LARGE-SCALE PERMEABILITY TESTING AT STRIPA

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The macropermeability experiment at Stripa, Sweden, is an attempt to measure the average permeability of a very large volume of low-permeability, fractured rock. Flow into and pressure surrounding a 33 m drift will be measured. This experiment will also help to determine the size of the representative elementary volume for the Stripa granite. Problems in pressure field characterization include the perturbation resulting from drainage into the rest of the mine and vagaries of the fracture system itself. To measure pressure, 15 boreholes have been drilled from the drift into the surrounding rock and instrumented with 94 packers and 90 pressure gages. Inflow to the drift is measured by evaporating the seepage into the ventilation air while measuring the change in water vapor content between incoming and exhaust air streams. In order to measure this change in water vapor content, the drift has been sealed off and measurements of the barometric pressure, air velocity in the exhaust duct, and the wet and dry bulb temperatures of the inlet and exhaust air are taken. A test at ambient temperature has been completed. Preliminary results estimate a hydraulic conductivity of about 6.5×10^{-11} m/s.

1. MOTIVATION FOR LARGE SCALE TESTING

The prospect of geologic storage of nuclear waste has created a need to determine the hydrologic material properties of low-permeability fractured rock. The macropermeability experiment at the Stripa mine in Sweden is an attempt to improve permeability characterization techniques for the analysis of regional groundwater flow through low permeability rock in the vicinity of a nuclear waste repository. The experiment is part of the Swedish-American Cooperative Program on Radioactive Waste Storage in Mined Caverns in Crystalline Rock(1,2). At Stripa we are monitoring flow into, and pressure surrounding a 5 m x 5 m x 33 m long drift called the ventilation drift at the 335 m level of the Stripa mine (Figure 1). This paper examines the theoretical problems associated with making such a measurement, and describes the actual experiment now in progress including preliminary results as of November 1979.

Three problems arise in determining flow parameters for low permeability fractured rock. The first is to determine the minimum volume of rock for which the permeability tensor is representative of a larger rock mass and is amenable to a porous media method of analysis. The second problem is to determine this permeability tensor from field tests. The third problem is to assign permeabilities to the volumes of rock that are not directly examined in the field. The macropermeability experiment at Stripa is an attempt to increase our understanding of the first two of these problems. The third is not discussed here.

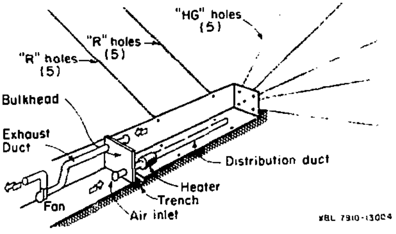

Fig. 1. Perspective section through the ventilation drift showing air flow pattern and hydrology instrumentation boreholes.

As the volume of the fractured rock sample increases from zero, the average permeability will oscillate as either fractured or solid rock is added to the sample. When the volume of rock becomes sufficiently large that permeability is no longer sensitive to the effects of individual fractures, the oscillations will cease. An average permeability can then be assigned to that volume of rock which is called the representative elementary volume (REV). Theoretically, volumes of rock the size of the REV can be treated as porous media for regional groundwater flow analyses. Increasing the volume further may ultimately cause additional oscillations if a different realm of fracturing is encountered. When a single permeability measurement is made on an arbitrary volume of rock there is no way of knowing a priori whether or not the measured permeability lies on the oscillating portion of the curve. A series of measurements on different scales must be made to determine if there is a REV smaller than the rock mass itself and to determine the permeability associated with that volume.

In fractured rocks, where the discontinuities themselves may occupy areas on the order of 10^2 m^2, it is reasonable to expect REV's, if they exist, to be on the order of 10^4 or 10^5 m^3. The macropermeability experiment at Stripa will permit a measurement of the average permeability of 10^5 of rock. There is no assurance that this volume will be as large as the REV; however, the experiment, taken along with other small-scale tests performed at the same site, should provide strong indications of the size and existence of the REV.

