using notations on all records where data are stored, including laboratory notebooks, strip charts, computer print-outs, and disks. The pressure transducers shall be identified by their model and channel numbers.

7.1.3 Calibration of the Laboratory Impedance Measurements for Fracture Flow (LIMFF) System

(This subsection pertains only to samples with emplaced electrode grids.)

A device will be fabricated to attempt to quantify the signal output from the electrodes to the Impedance Analyzer. The device will simulate a fracture by using parallel plates with a definable volume. The calibration will consist of two areas:

1. Establishment of the relationship of the magnitude of the signal output with the volume of water between the two tested electrodes.
2. Establishment of the relationship between the transient impedance response of an electrode pair and the shape of the fluid front.

The second calibration area is non-essential and is necessary only for more accurately interpreting the movement of water through a fracture. It is important for understanding the basic phenomenology involved in water movement through an unsaturated fracture with variable surface roughness characteristics. As such, it will support general research on water movement through fractures and is expected to provide data that is qualitative in nature. The first area of calibration is necessary for the quantification of fracture aperture with the signal response. These calibrations are necessary only for data reduction and analysis and will in no way affect the measurement or recording of the experimental data.

The following items shall be documented in an experimental logbook:

- The method of fabrication of the "calibration device;"
- A listing of all equipment used in measurements;
- The actual data obtained from these runs; and
- A description of the method(s) of the data reduction and analysis.

7.1.4 "Whole System" Calibration Check

This calibration check will attempt to simulate actual test conditions and verify that flow and pressure measurements are accurate, as well as evaluating seals for leaks. This check will be performed twice per year (during the time period of experimentation) and documented in an experimental logbook.

Description of device: A cylindrical core (5.525cm diameter x 6.35cm long) was machined from aluminum. A hole was drilled through the center of the cylinder axially of the following dimensions:

Length: 2.92×10^{-3} m L/d ~ 10
Diameter: 2.71×10^{-4} m

This "core" is to be mounted to the core holder using the same flexible jacketing materials to those used on rock cores. A confining pressure will be applied to its circumferential surface area. Steady state pore fluid flow ranging from 4 to 60 cm^3/minute will be forced through the capillary tube and the resultant pressure drop measured. The cylindrical core will be inspected by SNL standards to verify the capillary tube diameter prior to usage, and documented per Section 10.0.

The permeability of this device will be measured using flow meters and/or gravimetrically. If the permeability (k) obtained during this check deviates from the expected by greater than or equal to ± 5% and the discrepancy cannot be attributed to faulty seals, then Sections 7.1.1.1 through 7.1.3 should be followed to assess the accuracy of the flow and pressure indicating systems.

$k(\text{theoretical}) = (r^2/8) = 2.31 \times 10^{-9}\ m^2$

where r = radius = 1.36×10^{-4} meter

Therefore: ± 5% yields:

k minimum = $2.19 \times 10^{-9}\ m^2$
k maximum = $2.43 \times 10^{-9}\ m^2$

7.1.5 System Function Verification (This section pertains only to samples with emplaced electrode grids)

Just prior to testing a sample, there will be a two-part system function verification to check the electrical characteristics of the electrode grid pattern on the fracture face and to check the instrumentation/computer system electronics.

After the core holder has been assembled and electrically connected to the fusite connectors in the pressure vessel, the electrical characteristics of the electrode grid pattern will be checked using the system digital voltmeter and the results recorded in an experimental logbook. To verify that the instrumentation/computer system is functioning properly, the Soltec Calibrator will be used to input a known voltage to the scanner. The voltage will be fed through the entire instrumentation system and be recorded by the computer. Any voltage drop or other electrical problems in the system should be exposed during this procedure. The results will be recorded in an experimental logbook.

8.0 Posttest Sample Storage

Posttest samples and scrap will be handled per Section 5.6 of QAP XI-11 Rev. A.

9.0 Documentation Requirements

9.1 Pretest

Prior to sample testing, a letter of criteria (LOC) shall be written to the principal investigator and/or the investigator as defined on the sign-off sheet (page 1) of this document. The following list contains the minimum requirements to be addressed in a LOC.

1) Description of Test
2) Sample Identification and History
3) Sample Preparation Requirements
4) Sample Treatment Prior to Testing
5) Reporting and Documentation Requirements
6) Quality Assurance
7) Sample Disposition

