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THEORETICAL AND LABORATORY INVESTIGATIONS OF FLOW THROUGH FRACTURES IN CRYSTALLINE ROCK

Paul A. Witherspoon, David J. Watkins,
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June 1981

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THEORETICAL AND LABORATORY INVESTIGATIONS OF FLOW THROUGH FRACTURES IN CRYSTALLINE ROCK

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INTRODUCTION

The potential for escape of hazardous material to the biosphere by groundwater transport is one of the most important factors that must be considered in the siting and design of facilities for underground disposal of nuclear waste. In crystalline rocks the characteristics of the hydrologic regime are usually dominated by flow through fractures in the rock mass. Thus, to develop analytic models of flow and transport through these media, it is necessary to investigate the laws of fluid flow in fractures. The construction and operation of a waste repository produces changes in the state of stress in the surrounding rock due to the excavation of the underground openings and the heating and subsequent cooling that results from the decay of the radioactive material. These changes in the state of stress in the rock mass include variations in effective stress due to perturbations of fluid pressures that result from changes in total stress in the groundwater flow regime. Changes in the state of stress produce displacements in the rock mass that can effect the hydraulic properties of the fractures due to changes in aperture, contact area and other characteristics of the flow path. Models used to predict the movement of groundwater must therefore be able to account for changes in rock mass permeability

that result from these effects. Interpretation of data from well tests, pressure tests and other techniques designed to measure the hydraulic properties of a rock mass also requires understanding of the laws governing flow in fractures.

Laboratory tests designed to measure the hydraulic properties of fractures in crystalline rock have traditionally been performed on specimens with dimensions of several centimeters. While tests performed at this scale provide useful insights into the pheonenology of flow through discrete fractures, their ability to accurately represent conditions in situ is open to question. The hydraulic properties of a natural fracture are determined by the geometric and physical properties of the fracture. These properties are not homogeneous and therefore there is some mimimum sample size below which results obtained from laboratory specimens are not representative of the mean hydraulic characteristics of the in situ fracture. While the magnitude of these effects has not yet been determined experimentally the potential for a significant size effect has been observed in laboratory data from tests performed on specimens of different dimensions. Thus, to reduce uncertainty in parameters and to make reliable comparisons between empirical results and theoretical models, it is necessary to obtain measurements from specimens containing fractures with dimensions closer to those of practical concern - namely meters rather than centimeters.

MODELS OF FLOW THROUGH FRACTURES

Models of flow through fractures in crystalline rock have been based on solutions of the Navier-Stokes equation for steady, laminar, isothermal flow between smooth parallel plates (Boussinesq, 1868; Bear 1972).

For plates separated by a constant distance, b, the flow rate is proportional to b^3. This relationship, called the "cubic law", has been shown to be valid for flow between optically smooth plates of glass down to apertures of 0.2 μm (Romm, 1966). Lomize (1951) showed that the cubic law also applied to laminar flow between glass plates with variable, curvilinear profiles. He defined the distance between the plates as the mean aperture and introduced a roughness factor to account for local variations in aperture. Independent investigations by Louis (1969) and others (Baker, 1955; Huitt, 1956; Parrish, 1963; Rayneau, 1972 and Gale, 1975) on flow in fractured rock support Lomize's findings for laminar flow under conditions where the Reynolds number is less than 2400. These studies established the validity of the cubic law for flow in rough open fractures, i.e. fractures where the parallel surfaces are not in contact.

In their natural state, fracture surfaces usually have some degree of contact and the aperture and contact area will depend upon the stress acting across the discontinuity. In this type of closed fracture, flow occurs along the paths that are not blocked by asperities that bridge between the fracture surfaces. In the nearly impermeable rocks that would be suitable sites for disposal of nuclear waste closed fractures will predominate. Witherspoon et al. (1980) expressed the cubic law for flow in a rough fracture in a simplified form by introducing a factor, f, to account for deviations from ideal conditions so that in the case where $f \geq 1.0$ (i.e. for a rough fracture);

$$Q/\Delta h = (C/f)b^n \qquad (1)$$

where Q is the flow, Δh is the difference in hydraulic head, C is a constant depending upon flow geometry and fluid properties and $n = 3$. The

results of Iwai's (1976) laboratory investigations on the hydralic properties of tension fractures induced in basalt, granite and marble samples were used to study the validity of the cubic law for flow in closed, deformable fractures. Iwai (1976) measured the change in conductivity of single fractures during loading and unloading under normal stresses up to 20 MPa and measured the normal displacements across the fractures. Typical results from his experiments on radial flow through a fracture in granites are given in Figure 1 which plots flow-per-unit head ($Q/\Delta h$) versus normal stress for one complete cycle of loading and unloading. To check the validity of Equation (1) it is necessary to know the true fracture aperture b. Witherspoon et al. (1980) developed the following expression for the true aperture;

$$b = (b_d + b_r) \tag{2}$$

where b_r is the residual aperture after a given stress history and b_d is the apparent aperture obtained from

$$b_d = \Delta V_m - \Delta V \ . \tag{3}$$

ΔV is the net deformation due to the stress history and ΔV_m is the maximum fracture deformation due to application of a high stress. b_d is not the true aperture appropriate for use in Equation 1 because unless the fracture is subjected to extremely high stress the flow paths through the fracture are not closed, nor do the hydraulic properties of the fracture become similar to those of intact rock (Kranz et al., 1979). As illustrated in Figure 2, in practical experiments ΔV_m is measured at a stress under which the fracture has some residual aperture, b_r. Using Equations (2) and (3), Equation (1) can be rewritten;

$$Q/\Delta h = C/f\ (\Delta V_m - \Delta V + b_r)^n \tag{4}$$

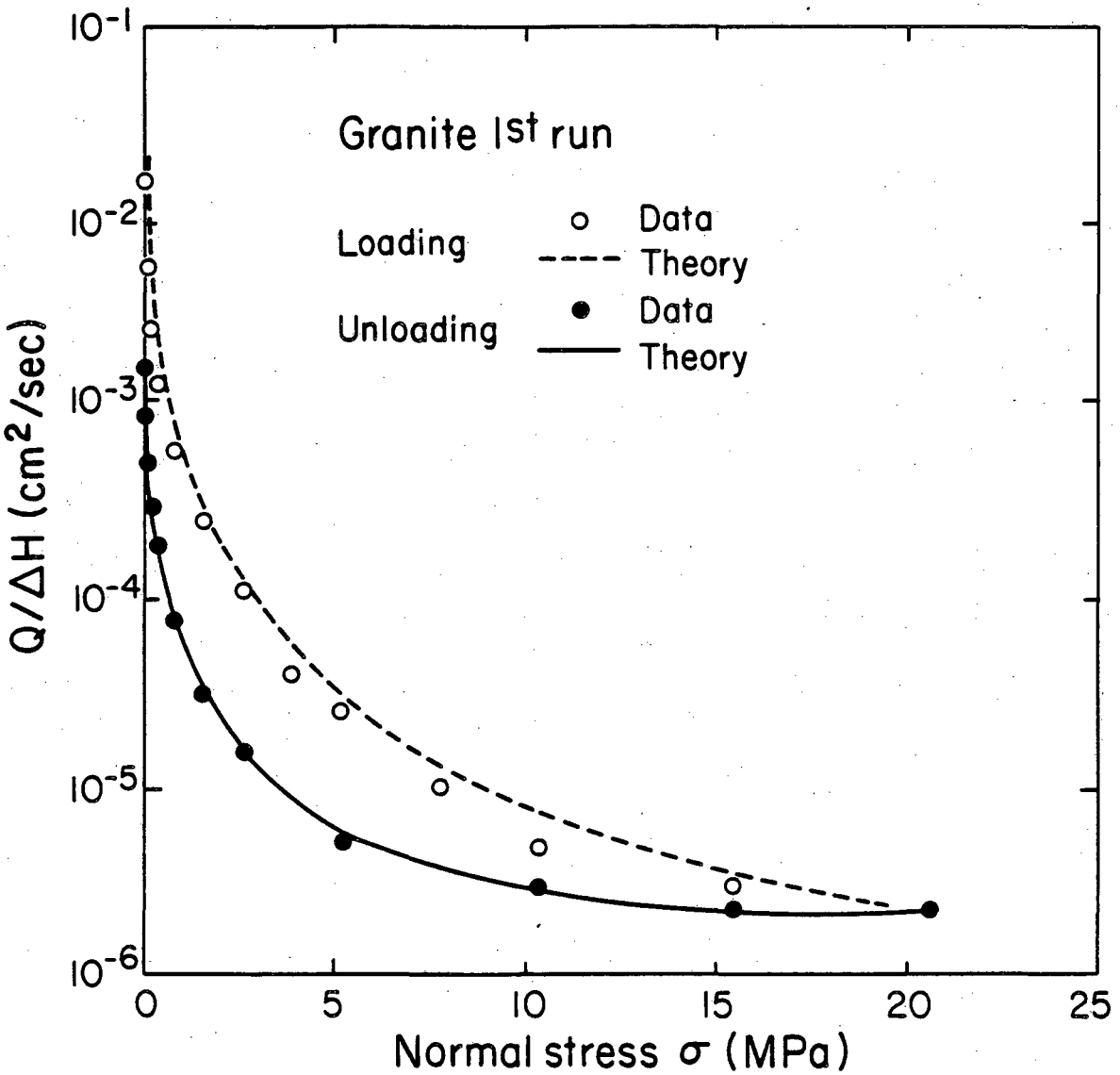

Fig. 1. Experimental and Theoretical Flow through a Fracture in Granite as a Function of Normal Stress. XBL 8011-2989

