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SUMMARY

Access to a granitic rock mass in an iron ore mine in Sweden has provided a unique opportunity to conduct a comprehensive suite of underground experiments related to the geologic disposal of radioactive waste. Results of these field tests demonstrate the importance of hydrogeology and the difficulties in predicting the thermo-mechanical behavior of fractured granitic rocks. To characterize a site fully, measurements made from the surface must be supplemented by extensive subsurface measurements and experiments. Much effort is needed at this stage to generate the technology required for the development of waste repositories.

INTRODUCTION

Safe disposal of hazardous materials has become a topic of much concern in the U.S., particularly within the past decade. Disposal of radioactive waste has aroused much scrutiny from the general public although it is only one part of the entire problem.

Radioactive wastes have special properties, however, which distinguish them from other hazardous wastes. Nuclear wastes range from dilute and short-lived materials to "high level wastes" (HLW), that is, wastes either in the form of spent fuel rods or the products from the first cycle of reprocessing(1). High level wastes are intensely radioactive and produce large quantities of heat as a result of radioactive decay.

This article is concerned with the geologic aspects of storing HLW underground. Most current plans for disposal contain a multiple-barrier approach(2). In this approach, redundant components are built into an underground system to serve as barriers to the migration of groundwater and waste. The multiple barriers include: (a) the waste form, (b) the canister in which the waste will be contained, (c) the backfilling material used to surround and isolate the canister, and (d) the geologic system surrounding the repository. All components should be readily characterizable, although the geologic system tends to lack this quality. Ultimately, the ability to characterize the geologic system may dictate the choice of the best host rock for a repository and the disposal system.

A principal attribute of deep geologic disposal of HLW is the high degree of physical inaccessibility it provides against human activities and natural events. However, transport to the biosphere even in a geologically suitable area may occur via groundwater. There are therefore a number of attributes that the rock repository at any potential site should have: low permeability, low interconnected porosity, low hydraulic gradient, and a high capacity for sorption. The generation of heat by the waste also introduces the requirement of chemical and mechanical stability under the controlling stress fields. Basic questions concerning the effectiveness of different rock types to safely isolate wastes underground over extremely long time periods arise in the selection and characterization of any potential repository site. Although mining and civil engineering provide a wealth of experience concerning underground excavations, very little experience exists to guide one in these matters, and there is no general agreement as to the best rock type. Hence, a number of different rock types are currently being considered: plutonic and high grade metamorphics, flood basalts, bedded and domal salt, argillites and tuff.

In mining, economy is maximized to a degree consistent with short-term safety whereas in the development of a waste repository, safety in both the short- and the long-term must take precedence. New knowledge must be obtained to supplement existing experience through experiments specifically designed to assess the ability of a rock mass to isolate waste at depths typical of proposed repositories. In this article results of recent field experiments are presented and the critical importance of the new technology that must be developed is discussed. The need for a basic understanding of rock behavior under the special conditions that will arise in an underground repository in the presence of heat-generating, radioactive wastes, and the complex processes of waste migration(3) in slowly moving groundwaters cannot be overstated.

THE FIELD TEST SITE

Over the past three years, thermo-mechanical, fracture hydrology and geochemical investigations have been conducted in crystalline rock at a depth of about 340 meters below surface in Sweden as part of a Swedish-American cooperative program(4). Lead organizations for the study are Kärnbränslesäkerhet (KBS, Nuclear Fuel Safety Program) for Sweden and Lawrence Berkeley Laboratory (LBL) under the Battelle Office of Nuclear Waste Isolation for the U.S. Department of Energy. The experimental program is being conducted in a quartz monzonite rock mass adjacent to a depleted iron ore mine at Stripa, 150 km west of Stockholm. Mining at Stripa began in 1485 and continued intermittently until late 1976. The underground workings are 250 km in length on 15 levels down to 410 m below surface.

The banded hematite ore at Stripa is situated almost entirely in leptite, predominantly a silica-rich, high grade metamorphosed volcanic rock of Precambrian age(5). The leptite was subjected to E-W compression during which the NNE trending Vikern syncline, containing the ore deposit, was formed. Late in a second period of folding, caused by N-S compression, the plutonic rock at Stripa intruded the leptite. The plutonic rock, 1.7 billion years old, is predominantly quartz monzonite. A series of pegmatitic and aplitic dikes transect the reddish, medium-grained massive quartz monzonite, which has been fractured in at least two stages. In order to mine the ore, some of the workings intersected the quartz monzonite; hence the easy access for these investigations.

THERMO-MECHANICAL INVESTIGATIONS

The thermo-mechanical investigations at Stripa were designed to study in situ rock behavior at depths below surface and under thermal loads comparable to those envisaged for an actual waste repository. The experiments comprised: (a) two full-scale heater tests in which the near-field response of the rock mass was studied under simulated short-term and long-term conditions, and (b) an intermediate term, scaled experiment (scaled in time, distance and heat output). These experiments were instrumented to obtain measurements of temperature fields, displacements and stresses as functions of time and space, data needed to test predictions of the thermo-mechanical response.

Full-Scale Heater Experiments

The energy output from HLW canisters could be as much as 5 kW per canister depending on waste form and age at burial, although the heat output from fresh