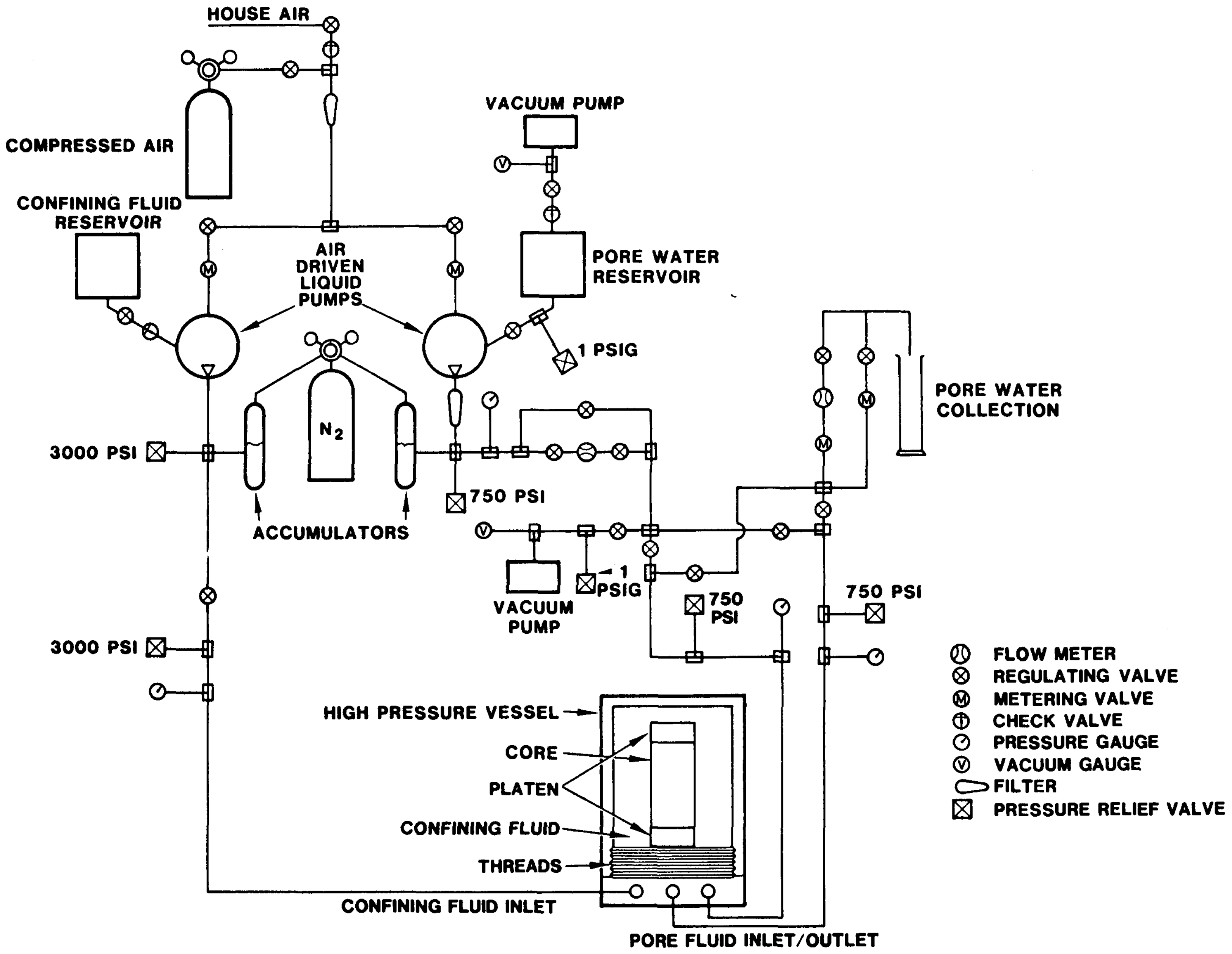
9.2 Posttest

At the end of each quarter in which testing has occurred, all calibration and test data are to be copied and sent to the appropriate 6313 file guide including 6330 NNWSI CF. A cover letter verifying that the contents have been furnished will be sent with the data. The Org 6310 Department Manager and Org 6313 Division Supervisor will be on distribution of the cover letter (without attachments). At the end of each quarter, copies of the data stored on floppy discs will be duplicated and kept in a separate location from the original test data.

10.0 Deviations

Any deviation(s) from these procedures will be documented in the experimental logbook.

FRACTURE FLOW EXPERIMENTAL APPARATUS SCHEMATIC



References

Schwartz, B. M., "Quality Assurance Procedure for Operation of the SNLA NNWSI Core Library", (QAP XI-11 Rev A) February 13, 1984.

Schwartz, B. M., "Pressure Safety Analysis for Fracture Flow Apparatus," internal memo dated January 31, 1984.

Schwartz, B. M., "Safe Operating Procedure for Fracture Flow Apparatus at SNL Building 823, Room 4270. SNL SOP #17000 8410," dated 10/4/84.

Klavetter, E. A., Peters, R. R. and Schwartz, B. M., "Experimental Plan for Investigating Water Movement Through Fractures," SAND84-0468, Sandia National Laboratories, Albuquerque, New Mexico. (In preparation)

APPENDIX D

Safe Operating Procedure

SAFE OPERATING PROCEDURE
FOR
FRACTURE FLOW APPARATUS
AT SNL
BUILDING 823 ROOM 4270

Page:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Revision:	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A

The purpose of the Division 6313 Fracture Flow Apparatus is to evaluate flow of water through fractured tuff rock cores in support of the Nevada Nuclear Waste Storage Investigations (NNWSI) program. Potential hazards include high-pressure fluids, whipping hardware, and stored energy release.