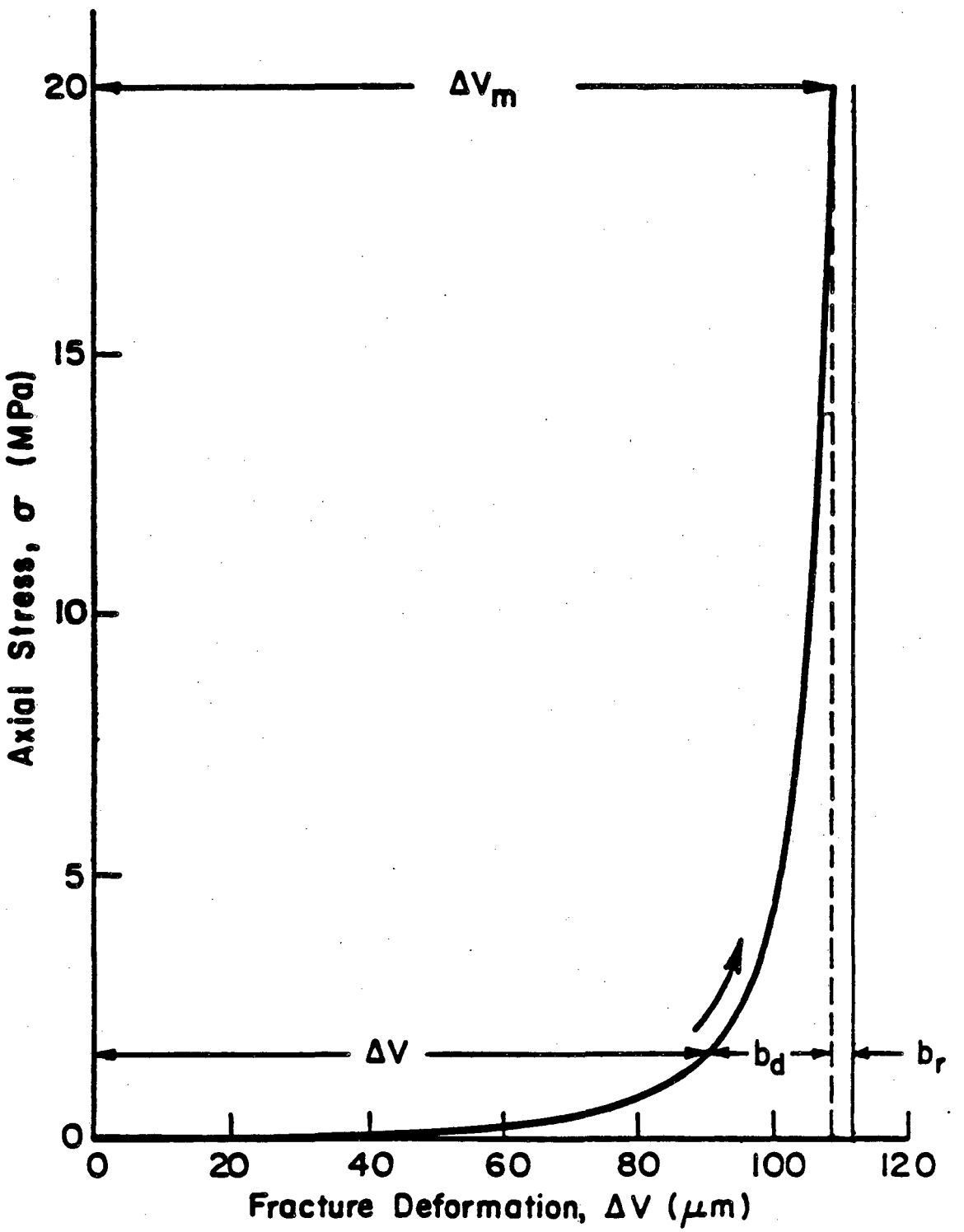

Fig. 2. Stress-deformation Behavior of a Fracture. XBL 8111-4816

This equation has three unknowns, f, b_r and n. For the cubic law to be valid n must take the value 3. Witherspoon et al., (1980) initially assumed that f = 1.0 which would imply that the fractures are in fact smooth and the surfaces are not in contact. The unknowns n and b_r were then evaluated by applying a least squares curve fitting procedure to Iwai's (1976) data. Values of n obtained in this way ranged from 3.01 to 3.10. The values of b_r obtained from Equation (4) for f = 1 differed from values of b_r computed from Equations (1) and (2) with f = 1.0 by less than 3%. From this it was concluded that for closed deformable fractures n ≈ 3.0. Then by assuming n = 3.0 in Equation (1), values of f ranging from 1.0 to 1.21 were obtained. These values are all greater than 1.0 and agree with Lomize's (1951) findings. Using these values of f in Equation (1), Witherspoon et al. (1980) found good agreement with Iwai's experimental data and concluded that, at least for the range of conditions in Iwai's (1976) experiments, the cubic law is valid for closed, deformable fractures.

Models of fractures that explicitly consider the geometry of the asperities and the deformation of the fracture under load have been developed by Gangi (1978) and Tsang and Witherspoon (1981). Gangi's (1978) "bed-of-nails" model treated the asperities as a series of elastic rods of varying heights and cross-sectional areas occuping the space between two flat parallel plates. By selecting appropriate functions for the height and cross-sectional distributions of the rods, Gangi (1978) was able to model the non-linear deformation of the fracture aperture in response to applied normal stress and, by assuming the cubic law to hold, predicted the resulting changes in fracture conductivity. Using these techniques,

Gangi (1978) obtained good agreement with experimental data obtained by Nelson (1975) from Navajo sandstone and reasonable agreement with Jones' (1975) results from fractured carbonate rocks.

Tsang and Witherspoon (1981) developed the model shown in Figure 3 which, like Gangi's (1978), describes the fracture surface conditions as a series of asperities of various heights and cross sections. However, when they modeled the closure of the fractures in response to applied normal stress by analysis of the elastic deformation of the asperities, they found poor agreement with Iwai's (1976) data for flow through fractures in granite. Iwai (1976) measured the contact areas on the fracture surface at a stress of 20 MPa and found them to be between 10 and 20 percent of the total surface area. Contact areas computed from the asperity model amounted to only 0.1 percent of the total area unless the Young's Modulus of the asperities was assumed to be two orders of magnitude less than that of the intact rock. This discrepancy was considered unreasonable and Tsang and Witherspoon (1981) developed an alternative method to evaluate the deformational characteristics of a fracture and the influence of applied normal stress on fracture conductivity.

As shown in Figure 4, Tsang and Witherspoon's (1981) model considers the fracture to be composed of a series of voids with lengths $2d_j$. When the normal stress, σ, is increased the number of asperities in contact with the fracture surfaces increases and the width of the voids between contact points decreases. Walsh (1965) derived an expression for the effective modulus, E_{eff}, of rock containing a number of voids oriented normal to the direction of loading. As shown in Figure 5, E_{eff} is given by

$$\frac{1}{E_{eff}} = \frac{1}{E} + \frac{4\pi\langle d^3\rangle}{E\langle u\rangle} \qquad (5)$$

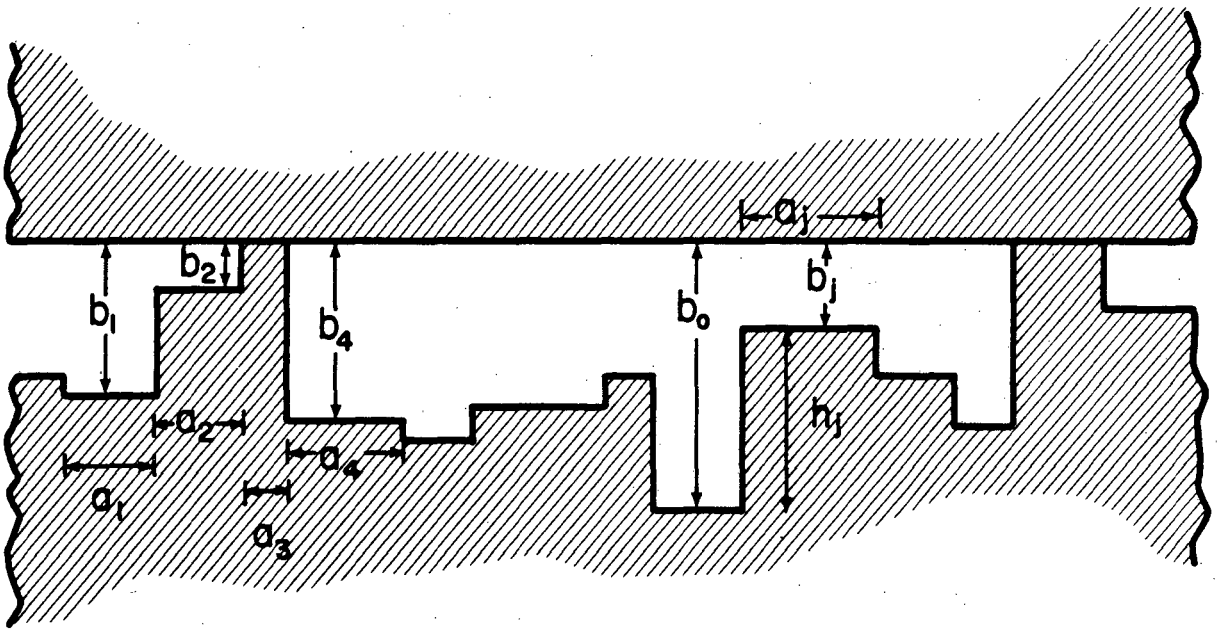

Fig. 3. Schematic Representation of a Fracture by an Asperity Model.
XBL 8011-2970

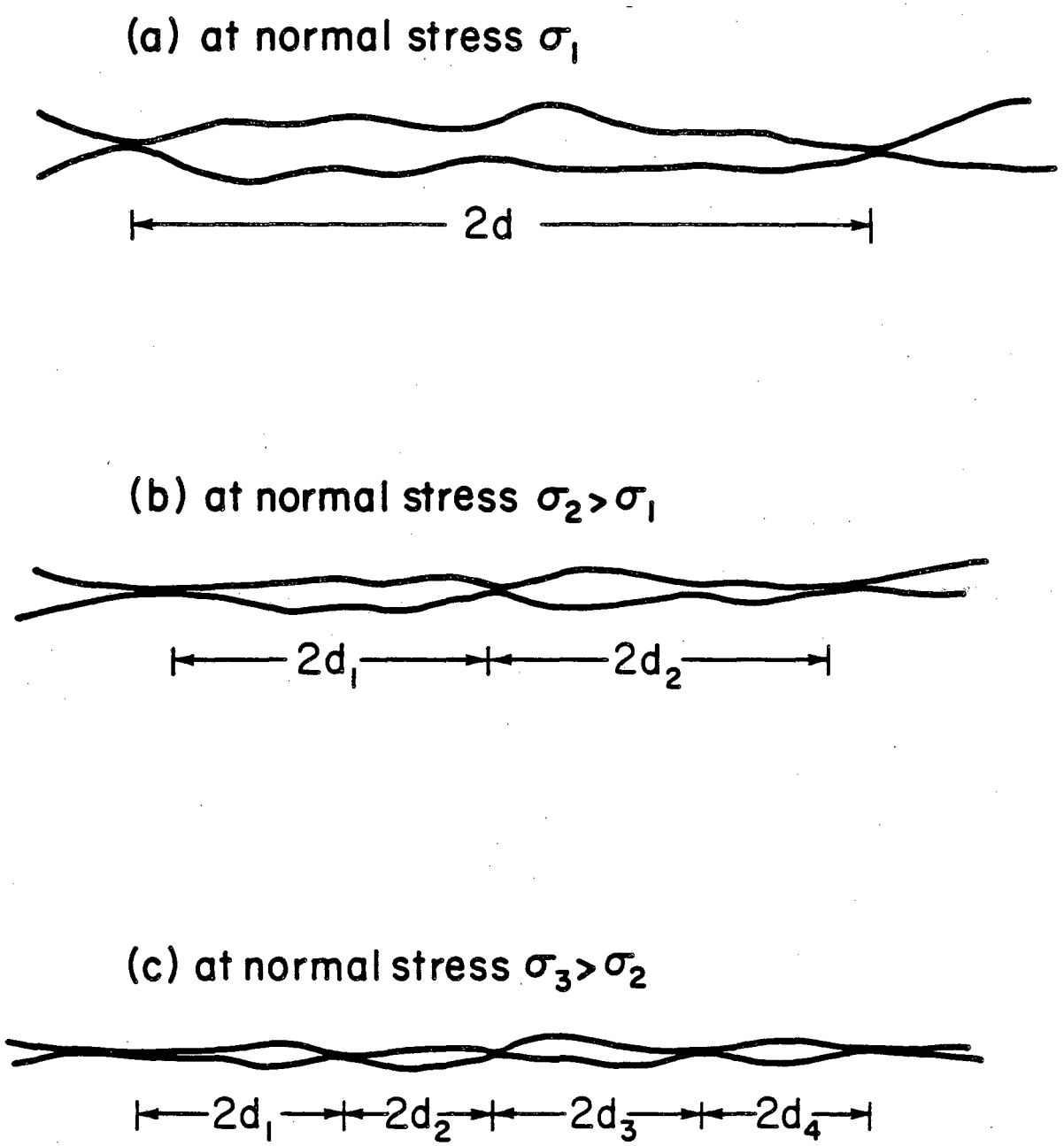

Fig. 4. Deformation of Voids under Increasing Normal Stress. XBL 8011-2975

where the half void length cubed, d^3, and the small volume of rock, $u = \Delta x \Delta y \Delta z$, immediately surrounding each void have been averaged over all the voids in the sample and where E is the intrinsic modulus of the rock containing no voids. Equation (5) describes a system of sparse voids where the perturbation of the stress field due to the presence of one void does not influence conditions in the near field of another void. However, as shown in Figure 4, a fracture is more accurately represented by a large number of voids in close proximity and the total fracture area in contact is small so that if there are a spatially random number of voids, M, in the fracture;

