Geologic Storage of Radioactive Waste: Field Studies in Sweden

P. A. Witherspoon, N. G. W. Cook, J. E. Gale

Safe disposal of hazardous materials has become a topic of much concern in the United States, 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. They range from dilute and short-lived materials to high-level wastes (HLW)—that is, wastes 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 ground water and waste. The multiple barriers include (i) the form of the waste, (ii) the canister in which the waste will be contained, (iii) the backfilling material used to surround and isolate the canister, and (iv) 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, even in a geologically suitable area, transport to the biosphere may occur through ground water. 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 high capacity for sorption. Generation of heat by the waste introduces the additional requirement of chemical and mechanical stability under the controlling stress fields. In the selection and characterization of a potential repository site, questions arise concerning the effectiveness of different rock types for safely isolating wastes underground over extremely long time periods. Although mining and civil engineering provide a wealth of information about underground excavations, there is very little experience to guide one in these matters and there is no general agreement about 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 through experiments designed to assess the ability of a rock mass to isolate waste at depths typical of proposed repositories. In this article the results of recent field experiments are presented and the 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 containing heat-generating, radioactive waste and of the complex processes of waste migration (*3*) in slowly moving ground waters cannot be overstated.

Summary. Access to a granitic rock mass in an iron ore mine in Sweden provided a unique opportunity for underground experiments related to the geologic disposal of radioactive waste. These field tests demonstrated the importance of hydrogeology and the difficulties in predicting the thermomechanical 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.

The Field Test Site

Over the past 3 years, thermomechanical, fracture hydrology, and geochemical investigations have been conducted in crystalline rock at a depth of about 340 meters below the 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 kilometers 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 the 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 east-west compression, during which the north-northeast-trending Vikern syncline, containing the ore deposit, was formed. Late in a second period of folding, caused by north-south 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. Some of the workings for mining the ore intersected the quartz monzonite, hence the easy access for these investigations.

P. A. Witherspoon is professor of geological engineering and head of the Earth Sciences Division, Lawrence Berkeley Laboratory, University of California, Berkeley 94720. N. G. W. Cook is professor of mining engineering, University of California, Berkeley. J. E. Gale is associate professor of geological engineering, University of Waterloo, Waterloo, Ontario N2L 3G1 Canada.

Thermomechanical Investigations

The thermomechanical investigations at Stripa were designed to study in situ rock behavior at depths below the surface and thermal loads comparable to those envisaged for an actual waste repository. The experiments consisted of (i) 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 (ii) an intermediate-term experiment scaled in time, distance, and heat output. Temperature fields, displacements, and stresses were measured as functions of time and space, data needed to test predictions of the thermomechanical response.

Full-scale heater experiments. The energy output from HLW canisters could be as much as 5 kilowatts per canister, depending on the form of the waste and its age at burial, although the heat output from fresh waste drops significantly in the first few years after it is removed 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 in diameter simulated the power output of the waste. Two such canisters were positioned in vertical holes (406 millimeters in diameter) 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. The power output of one canister-heater was adjusted to 5 kW to simulate the power level of reprocessed waste 3 years after removal from a light-water reactor; that of the other was set at 3.6 kW to simulate 5-year-old waste. These power levels were selected 3 years ago; currently, somewhat lower levels are preferred.

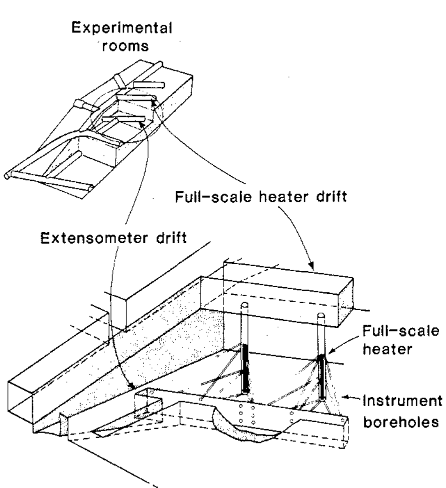

Fig. 1. Arrangement of experimental rooms in quartz monzonite rock mass some 340 m below the surface, showing detail of full-scale heater drift and location of instrument boreholes from adjacent extensometer drift.