Thomas O. Hunter 9/24/84
T. O. Hunter - 6310 Date

J. R. Doyle 10/4/84
D. L. Rost - 3442 Date

Jack R Tillerson 9/24/84
J. R. Tillerson - 6313 Date

Don Joe 10/4/84
Don Joe - 3442 Date
(Safety)

Barry Schwartz 9/18/84
Written by
B. M. Schwartz - 6313 Date

Tom Cabe 9/18/84
T. J. Cabe - 6255 Date
(Pressure Safety Advisor)

1.0 General

This SOP is provided as a guide for use by personnel of the NNWSI Geotechnical Projects, Division 6313, who are authorized to operate the Fracture Flow Apparatus. Use of this document will help ensure that operations are performed in a safe manner and that hazards are minimized.

The Fracture Flow Apparatus is a high-pressure facility used to evaluate fracture flow through tuff rock cores. A detailed description of the apparatus is contained in the Pressure Safety Analysis (PSA) included as Attachment 1 of this document.

This procedure will be reviewed once per year by persons in the respective positions as defined on the sign-off page. Personnel authorized to operate the facility will review this SOP as often as necessary to ensure familiarity with these procedures, but not less than once per year.

1.1 Authorized Personnel: The following personnel are authorized to conduct tests using the Fracture Flow Apparatus:

B. M. Schwartz	6313
E. A. Klavetter	6313

- One operator is sufficient during normal working hours except where noted due to lifting of heavy objects.

- Two operators are required before or after normal working hours and on weekends and/or holidays.

Barry Schwartz is responsible for any design changes, operation of the apparatus and for all safety-related requirements. He will see that the provisions of this SOP are observed and that all operation, certification, calibration, and documentation requirements are followed.

1.2 Visitors: The authorized operating personnel shall inform all visitors of potential hazards within the testing area.

1.3 Safe Operating Procedure (SOP) Location: A copy of the SOP shall be kept on the "safe" side of the safety shield for quick access when necessary.

2.0 Hazards: The primary hazard source is the circulating fluid (silicon oil confining fluid at $\leq$ 3000 psi and water at $\leq$ 750 psi). Temperature of the fluids will be at ambient conditions for operation under revision A of this SOP. A schematic of the entire system including the pressure relief system for the apparatus is shown in Figure 1. Potential hazards in the design of the system are addressed in the PSA (Appendix A). Hazards associated with operation of the apparatus are minimized if the operating procedures in Section 6.0 are rigorously followed.

3.0 Other Precautions:

o The pressure cell weighs approximately 150 lbs. Care should be exercised in handling it. Two or more people should be used to remove the cell from its base. Steel toed safety shoes shall be worn during this procedure.

o The amount of time that the apparatus is at pressure shall be kept to a minimum. Casual personnel shall be kept out of the laboratory and operators shall stay behind the safety shield whenever possible to avoid unnecessary risk.

4.0 Protective Equipment

o Hose tie-downs: The hardware is fastened to the steel table utilizing braces primarily on the valves which are the major torque points. Tie-downs are also located at fittings throughout the tubing network. These devices should always be kept in place to prevent injury from whipping action of loose hardware.

o The pressure relief valves (PRV) are of the in-line type. Prior to usage, they have been checked for proper operation by Sandia Labs Safety Division 3441 and are tagged to verify that this check has been performed. The tag also indicates when this check should be performed in the future. Any fluid flow downstream of the PRVs is transported directly to heavy aluminum overflow canisters located under the work table. Small holes at the top of the canisters allow fluid in and prevent pressure buildup but will not allow for any significant release of fluid to the room. There are separate canisters for the silicone fluid and the water lines which are clearly identified. The volume of each canister is much greater than the amount of fluid that can exit the respective fluid loops. Schematics of the fluid loops and the identification system used for the PRVs and the regulating valves are shown in Figures 1 and 2.

o Safety shield: A shield made of a lexan plate in a wood frame will be stationed in front of the work table. The operators will stay on the safe side of the shield whenever possible during operation of the apparatus.

o Lexan safety plates are in place in front of and behind the Ashcroft 0-1000 psi pressure gauge located in the pore fluid loop.

o A transparent safety box is to be used at the downstream sides of valves P14 and P16. A non-glass container will be placed inside this box as will a battery-operated analytical balance. A feed-through at the bottom of the box will be connected to the pore fluid loop overflow canister (sump). The fluid entering this box will be at ambient pressure although possibly under high flow conditions in case of accident.

- Protective clothing: Non-slip soled safety shoes are provided and shall be worn by the operators whenever operating this facility. Lab coats are provided for each operator to shield their street clothing from contact with oils and adhesives. Safety glasses shall be worn when operating components under pressure or when connecting or disconnecting lines.

5.0 Emergency Procedures:

- Emergency shutdown: If a rupture occurs in the high pressure system or a similar emergency occurs, shut the air pressure off to the Haskel liquid pumps immediately. This is done by turning the blue-handled Jamesbury valves off (horizontal position) on both valve C1 (confining loop) and valve P1 (pore loop).

- Electrical power loss: There are no electrical connections to these liquid pumps; therefore, in case of a power failure when pressure indicating devices are not functioning it is still possible to be generating pressure. Due to this fact, during a power failure the run should be aborted and valves C1 and P1 closed per the above emergency shutdown procedure.

