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INTRODUCTION

Significant quantities of nuclear wastes exist already and continue to be produced (U.S. DOE, 1978). To provide better protection for man and the environment from the potential hazard posed by these wastes than does the present practice of near surface storage, disposal by deep burial in suitable geologic sites is favored (NRC, 1957; IRG, 1978).

The principal attraction of deep geologic disposal is that it provides a practicable method for isolating these wastes physically from the biosphere for long periods of time. The principal uncertainty about deep geologic disposal concerns the rate at which toxic components of the wastes may leak back into the biopshere.

There are two major aspects to the design of a suitable underground repository for nuclear wastes, namely, the intrinsic properties of the geologic media, and the effects which the excavation of a repository, emplacing radioactive waste in it and, finally, sealing the excavations will have on the isolation of these wastes. The evaluation of these aspects involves concepts familiar to most mechanical engineers. The extent to which this is not true arises from geologic terminology and the inherent variability and uncertainty of the properties of sub-surface media.

Although there are some places where an underground repository could be sited above the present water table, it cannot be assumed that climatic or other changes will not alter this condition during the period over which isolation of wastes is required. Accordingly, it must be assumed that the repository and rock mass will become saturated after the excavations have been sealed.

The porosity and permeability of intact specimens of granite are of the order of one percent and 10^{-21} meters^2 (10^{-14}m/sec), respectively. It may seem that these and the ratio of permeability to porosity are such that the time taken for groundwater contaminated with radioactive materials from the waste to move 1 kilometer to surface from the repository would be about 30 million years, even for a highly adverse hydraulic gradient of unity. Unfortunately, the continuity of most hard rock, including granite, is interrupted by sets of tensile fractures, known as joints, and shear fractures resulting from tectonic and thermal stresses to which they have been subjected in geologic history. The hydraulic permeability of such rock masses is dominated by the flow of water through these discontinuities.

The changes in temperatures of the nuclear waste and of the geologic media around it, resulting from the radioactive decay of the waste, are fundamental to the design and performance of an underground repository.

The purpose of this paper is to examine the questions of the permeability and thermomechanical response of a granitic rock mass in the light of preliminary results from field experiments being conducted in a defunct mine some 340 m below surface at Stripa, situated about 200 kilometers west-north-west of Stockholm, Sweden (Witherspoon and Degerman, 1978).

GEOHYDROLOGIC MEASUREMENTS

The flow of groundwater through geologic discontinuities has been likened to laminar fluid flow between closely spaced parallel plates (Huitt, 1956; Snow, 1968). Using this analogy, the volume rate of flow per unit width of the discontinuity measured normal to the direction of flow is given by:

$$q = \frac{(2b)^3}{12\mu} \rho g i, \qquad (1)$$

where q = the volume rate of flow per unit width of the discontinuity measured normal to the direction of the flow ($m^3/m.s$);
$(2b)$ = the aperture of the fracture (m);
ρ = the density of water (kg/m^3);
g = the gravitational acceleration ($9.81 \ m/s^2$);
i = the hydraulic gradient (m/m), and
μ = the dynamic viscosity of water (kg/m.s).

Discontinuities in a rock mass are seldom orientated randomly; generally they occur in sets of three or more preferred orientations with a degree of statistical distribution about these directions. The apertures of discontinuities have been found to follow approximately a log-normal distribution (Snow, 1970) and, obviously, the aperture decreases with increasing compressive stress across the discontinuity.

To evaluate the permeability of a rock mass containing such discontinuities, it is necessary to determine their orientations, the spacing between discontinuities, and the distribution and magnitude of their apertures. This can be done in part by mapping of the discontinuities exposed on the walls of underground excavations and surface outcrops; measurements of discontinuities in core recovered from holes diamond drilled in the rock mass from surface and underground; optical surveys of the walls of these boreholes and, finally, the analysis of the results of hydraulic tests conducted in lengths of boreholes and tunnels. All of these approaches are being used at Stripa.

Figure 1 is a plan of the site showing the location of the principal boreholes for geohydrologic measurements. There are three boreholes from surface, SBH1, 2, and 3, 15 subsurface boreholes, and a length of tunnel.

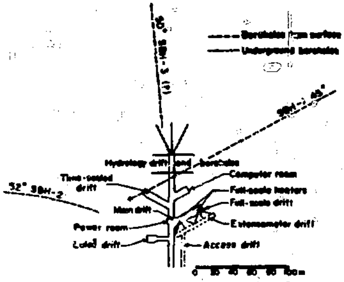

Fig. 1. **A plan of the test site at Stripa showing the time-scale and full-scale drifts and the extensometer drift for the latter, which is located at a lower elevation, as well as other drifts and boreholes.**

In addition to visual observations of discontinuities, the hydrologic properties of the rock mass are being evaluated by analyzing the results of pressure measurements made in lengths of each borehole shut off for test purposes by packers, and by measurements of the water pressure distributions around, and the rate of water flow into, the test drift (Gale and Witherspoon, 1978).

THERMOMECHANICAL MEASUREMENTS

The rate at which heat is released by spent fuel from light water reactors and by reprocessed high level waste from such reactors, decays more rapidly than time to the power -1/2, so that for dissipation of the heat into the rock mass, even by thermal conduction in one dimension only, the temperature of an underground repository must reach some peak value and then diminish (Cook and Witherspoon, 1978).

The average peak temperature of a planar repository is proportional to the initial power loading density of the repository. The diffusion of heat by conduction causes the temperature in the rock above and below such a repository to increase with time. These changes in temperature have significant mechanical and hydrological consequences for the performance of a repository.