$$\langle (2d)^2 \rangle M \simeq A \tag{6}$$

and

$$\langle d^3 \rangle \simeq \langle d^2 \rangle \langle d \rangle \tag{7}$$

where A is the total area of the fracture surface. For these conditions Tsang and Witherspoon (1981) propose that the deformation modulus of the fracture is best represented by E_{eff} so that Equation (5) may be nodified to;

$$\frac{1}{E_{eff}} = \frac{1}{E} + \frac{4\pi \langle d^3 \rangle}{E_{eff} \langle u \rangle} \tag{8}$$

and from Equations (6) and (7) may be further simplified to yield the approximation;

$$\frac{E_{eff}}{E} \simeq 1 - \frac{\pi \langle d \rangle}{\Delta z} \tag{9}$$

where Δz is the distance across the fracture plane over which E_{eff} applies. Values for E and E_{eff} may be obtained from stress-displacement data from intact and fractured specimens of the same rock type, such as those shown in Figure 6.

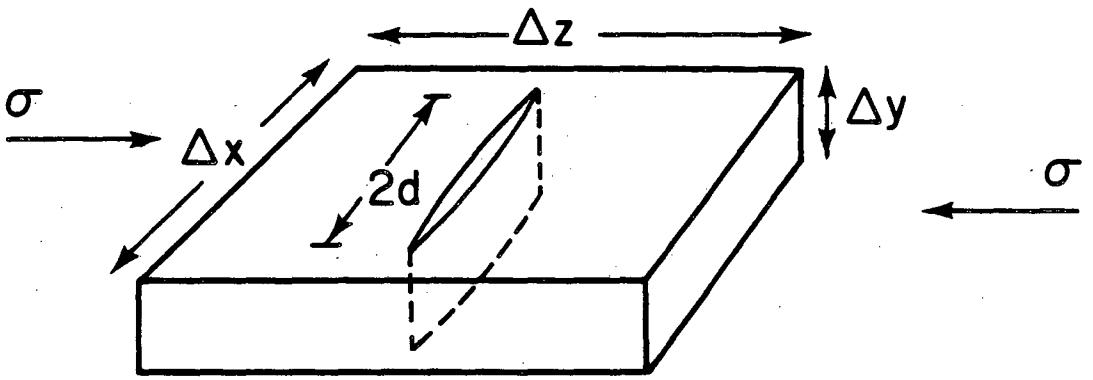

Fig. 5. Geometry of a Flat Elliptical Void in Rock under Stress.

XBL 8011-2973

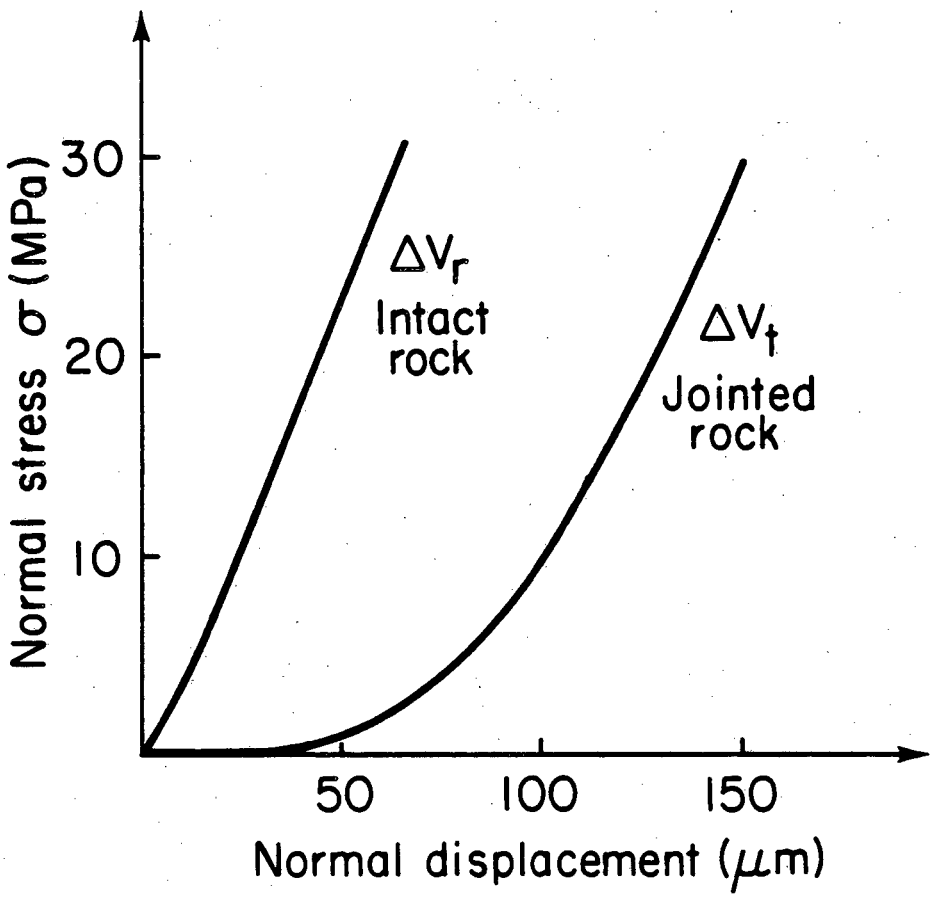

Fig. 6. Typical Normal Stress-displacement behavior for Intact and Jointed Rock. XBL 8011-2971

As illustrated in Figure 4, increasing normal stress on the fracture reduces the average void length $2\langle d\rangle$ and increases the number of contract points, N_c, where asperities bridge between the surfaces of the opening. In Figure 3 the fracture roughness is represented by an array of asperities with varying heights h_j. At zero applied stress the maximum aperture is b_o corresponding to an asperity height of zero. Application of normal stress produces fracture closure ΔV and the correspondence between aperture and asperity height is:

$$b = \begin{cases} (b_o - \Delta V - h) & h<(b_o - \Delta V) \\ o & h \pm (b_o - \Delta V) \end{cases} \tag{10}$$

If $n(h)$ is the characteristic asperity height distribution function prior to loading, the total number of asperities in contact is given by:

$$N_c(\Delta V) = \int_{b_o - \Delta V}^{b_o} n(h)dh \tag{11}$$

The asperity height distribution $n(h)$ can thus be computed from the derivative of N_c. However, because b_o is not known and Equation 9 only provides the change in $\langle d\rangle/\Delta z$ relative to conditions at zero stress, $n(h)$ can only be determined to some constant multiplier. However, if a functional form exists for $N_c(\Delta V)$ and the fractional areas, ω, of the total fracture surface occupied by the contact points is known at a specified deformation ΔV, then b_o can be determined because:

$$\omega = \frac{N_c(\Delta V)}{N_c(b_o)} \quad . \tag{12}$$

Based on the asperity model shown in Figure 3, Tsang and Witherspoon (1981) expressed the cubic law in the form

$$Q/\Delta h = C\langle b^3\rangle \tag{13}$$

where C is a proportionality constant that depends on the macroscopic fracture dimensions and the properties of the fluid. The statistical average of the variation of aperture is then obtained from;

$$\langle b^3(\Delta V, \delta)\rangle = \frac{\int_0^{b_o - \Delta V} (b_o - \Delta V - h)^3 n(h)dh}{\int_0^{b_o} n(h)dh} \tag{14}$$

Thus, if an estimate of the contact area of the fracture can be made for any stress, and stress-displacement data are available for the intact rock and for a specimen containing a fracture, the flow through the fracture may be obtained from Equation (14).

Flows predicted by Equation (13) were compared with Iwai's (1976) experimental data from radial flow tests on a normally loaded fracture in a granite specimen. The theoretical and experimental relationships between flow-per-unit-head and normal stress are compared on Figure 1 for one cycle of loading and unloading. Stiffness properties in Equation (9) were obtained from the deformation measurements made on the fractured specimen and from the deformation properties of intact specimens of the same rock. The contact area, ω, at maximum applied stress was assumed to be 15% of the total surface area based on Iwai's (1976) measurements that showed ω to be between 10% and 20%. No curve fitting was involved in making the flow predictions and the good agreement between the theoretical and experimental results suggests that the analytic procedure reliably models the phenomena controlling flow through a rough, deformable fracture under applied normal

stress.

TESTS ON ULTRA-LARGE SPECIMENS OF FRACTURED ROCK

Permeability tests on an ultra-large specimens of rock containing a fracture were first performed by Gale (1975) who investigated the hydraulic properties of an artificially induced fracture in a 1 m diameter by 2 m high cylindrical specimen. This work was performed using the very large triaxial testing machine shown in Figure 7. This equipment, originally designed to study the constitutive properties of rock fill materials (Becker et al., 1972), has an axial load capacity of 17.8 MN and the vessel is rated for 5.2 MPa working pressure. The facility has been adapted for fracture conductivity and permeability experimentation on ultra-large specimens of rock. To evaluate the feasibility of sampling, instrumenting and testing a very large volume specimen of a fractured rock mass, a one meter diameter by two meter high cylindrical specimen of granitic rock (quartz-monzonite) was obtained from the Stripa mine in Sweden. The Stripa mine is the site of a series of large-scale, in situ, hydrologic and geotechnical experiments that are part of the Swedish-American Cooperative Program on Radioactive Waste Storage in Mined Caverns in Crystalline Rock (Witherspoon and Degerman, 1978). The specimen (see Figure 8) was recovered from the rib of a mine entry by drilling a circular pattern of horizontal holes around its periphery. This was done while the rock was held in compression by a rock bolt through the central axis (Andersson and Halen, 1978). After shipping to the laboratory, the specimen was prepared for testing by capping with reinforced concrete. As shown on the fracture map of the surface of the specimen (Figure 9) the rock was pervasively fractured with two sets of principal discontinuities, one oriented normal