- Loss of building water pressure: There is no connection to the building water supply; therefore, no action need be taken due to the loss of this utility.

o Loss of building compressed air supply: If the liquid pumps are being driven by the building compressed air supply and the supply is interrupted, the pumps will either work intermittently or not at all. Since this could adversely affect the desired confining fluid/pore fluid pressure ratio, the run should be aborted and valves C1 and P1 closed per the above emergency shutdown procedure. Tests run over an extended period should use compressed air from individual gas bottles located in Room 4270. This will minimize the chance of accidental air pressure loss to the Haskel liquid pumps.

o The emergency telephone number is 144. This number can be used to report any medical or other emergency. Be sure to give your name, location and nature of the emergency. If the emergency is fire-related, call 117.

Fracture Flow Apparatus

Authorized Operators

By my signature, I acknowledge I have read, understand, and will follow these procedures.

Barry Schwartz 9/11/84

Barry Schwartz 6313 Date

Elmer Klavetter 9/11/84

Elmer Klavetter 6313 Date

6.0 OPERATING PROCEDURE FOR SNLA FRACTURE FLOW APPARATUS (BLD. 823, RM. 4270)

Refer to the System Schematic (Figures 1 and 2) for component identification.

A. Test Preparation (All Tests). Verify the following prior to each test:

1. The top of the pressure cell is screwed down, hand tight and all four 1/8" NPT plugs on the sides of the cell are in place and tightened down.

2. All pressure transducers and flow meters are connected per Figure 1 and cables are attached to the indicating devices.

3. All safety tie-downs are secure.

4. All PRVs per Figures 1 and 2 are installed and that their pressure safety tags are up to date.

5. Overflow canisters (sumps) are empty of liquids and the proper overflow tubing lead to each canister.

6. The accumulators have been filled with nitrogen gas to the desired pressure, usually 2/3 the working pressure of the fluid loop for maximum damping effect. Do not change the gas charge to either accumulator after starting the procedures in subsection B of this section.

7. The yellow safety plugs are secured into the gas inlet fittings on the confining and pore loop accumulators.

8. There is sufficient compressed air bottle pressure to last the duration of the test if the Haskel pumps are to be powered using bottled air.

9. That silicone fluid will enter the confining fluid loop and deionized/distilled water will enter the pore fluid loop.

B. Procedures for Operation of the Confining Pressure Fluid Loop.

Note 1. Pressurization of the confining fluid loop is performed prior to pore fluid loop pressurization.

Note 2. Except when noted in parentheses, the closed position of a valve is obtained by turning it clockwise and the open position counterclockwise.

Note 3. All Autoclave "speedbite" connectors are tightened 3/4 of a turn past finger tight.

1. Check that the rock sample, porous stones, and platens are in place, have been sealed using silicone adhesive, and are connected to the pore fluid inlet/outlet fittings.

2. Check that the o-ring and the threads on the pressure cell base plate are well lubricated with anti-seize compound and that there are no visible cuts or tears in the o-ring.

3. Lift the top of the pressure cell (2-person job) and place on the baseplate. Tighten (clockwise) until the pressure cell is together using hand pressure only.

4. Tighten all 4 of the plugs located in the pressure cell wall. Three are located midway up the pressure cell. The one located near the top of the pressure cell is used for bleeding air out of the confining fluid.

5. Check that PRV 1 and 2 are properly installed and that the tubing connected to the outlets are connected to the confining fluid sump.

6. Close valves C1, C2 (counterclockwise), C5, P1 and P2 (counterclockwise)

7. Open valves C3 and C4.

8. Adjust the air pressure into the Haskel pump (labeled confining fluid) to the desired air pressure not to exceed 150 psi.

9. Slowly open valve C1.

10. Slowly open valve C2 (clockwise) watching pressure transducers channels 1 and/or 2. When the pressure is between 50 and 100 psi, close valve C2 (counterclockwise) then crack open the bleed plug on the pressure cell until any trapped gas is removed and fluid starts to drip out. Retighten the 1/8-inch NPT bleed plug.

11. Open valve C2 (clockwise) and pressurize slowly until the desired operating pressure is obtained, not to meet or exceed the lower rating of PRV 1 or PRV 2.

12. Monitor the confining fluid loop pressure using pressure transducer channels 1 and 2.

13. Check all fittings and connections for leaks. Abort the run and follow the shutdown procedures (Subsection C) if a leak is found.

C. Confining Fluid Loop Shutdown Procedures (To be performed only after the sample pore fluid pressure is ambient)

1. Close valves C2 (counterclockwise), C1, and C3.

2. Open valve C4.

3. Crack open valve C5, watching pressure transducer channels 1 and 2. The confining fluid should be drained into the overflow canister (sump) at a slow and steady rate. The confining fluid exits the pressure cell at orifice L2 (scribed on cell base by the manufacturer).

D. Procedures for Operation of the Pore Fluid Loop When the Inlet to the Pressure Cell is R1 and the Outlet is R2.

Note 1. Do not proceed with pore fluid pressurization until the confining pressure fluid loop procedure (Subsection B) has been completed. The confining fluid pressure must be greater than the ultimate pore fluid pressure.

Note 2. Except where noted in parenthesis, the closed position of a valve is clockwise and the open position is counterclockwise.

Note 3. All Autoclave "speedbite" connectors are tightened 3/4 turn past finger tight.