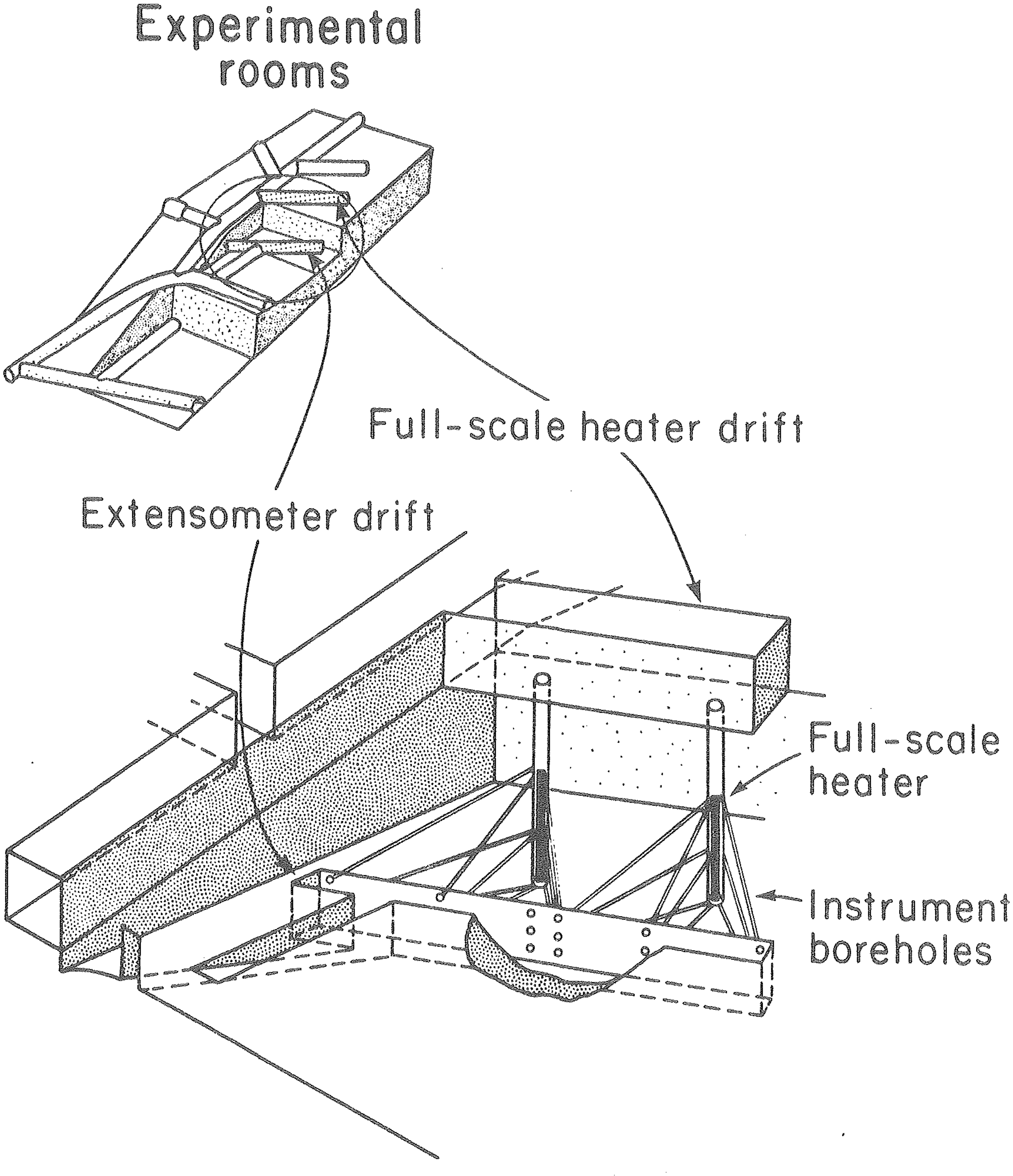

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Fig. 1. Arrangement of experimental rooms in quartz monzonite rock mass some 340 m below surface showing detail of full-scale heater drift and location of instrument boreholes from adjacent extensometer drift.

waste drops significantly in the first few years after removal from the reactor. To determine the maximum safe power output of such canisters, it is important that field experience be gained concerning thermal effects on the rock immediately adjacent to the canister.

Full-scale heater experiments permitted investigation of the short-term effects on quartz monzonite. Electric heaters housed in canisters 3 m long and 0.3 m diameter simulated the power output of the waste. Two such canisters were positioned in 406 mm diameter vertical holes drilled to a depth of 5.5 m in the floor of the drift (Fig. 1). These heater holes were spaced 22 m apart so that the canisters would remain thermally separated. Power output for one canister-heater was adjusted to 5 kW to simulate the power level of reprocessed waste three years after removal from a light water reactor; power output of the other was set at 3.6 kW to simulate five-year old waste. These power levels were selected three years ago; currently, somewhat lower levels are preferred.

Response of the rock mass near the canisters was monitored extensively. Thermally induced displacements were measured using arrays of multiple-point extensometers (Fig. 1), and thermally induced stresses were measured using several USBM borehole deformation gauges and IRAD (Creare) vibrating-wire gauges. Each instrument had a thermocouple associated with it, and many more thermocouples were positioned around each heater to provide data on the three-dimensional temperature field.

The low thermal conductivity of rock caused temperatures in the immediate vicinity of the heaters, and therefore temperature gradients within the rock, to approach maximum values in a few months (Fig. 2). Heating lasted 398 days; total monitoring time was nearly 1-1/2 years. Temperature predictions were based on a semi-analytical solution(6) using properties from laboratory measurements on intact specimens. The data used in making these predictions were as follows: density, 2600 kg/m^3; specific heat, 837 J/(kg°C); thermal conductivity, 3.2 W/(m°C); and thermal diffusivity, 1.47 x $10^{-6}m^2$/sec.

Fig. 3 shows temperatures measured on the midplane passing through the center of the 5 kW heater, compared with predicted isotherms. Note the excellent agreement between predicted and measured values in all directions away from the axis of the heater. This is typical of results that have been obtained throughout both full-scale heater experiments. Despite extensive fractures and joints in the quartz monzonite, the presence of discontinuities (and the water filling them) had a negligible effect on the temperature field.

Scaled Heater Experiment

An important factor in repository design is the effect of long-term thermal loading. Calculations show that thermal interactions for the power levels used here begin to occur within three years between canisters spaced 10 m apart. Thereafter, the effect of individual canisters diminishes and, after 10 to 100 years, maximum temperatures in the repository are reached and substantial quantities of heat flow upward and downward. Under these conditions, the 100°C isotherm should have migrated approximately 50 m from the repository, and the resulting thermal expansion of the roughly oblate spheroid of rock will be about 10^{-3}, a significant amount.

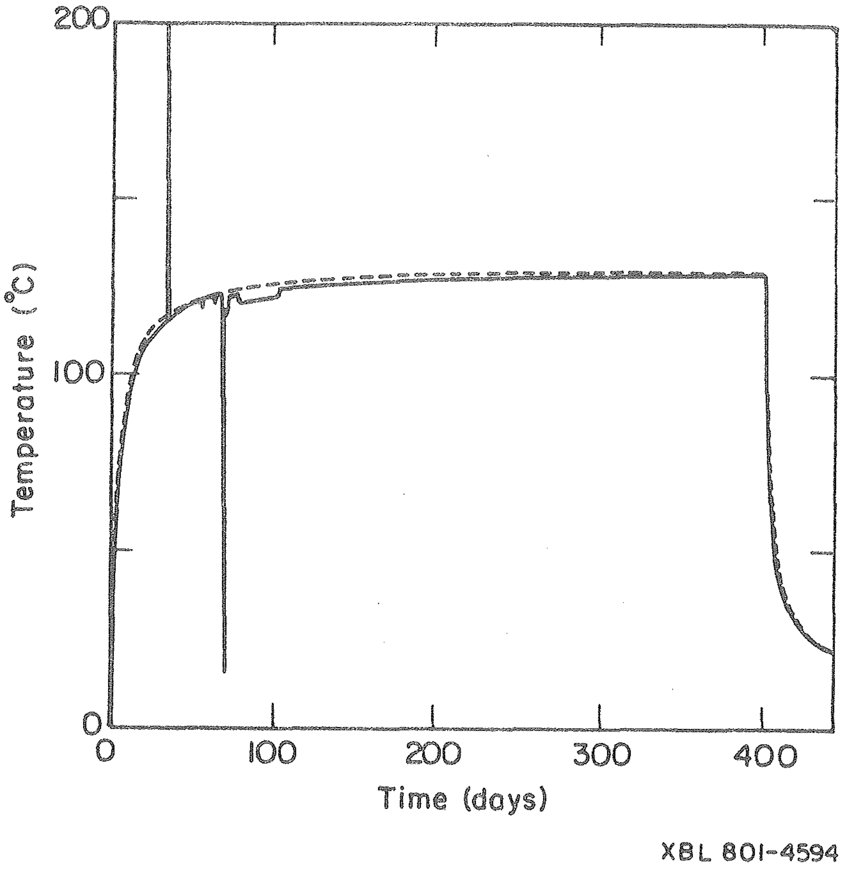

Fig. 2. Predicted (dashed line) and measured (solid line) temperatures plotted as a function of time at a radius of 0.4 m from 3.6 kW heater along heater midplane. Variations in measured signals early in the experiment were caused by corrosion of the stainless steel thermocouple sheath.