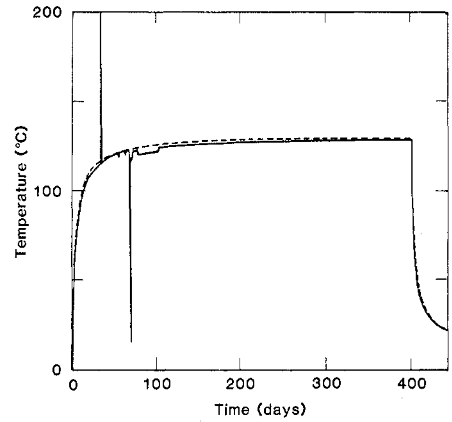

Fig. 2. Predicted (dashed line) and measured (solid line) temperatures plotted as a function of time at a radius of 0.4 m from the 3.6-kW heater along the heater midplane. Variations in measured signals early in the experiment were caused by corrosion on the stainless steel thermocouple sheath.

Response of the rock mass near the canisters was monitored extensively. Thermally induced displacements were measured with arrays of multiple-point extensometers (Fig. 1), and thermally induced stresses were measured with several U.S. Bureau of Mines 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 semianalytical solution (*6*), using properties from laboratory measurements on intact specimens. The data used in making these predictions were density, 2600 kg/m^3; specific heat, 837 J/kg-°C; thermal conductivity, 3.2 W/m-°C; and thermal diffusivity, 1.47×10^{-6} m^2/sec.

Figure 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. There were extensive fractures and joints in the quartz monzonite, but 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 3 years between canisters spaced 10 m apart. Thereafter, the effect of individual canisters diminishes. 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; the resulting thermal expansion of the roughly oblate spheroid of rock will be about 10^{-3}, a significant amount.

It is impractical to check these thermomechanical effects in the critical period from 10 to 100 years through a full-scale heater experiment. In the scaled heater experiment at Stripa, times have been compressed in the ratio of 1:10 by 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 $1/\sqrt{10} \simeq 0.32$ of the full scale, still allows for realistic field dimensions.

An array of eight heaters, spaced 7 m apart along the axis of a drift and 3 m apart in the direction perpendicular to

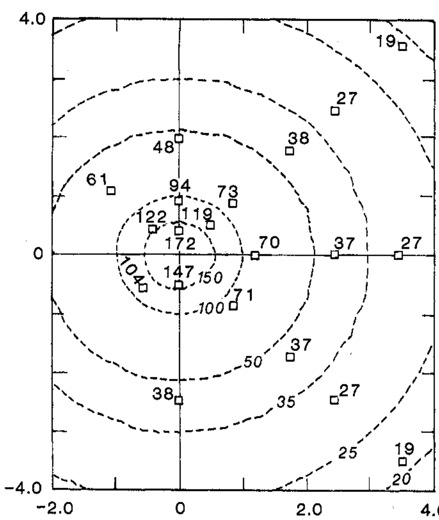

Fig. 3. Predicted isotherms (dashed lines) and measured temperatures (□) in a horizontal plane through the center of the 5.0-kW heater 190 days after the experiment began. Temperatures are in degrees Celsius. Values on axes are distances in meters from the axis of the heater.

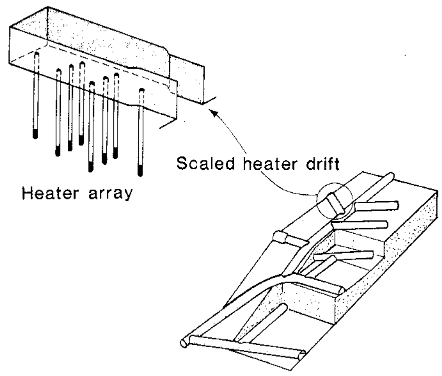

Fig. 4. Experimental rooms in quartz monzonite rock mass showing detail of scaled heater drift with eight 1.0-kW electric heaters. Heaters are 1.0 m long and have been placed so that the heater midplane is 10.5 m below the floor.

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 conduction. The temperature field is therefore amenable to prediction by relatively simple semianalytical methods (6).