Note 4. Steps 1-10 pertain to operation of the pore fluid loop when the flow meter upstream of the sample is closed.

1. Check that PRVs 3, 4, 5, and 6 are properly installed and that tubing is connected to the pore fluid overflow canister.

2. Open valves P3 or P4 so that water is sent to the Haskel pore fluid liquid pump.

3. Close valves P1, P2 (Counterclockwise),P5, P6, P8, P9, P10, P11, P12, P13, P14, P15, P16, and P17.

4. Open valves P7, P15, P16, and P17.

5. Crack open valve P11.

6. Adjust the air pressure into the Haskel liquid pump (labeled pore fluid) to the desired air pressure (not to exceed 150 psi).

7. Slowly open valve P1.

8. Slowly open valve P2 (clockwise) watching the Ashcroft pressure gauge and pressure transducers channels 3 and 4. When the desired pressure in the pore fluid loop has been obtained as shown on pressure transducer channels 3 and 4 (not to meet or exceed the lower rating of PRVs 3, 4, 5, and 6) slowly open valve P10 then carefully adjust valve P2 until the sample is at the desired pore pressure.

9. Adjust the setting of valve P16 until the desired back pressure is obtained while monitoring pressure transducer channels 3 and 4. Collect the fluid output from valve P15 into a nonglass beaker which is housed inside the transparent safety box.

10. Adjust valve P2 during the test as necessary to maintain the desired sample pore pressure.

Note: When the flow meter(s) are opened to liquid flow then Steps 11-15 should be followed to avoid damage to the flow meter electronics. There is no danger of affecting the pressure safety rating of these devices. Their use as calibrated devices, however, may be affected by improper usage.

11. Close valves P7, P15, and P16.

12. Slowly open valve P5.

13. Slowly open valve P6.

14. Slowly open valves 15 and 16 or valves 13 and 14 (if the flowmeter downstream from the sample is to be used).

15. Adjust the system pressure as desired using valves P2 and P14 or P2 and P16.

E. Procedures for Operation of the Pore Fluid Loop When the Inlet to the Pressure Cell is R2 and the Outlet is R1.

Note 1. Do not proceed with pore fluid pressurization until the confining pressure fluid loop procedure (Section B) has been completed. The confining fluid pressure must be greater than the ultimate pore fluid pressure.

Note 2. Except where noted in parenthesis, the closed position of a valve is clockwise and the open position is counterclockwise.

Note 3. All Autoclave "speedbite" connectors are tightened 3/4 turn past finger tight.

Note 4. Steps 1-10 pertain to operation of the pore fluid loop when the flow meter upstream of the sample is closed.

1. Check that PRVs 3, 4, 5, and 6 are properly installed and that tubing is connected to the pore fluid overflow canister.

2. Open valves P3 or P4 so that water is sent to the Haskel pore fluid liquid pump.

3. Close valves P1, P2 (Counterclockwise), P5, P6, P8, P11, P12, P13, P14, P15, P16 and P17.

4. Open valves P7, P9, P15 and P16.

5. Crack open valve P10.

6. Adjust the air pressure into the Haskel liquid pump (labeled pore fluid) to the desired air pressure (not to exceed 150 psi).

7. Slowly open valve P1.

8. Slowly open valve P2 (clockwise) watching the Ashcroft pressure gauge and pressure transducers channels 3 and 4. When the desired pressure in the pore fluid loop has been obtained as shown on pressure transducer channels 3 and 4 (not to meet or exceed the lower rating of PRVs 3, 4, 5, and 6) slowly open valve P12 then carefully adjust valve P2 until the sample is at the desired pore pressure.

9. Adjust the setting of valve P16 until the desired back pressure is obtained while monitoring pressure transducer channels 3 and 4. Collect the fluid output from valve P15 into a nonglass beaker which is housed inside the transparent safety box.

10. Adjust valve P2 during the test as necessary to achieve the desired sample pore pressure.

Note: When the flow meter(s) are opened to liquid flow then Steps 11-15 should be followed to avoid damage to the flow meter electronics. There is no danger of affecting the pressure safety rating of these devices. Their use as calibrated devices, however, may be affected by improper usage.