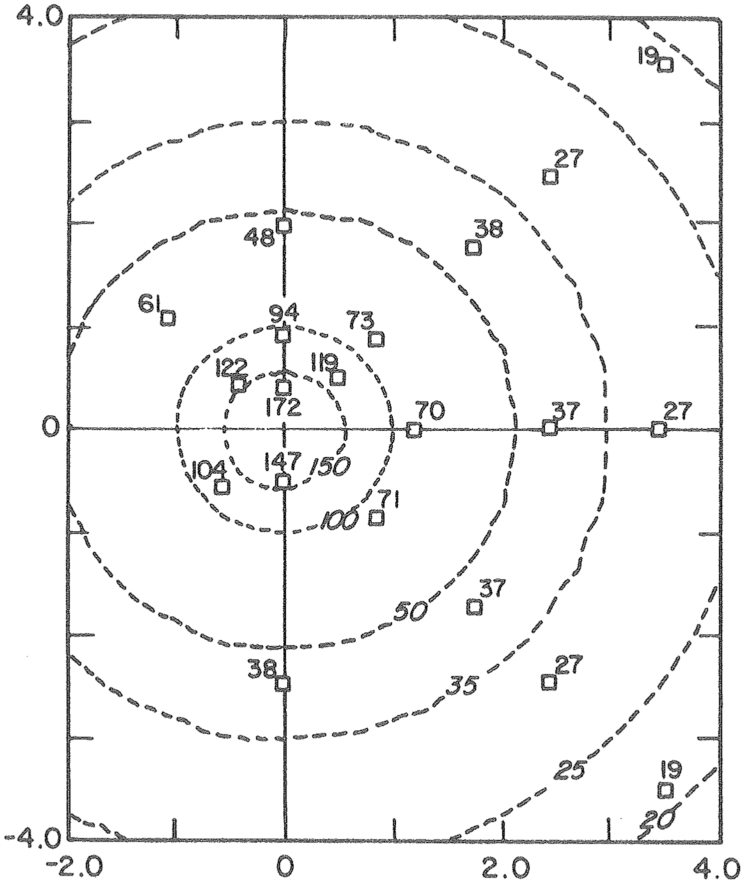

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Fig. 3. Predicted (dashed lines) isotherms and measured temperatures in a horizontal plane through the center of the 5.0 kW heater 190 days after starting experiment. Temperatures are in degrees Celsius and distances in meters from the axis of the heater.

It is impractical to check these thermo-mechanical effects in the critical period from 10 to 100 years using a full-scale heater experiment. In the scaled heater experiment at Stripa, times have been compressed in the ratio of 1:10 using laws of heat conduction. Each year of data is therefore equivalent to 10 years of data from the full-scale system. The linear scale, which must be reduced to $1/\sqrt{10} \approx 0.32$ of the full scale, still allows for realistic field dimensions.

An array of 8 heaters, spaced 7 m apart along the axis of a drift and 3 m apart in the direction perpendicular to the axis of the drift, was used for this investigation (Fig. 4). The power output was also scaled appropriately and was progressively lowered to simulate the decrease in energy output resulting from radioactive decay. We calculated that thermal interaction would occur within a few months of the start of this experiment and this was confirmed by field observation(7). As in the case of the full-scale heater experiments, remarkably good agreement was found between measured and predicted rock temperatures. We concluded that the dominant mode of heat transfer in a discontinuous rock mass is by conduction. The temperature field is therefore amenable to prediction using relatively simple semi-analytical methods(6).

Rock Displacements and Stresses

Extensometers measurements in the rocks adjacent to each full scale heater (Fig. 1) reveal the complexity of attempting to predict thermo-mechanical behavior in a discontinuous rock mass. As a first approach, the rock was assumed to be homogeneous and intact, and displacements were

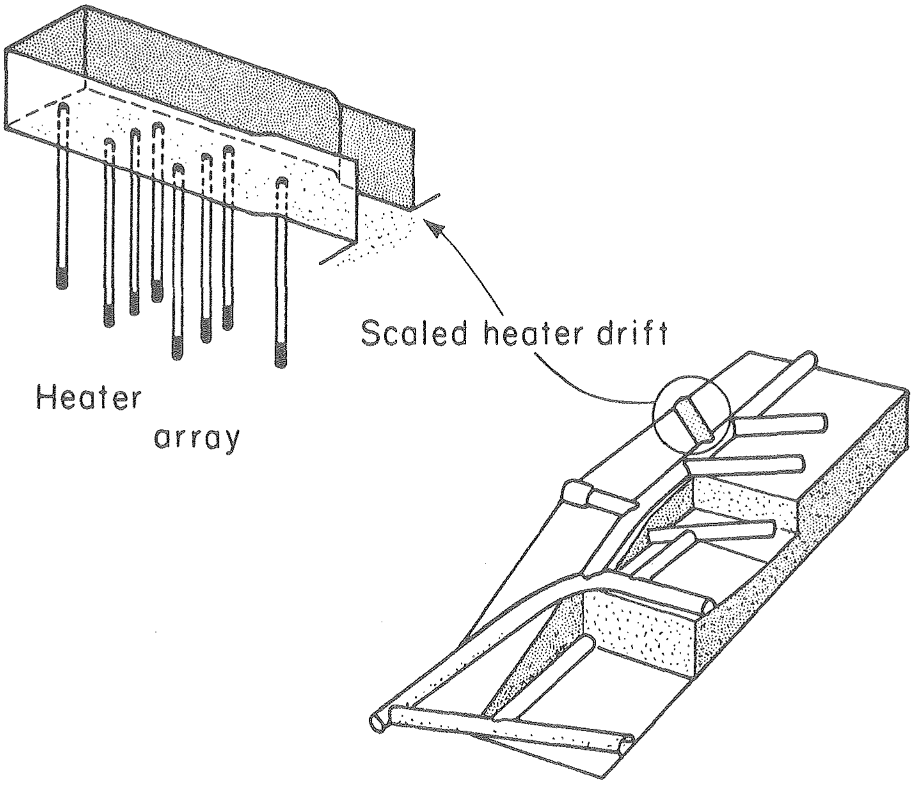

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Fig. 4. Experimental rooms in quartz monzonite rock mass showing detail of scaled heater drift with eight 1.0 kW electric heaters. Heaters are 1.0 m in length and have been placed so that the heater midplane is 10.5 m below the floor.

predicted prior to heating using the theory of linear thermoelasticity and the following: coefficient of thermal expansion, $\alpha = 11.1 \times 10^{-6}/°C$; Young's modulus, $E = 51.3$ GPa; Poisson's ratio, $\nu = 0.23$; and thermal conductivity, $k = 3.2$ W/(m°C). These values are averages for intact rock as measured in the laboratory over a range of 100-150°C.