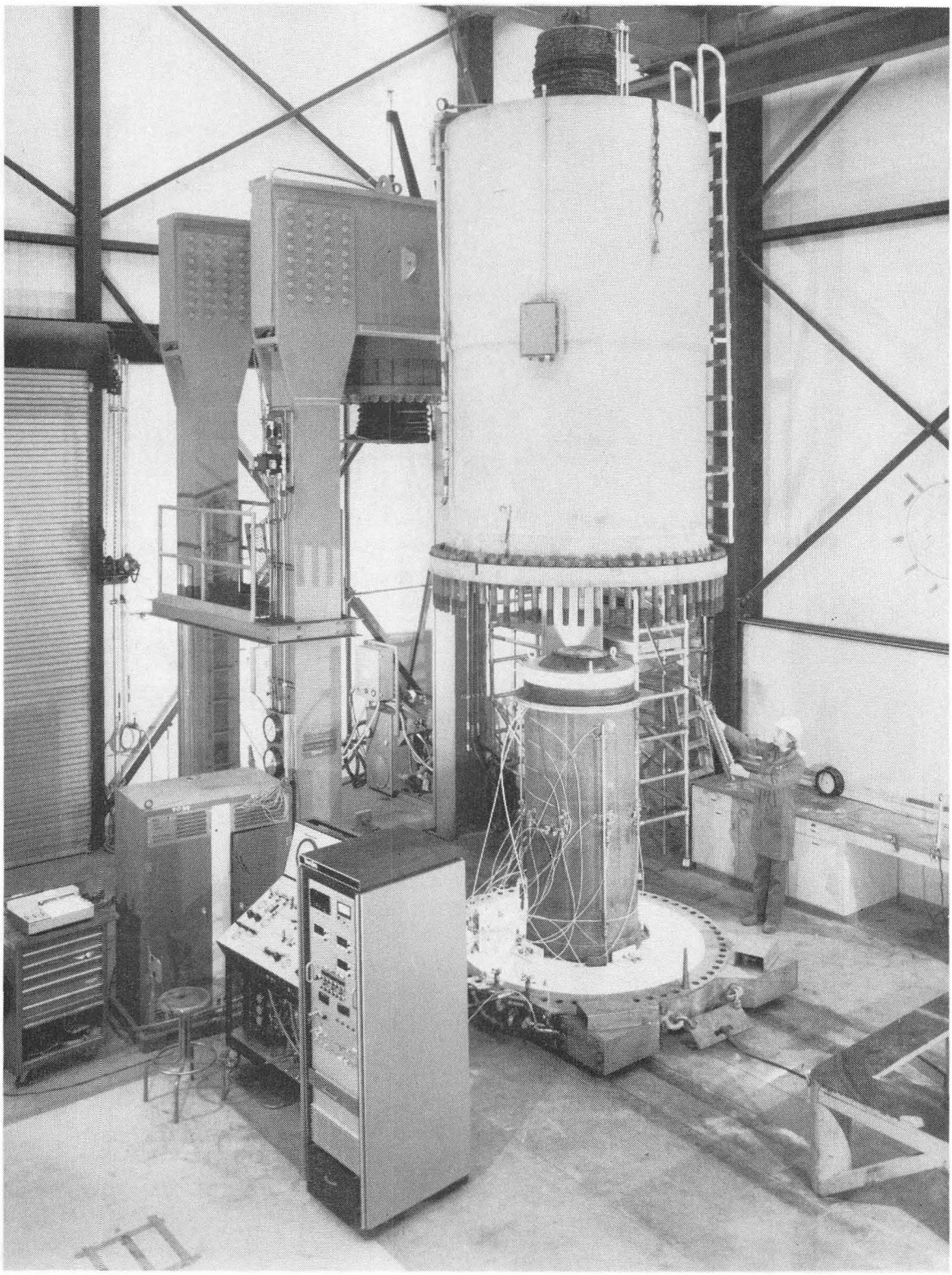

Fig. 7. Large Triaxial Testing Machine. CBB 800-11819

Fig. 8. Ultra-large Core of Granitic Rock from Stripa, Sweden.
CBB 796-8236

to the long axis (A, B and C) and one steeply inclined (D, E and F). The fracture filling material was predominantly chlorite and sercite with lesser amounts of epidote, calcite and other minerals.

The specimen was tested in the large triaxial machine (Figure 7). The test procedure took the form of a modified unconfined compressive strength test in which the axial loading, at a rate of 0.5 MPa/min, was interrupted and held constant at several stages. At each constant load stage permeability tests were performed by injecting water into (divergent flow) and withdrawing water from (convergent flow) a borehole drilled through the axis of the specimen. The test configuration is shown schematically in Figure 10. To ensure saturation of the sample and to keep air in solution, the triaxial vessel was filled with water at a pressure of 1,400 kPa throughout the test. Linear variable differential transformers (LVDTs) and strain gauges were mounted on the specimen to measure overall axial deformation, circumferential strain at mid-height, deformation of the principal fractures, and strains in the rock matrix. The locations of these instruments are shown in Figure 9.

The results of the experiments performed on the Stripa specimen have been reported in detail by Thorpe et al (1980). A peak stress of 7.4 MPa was attained at 0.06% axial strain before the onset of generalized failure of the specimen. This peak stress was much lower than the average unconfined compressive strength of 100 MPa measured from small 5.2 cm diameter samples of granitic rock obtained from the Stripa mine. However, the tangent modulus of deformation measured prior to failure of the large specimen was 52.3 GPa which is within the range obtained from small diameter samples. The failure kinematics were complex, involving tilting of

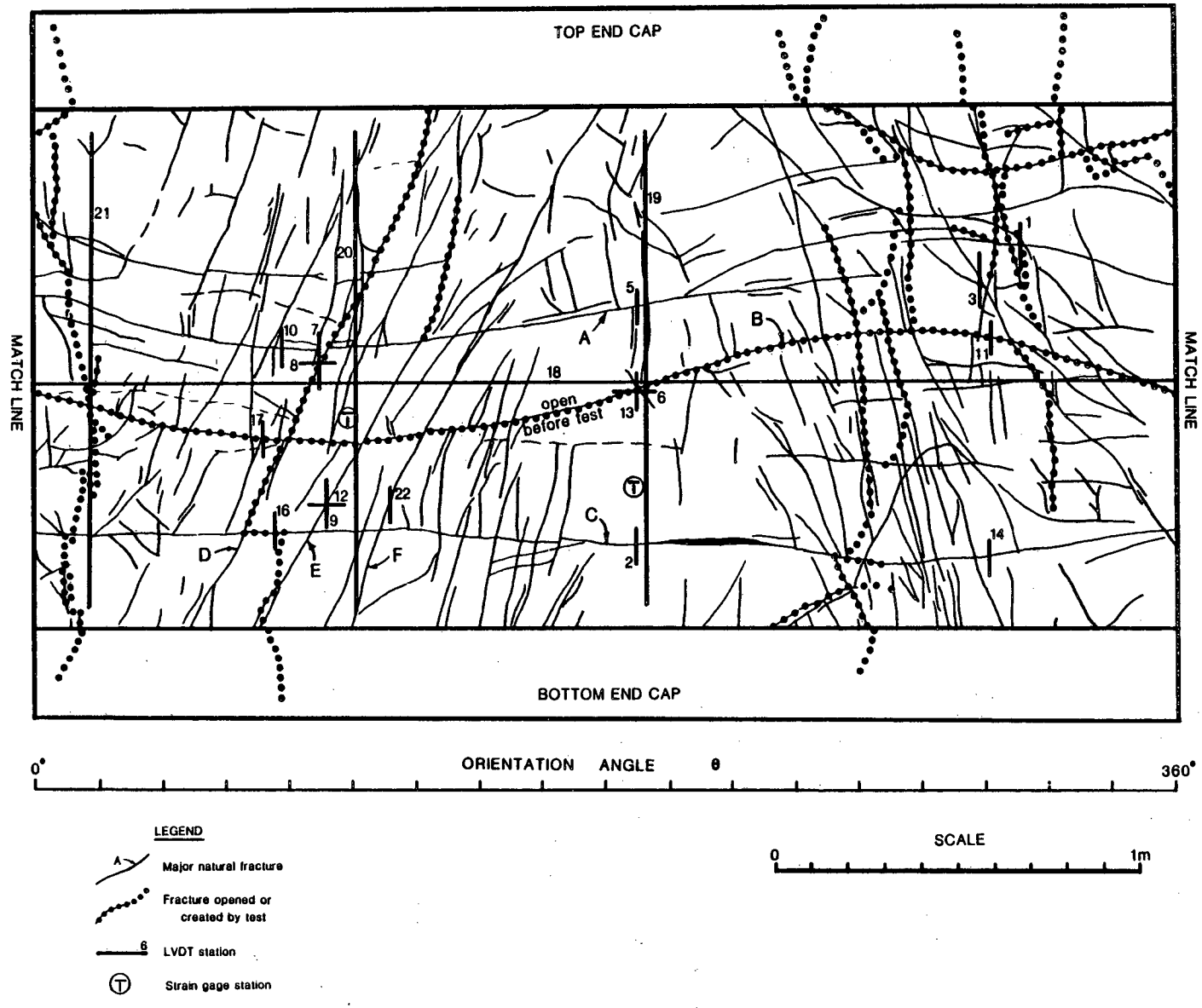

Fig. 9. Fracture Map Showing Locations of Instrumentation on Stripa Granite Specimen. XBL 806-10319