11. Close valves P7, P15, and P16.

12. Slowly open valve P5.

13. Slowly open valve P6.

14. Slowly open valves 15 and 16 or valves 13 and 14 (if the flowmeter downstream from the sample is to be used).

15. Adjust the system pressure as desired using valves P2 and P14 or P2 and P16.

F. Pore Fluid Loop Shutdown Procedures

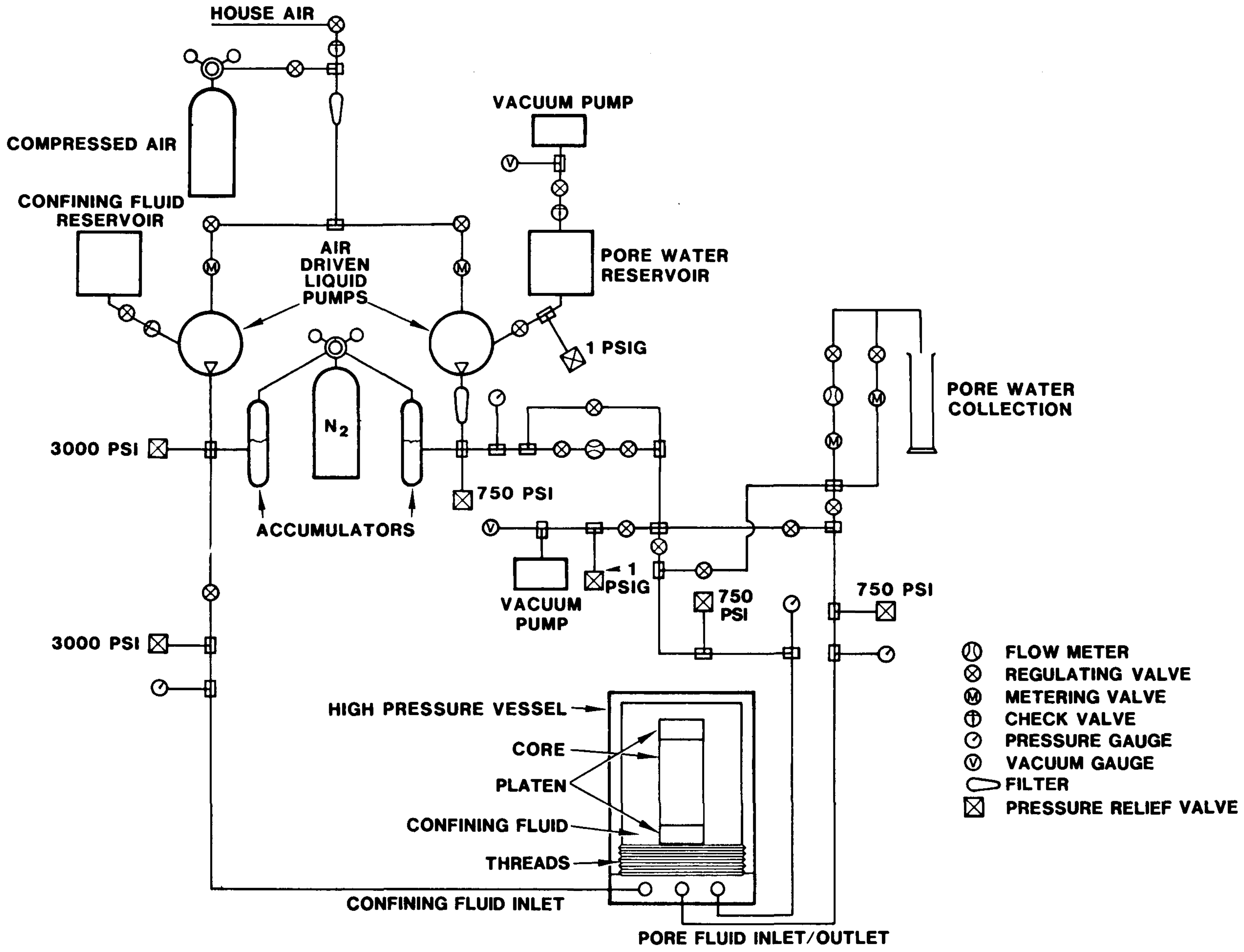
1. Close valves P2 (counterclockwise), P1, P3, P4, P6, P14, P5, and P13.

2. Open valves P7, P10, P12, P16, and 17.

3. Crack open valve P15 until the pore pressure in the fluid loop is reduced to the desired pressure.

Figure 1

FRACTURE FLOW EXPERIMENTAL APPARATUS SCHEMATIC



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date: **January 31, 1984**

to: **Tom Cabe, 6255**
Pressure Safety Advisor

1/31/84

from: **B. M. Schwartz, 6313**

subject: **Pressure Safety Analysis for Fracture Flow Apparatus**

List of Subjects

1. Introduction
2. System Description
3. Stored Energy Calculations
4. Toxic Materials
5. Safety Factors
6. Material Behavior
7. Schematic of Fracture Flow Apparatus
8. Conclusions

Introduction

In accordance with policies and practices set forth by Sandia National Laboratories Pressure Advisory Committeee (Pressure safety practices manual SAND76-0424, Change 1) the pressure system for fracture flow experiments is herein being presented, including an estimate of contained energy of the system. The purpose of this Pressure Safety Analysis (PSA) is to document that the system has been designed to operate safely and will not require a Pressure Safety Analysis Report (PSAR).

A signature sheet is provided at the end to indicate that this analysis has been reviewed by the 6313 pressure safety advisor, Safety Engineering (Division 3442) and approved by the 6313 supervisor.

2. System Description

In support of the Nevada Nuclear Waste Storage Investigations (NNWSI) program, flow through fractures in tuff rocks is being investigated. A core sample approximately 2-2.5 inches in diameter by 2-6 inches in length will be enclosed in a core holder containing electrical leads attached to the sample. The core holder is enclosed in a pressure vessel which will provide a confining pressure of less than or equal to 2,500 psi to simulate the in situ pressures on the sample. One pump and an accumulator will maintain the confining pressure.