The rock displacements show two distinct types of behavior. During the first few weeks, measured displacements were very much less than those predicted by theory using the above laboratory values. After the initial period, the measured displacements increased uniformly but at a more or less constant percentage of the predicted values. For many extensometers, the ratio of measured to predicted displacements during this second phase was 0.4 (Fig. 5).

An explanation why the experimental results show far less rock movement than predicted from theory for intact rock (8), may be the temperature dependence of the rock properties. Displacements predicted using temperature-dependent values of α, E, ν, and k for intact rock and based on limited laboratory tests (9) are shown in Fig. 5. Although much better agreement with field data has been obtained, the laboratory values are too few to be regarded as representing the properties of the rock at Stripa sufficiently well. Accordingly, laboratory measurement of the thermo-mechanical properties of cores from the Stripa quartz monzonite is receiving high priority.

Measurements of stress changes in the rock mass using vibrating-wire Creare gauges show trends similar to the extensometer results. The observed values of stress were half or less of values predicted using the averaged thermo-mechanical properties cited above. Predicted stresses are still considerably higher than the measured values even after temperature dependence of

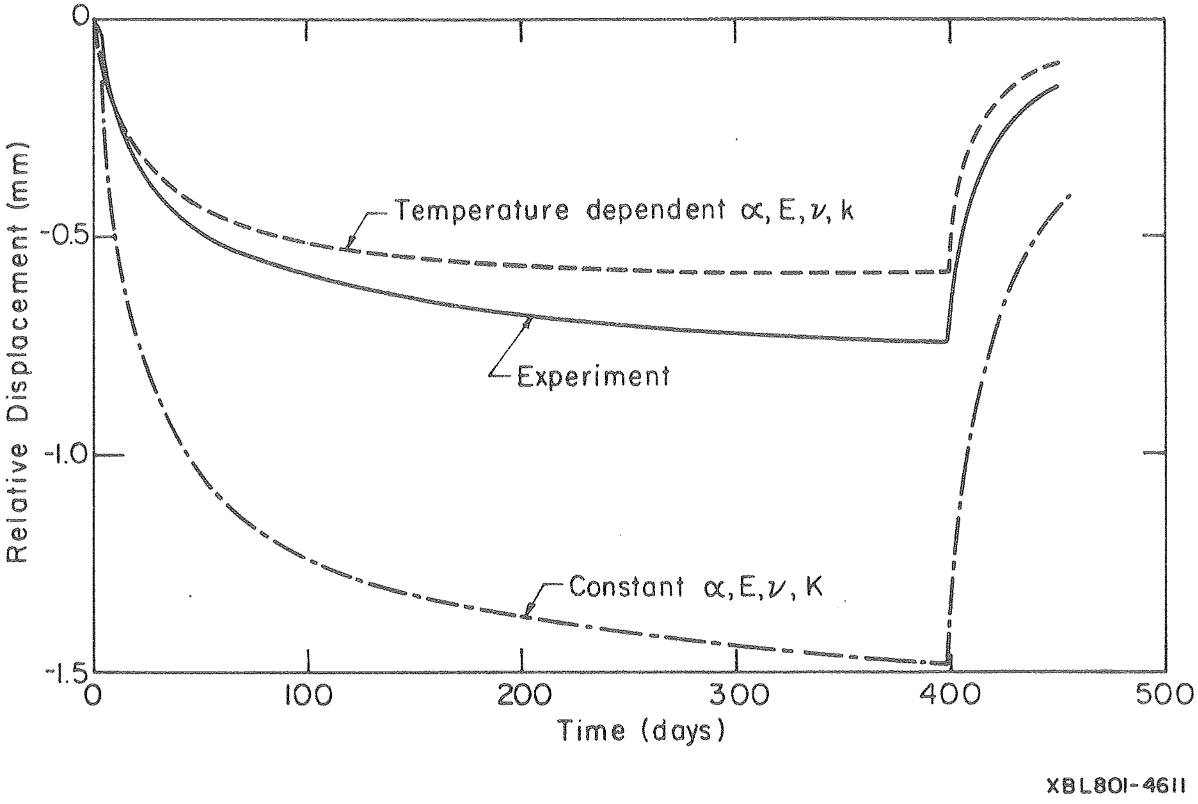

Fig. 5. Measured rock displacements in a vertical direction between anchor points 2.24 m above and below the heater midplane for an extensometer at a radial distance of 1.0 m from the 3.6 kW full-scale heater. Also included are displacements predicted using constant and temperature dependent properties (dashed lines).

rock properties has been taken into account(9). Nevertheless, the stress results support the conclusion from extensometer measurements that thermo-mechanical effects induced in the rock mass are significantly less than predicted from theory(8) using published values for the properties of intact laboratory specimens of rock. The role of discontinuities in controlling the thermo-mechanical behavior of rock masses needs much more study.

FRACTURE MAPPING

The disparities between the measured displacements and those predicted using the linear theory of thermoelasticity clearly indicate that the quartz monzonite, when subjected to a thermal pulse, does not behave in a linear isotropic manner with constant thermoelastic properties. Discontinuities in the system probably play a major role in controlling thermo-mechanical behavior, but to understand the behavior of the rock mass raises the difficult question of the level of detail at which fracture geometry must be investigated. A comprehensive program of fracture mapping was initiated at the beginning of these experiments in anticipation of the need to answer this question.

The methods employed in studying the fracture system in the scaled heater experiment have been described(10). First, major discontinuities were identified so that they could be modeled as discrete elements(11). Second, all fractures were defined through careful measurement of orientation, spacing, and joint length. It is presently impractical to model such ubiquitous joints as they actually exist; techniques are being developed to represent them stochastically(12, 13).