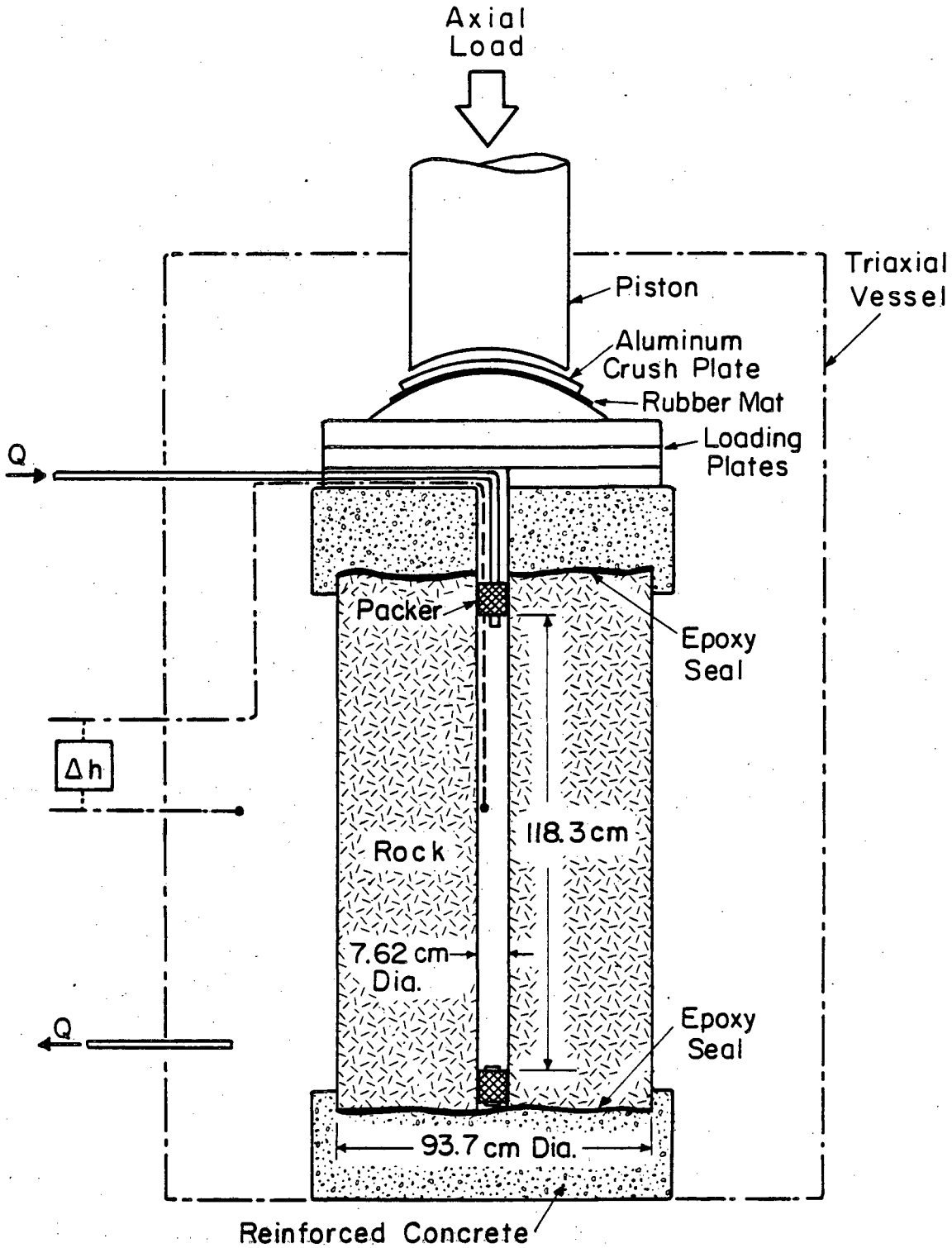

Fig. 10. Schematic of Test Arrangement for Stripa Specimen. XBL 809-5921

the top of the specimen, creep deformation and non-linear shearing motions. New fractures were developed in previously intact portions of the specimen and pre-existng fractures were opened as shown in Figure 9.

Results from the permeability tests on the Stripa specimen are shown on Figure 11 in the form of hydraulic conductivity versus applied axial stress. The results from the Stripa rock are compared with results of previous laboratory and in situ tests in which normal stresses were applied to a single fracture. Although the permeability of the pervasively fractured specimen was much greater than that of the others, it initially exhibited the characteristic reduction in permeability with increasing axial loading. As the axial stress was increased from zero to 5.56 MPa the permeability decreased from 14.64 cm/sec to 3.04 cm/sec. However, prior to generalized failure of the sample there was a rapid increase in permeability to some 7.67 cm/sec associated with shear dilatency and fracture opening. This latter effect was not unexpected but has not previously been observed in laboratory tests. Similar changes in rock mass permeability due to shear deformations can be expected to occur in the near field of a nuclear waste repository due to perturbations of the stress field resulting from excavation and thermal loading.

Due to the complexity of the flow regime through the pervasively fractured specimen it was not possible to establish a simple relationship between permeability and fracture deformations. However, there was evidence from preliminary falling-head permeability tests that the horizontal fracture B (see Figure 9) was the dominant flow-path. The inclined fracture D showed the second highest conductivity but carried only some 10 percent of the flow through fracture B. Flow through fracture C, the third

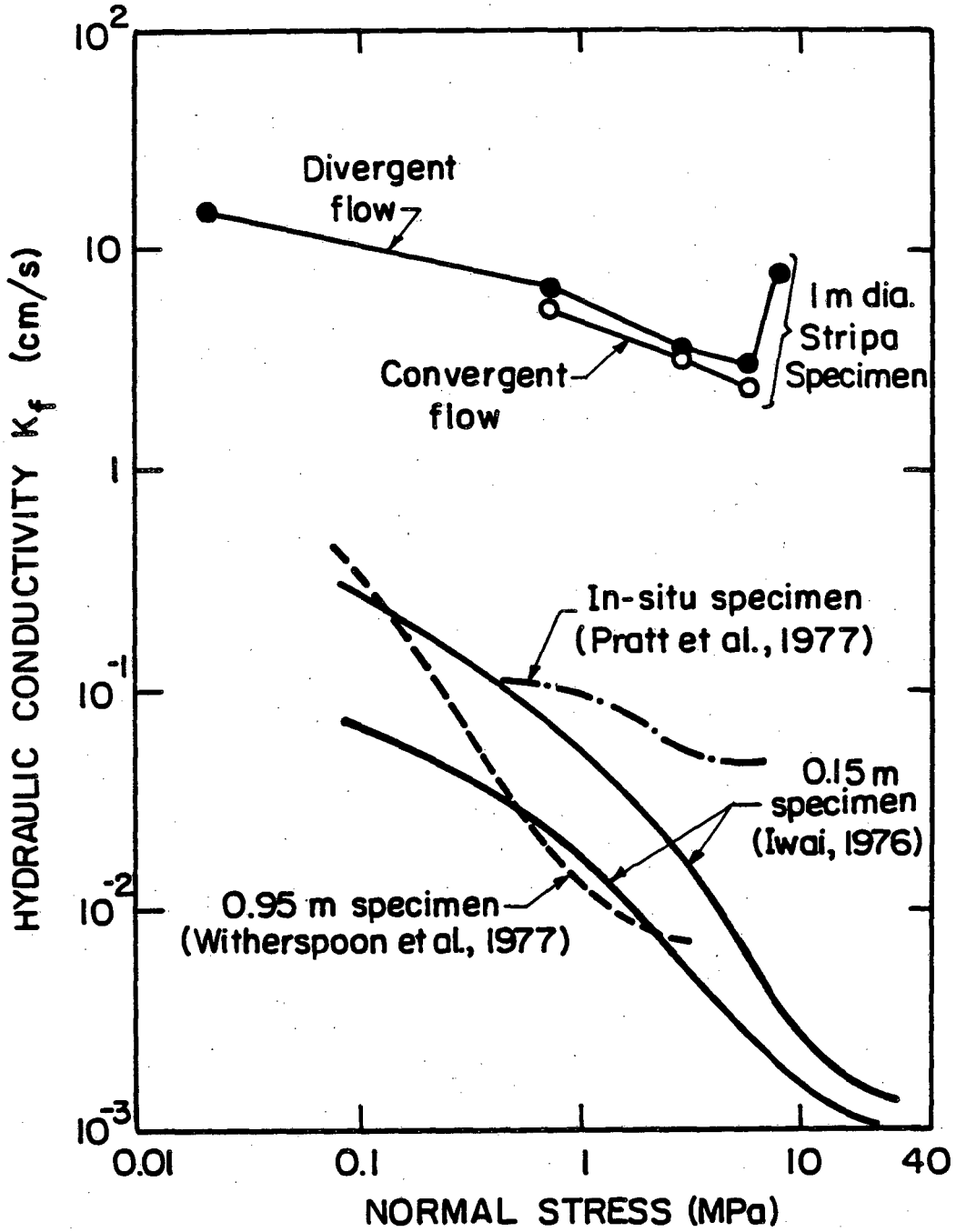

Fig. 11. Changes in Conductivity in Response to Applied Stress. XBL 808-11520

most conductive, was less again by an order of magnitude. Based on these observations, Thorpe et al. (1980) performed an analysis that considered flow through fractures B and D only and investigated the ability of a simplified model to predict the changes in hydraulic properties of the rock mass due to fracture deformation. The model assumed that all flow occurred through fractures B and D and that they could be treated as hydraulically independent systems of flow in which the cubic law for laminar flow between smooth parallel plates is valid. Total flow through the model was the sum of the flows through B and D. Estimates of the absolute aperture of the fractures were made in two ways. In one method the initial apertures at zero applied stress were estimated from the asymptotes of the load-displacement data obtained from the LVDT instrumentation. Absolute apertures at higher loads were then computed by subtracting the observed fracture displacements from these values. In the second method initial apertures were estimated by applyng the cubic law to flow data obtained in preliminary falling-head permeability tests performed under zero axial load. Figure 12 compares values of flow measured during the laboratory tests with those estimated from the simplified two-fracture model using both methods for calculating the initial apertures of fractures B and D. While there is considerable discrepancy between the measured and estimated flows, the general characteristics of the relationship between permeability and applied stress are predicted by the simple two-fracture model. The initial decrease in permeability due to application of axial stress is reproduced by the model as is the rapid increase in permeability associiated with the onset of shear dilatency and fracture opening that occurred during failure of the specimen. Considering the complexity of the fracture

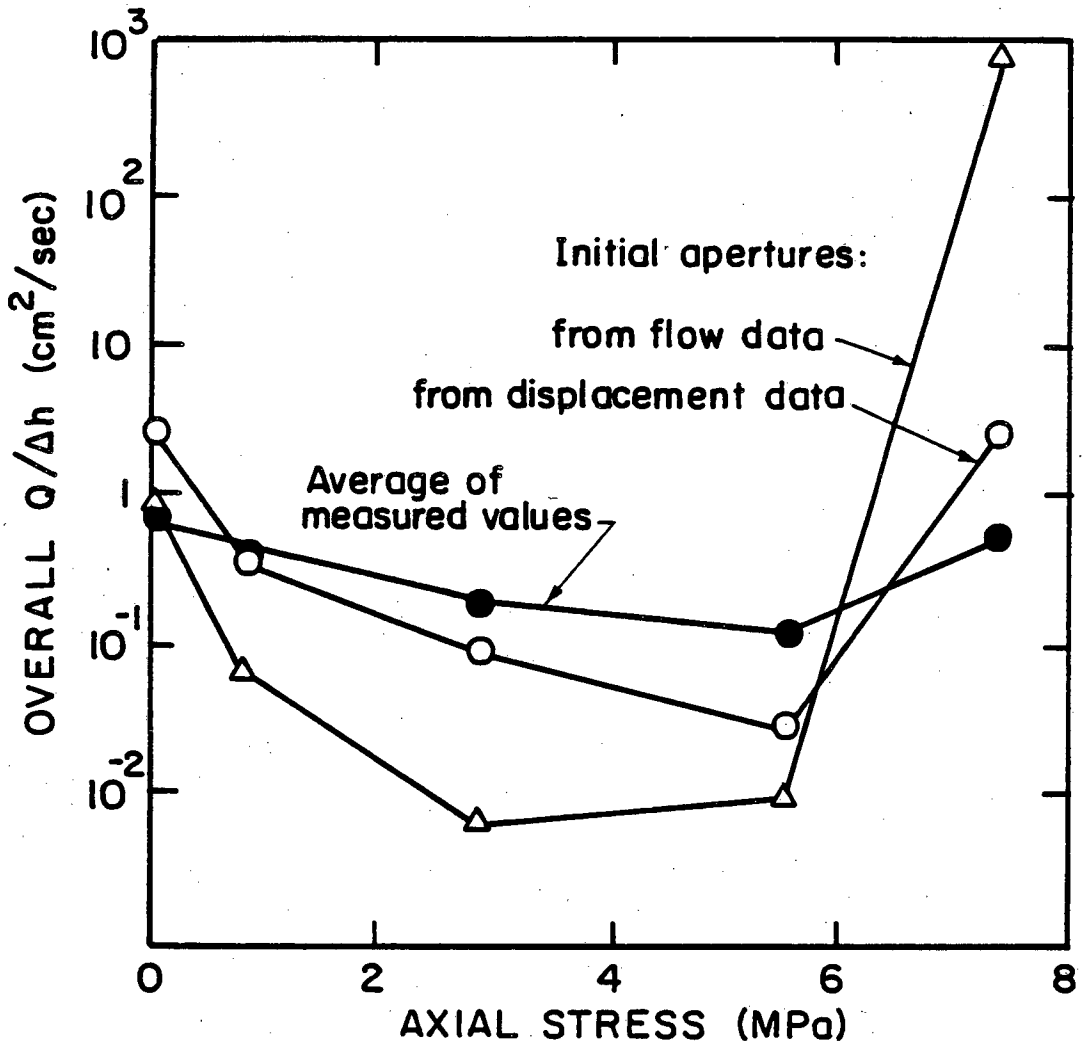

Fig. 12. Flow through the Stripa Specimen Compared with Flows Estimated from Simplified Model. XBL 809-11701

system in the Stripa specimen and the gross simplyfing assumptions made in the analysis, the correlation between the measured and computed values, although they differ by approximately an order of magnitude, are surprisingly good. This suggests that, in rock masses containing well defined systems of fractures, analytic procedures based on available models of flow through discrete fractures could be used to predict changes in rock mass permeability due to thermomechanical loading. However, it must be recognized that in rock masses where flow is not dominated by a few discrete discontinuities analytic methods based on a continuum model may be more appropriate (Hubbert 1956; Witherspoon et al. 1981). In practice, analysis of the hydrologic aspects of site selection and design of nuclear waste repositories will rely upon data obtained by a variety of techniques that include not only laboratory and in situ test programs but also call upon important contributions from the disciplines of geology and geophysics (Watkins and Thorpe, 1981).