Rock displacements and stresses. Extensometer measurements in the rocks adjacent to each full-scale heater (Fig. 1) reveal the complexity of attempting to predict thermomechanical behavior in a discontinuous rock mass. As a first approach, the rock was assumed to be homogeneous and intact, and displacements were predicted from the theory of linear thermoelasticity and the following values: coefficient of thermal expansion $\alpha = 11.1 \times 10^{-6}$ °C^{-1}; Young's modulus $E = 51.3$ GPa; Poisson's ratio $\upsilon = 0.23$; and thermal conductivity $k = 3.2$ W/m-°C. These values are averages for intact rock as measured in the laboratory over the range 100° to 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 from the laboratory values above. After this initial period, the measured displacements increased uniformly but at a more or less constant percentage of the preducted values. For many extensometers, the ratio of measured to predicted displacements during the second phase was 0.4 (Fig. 5).

An explanation of why the experimental results show far less rock movement than is predicted from theory for intact rock (8) may be the temperature dependence of the rock properties. Displacements predicted from 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 thermomechanical properties of cores from the Stripa quartz monzonite is receiving high priority.

Measurements of stress changes in the rock mass with vibrating-wire Creare gauges show trends similar to those of the extensometer results. The observed stress values were at most half of those predicted from the averaged thermomechanical properties cited above. Predicted stresses are still considerably higher than measured values when the temperature dependence of the rock properties is taken into account (9). Nevertheless, the stress results support the conclusion that thermomechanical effects induced in the rock mass are significantly less than predicted (8) from published values for the properties of intact laboratory specimens of rock. The role of discontinuities in controlling the thermomechanical behavior of rock masses needs much more study.

Fracture Mapping

The disparities between measured displacements and those predicted from the linear theory of thermoelasticity 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 thermomechanical behavior, and this raises the difficult question of the level of detail at which fracture geometry must be investigated to understand the behavior of the rock mass. 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

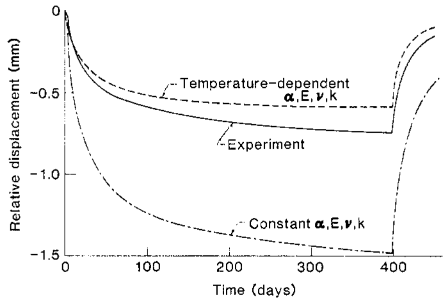

Fig. 5. Measured rock displacements in a vertical direction between anchor points 2.24 m above and below the heater midplane for an extensometer at a radial distance of 1.0 m from the 3.6-kW full-scale heater. Also shown are displacements predicted on the basis of constant and temperature-dependent properties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

elements (11). Second, all fractures were defined through careful measurement of orientation, spacing, and joint length. At present, it is 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, based on 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 by conventional methods with boreholes drilled from the surface only.

Fracture Hydrology

Migration of radionuclides away from a repository may occur by solution in ground water seeping through the site. The rates of nuclide movement depend on three basic rock properties: (i) permeability, (ii) effective porosity, and (iii) capacity for sorption. Thus far, research at Stripa has been concerned only with the first of these properties.

Evaluating the 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 (*15–18*).

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 investigations described above 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 with 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 airflow rate and the differences in humidity and temperature between the entering and exiting airstreams. This new technique enables measurement 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° to 40°C.

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 five holes each were drilled radially outward, and one group of five holes was drilled at the end of the room to distances of 30 to 40 m (Fig. 7). Figure 8 shows the orientation of one of the radial groups of boreholes. Each borehole was sealed off with six packers placed so that pressures and tempera-