The second problem is to determine the permeability of these large volumes from in situ tests. In high permeability soils or rocks, standard well tests can be run such that large volumes of the flow system are perturbed by the test in reasonable periods of time. However, in low permeability rocks, standard well tests may only affect the flow system within a few meters of the well. Determination of large-scale permeability values can therefore be attempted in two ways. The first way is to synthesize large scale values from a series of small-scale tests done in boreholes. The second way is to create a large scale sink (or source) which will perturb a large volume of the flow system, i.e., a macroscopic permeability test.

Small scale borehole tests will probably remain the mainstay of hydrologic investigations since boreholes are the only practical means of extensively exploring deeply buried rocks. Therefore, reliable methods for predicting macroscopic permeability from borehole data are needed. In order to perfect such methods they will have to be checked by performing large-scale in situ tests at the same site where the borehole data has been collected. The macroscopic permeability test at Stripa represents a large-scale measurement that will be used to check the analysis of an extensive series of small-scale borehole tests$^{(3)}$.

II. MEASURING MACROSCOPIC PERMEABILITY

Any measurement of permeability must be made on a flow system with specified boundaries. The potential distribution on these boundaries as a function of time and the flux through each boundary as a function of time must be inferred or measured. Then the effective permeability can be calculated using Darcy's law. Most in situ tests cannot be constructed such that all these conditions are exactly met. Some assumptions about boundary conditions are usually made in the analysis.

Theoretically, flow into the ventilation drift will approach steady conditions, but will never actually reach equilibrium. In order to use steady state analysis the experiment will continue for 3 to 6 months or until there is no discernible change in pressure and temperature. However, both the definition of boundary conditions and the measurement of flow into the drift are problems of some magnitude.

Theoretical Considerations in Pressure Measurement

The ventilation drift can be idealized as a long, but finite cylindrical sink. The inner boundaries of this flow system are well defined. The location of the boundary is the wall of the drift. The pressure on that boundary is essentially zero since the drift is kept dry.

The outer boundaries of the flow system are more difficult to characterize. Several possible approaches can be taken. One is to assume that at some distance from the drift the flow field is undisturbed and the hydraulic potential is constant. However, the hydrology of the region surrounding the drift is to a large extent dominated by the extensive Stripa mine workings. Piezometric profiles in the vicinity of the ventilation drift are irregular. An assumption of undisturbed conditions would not be valid.

Another method is to define a convenient boundary surface and measure the pressure distribution on this surface. Alternatively, pressure could be measured at an array of points in space such that an isopotential surface could be located in space. In an ideal, homogenous porous medium this method would present little problem. The open interval of the piezometer would intersect a large number of pores and grains and the pressure measured would be a physically averaged pressure. In a fractured system, however the piezometer interval may only intersect a few fractures. Since the direction of flow in these particular fractures is not necessarily in the direction of the average gradient as shown in Figure 2, the fractures sampled will not necessarily yield the average gradient. Without knowledge of the average gradient, the average or equivalent permeability cannot be calculated. The problem is equivalent to predicting the permeability of a porous medium from measurements of pressure in only a few pores.

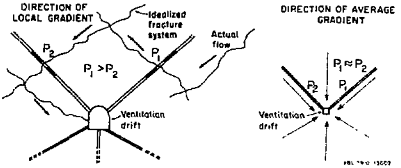

Fig. 2. Comparison of local and average gradients, P_i = pressure at point i.

As a partial solution to the above problem, piezometers can be installed parallel to the theoretical isopotential surfaces. These piezometers can then be open the whole width of the flow zone. In this case many fractures will intersect the piezometer and a physically averaged pressure will be recorded. Two problems are presented by this arrangement. The first is that long sections of open borehole may create a significant leakage paths and increase the flow into the drift. This will in turn increase the measured permeability. The closer the open borehols is to the drift the worse this problem is likely to be. Another problem is that this method of pressure measurement allows axial averaging but no circumferential averaging. The variability of pressure in the circumferential direction can be just as erratic as in the longitudinal direction.

The only way to ultimately insure a given set of boundary conditions is to create those conditions artificially. This can be accomplished by drilling a ring of closely spaced boreholes around the drift and maintaining them at constant hydraulic head. This method may be difficult and costly to construct, and it will not provide any information about anistropy.