Witherspoon et al. (1979) compiled the data from tests on single, normally loaded fractures that are presented on Figure 11. Because the conductivity of fractures under high normal stress obtained from large specimens was considerably greater than conductivities measured from small specimens, it was concluded that there may be a significant size-effect influencing the measured hydraulic properties of fractures in rock. To investigate this phenomenon further, and to make more detailed studies of the relationships between fracture conductivity, stress and deformation, an experimental program has been initiated to test single natural fractures with areas up to 0.66 m^2. Cylindrical specimens containing a natural fracture at mid-height and oriented normal to the long axis have been pre-

pared from large blocks of Charcoal Black granite quarried near Cold Spring, Minnesota. Figure 13 shows a massive block of granite from which the 0.914 m diameter by 1.83 m high specimen shown in Figure 14 was prepared. To minimize disturbance to the natural fracture a rock bolt was installed in a hole drilled through the granite block before it was reduced to cylindrical form using the wire saw jig shown in Figure 15 (Watkins, 1981). Figure 16 is a map of the periphery of the finished specimen showing the location of the principal fracture, B, that passed through the diameter and the LVDT and strain gauge instrumentation used to monitor the deformations due to applied axial load. Preliminary tests showed that the secondary fractures A, C, D and E did not have significant hydraulic connectivity with fracture B. The test procedure used to study the hydraulic characteristics of the fracture was similar to that used in the experiments on the Stripa specimen except the central borehole was packed off immediately above and below fracture B to minimize flow through the rock matrix and measurements of conductivity were made through several cycles of loading and unloading.

The experimental program on the ultra-large specimens of Charcoal Black granite is still in progress but Figure 17 summarizes the relationships between fracture conductivity and axial stress that have been obtained to date. Results are presented from two series of tests. One performed on the 0.914 m diameter specimen and a second series performed on the same specimen after it had been reduced in size to 0.764 m diameter. In each case the data show the effect of successive cycles of axial loading and unloading. The conductivities of the fracture measured from the 0.764 m diameter size were typically two orders of magnitude greater than

Fig. 13. Fractured Block of Charcoal Black Granite. CBB 798-10084

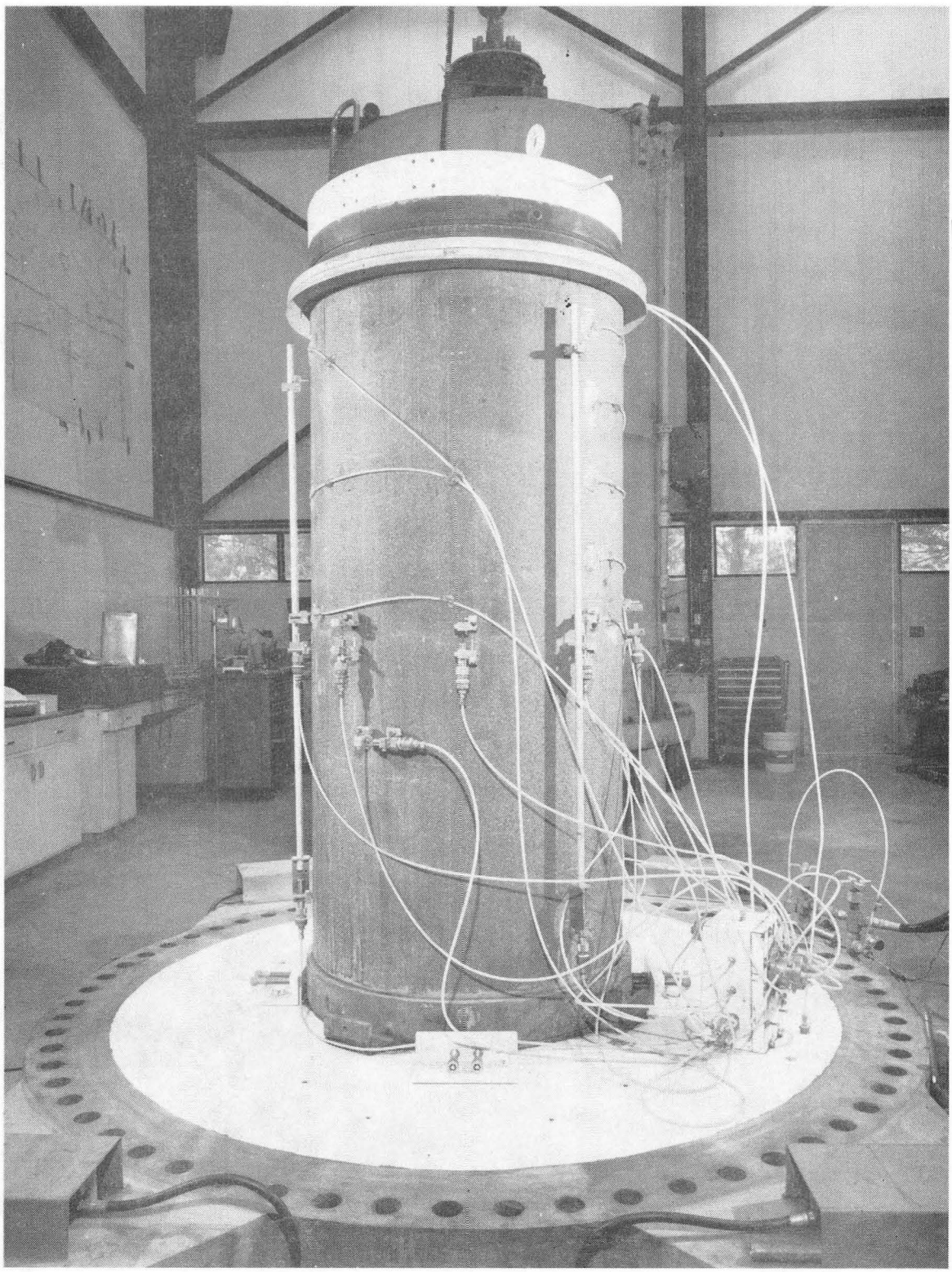

Fig. 14. Instrumented Specimen of Charcoal Black Granite.
CBB 800-11823

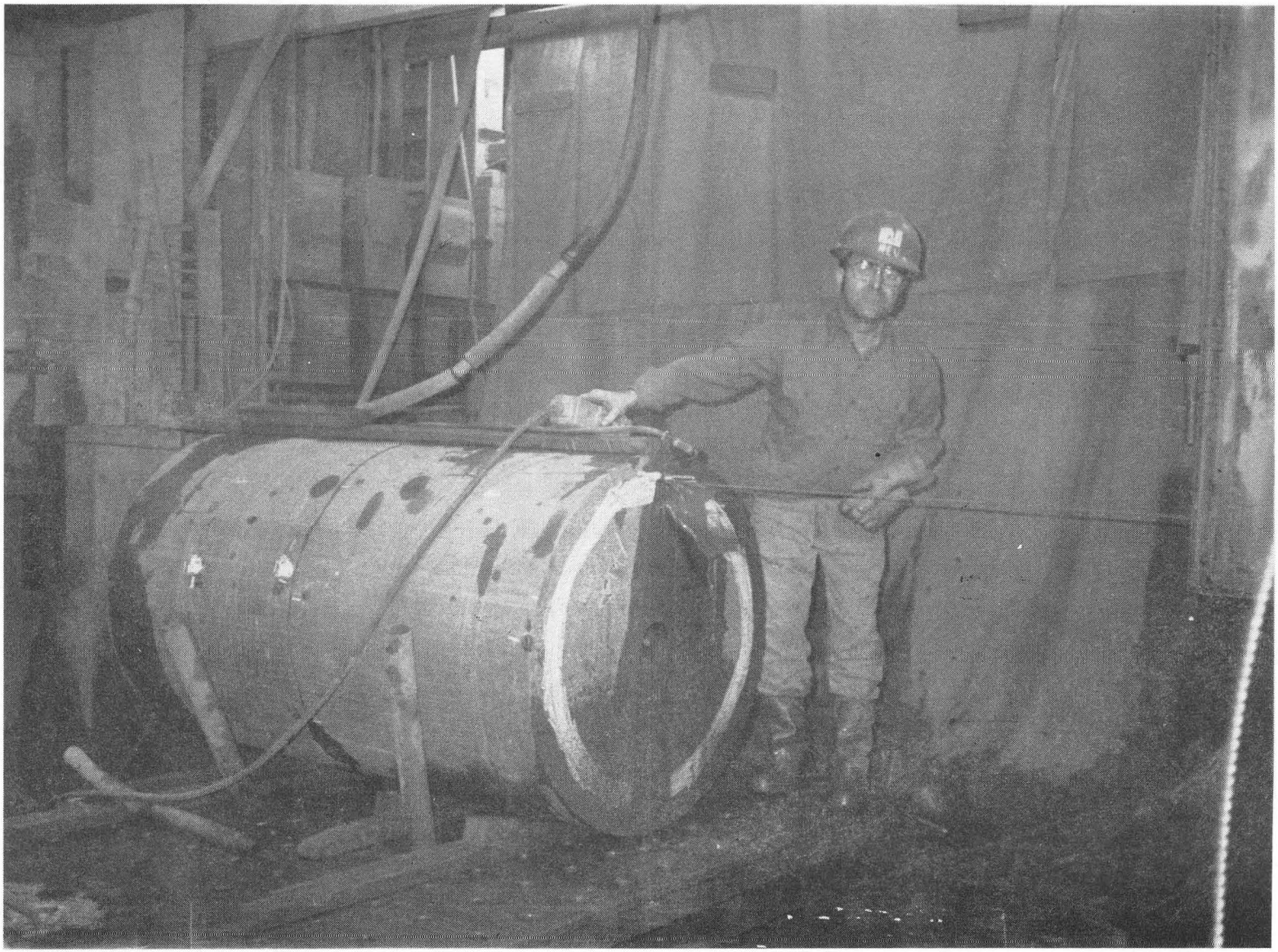

Fig. 15. Cutting Granite Specimen with Wire Saw.
(Photograph Courtesy of Cold Spring Granite Co.).