The fluid passing through the sample will be distilled water or J-13 water (from a well near the drill holes). An electrolyte may be added to enhance impedance measurements across the sample. A pore pressure of less than or equal to 650 psi will be used to drive water through the sample. A flow meter upstream from the inlet will monitor the flow rate. The outlet fluid flow will be monitored with a second flow meter. Back pressure may be maintained with a fine metering valve.

Pressures will be measured at the inlet and outlet ports of the pressure vessel using pressure transducers. This document defines testing to be performed at ambient temperatures. However, future testing may incorporate elevated temperatures. Although the equipment defined in this study have been designed to operate at elevated temperatures, a revision of this PSA will be made prior to any high pressure/temperature testing.

3. Stored Energy Calculations

Requirement: The contained energy of a liquid system (E_T) must be below 4.0×10^4 Joule (Section 3.5.2.1 paragraph d.1)

Total stored energy in a single phase liquid system (E_T)

$$E_T = e_L + e_S$$

where

e_L = Energy stored in the compressed liquid

e_S = Strain energy stored in the vessel

Note: Multiply ft - lbs by 1.356 to get Joules

$$e_L = \frac{P^2 V}{kB}$$

where P = 3000 psi = Maximum Allowable Working Pressure (MAWP)
V = Volume of Pressure Vessel = 236 in^3
B = Liquid bulk modulus = 225,000
k = constant = 24 when P, B are in psi units

$$e_L = \frac{(3000)^2\ 236}{(24)\ 225{,}000} = 394 \text{ ft - lb or } 535 \text{ Joules}$$

$$e_s = \frac{P^2 Vd}{kEt} (1.25 - u)$$

where P = 3000 psi = MAWP
V = 236 in^3
d = Inside Diameter of Vessel = 5 in.
k = constant = 24 when P is in psi units
E = Youngs Modulus = 28.5 x 10^6 psi (*)
t = Wall thickness of vessel = 1 in.
u = Poisson Ratio 0.3 (*)

(*) For Vessel Material 17-4PH Stainless Steel Aged at 900°F

$$e_s = \frac{(3000^2)\ (236)\ (5)}{(24)\ (28.5x10^6\ (1)} (1.25 - 0.3) = 14.8 - lb \text{ or } 20.0 \text{ Joules}$$

E_T = 535 Joules + 20 Joules
E_T = 5.55 x 10^2 Joules

Therefore, our calculated total stored energy of 5.55 x 10^2 Joules is less than the value of 4.0 x 10^4 Joules at which a Pressure Safety Analysis Report is required.

4. Toxic Materials

Requirement: No toxic or flammable materials are involved (Section 3.5.2.1 paragraph d.2)

The confining fluid will be silicone based.* Silicone fluids are essentially nontoxic and nonflammable. The silicone fluid used will have a flash point of greater than or equal to 450°F (232°C). The sealant used in the core holder will be silicone or fluorosilicone based. They are both essentially nontoxic and nonflammable. Both sealants have a flash point greater than 392°F (200°C).

5. Safety Factors

Requirements: No credible potential for serious injury or unacceptable property damage (Section 3.5.2.1, paragraph d.3)

Table 1 documents the safety margins designed into each component of the system. Section 3.24 recommends that the highest operating pressure be less than or equal to 85 percent of the MAWP.

---

*Dow Corning 200 fluid (200cs).

TABLE 1
Safety Factors of Equipment

Component	Manufacturer	Operating Pressure @25°C (PSI)	MAWP @ 25°C (PSI)	Proof Test @ 25°C (PSI)	Predicted Rupture @ 25° C (PSI)
Pressure Vessel	S-Bell	2500	3000	10,000	>15,000
Flow meters	Flow Measurement Systems	650	750	(1)	15,000
Pressure Transducer	Precise Sensors	650	750	1,200	3,000
		2500	3000	5,000	>12,000
Air Driven Liquid Pumps	Haskel	650	750	(1)	9,000
		2500	3000	(2)	12,000
Accumulators	Hydrodyne	650	750	4,500	12,000
		2500	3000	4,500	12,000
316 Stainless Steel 1/4" OD Tubing	0.125 I.D.	2500	3000	-	Safety Factor of 8
	0.180 I.D.	650	750	-	
Valves		2500	3000	-	Safety Factor of 8
316 Stainless Steel Fittings		2500	3000	-	Safety Factor of 8

*Maximum allowable working pressure

(1) Will proof test at SNLA to 1,200 PSI

(2) Will proof test at SNLA to 4,500 PSI

6. Material Behavior

Requirement: Material Behavior is predictably nonbrittle.

Jon Munford of Physical Metallurgy (Division 1832) has evaluated the material and heat treatment used in fabricating the pressure vessel. In a memo to Schwartz dated 3/2/84, Munford approved the pressure vessel for its intended use as described in this analysis.

The following recommendations made by Munford will be addressed in the Safe Operating Procedure (SOP) which shall be written simultaneously with the assembly of this experimental apparatus.

1) The MAWP shall be less than or equal to 3000 PSI.

2) The maximum temperature shall be less than or equal to 200°C.

   The minimum temperature shall be greater than or equal to the ambient laboratory conditions and no means shall be used to lower the vessel temperature below ambient temperature conditions.