Pressure Measurement at Stripa

At Stripa 15 boreholes 30 to 40 m long have been drilled from the ventilation drift into the surrounding rock (Figure 1). These boreholes are divided into 3 groups of 5 each. Two groups (the R-holes) are radial holes and one group (the HG holes) extend from the face of the drift. Each of these holes has been instrumented to monitor pressure. A total of 94 packers have been installed at approximately 5 m intervals. This prevents the boreholes from acting as drains into the drift and creates a 3-dimensional array of 94 zones, 90 of which are individually connected by tubing to pressure gages. Zones are numbered such that zone 1 in each hole is approximately 0 to 5 m from the drift; zone 2 in each hole is 5 to 10 m from the drift, and so on.

During the experiment air in the drift was kept at ambient temperature. Pressures in the boreholes and water flow into the drift are monitored until they are quasi-steady. In further experiments air temperature in the drift will be raised and the measurements repeated.

Between constant temperature experiments two further experiments will be conducted. The first will be small-scale permeability tests in which each zone in one or two boreholes will be drained. The flow rate from each zone will be monitored separately until approximately steady conditions are reached. By repeating this test after each constant temperature experiment it may be possible to detect local changes in permeability due to changes in temperature. These changes can then be correlated to changes in permeability detected for the whole macroscopic test.

The second test will be a pressure shunt test. At Stripa we will not be able to examine average pressures parallel to the theoretical average isopotentials. However, since the average gradient is not expected to be very large at the outer ends of the boreholes, we will be able to approximately examine the effect of zone length on pressure by hydraulically interconnecting adjacent zones through the pressure tubing and allowing the system to come to equilibrium. Head losses in the tubing will be known and the pressure in each of the interconnected zones can be calculated. Since flow rates between zones are in most cases expected to be quite low, the pressure in the zones should be nearly equal. The average of the pressures will be taken as an estimate of the pressure the zones would have if the packer between them were removed.

Theoretical Considerations in Flow Measurement

In most permeability tests, the water can be collected in a tube or pipe and the flow rate measured in a straight forward manner. However, in the low permeability rock of this experiment, the flow rate into the drift is so low and the surface area is so great that a significant proportion of the inflow would be lost to evaporation and the remainder would collect on the floor of the drift too slowly to measure in a reasonable amount of time. For example, inflow to the drift of Stripa is currently measured at 45 to 55 cm^3 per minute which is equivalent to collecting about 0.050 cm per day over the floor area of the drift.

One of the purposes of this experiment is to examine the utility of measuring these low flow rates by evaporating all the water into the ventilation air while measuring the change in water vapor content between the incoming and exhaust air streams. To operate successfully, the ventilation system should provide an air flow rate and temperature capable of vaporizing and carrying away all of the influx water[4]. In addition, all parameters must be steady enough to allow identification of the equilibrium conditions. Also, the differential relative humidity between the air entering and leaving the experiment area must be great enough to provide acceptable water vapor measurement accuracy. As a point of reference, .05 m^3/s (100 cfm) of air flowing at normal atmospheric pressure, 20°C, and 100% relative humidity will transport about 50 cm^3 of water vapor per minute.

For the macropermeability experiment it is necessary to measure: (1) the barometric pressure; (2) the air velocity in the exhaust duct; and (3) the wet and dry bulb temperatures of the incoming and exhaust air streams. These measurements allow us to calculate the incoming and exhaust mass flow rates of both the air and the water vapor associated with it. The difference between the incoming and exhaust water vapor flow rates is the amount of water which has evaporated from the surfaces of the drift. The floor of the drift and the surfaces of the walls can be observed to assure that all of the water is being evaporated as it arrives, without significant puddling.

To maximize the accuracy of water vapor transport calculations, one wishes to operate with the exit air stream as near to saturation as possible. Nomograms have been prepared for a variety of exit air temperatures to assist in the selection of air flow rates and heater power levels that will maintain an acceptable (± 20%) level of accuracy. One of these is shown in Figure 3.

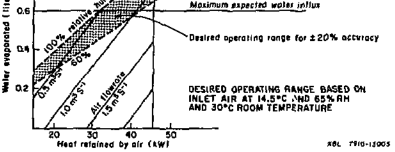

Fig. 3. Plot of heat retained versus evaporation rate.