XBB 8012-15039

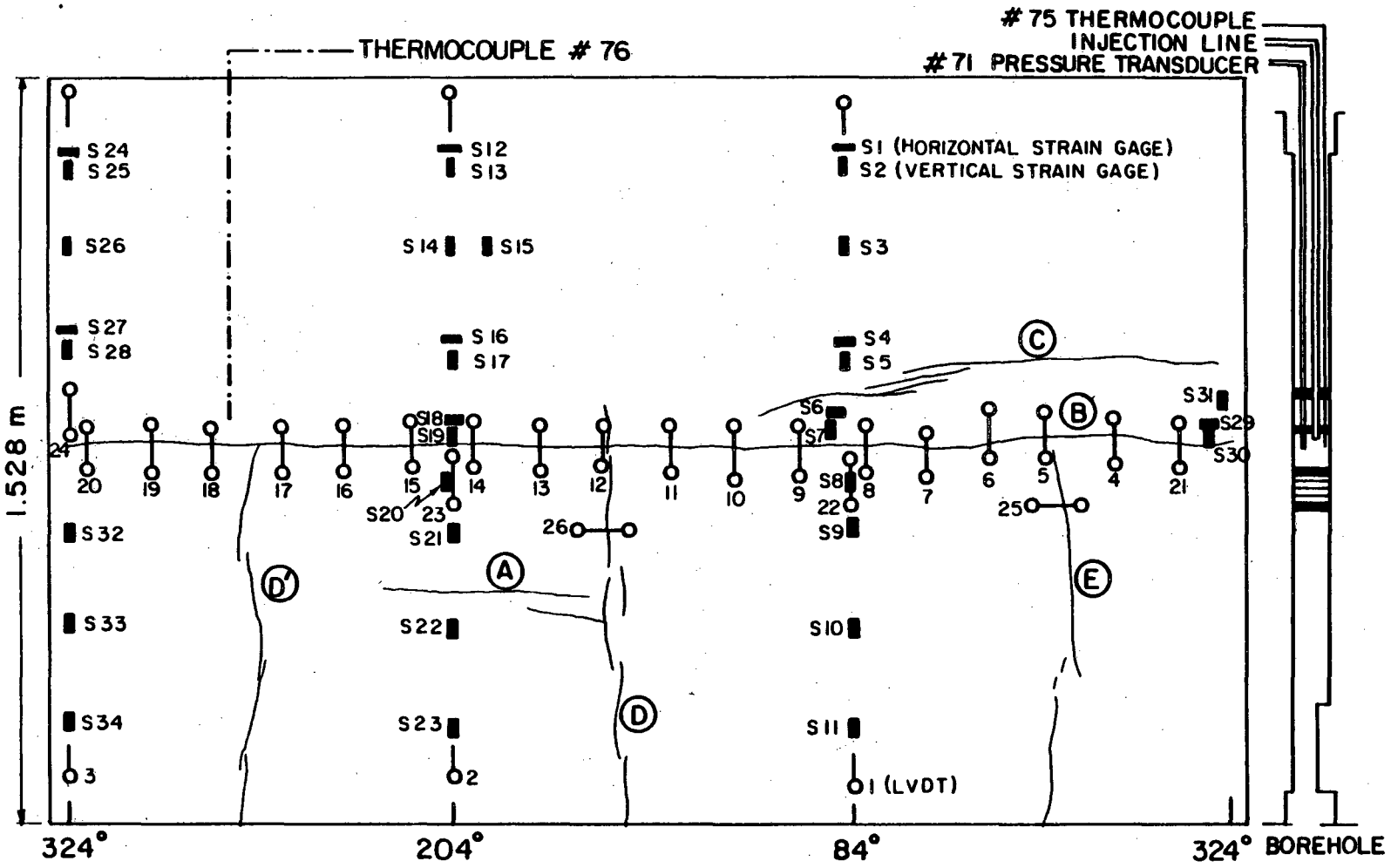

Fig. 16. Map of the Surface of Charcoal Black Granite Specimen showing Fractures and Locations of Instruments. XBL 813-5237 A

those measured from the specimen when its diameter was 0.914 m. This result would appear to contradict the observation of decreasing conductivity with decreasing specimen size that was made from the data compiled on Figure 11. However, a carefull analysis showed that the fracture had suffered small but significant disturbance while the sample was being reduced in size. This sensitivity of the hydraulic properties of fractures to disturbance illustrates the importance of mining induced changes in rock mass permeability that can occur around underground openings constructed for disposal of nuclear waste.

As shown in Figure 17, the effect of repeated cycles of loading and unloading on fracture conductivity is to progressively decrease the conductivity. Figure 18 plots unit-flow-rates measured at similar levels of normal stress after application of different numbers of load cycles. These data illustrate a number of phenomena that reflect the effects of cyclical loading on the consitutive properties of the material forming the walls of the fracture. The permanent reduction in conductivity due to hystesis is greatest due to the first loading cycle but the change due to each successive cycle is progressively less. Reduction in conductivity per cycle of loading is significanty reduced after the fracture has been subjected to high normal stress as is shown by the relatively flat curve on Figure 18 that plots unit-flow-rates measured at a normal stress of 13.5 MPa. These findings are compatible with the stress-deformation data obtained from the LVDT's mounted accross the fracture and are further evidence that permeability is a function of the stress-history of a rock mass. Cyclical changes in stress in the rock surrounding a waste repository will occur due to construction of openings and temperature changes resulting from

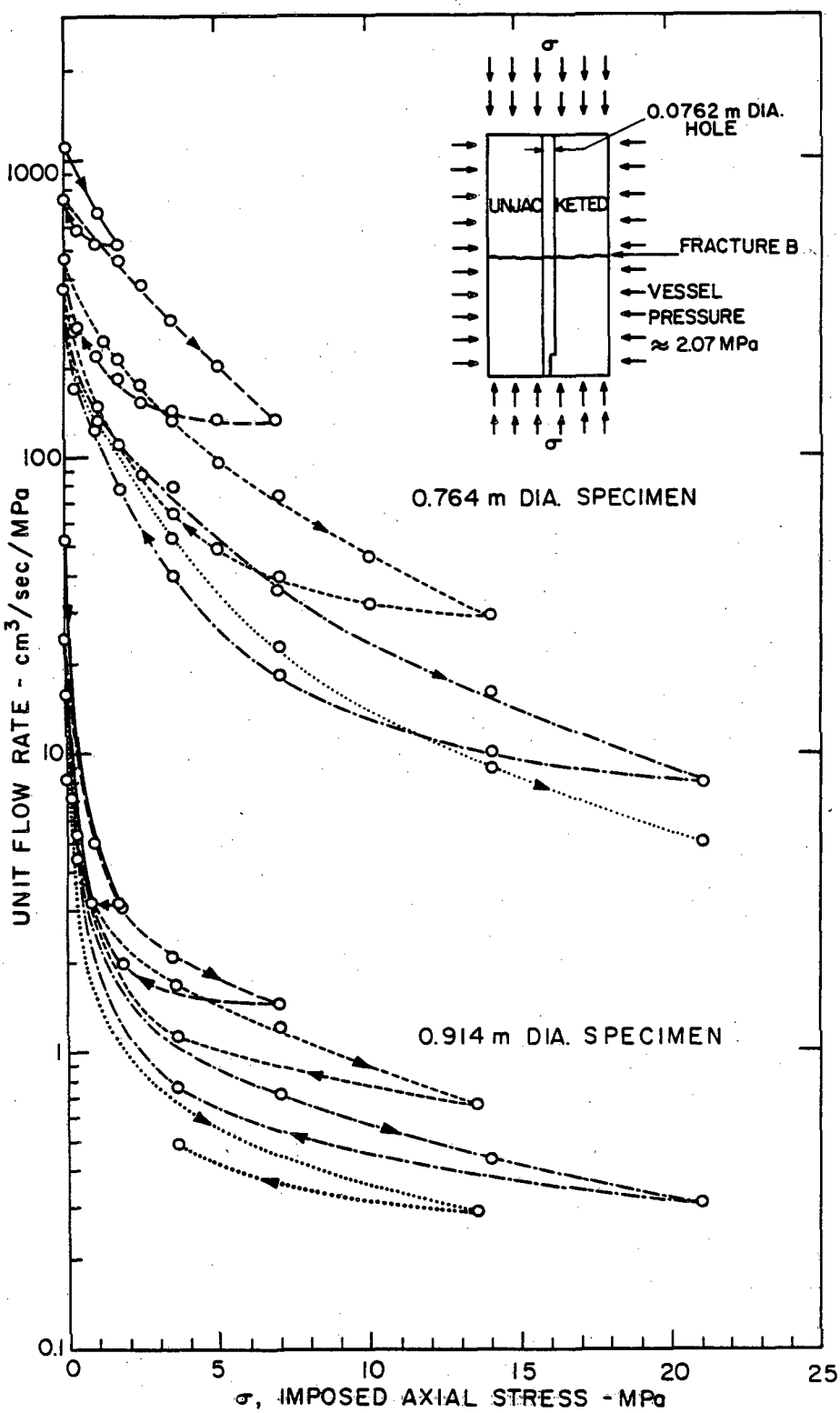

Fig. 17. Relationships between Flow through a Natural Fracture and Axial Stress for Specimens of Charcoal Black Granite. XBL 811-50953A