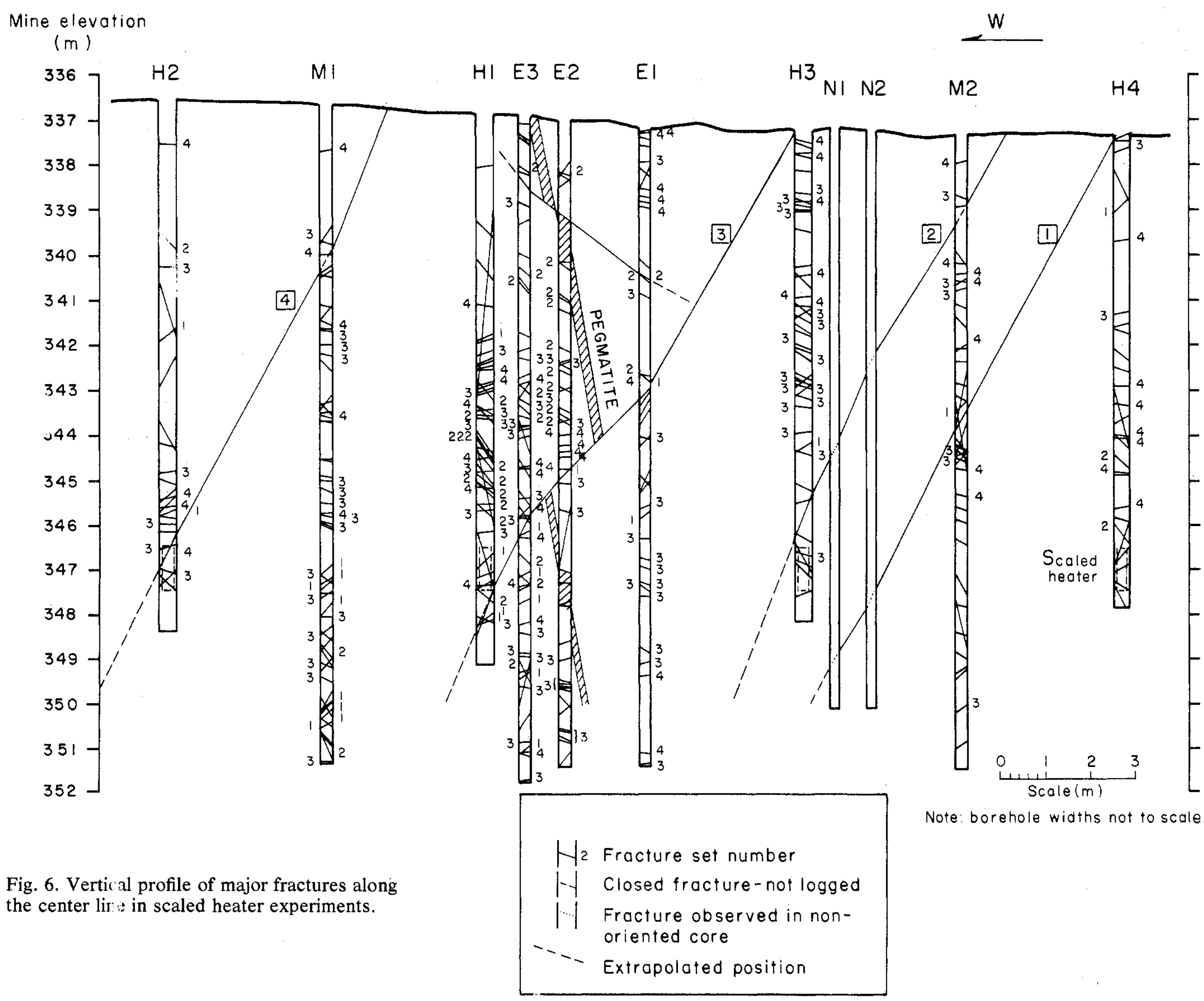

Fig. 6. Vertical profile of major fractures along the center line in scaled heater experiments.

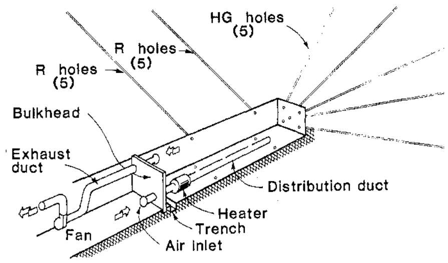

Fig. 7. Large-scale permeability experiment showing instrumentation boreholes and system to capture water seepage through evaporation into a controlled pattern of airflow.

tures could be measured over 5-m 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 pressure buildup in the other boreholes could be monitored, as shown in Fig. 8. The dashed lines represent pressures measured just before R01 was packed off on 31 October 1979. The solid lines represent pressures measured on 8 November 1979, and the stippled areas show how pressure increases occurred more or less uniformly throughout this fractured rock after instrumentation of R01. Similar effects were noted in all the other boreholes. Note that the pressures increase with distance from the drift and are all about 1 megapascal (145 pounds per square inch) 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 the 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 milliliters per minute was measured. On the basis of this rate and the observed pressure gradients, a preliminary value for the average hydraulic conductivity of the order of 10^{-11} m/sec 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 ground waters provide an independent approach to the problem of the overall permeability of a rock system. If surface waters moved rapidly to the experimental level (338 m), shallow and deep waters should be similar in chemistry and age. On the other hand, if the deep waters entered the ground-water 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 geochemical investigations of the Stripa ground waters 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 the surface.