Several months were required to establish near-equilibrium conditions in the rock temperature and water vapor flow regimes. The experiment was initiated with a room temperature control setting as near as possible to the preexisting ambient air temperature. Some heat was added to assure that all available water is evaporated. Subsequently warmer equilibrium room temperatures will be established to investigate the impact of that temperature upon the water influx.

Flow Measurement at Stripa

A sketch of the experimental setup was shown in Figure 1. An air- and vapor-tight bulkhead seals off a 33 m length of the ventilation drift. This wall consists of a structural wooden frame covered with an 0.15mm thick sheet of PVC, as a vapor barrier, and fiberglass insulation to prevent condensation. The vapor barrier and the structure are keyed into a 20 mm deep notch on all four sides, with foamed plastic sealing in the notch to prevent the loss of water through the blast damaged surface rock. A frozen-food-locker type door provides access through the bulkhead.

The general mine ventilation system delivers about 1.4 m^3/s of fresh air to a point just outside the bulkhead. The experimental ventilation system admits a portion of this fresh air into the sealed room to pick up the water (as vapor) which flows into the sealed room through the surrounding rock. This secondary ventilation system is driven by a fan located in the exhaust duct so that a slightly negative pressure exists within the sealed room. Any air leaking through the bulkhead is into the room and it is the same air as that entering through the inlet duct. In this way, the inlet wet and dry bulb measurements are representative of both the intentionally admitted air and the leakage air. The flow measuring station as well as the exhaust wet and dry bulb sensors are in the exhaust duct. These sensors sense the total air flow including leakage.

The air entering the sealed room passes through an electric duct heater. It is then distributed through an insulated duct with multiple openings along the length of the room. The air issuing from these openings is directed preferentially onto any damp spots on the rock surface (most of the water arrives by seeping along discrete fractures). The walls of the drift are maintained in an almost-dry condition, with fans used where necessary to provide a high air velocity over particularly damp spots. The arrangement shown in Figure 1 will be modified for operation at higher room temperature. The air inlet duct will open directly into the room and a separate fan will recirculate room air through the heater and the distribution duct. This arrangement will separate the flow system for heating and circulating air within the room, where high air flow rates are desired, from the flow system for room ventilation (water vapor removal), where very low flow rates are required for accurate water vapor flow measurement.

The climatic conditions within the room are controlled by manually selecting a suitable air flow rate (by adjusting a damper on the fan exhaust) and then adjusting the heater power as required to maintain the desired air temperature in the room. The energy input from the heater is utilized in three ways: (1) the sensible heat of the exhaust air will be increased; (2) the heat of vaporization for the water will be provided; and (3) the rock will be heated. As equilibrium conditions are approached the third contribution would become negligible. The 45 kW heater is divided into six sections which are separately controlled. Five sections are under manual control and one is under automatic on-off control with feedback from a room-temperature sensor. The heater voltage is regulated to isolate it from the large voltage fluctuations observed in the mine power system.

A 75 mm-deep trench has been cut across the floor of the drift just inboard of the bulkhead. The trench and floor of drift are dry, therefore we conclude that lateral flow through fractures in the floor of the drift is negligible.

Preliminary Results from the Ambient Temperature Experiment

Instrumentation of the 15 boreholes was begun in June 1979 and completed in November 1979. Before fitting the holes with packers, the holes drained the surrounding rock into the drift. As such the upgrade holes were dry and the downgrade holes were filled with water under hydrostatic pressure. As each hole was fitted with packers the pressure in the hole began to rise. Example pressure records for R07, HG2, HG1, and R01 are shown in Figure 4, 5, 6, and 7 respectively.

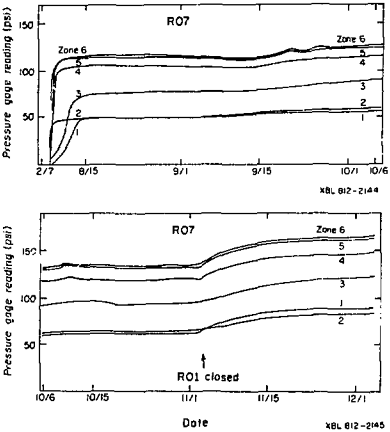

Figure 4. Example pressure gage readings for R07.