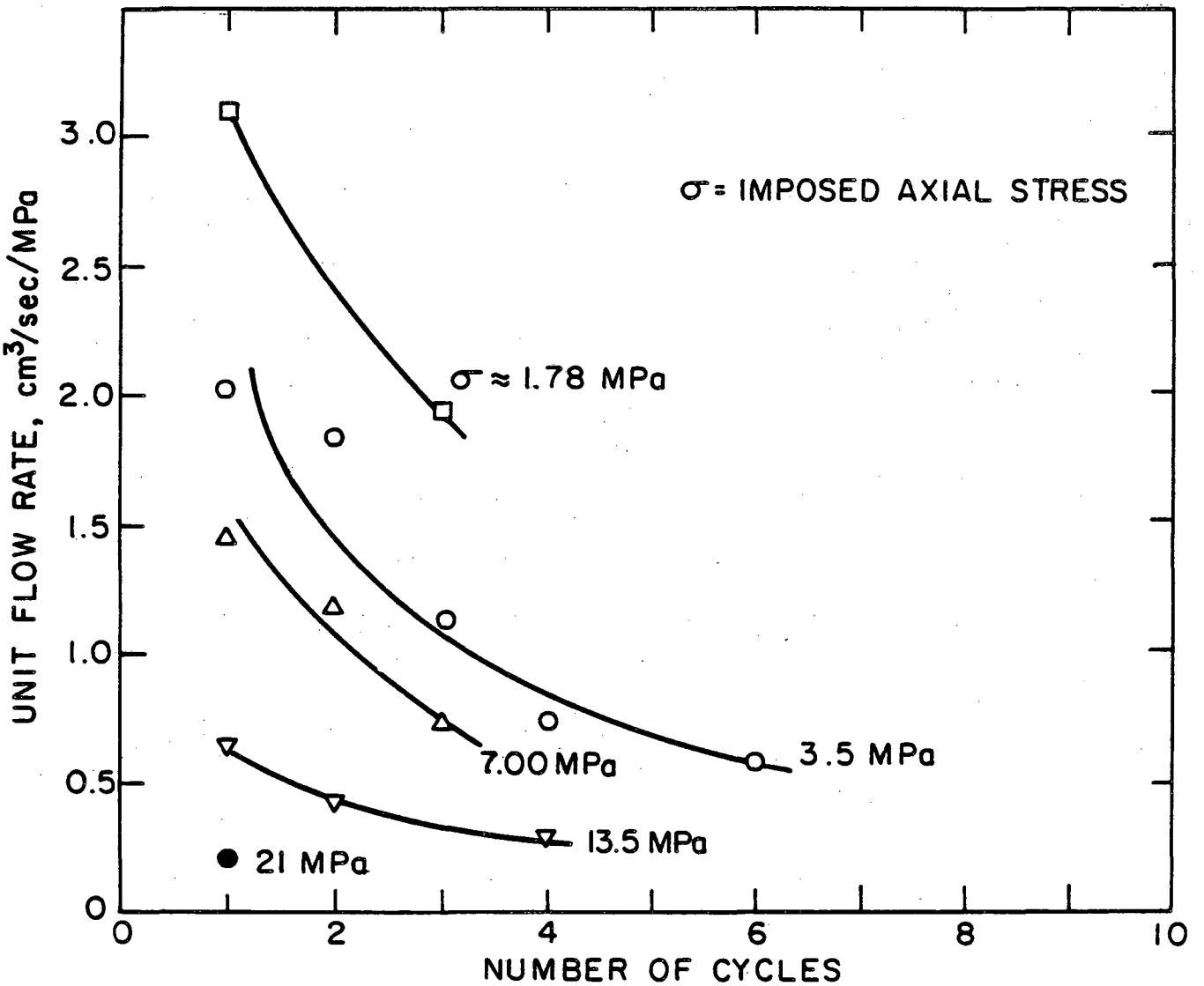

Fig. 18. Change in Unit-flow-rate with Cycles of Loading and Unloading (0.914m dia specimen) XBL 812-5311

ventilation and the heating and subsequent cooling that accompanies from radioactive decay of the waste. The results shown on Figures 17 and 18 show that cyclical changes in the normal stress on fractures in a rock mass should not result in increased permeability if the stress at the end of the loading cycle is at least equal to the initial in situ stress.

CONCLUSIONS

The "cubic-law" of flow through fractures in rock is based on the analogy of flow through smooth parallel plates and states that the flow-per-unit-head is proportional to the cube of the fracture aperture. By introducing suitable parameters to account for fracture roughness and contact area, it has been shown that the cubic-law is valid for flow through rough deformable fractures in crystalline rocks subjected to normal stresses over a wide range of practical interest (0-20 MPa). A model for flow through deformable fractures that explicitly incorporates fracture roughness and contact area has been developed and successfully tested against laboratory experiments. The model accounts for changes in conductivity due to changes in normal stress by treating the flow paths as a series of interconnected deformable voids. The model can be used to predict flow rates through natural fractures if an estimate of the fractional contact area of asperities that bridge the fracture aperture can be made and stress-deformation data for the intact rock and a specimen containing the fracture is available. These data can be obtained from laboratory or in situ tests so that the model has considerable potential for practical application in modeling flow through fracture systems of the type expected to be encountered in the rock mass surrounding a deep underground nuclear waste repositories constructed in crystalline rock.

Measurement of the permeability of a rock mass and the conductivity of fractures can be influenced by the size of specimens used in laboratory experiments. To investigate these effects and to study the basic pheomenology controlling flow through fractures, sample gathering, preparation and testing techniques have been developed to test naturally fractured cylindrical specimens up to 1 m diameter by 2 m high. Work completed to date has shown that the hydraulic properties of fractures are sensitive to sample disturbance and stress history. Although gross simplifying assumptions must be made to apply theoretical models to a pervasively fractured rock mass, comparison of model predictions with experimental results from an ultra-large specimen of fractured granite showed that simple models successfully reproduce the trend of reducing permeability due to initial application of axial stress and also reflect the increase in fracture conductivity that is associated with dilatancy due to shear displacements. Based on these studies it appears reasonable to expect that, with further refinement of the theoretical models and experimental techniques, reliable procedures can be developed to analyse the flow regime in a crystalline rock mass surrounding a nuclear waste repository and to predict the effects of changes of stress that are induced by construction and the heat generated by the waste form.

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NOMENCLATURE

A	Total area of fracture surface
b	Fracture aperture
b_d	Apparent aperture
b_r	Residual aperture
C	Proportionality constant
d	Half-length of a void
b_o	Maximum fracture aperture
E	Young's Modulus of intact rock
E_{eff}	Effective modulus of fractured rock
f	Factor accounting for fracture roughness etc.
k_f	Fracture conductivity
M	Number of voids
$Nc(\Delta V)$	Number of areas of contact in fracture
$n(h)$	Asperity height distribution function
Q	Flow
$Q/\Delta h$	Flow-per-unit-head
x,y,z	Cartesian coordinates
ΔV	Normal deformation of fracture
ΔV_m	Maximum normal deformation of fracture
σ	Normal stress
ω	Fractional contact area of fracture

REFERENCES

Andersson, B. and Halen, P.A., 1978. Mining Methods Used in the Underground Tunnels and Test Rooms at Stripa, Lawrence Berkeley Laboratory LBL-7081, SAC-08 Berkeley, California.

Baker, W.J., 1955. "Flow in fissured formations" Proceedings Fourth Petroleum Congress, Rome, Vol II, pp 379-393.

Bear, J., 1972. Dynamics of Fluids in Porous Media, American Elsevier Co., New York.

Becker, E., Chan, C.K., and Seed, H.B., 1972. Strength and Deformation Characteristics of Rockfill Materials in Plane Strain and Triaxial Compression Tests, Geotechnical Engineering Report No. 72-3. Department of Civil Engineering, University of California, Berkeley.

Boussinesq, J., 1868. Journal de Liouville, v. 13, pp 377-424.

Gale, J.E., 1975. A Numerical Field and Laboratory Study of Flow in Rock with Deformable Fractures, Ph.D. Thesis, Department of Civil Engineering, University of California, Berkeley.

Gangi, A.F., 1978. Variations of Whole and Fractured Porous Rock Permeability with Confining Pressure, International Journal of Rock Mechanics and Mining Science, Vol 15, pp 249-257.

Hubbert, M.K., 1956. Darcy's Law and the Field Equation of the Flow of Underground Fluids. Petroleum Transactions, AIME Vol 207, pp 222-239.

Huitt, J.L., 1956. "Fluid flow in simulated fractures" Journal of the American Institute of Chemical Engineers, Vol 2. p 259.

Iwai, K., 1976. Fundamental Studies of Fluid Flow Through a Single Fracture, Ph.D. Thesis, Department of Civil Engineering, University of California, Berkeley.

Jones, F.O. Jr., 1975. A Laboratory Study of the Effects of Confining Pressure on Fracture Flow and Storage Capacity in Carbonate Rocks, Journal of Petroleum Technology, 21.

Kranz, R.L., Frankel, A.D., Engelder, T., and Scholz, C.H., 1979. The permeability of whole and jointed Barre granite, International Journal of Rock Mechanics and Mining Science, Vol. 16, pp 225-234.

Lomize, G.M., 1951. Filtratsiya v Treschehinovatykh Paradakh, Gosenesgoizdat, Moscow.

Louis, C., 1969. A Study of Groundwater Flow in Jointed Rock and its Influence on the Stability of Rock Masses, Rock Mechanics Research Report No. 10, Imperial College of Science and Technolgy, London.

Nelson, R., 1975. Fracture Permeability in Porous Reservoirs: Experimental and Field Approach. Ph.D. Dissertation, Department of Geology, Texas A and M University, College Station, Texas.

Parrish, D.R., 1963. "Fluid flow in rough fractures," Paper SPE 563, presented at the Production Research Symposium, University of Oklahoma.

Pratt, A.R., Swolfs, H.S., Brace, W.F., Black, A.D. and Handin, J.W., 1977. Elastic and Transport Properties of In Situ Jointed Granite, International Journal of Mining Science and Geomechanics Abstract, 14, pp 35-45.

Rayneau, C., 1972. Contribution a L'Etude des Ecoluments Autor D'un Forage en Milieu Fissure, These, Docteur-Ingenier Universite des Sciences et Technique du Languedoc, Academie de Montpellier, France.

Romm, E.S., 1966. Flow Characteristics of Fractured Rocks, Nedra, Moscow (in Russian).

Thorpe, R., Watkins, D.J., Ralph, W.E., Hsu, R., and Flexser, S., 1980. Strength and Permeability Tests and Ultra-Large Stripa Granite Core, LBL-11203, SAC-31, Lawrence Berkeley Laboratory, Berkeley, California.

Tsang, Y.W. and Witherspoon, P.A., 1981. Hydromechanical Behavior of a Deformable Rock Fracture Subject to Normal Stress, Journal of Geophysical Research, Vol. 86, pp. 9287-9298.

Walsh, J.B. (1965) The Effects of Cracks on the Uniaxial Elastic Compression of Rocks, Journal of Geophysical Research, Vol 70, pp 399-411.

Watkins, D.J., 1981. Aquisition and Preparation of Specimens of Rock for Large Scale Testing. Geophysical Research Letters, Vol. 8, No. 7, pp. 679-682.

Watkins, D.J. and Thorpe, R.K., 1981. Large Volume Tests in Rock Mechanics, presented at the Conference on Properties of Materials under Extreme Conditions, Los Alamos, New Mexico, May 18-19. LBL-12467, Lawrence Berkeley Laboratory, Berkeley, California.

Witherspoon, P.A., Amick, C.H., Gale, J.E. and Iwai, K., 1979. Observations of a Potential Size Effect in Experimental Determination of the Hydraulic Properties of Fractures, Lawrence Berkeley Laboratory, Report No. LBL-8571, SAC-17, Berkeley, California.

Witherspoon, P.A., Wang, J.S.Y., Iwai, K., and Gale, J.E., 1980. Validity of Cubic Law for Fluid Flow in a Deformable Rock Fracture, Water Resources Research, Vol 16, No. 6, pp 1016-1024.

Witherspoon, P.A. and Degerman, O., 1978. Swedish-American Cooperative Program on Radioactive Waste Storage in Mined Caverns in Crystalline Rock--Program Summary, Lawrence Berkeley Laboratory, LBL-7049, SAC-01, Berkeley, California.

Witherspoon, P.A., Amick, C.H. and Gale, J.E., 1977. Stress-Flow Behavior of a Fault Zone with Fluid Injection and Withdrawl, Report No. 77-1 Department of Materials Science and Mineral Engineering, University of California, Berkeley.

Witherspoon, P.A., Tsang, Y.W., Long, J. and Noorishad, J., 1981. New Approaches to Problems of Fluid Flow in Fractured Rock Masses, Proceedings of the Twenty Second U.S. Symposium on Rock Mechanics, pp. 1-20, Massachusetts Institute of Technology, Cambridge, Mass.

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