The high chloride concentrations and relatively low deuterium and oxygen-18 contents of the deep mine waters, in comparison to near-surface waters, indicate that these waters had different sources. The low deuterium and oxygen-18 values also indicate that when the deep waters were originally at the surface (that is, before they seeped into the ground-water system), their temperatures were considerably cooler than that of present-day conditions, 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 ground waters, especially those at 811 to 838 m, are distinctly different from the shallow ground waters. This is interpreted as an indication that the different fracture systems are isolated from each other.

Isotopic dating of the various ground waters was also carried out (*21*). In contrast to the surface waters, where appreciable amounts of tritium were observed, the deep ground waters from the quartz monzonite are essentially devoid of tritium, which indicates that they are at least 30 to 40 years old. Waters from the deep levels are also very low in dissolved inorganic carbon; 2000 to 3000 liters of water were needed for ^{14}C analysis. On the basis of this method, the age of the waters at the 330-m level, and probably also from the 410-m borehole, exceeds 20,000 years.

Three different approaches to dating based on the uranium decay series were also investigated; these involved (i) uranium activity ratios, (ii) helium contents,

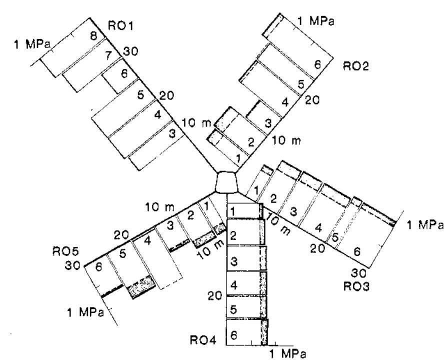

Fig. 8. Pressure measurements in radial boreholes of large-scale permeability experiment at Stripa. Stippled areas show pressure increases 8 days after packing off borehole R01.

and (iii) radium-radon relations (*21*). Although the $^{234}U/^{238}U$ method is still under development and is subject to some uncertainties, ages exceeding 100,000 years have been inferred from these data. Similar ages have been determined from ^{4}He concentrations. A method proposed by Marine (*22*), relating ^{4}He to its parent ^{238}U, yields ages ranging from tens of thousands to hundreds of thousands of years. The results of the radium-radon method indicate ages for the ground waters ranging from 10,000 to 35,000 years.

These data support the concept that the waters found in the quartz monzonite rock mass at Stripa, especially at the deepest levels (811 to 838 m), are indeed many thousands of years old. They also support the inference from the geochemical differences cited above that the shallow and deep ground waters are isolated. It is apparent that geochemical and isotope hydrology investigations provide independent approaches to evaluating the degree of isolation in a ground-water system.

Importance of Full-Scale Field Testing

Important results have been obtained from the investigations at Stripa that would not have emerged if these experiments had not 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 they must be supported by meaningful field experiments.

The behavior (mechanical, thermal, hydraulic, and chemical) of a repository in a crystalline rock mass of low permeability is determined by the properties

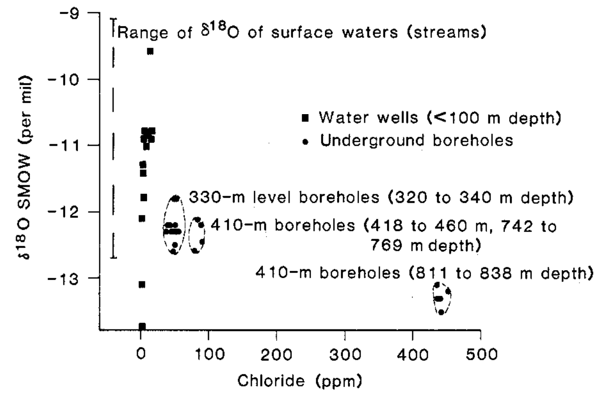

Fig. 9. Comparison of chloride concentrations with $\delta^{18}O$ values from geochemical investigations shows that there are distinct differences between waters at different depths. Oxygen isotopic values are referred to standard mean ocean water (*SMOW*).

of the rock matrix and, more importantly, by discontinuities that pervade the rock mass. This raises the first critical question: Can one determine the geometry of fractures in sufficient detail from 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.

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 thermomechanical 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 stresses in situ. Isolation of waste requires that the repository be constructed at sufficient depth to keep the fractures closed and maintain low permeability, even in a perturbed rock mass containing discontinuities, yet not so deep as to generate stresses that cause stability problems.