Since heaters for the scaled experiment were placed 10.5 m below the floor of the drift, only the most prominent and continuous features are likely to persist from the floor through the heated region. Accordingly, only the major fractures striking transverse to the drift were extrapolated downward and correlated with discontinuities found in the boreholes. Four shear surfaces probably pass through the heater array (Fig. 6) and offset or truncate other discontinuities, which are filled with chlorite, calcite, epidote, and clay. The most prominent and well-defined fault of the set apparently offsets a pegmatite dike some 20 cm wide.

Statistical analyses of joint geometries using results from logging of underground boreholes and comprehensive surficial mapping of the underground drifts show four distinct sets of joints(10). The directions of three of these sets can be correlated with the directions of the current principal stresses(14). Detailed fracture mapping such as this cannot be accomplished with conventional methods using boreholes drilled from the surface only.

FRACTURE HYDROLOGY

Migration of radionuclides away from a repository may occur by solution in groundwater seeping through the site. The rates of nuclide movement depend on three basic rock properties: (a) permeability, (b) effective porosity, and (c) sorptive properties of the host rock. Thus far, research at Stripa has been concerned only with the first of these three properties.

Evaluating permeability of a rock, such as the quartz monzonite at Stripa, is essentially a problem of understanding the hydraulic behavior of a complex network of fractures. A permeability tensor for the rock mass can be developed from measured orientations and spacings of fractures and an assumed model of aperture distributions. This approach has been used by a number of workers (15, 16, 17, 18).

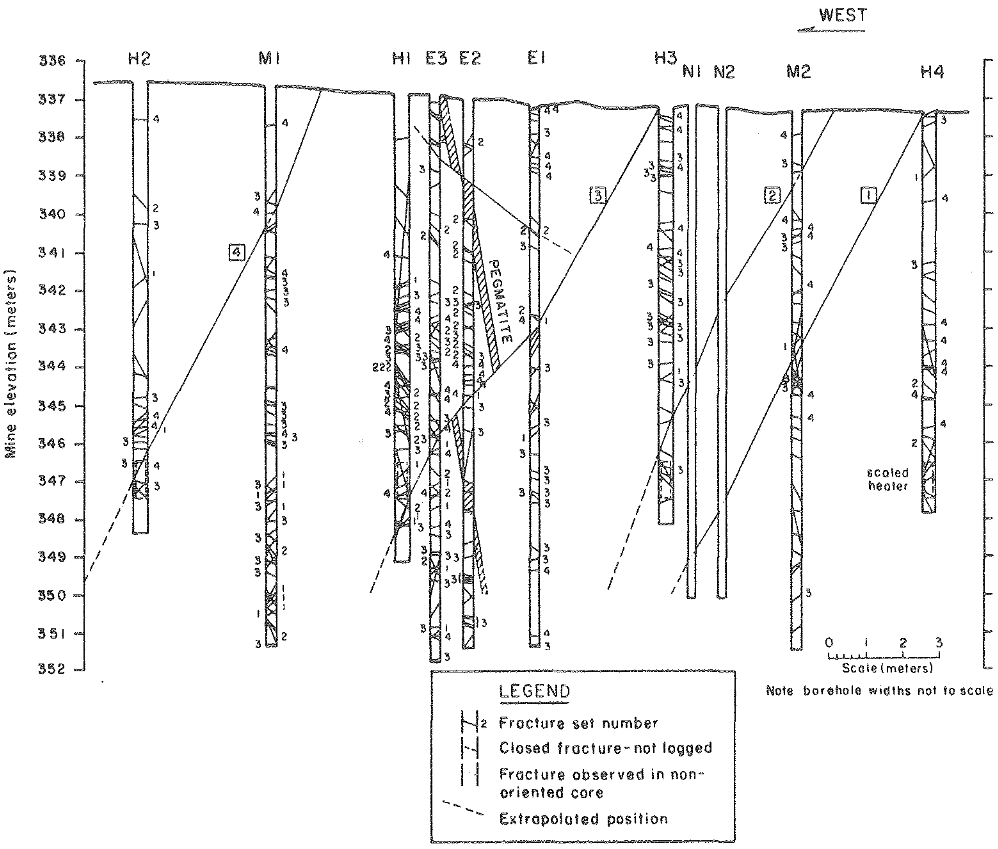

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Fig. 6. Vertical profile of major fractures along centerline of scaled heater experiments.

Basic data on fracture orientations, spacings and continuity have been obtained by mapping the fractures in surface outcrops and underground rooms(10). Data have also been obtained from three boreholes that were drilled from the surface down to the level of the heater experiments at angles of 38° to 45° from the vertical. Each hole was carefully cored so the rock samples could be orientated and the fracture geometries reconstructed. Borehole injection tests have been made to obtain hydraulic measurements of the effective fracture apertures. All of these data are being combined in an attempt to define a permeability tensor for the rock mass(19). This work is not yet complete.

Large-Scale Permeability Measurement

The above investigations represent the conventional approach to fracture hydrology for a discontinuous rock mass, but the bulk permeability of the Stripa quartz monzonite is not particularly low. The permeability of the rock mass at a preferred repository site could be two to three orders of magnitude less than that at Stripa. To obtain meaningful measurements for such low permeabilities in a very large rock mass, special techniques may be required.

To investigate this problem, a new concept involving a large-scale permeability test has been carried out at Stripa(20). A 33 m length of drift was sealed off and equipped with a ventilation system by which the air temperature could be controlled to evaporate all water seeping into the room (Fig.7). The flow of water into this drift was determined from careful measurements of the air flow rate and the differences in the humidities and temperatures of the entering and exiting air streams. This new technique enables measurements to be made of the average permeability of a large volume of rock of the order of 10^5 to 10^6 m^3, over a range of air temperatures from about 20°C to 40°C.

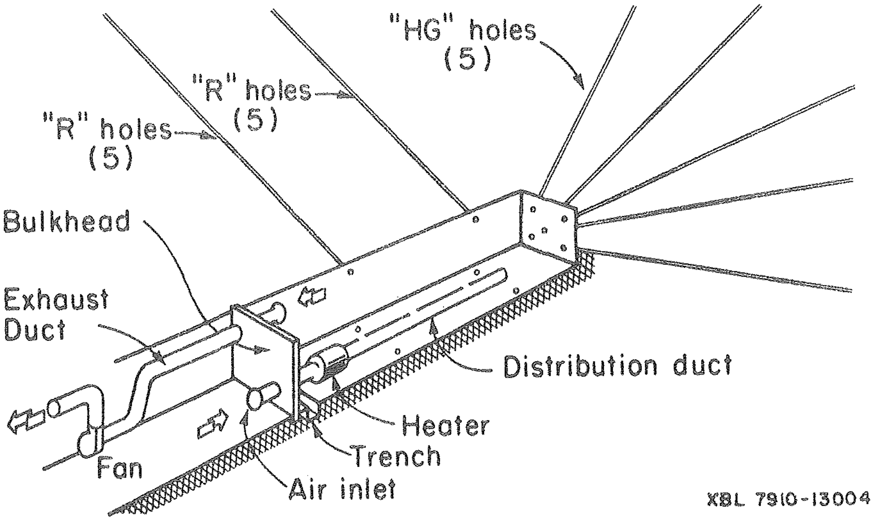

Fig. 7. Large-scale permeability experiment showing instrumentation boreholes and system to capture water seepage through evaporation into a controlled pattern of air flow.