Before instrumentation, when all the holes were draining freely, hole R01 produced about as much water as all the other 14 holes combined. Earlier injection tests in R01 resulted in pressure responses in many of the other holes in the drift. Consequently we instrumented R01 last and monitored the response to pressure build-up in R01 in all the other holes.

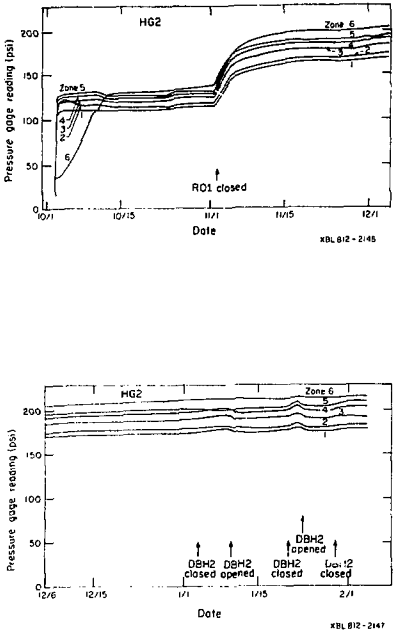

Figure 5. Example pressure gage readings for HG2.

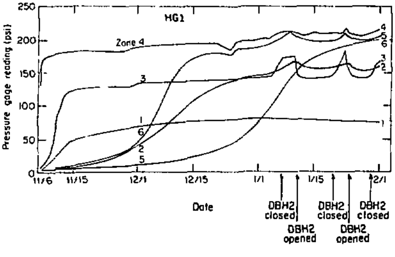

Figure 6. Example pressure gage readings for HG1.

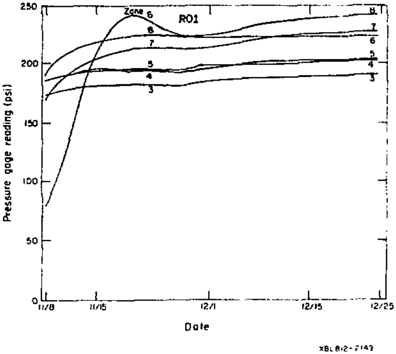

Figure 7. Example pressure gage readings for R01

The effect of closing R01 can be seen in the pressure records for R07, HG2, and in Figures 8 and 9. Figures 8 and 9 illustrate the increase in pressure experienced in the R-holes and the HG-holes. The dashed lines represent pressures measured on October 30, 1978; the solid lines represent pressures measured on November 8, 1979. Instrumentation and pressurization of R01 began October 31, 1979. The stippled area between the dashed and solid lines shows the initial pressure increase in each hole due to pressurization of R01. No pressure increase is shown for R10 because it had been dissassembled to fix a faulty packer. HG1 was instrumented just prior to R01 and had not yet reached equilibrium when R01 was installed. Pressure appears to decrease in zones HG33 (i.e., zone 3 in hole HG3) and R054 because HG33 and R054 had been bled during the period October 30 to November 8. The pressure declined in HG41, HG43, and HG44 without interference. All other zones throughout the drift increased in pressure. DSH2, a hole parallel to the drift was also instrumented. In December and January this hole was reinstrumented twice to

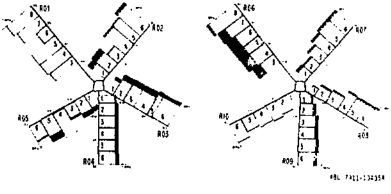

Figure 8. Pressure increase (stippled) in the R- holes due to instrumentation of R01.