The thermomechanical results obtained thus far at Stripa show that much more work will be needed 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 for reliably predicting the global thermal response of a repository in a discontinuous rock mass? In our view, this can be done only in an underground test facility that has been properly designed and instrumented. It is difficult to say whether more than one type of crystalline rock needs to be tested underground in this fashion, because the physics of the thermomechanical 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 as opposed to bedded forms of igneous rock, they would 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 utilizing 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 effect could undoubtedly be eliminated by keeping temperatures below some maximum value, and it would be investigated as part of the field experiments suggested above. Low temperatures would also minimize effects on backfill materials and the possibility of generating thermal convection in the ground-water system. In our opinion, a definitive answer to the question of how long to store waste at the surface in order to minimize thermomechanical 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 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 thermomechanical response through the discontinuities. Fractures in any type of rock will deform under the influence of stress changes. 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 these concerns raise a fourth critical question: How should one measure rock properties in the field that must be known in order to understand the hydraulic-chemical effects? These properties are (i) permeability (hydraulic conductivity), (ii) both total and effective porosity, and (iii) sorption behavior.

At Stripa, attempts are being made to measure the permeability tensor by 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/sec. 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 be easily adaptable to rock masses with permeabilities far less than those 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 techniques.

In a rock mass with very low permeability the problem of measuring the effective porosity by tracer tests in situ is not easily resolved. Because the tests must be made at considerable depth with volumes of rock sufficient to be representative of the total mass, they 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 ground water through the fracture system toward such an underground opening is greatly enhanced, and tests with tracers can be designed for use in very large volumes of rock. Actual velocities can be measured by introducing a tracer at a point along a known flow path and observing its time of arrival downstream. Although standard borehole tracer tests contribute to an understanding of fracture flow in rock masses with higher permeabilities, 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 lack of basic data. Information is needed on the behavior of the aqueous and solid actinide species that are important in ground-water transport and also on the potential for actinides to form colloids in ground water. Recent work (*25*) suggests that actinides may form complexes with organic materials that occur naturally in ground water. 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 effectively in the laboratory, and a large effort in this direction is under way. Eventually, geochemists will require field tests to validate their laboratory findings. If underground test facilities are already in use for other purposes, it will be possible to incorporate various geochemical tests conveniently; such tests are already being planned for the Stripa project.

The importance of being able to determine the velocity of ground-water movement through a rock mass with very low permeability cannot be overstated. A good understanding of the geochemistry and age of the ground waters at different points in the total system provides important data. There is also a need to integrate geochemical and isotopic data with the data on physical hydrology, as is being done at Stripa. This raises a fifth critical question: How should one gather ground-water 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 contaminate natural waters because the pressures required for circulation of the drilling fluids often exceed those of the fluids in the rocks being drilled. This is usually overcome before sampling by producing water from such rocks until the contaminants are removed. In rocks with very low permeability this may not be practicable because the influx of ground water into boreholes may be very slow.

Experience at Stripa has shown the superiority of collecting ground-water samples from boreholes drilled from underground drifts and rooms. The hydrostatic water pressure in rock is about 1 MPa per 100 m of depth, whereas the pressure within the mined openings is only about 0.1 MPa (1 atmosphere). Thus, a borehole drilled from an underground excavation into the rock mass around the opening encounters a hydrostatic pressure that far exceeds the pressure necessary to circulate the drilling fluid. This creates an artesian condition that minimizes contamination and greatly simplifies the collection of ground-water samples for geochemical and isotopic studies.

The effectiveness of backfill materials in isolating canisters of radioactive waste and 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 of aqueous solutions of radionuclides, many fundamental aspects can be investigated effectively in the laboratory, especially in conjunction with the study of naturally occurring geological materials. This is already being done. Ultimately, however, field tests will be needed to determine how such materials can be used best under repository conditions. It will be necessary to carry out field demonstrations with selected materials under appropriate levels of stress, temperature, and moisture content. This can be done meaningfully only in an underground test facility.

Answers to the six questions raised above cannot be obtained from current experience or numerical modeling alone. Their resolution will require investigations in full-scale underground test facilities at the depths and other conditions that are expected in an actual repository. For speed and economy, preference may be given to 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 they are subjected to the perturbations of an underground waste repository. Experience with underground experiments at Stripa indicates that site characterization must include extensive subsurface experiments 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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