Hydraulic pressures in the rock mass around this drift were measured at 90 points in 15 holes that radiate out from the drift in different directions. Two groups of 5 holes each were drilled radially outward, and one group of 5 holes was drilled at the end of the room to distances of 30 to 40 m (Fig. 7). Fig. 8 shows the orientation of one of the radial groups of boreholes. Each borehole was sealed off with six packers placed to enable the measurement of pressures and temperatures over five-meter intervals.

Before the installation of packers, all holes had been draining freely. Borehole R01 (Fig. 8) 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 boreholes in the drift; consequently R01 was packed off and instrumented last, so that the effects of the pressure buildup in the other boreholes could be monitored, as shown in Figure 8. The dashed lines represent pressures measured just before R01 was packed off on October 31, 1979. The solid lines represent pressures measured on November 8, 1979, and the stippled areas show how pressure increases occurred more or less uniformly throughout this fractured rock after instrumenting R01. Similar effects were noted in all the other boreholes. Note that pressures increase with distance from the drift and are all about 1 MPa (145 psi) at a distance of 30 m from the drift. These unusually low pressures are the result of the effects of drainage into the adjacent mine workings over many years.

After all boreholes were packed off, a marked increase in drips and wet spots in the drift was observed. The temperature and mass flow rate of the circulating air were adjusted to evaporate all incoming water, and an initial seepage rate of about 50 ml/min was measured. On the basis of this rate and

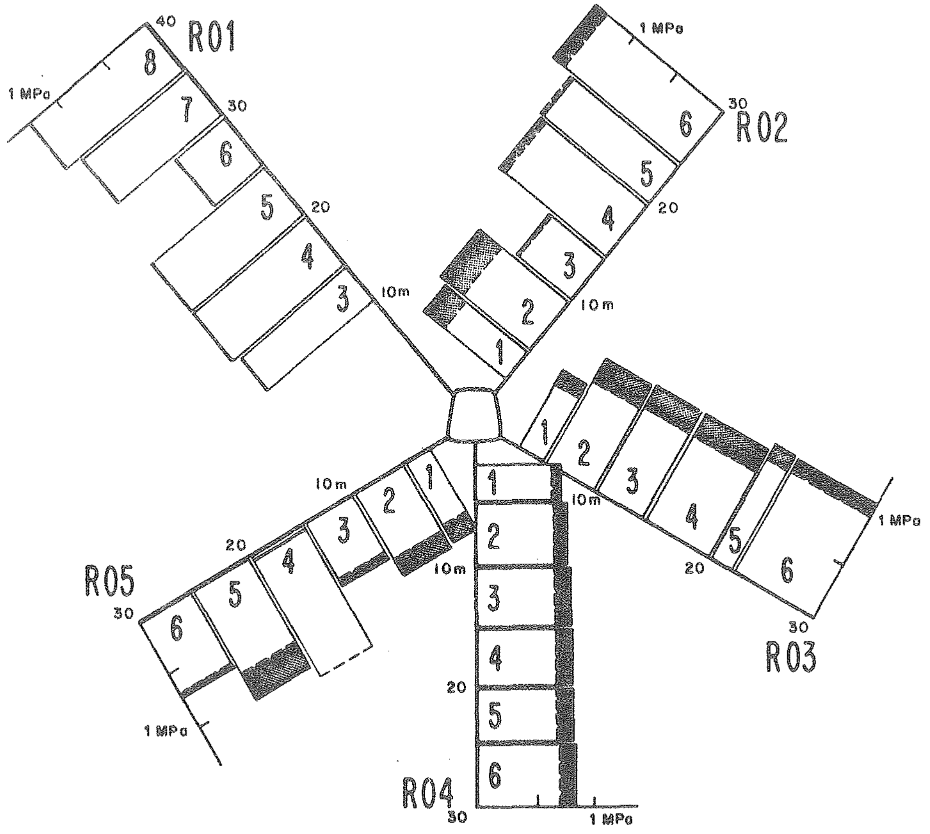

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Fig. 8. Pressure measurements in radial boreholes of large-scale permeability experiment at Stripa. Stippled areas show pressure increases eight days after packing off R01. 1MPa = 145 psi.

the observed pressure gradients, a preliminary value for the average hydraulic conductivity of the order of 10^{-11} m/s has been calculated. This new method of measuring permeability in situ is an important advance in fracture hydrology.

GEOCHEMISTRY AND ISOTOPE HYDROLOGY

Geochemistry and isotope hydrology of groundwaters provide an independent approach to the problem of the overall permeability of a rock system. If there were rapid movement of surface waters to the experimental level (338 m), similarities in chemistry and age between shallow and deep waters should exist. On the other hand, if the deep waters entered the groundwater system many thousands of years ago or at a considerable distance from the present site to which they percolated slowly, there should be significant differences between waters at different depths.

A comprehensive program of investigations on the geochemistry of the Stripa groundwaters has been carried out by Fritz et al.(21). Water samples were collected from the surface, shallow private wells, and boreholes drilled in the heater drifts at the 338 m level. In addition, samples were collected from a deep borehole drilled by the Swedish Geological Survey from 410 m (the deepest operating level in the mine) to about 840 m below surface.

High chloride concentrations and relatively low deuterium and oxygen-18 contents of the deep mine waters, in comparison to near surface waters, indicate that the deep waters had a different source than the near surface waters. The low δ^2H and $\delta^{18}O$ values also indicate that the original surface temperatures of the deep waters were considerably cooler than at present, and the high chloride contents suggest a much different geochemical environment than presently exists at Stripa. This conclusion is substantiated by comparing $\delta^{18}O$ with the chloride concentrations as shown in Fig. 9. It is apparent that the deep groundwaters, especially those at 811-838 m depth, are distinctly different from the shallow groundwaters. This is interpreted as an indication that the different fracture systems are isolated from each other.

Isotope age dating of the various groundwaters was also carried out(21). In contrast to the surface waters where appreciable tritium was observed, the deep groundwaters from the quartz monzonite are essentially devoid of tritium, indicating that the deep waters are older than at least 30-40 years. Waters from the deep levels are also very low in dissolved inorganic carbon, requiring 2000 to 3000 liters of water for ^{14}C analysis. Based on this method, the age of these waters at the 330 m level, and probably also from the 410 m borehole, exceeds 20,000 years.