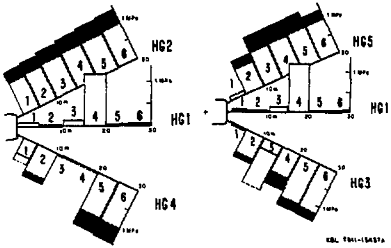

Figure 9. Pressure increase (stippled) in the HG- holes due to instrumentation of R01.

repair packer leaks. The effects of these procedures can be seen in the pressure records for HG1 and HG2. The pressure record for R01 shows the complex, dynamic buildup process in that hole. These dramatic hydraulic responses illustrate the complex nature of the fracture system at Stripa. The hydrology of this rock may well be dominated by a few high permeability fractures. Figures 10 and 11 show the pressure distributions at the end of the ambient test, March 20, 1980.

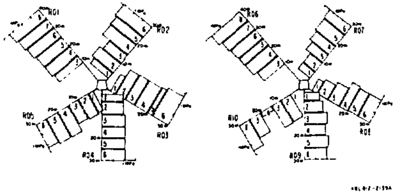

Figure 10. Pressures in the R- holes at the end of the ambient temperature run.

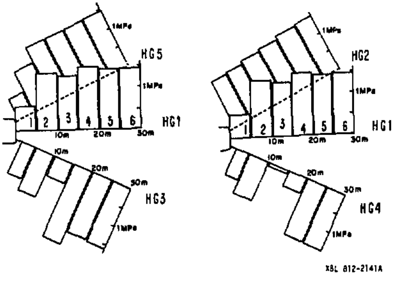

Figure 11. Pressures in the HG- holes at the end of the ambient temperature run.

Sealing the boreholes with packers decreased the flow into the drift from about 1000 cm^3/min to 20 to 30 cm^3/min. As the pressure in the holes built up the flow of water into the drift increased to 45-55 cm^3/min. (The 1000 cm^3/min represents cumulative flow from the open boreholes; after the boreholes were closed flow was measured with the ventilation system.) This decrease in flow is much greater than was expected. In order to maintain humidity of the exhaust air at 85% we have had to lower the air flow rate to 0.5 m^3/s. This air flow rate is at the lower end of the linear range of our airflow measurement system.

The record of flow rate is shown in Figure 12. Erratic variation at the beginning of the record is due to changes in operation of ventilation system and ongoing instrumentation of boreholes. However a gradual increasing trend can be discerned until late January when all the holes were instrumented. The most accurate data was recorded after February 26th when the room was consistently kept dry for almost a month.

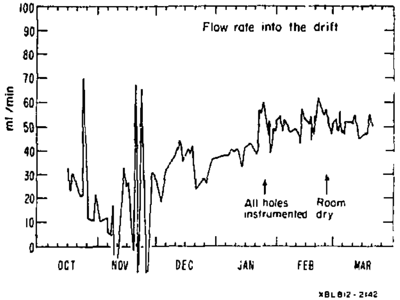

Figure 12. Inflow Record.

Figure 13 shows three separate values of conductivity that were calculated based on the assumption of steady state flow and using the pressure records in (1) all zone 4's, (2) all zone 5's, and (3) all zone 6's. Thus conductivity can be plotted against the volume of rock represented by the zones 4, 5, and 6, respectively. The calculated conductivity is fairly stable or about 6.5×10^{-11} m/s. This may be an indication that the volume of the REV is at least as small as 5×10^4 m^3, but further analysis may be needed.

Summary

The macropermeability experiment will provide: (i) a direct, in situ measurement of the permeability of 10^5 m^3 of rock on the order of 6.5×10^{-11} m/s; (ii) a potential method for confirming the analysis of a series of small scale permeability tests performed in surface and underground boreholes; (iii) a better understanding of the effect of open borehole zone length on pressure measurement; (iv) increased knowledge of the size and existence of a representative elementary volume in fractured rock; and (v) a basis for evaluating the ventilation technique for flow measurements in large-scale testing of low-permeability rocks.

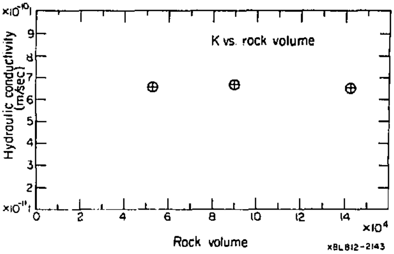

Figure 13. Permeability versus rock volume.

III. ACKNOWLEDGMENTS

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