3) The total number of pressure cycles on the vessel shall not exceed 500 at which time the vessel shall be discarded.

4) The vessel shall not be "shock loaded" i.e., pressure cycling from ambient to the MAWP and/or cycling from the MAWP to ambient pressure should take at least ten seconds.

5) The pressure vessel shall not be exposed to corrosive environments.

7. Schematic of Fracture Flow Apparatus

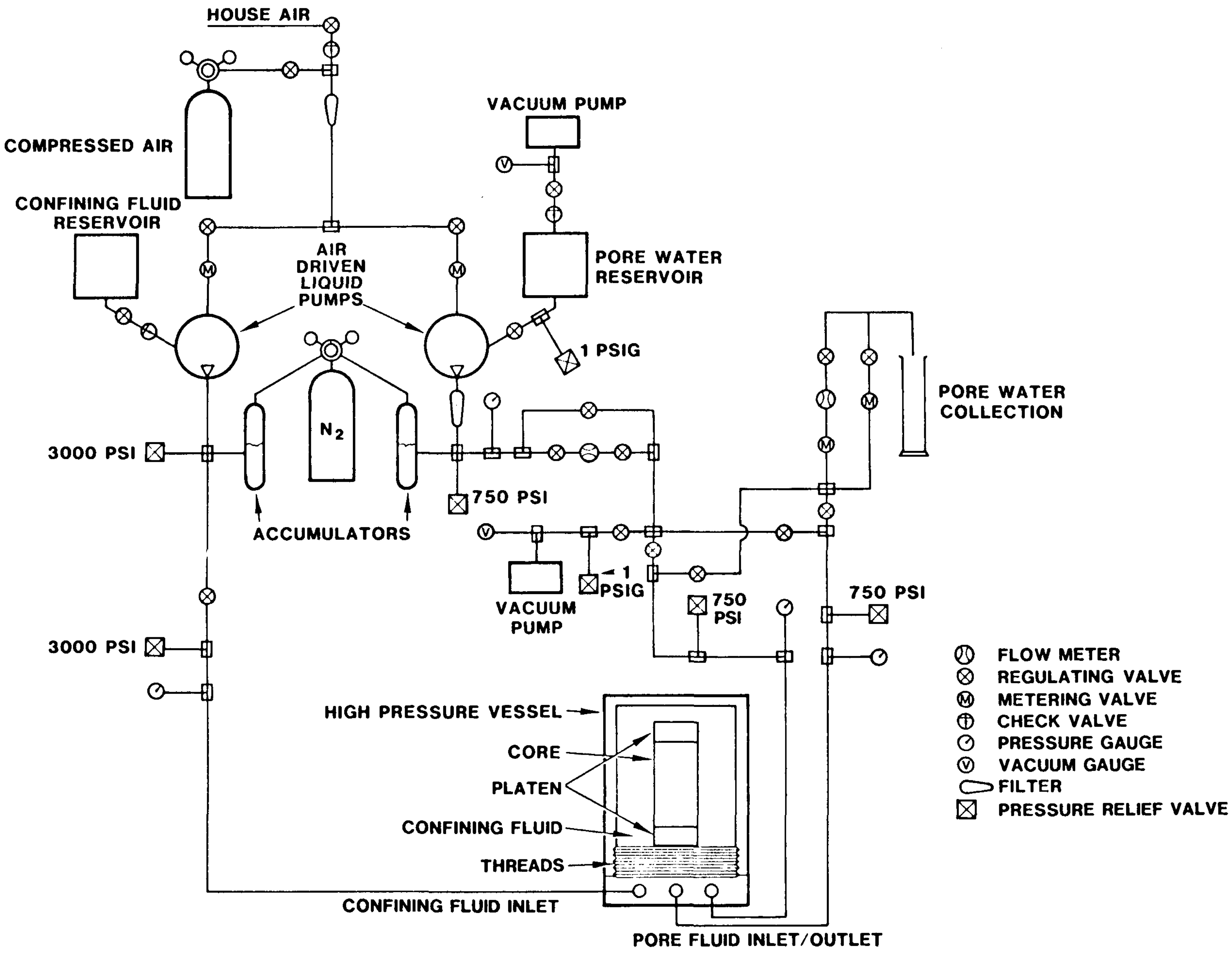
(See Figure 1)

8. Conclusions

The calculated total stored energy of the fracture flow apparatus is 5.55×10^2 Joules. This stored energy is less than the value of 4.0×10^4 Joules at which a PSAR is required. This analysis has also addressed the design of the system as concerns toxic materials, safety factors, and material behavior. A schematic of the apparatus has also been included. Consideration of the low stored energy, the lack of toxic materials, the presence of adequate safety factors and limitations related to material behavior lead to the conclusion that a PSAR is not required according to the Sandia Pressure Safety Manual, SAND76-0424, Change 1.

Figure 1

FRACTURE FLOW EXPERIMENTAL APPARATUS SCHEMATIC



Div. 6313 High Pressure Fracture Flow Experimental Apparatus Signature Sheet

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Reviewed by	Don Joe, 3442 Safety Consultant	3/21/84 Date
Reviewed by	D. Rost, 3442 Division Supervisor	3-21-84 Date
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