Three different approaches to age dating based on the uranium decay series were investigated also: (a) uranium activity ratios, (b) helium contents, and (c) radium-radon relationships(21). Although the $^{234}U/^{238}U$ ratio method is still under development and subject to some uncertainties, ages exceeding 100,000 years have been inferred from these data. Similar ages have been determined from the ^{4}He concentrations. Based on a method proposed by Marine(22) relating ^{4}He to its parent ^{238}U, ages computed from these data range from tens of thousands to hundreds of thousands of years. The results of the radium-radon method indicate ages for the groundwaters ranging from 10,000 to 35,000 years.

These data support the concept that the waters presently found in the quartz monzonite rock mass at Stripa, especially at the deepest levels

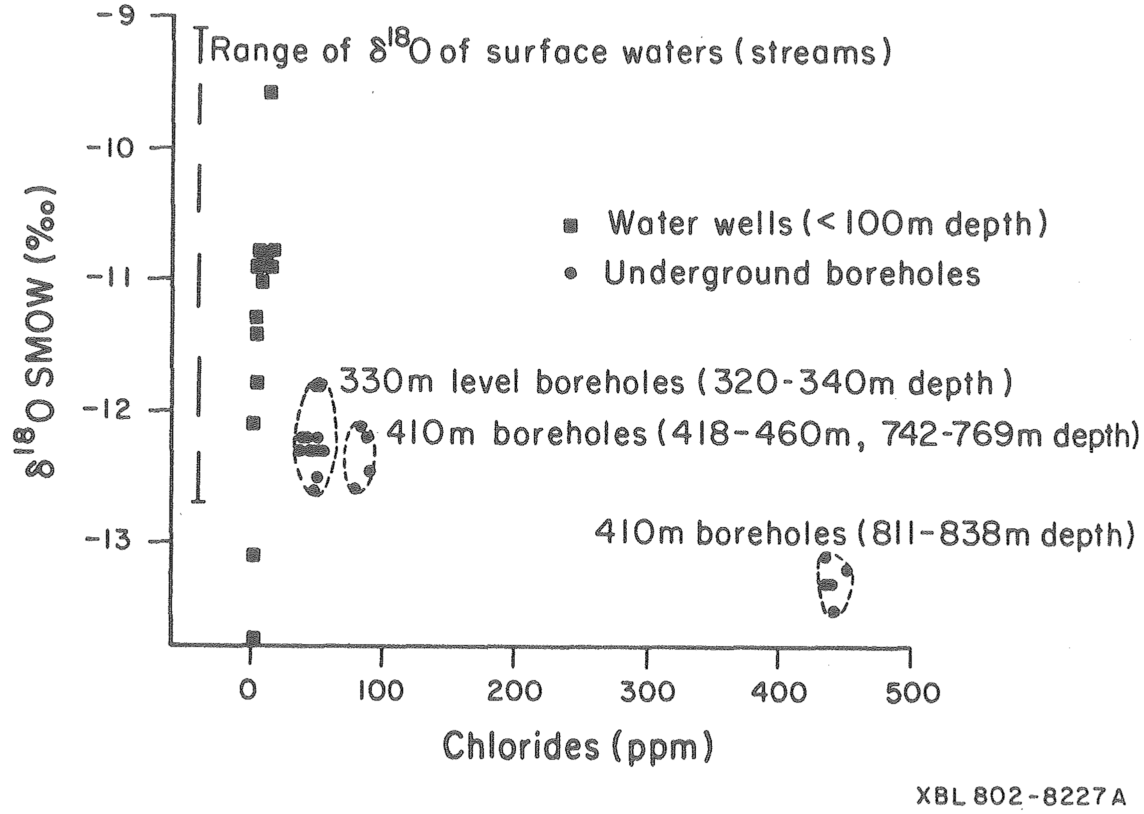

Fig. 9. Comparison of chloride with $\delta^{18}O$ values from geochemical investigations shows that there are distinct differences in waters at different depths.

(811-838 m), are indeed many thousands of years old. Also they support the interpretation of the apparent isolation between shallow and deep groundwaters inferred from the geochemical differences cited above. It is apparent that geochemical and isotope hydrology investigations provide an independent approach to evaluating the degree of isolation that exists in a groundwater system.

IMPORTANCE OF FULL SCALE FIELD TESTING

Important results have been obtained from the investigations at Stripa that would not have emerged unless these experiments had been carried out underground at depths comparable with those envisaged for an actual repository. Experiments at such depths give rise to unexpected and sometimes difficult problems which must be resolved if deep geologic disposal of radioactive waste is to become a reality. Scientific advances are needed in the laboratory but these must be supported by meaningful field experiments.

The behavior (mechanical, thermal, hydraulic, chemical) of a repository in a crystalline rock mass of low permeability is determined by the rock matrix properties and, more importantly, by discontinuities that pervade the rock mass. This raises the first critical question, "Can one determine in sufficient detail the geometry of fractures using surface measurements, that is, measurements made at the surface and in boreholes drilled from the surface?" Although some preliminary studies(23, 24) suggest that fracture orientations between surface and subsurface are similar, there are still no data to demonstrate that the important characteristics of length and continuity of such features can be predicted reliably from surface measurements.

The mapping of fractures must be carried out so that the geometry (orientation, spacing, continuity and aperture distribution) is determined in sufficient detail to enable the total behavior of the rock mass to be predicted. Over long time periods this is a complex problem involving the thermo-mechanical response of the rock system and the hydraulic-chemical behavior of aqueous solutions migrating through the discontinuities. Both of these coupled effects are affected by the magnitude of the in situ stresses. Isolation of waste requires that the repository be constructed at depths sufficient to keep the fractures closed so as to maintain low permeabilities, even in a perturbed rock mass containing discontinuities, yet not so deep as to generate stresses that cause stability problems.

It is apparent from the thermo-mechanical results obtained thus far at Stripa that much more work will be required to develop a reliable basis for predicting the thermally induced behavior of discontinuous rock masses. The behavior is complex and the mechanical and hydrological effects of the discontinuities are not yet understood. After a repository has been filled with waste canisters, the rock will undergo a thermal pulse of increasing temperature extending out to distances well beyond the limits of the excavations. The magnitude of this effect is, of course, primarily dependent on the energy and spacing of the canisters.

This thermal perturbation caused by the repository raises a second critical question, "How should one proceed to develop the technology to reliably predict the global thermal response of a repository in a discontinuous rock mass?" In our view, this can only be carried out in an underground test facility that has been properly designed and instrumented. Whether or not more than one type of crystalline rock needs to be tested underground in this fashion is a question that is difficult to answer because the physics of the thermo-mechanical and hydraulic-chemical behavior of large rock masses is not yet adequately understood. Since granite and basalt have distinctly different types of fracturing and are examples of massive versus bedded forms of igneous rock, they would appear to be prime candidates for underground investigation.

The heat output of radioactive waste decays with time, and the magnitude of the thermal perturbation depends on how long the emplaced waste was stored at the surface. This raises a third critical question, "What are the trade-offs between minimizing the thermally induced effects and the option of long-term surface storage of waste?" Decrepitation of the quartz monzonite was observed at Stripa when rock temperatures near the 5.0 kW heater exceeded 300°C. This could undoubtedly be eliminated by keeping temperatures below some maximum value, and this would be an important component of the field experiments suggested above. Low temperatures would also minimize effects on backfill materials and the possibility of generating thermal convection in the groundwater system. In our opinion, a definitive answer to the problem of how long to store waste at the surface in order to minimize thermo-mechanical effects will not be forthcoming until the ability to predict thermally induced effects is perfected through appropriate field tests underground.

Another body of knowledge that must also be developed involves the hydrogeology of the rock mass and the geochemical behavior of aqueous solutions, including radionuclides, as they migrate through that mass. This hydraulic-chemical response is coupled to the thermo-mechanical response through the discontinuities. Fractures in any type of rock will deform under the influence of changes in rock stress. As they deform, the permeability of the rock mass will be affected. The magnitude of these changes in permeability may be very important and will depend on the effects of the thermal perturbation as well as the disturbance caused by the excavation itself.

All of these concerns raise a fourth critical question, "How should one measure rock properties in the field that are necessary to understand the hydraulic-chemical effects?" The properties that one needs are: (a) permeability (hydraulic conductivity), (b) both total and effective porosity, and (c) sorption behavior.

At Stripa, a careful measure of the permeability tensor is being attempted using conventional methods in inclined boreholes drilled from the surface. These methods seem to be working well, but the hydraulic conductivity at Stripa is about 10^{-11} m/s. Less permeable rock masses may have values two to three orders lower than this, and whether conventional methods will still give reliable results remains to be seen. On the other hand, the large-scale method of measuring permeability(20) should easily be adaptable to rock masses with permeabilities far less than at Stripa. Thus, the accuracy of borehole methods must be assessed by comparison with results from the large-scale method. The latter method can produce a reliable value for the bulk permeability in the immediate vicinity of the repository and this information is needed to confirm the degree of isolation at a potential site. Conceptually, one could use this method to measure the permeability of the rock mass around individual drifts during their excavation. However, in the far field where it is not practical to use the large-scale method, one needs to know the reliability of conventional borehole testing techniques in measuring permeability.

In a rock mass with very low values of permeability the problem of measuring the effective porosity using in situ tracer tests is not easily resolved. Because they involve large volumes of rock at considerable depth and sufficient in size to be representative of the total mass, the tests may take months to years to complete. Under such circumstances, conventional tracer tests in deep boreholes drilled from the surface are not likely to yield reliable results. On the other hand, an underground room, similar to that at Stripa (Fig. 7), creates significant pressure gradients at the depths where a repository will be constructed. Movement of groundwater through the fracture system toward such an underground opening is greatly enhanced, and tests using tracers can be designed for use in very large volumes of rock. Actual velocities can be measured by introducing such a tracer at a point along a known flow path and observing time of arrival downstream. Although standard borehole tracer tests contribute to an understanding of fracture flow in higher permeability rock masses, it is our conclusion that the only feasible approach in rocks with very low permeabilities is an underground tracer experiment run in conjunction with a large-scale permeability test.

Predicting the geochemical sorption behavior of aqueous solutions of radionuclides in contact with mineral surfaces is complicated by a lack of basic data. Much work is needed on the behavior of the actinide aqueous and solid species that are important in groundwater transport processes; there is also a dearth of information on the potential for actinides to form colloids in groundwater. Recent work(25) suggests that actinides may form complexes with organic materials that occur naturally in groundwater. The movement of dissolved species involves several mechanisms for retardation, such as sorption on mineral surfaces, precipitation, ion exchange, and diffusion into the rock matrix. Because of the small scale of these phenomena, they can be studied very effectively in the laboratory, and a large effort in this direction is now underway. Eventually geochemists will require field tests to validate their laboratory findings. If underground test facilities are already in operation for other purposes, various geochemical tests could be incorporated conveniently; such tests are already being planned for the Stripa project.

The critical importance of being able to determine the velocity of groundwater movement through a rock mass with very low permeability cannot be overstated. A good understanding of the geochemistry and of the ages of the groundwaters at different points in the total system provides important data. There is also the need to integrate geochemical and isotopic data with the physical hydrology results, as is being done at Stripa. This raises a fifth critical question, "How should one gather groundwater samples for these investigations?"

The conventional approach to this problem is to collect water samples in vertical boreholes drilled from the surface. Drilling procedures normally cause contamination of the natural waters because the pressures required for fluid circulation often exceed those of the fluids in the rocks being drilled. This is usually overcome before sampling by producing a sufficient volume of water from such rocks until the contaminants are removed. In rocks with very low permeability this may not be practicable because the influx of groundwater into boreholes may be very slow.

Experience at Stripa, however, has shown clearly the superiority of collecting groundwater samples from boreholes drilled from underground drifts and rooms. Hydrostatic water pressures in rock are about a Megapascal per 100 m of depth, whereas the pressure within the mined openings is only about a tenth of a Megapascal (one atmosphere). Thus, any borehole that is drilled from an underground excavation into the rock mass around the opening encounters hydrostatic pressures that far exceed the pressure necessary to circulate the drilling fluids. This creates an artesian condition that minimizes contamination and greatly simplifies the subsequent problem of collecting water samples. This approach to the collection of samples of water for geochemical and isotopic studies of groundwater is far more effective than are methods using boreholes drilled from the surface.

The effectiveness of backfill materials in isolating canisters of radioactive waste and in plugging off underground openings is still another problem that must be investigated. This raises the sixth critical question, "What is the proper way to demonstrate the effectiveness of backfill materials?" As in the case of sorption behavior for aqueous solutions of radionuclides, many fundamental aspects can be investigated very effectively in the laboratory, especially in conjunction with the study of naturally occurring geological materials. A large effort in this direction is already underway. Ultimately, however, field tests will be required to demonstrate how such materials can be used best under repository conditions. It will be necessary to carry out field demonstrations on selected materials under appropriate levels of stress, temperature and moisture content. This can best be done meaningfully only in an underground test facility.

Answers to the above six questions cannot be found in terms of current experience nor through numerical modeling alone; these problems will require investigations to be conducted in full scale underground test facilities at the depths and other conditions that are expected to be encountered in an actual repository. For speed and economy, preference may be given to the process of evaluating a repository site on the basis of detailed exploration and testing carried out at the surface or in boreholes drilled from the surface. Such techniques, however, cannot yield the data needed to assess the total behavior of discontinuous rock masses when subjected to the perturbations of an underground waste repository. Experience with underground experiments at Stripa indicates that site characterization processes must include extensive subsurface experiments, carried out in conjunction with measurements made at the surface. Much effort is needed at this stage to generate the technology that is required. The Stripa investigations are a beginning.

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