Mechanically, the changes in temperature result in thermally induced compressive stresses within the heated zone of the rock mass and induced tensile stresses outside this zone. The latter stresses may increase the apertures of discontinuities in this zone by decreasing the value of the normal compressive stress across them.

Hydrologically, the enhanced permeability resulting from such increases in aperture, together with increased bouyancy and decreased viscosity of the groundwater as a result of increases in its temperature, may accelerate the transport of groundwater from the repository to the biosphere. These effects will have to be evaluated in the design of any nuclear waste repository.

In addition to the increase in the average temperature of a repository, the temperature of each canister of waste must increase, establishing a temperature gradient away from it to allow for the dissipation of the heat released as a result of radioactive decay within the canister by conduction into the rock around it. This temperature gradient induces compressive stresses parallel to the walls of holes containing canisters, which could result in decrepitation of the rock (Cook, 1977; St. John, 1978). Such decrepitation could decrease the thermal conductivity of the rock leading to unacceptable temperatures of the waste, or it may result in mechanical damage to the canisters and their contents.

The magnitude and characteristics of these thermomechanical effects can be estimated by calculating conductive temperature fields and the resulting thermally induced stresses and displacements. However, the results of such calculations depend upon the values used for the mechanical and thermal properties of the rock. In general, few of these properties have been measured and most have been obtained on intact specimens of rock in laboratory tests (Clark, 1966). The in situ properties of a rock mass containing discontinuities can be expected to differ significantly from those of intact laboratory specimens. The motivation for conducting heating experiments underground, using electrical heaters to simulate the thermal effects of canisters of radioactive wastes, is to obtain values for the thermomechanical properties of such a rock mass, and data with which to validate repository designs.

The near field thermal and mechanical effects, both in the short-term and in the long-term, can be studied using full-scale electrical heaters to simulate the heat released by the radioactive decay of waste in canisters. The interaction between adjacent canisters, which would occur in the long-term and result in an increase in the average temperature of a repository, can be simulated in the near field by increasing the temperature around a heater with a number of peripheral heaters (8) at a suitable radius (0.9 m) from the main heater and extending over a greater axial length (4.3 m) than that of the main heater (2.5 m).

As it is not practicable to study the far field, long-term effects, even for the period of a few decades needed to reach peak temperatures, before the need for such data arises, a time-scaled heater experiment can be used to study some of these aspects. Time and linear dimensions occur in solutions to all problems of heat conduction in solids in the form kt/x^2, where k is the thermal diffusivity, t is time and x is a linear dimension (Carslaw and Jaeger, 1959). This relationship has been used in the time-scaled experiment to accelerate time by an order of magnitude through a reduction in linear dimensions to a little less than a third of full size.

Using a finite element code to allow for the geometrical complexities introduced by the underground excavations and linear thermo-elasticity with values for the properties of the granite as measured in laboratory tests, the thermal fields (Chan et al., 1978a) and induced displacements and stress (Chan et al., 1978b) have been predicted as a function of time for the two heating experiments at Stripa. To date the methodology of the experiment has been to compare predicted and measured values of temperature, displacement and stress as a function of time, with the purpose of identifying disparities between the measured behavior of the rock mass in situ and predictions based on linearity and the properties of intact specimens of rock.

Some examples of comparisons between measured and predicted values of temperatures and displacements are illustrated in Figures 2 through 4. It appears linear heat conduction accounts well for changes in temperature even though the rock mass is discontinuous. However, measured displacements are consistently between 1/4 and 1/2 the predicted values, despite the fact that, theoretically, they should be a function only of the temperature field, the boundary conditions and a factor D given by:

$$D = \frac{1 + \nu}{1 - \nu} \alpha \quad , \qquad (2)$$

where ν = Poisson's ratio, and
α = the coefficient of linear thermal expansion

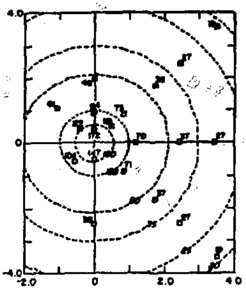

Fig. 2. Predicted isotherms and measured temperatures in a horizontal plane through the middle of the 5 kW full-scale heater, 150 days after heating had started. (Scale for both x and y axes is given in meters.)

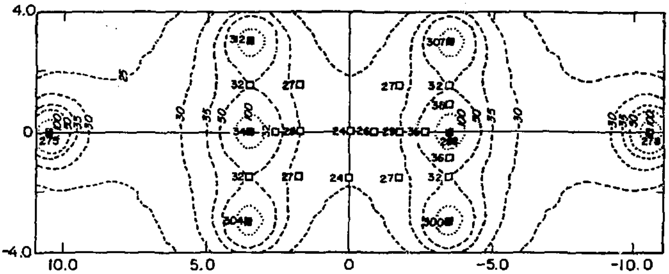

Fig. 3. Predicted isotherms and measured temperatures in a horizontal plane through the middle of the time-scale experiment 190 days after heating had started. (Scale for both x and y axes is given in meters.) (Squares marked in black indicate temperatures at heater locations.)

An analysis of the ratio between measured and predicted values of displacement as a function of time, that is, increasing temperature and displacement in the rock is shown for a number of measurements in Figure 5. This analysis suggests that the rock mass is behaving in a non-linear manner, as would be expected from the presence of discontinuities, and that the value of D for the rock mass is less than that deduced from laboratory tests.

Thermally induced stresses should be a function only of the temperature field, the boundary conditions and a factor S given by:

$$S = \frac{\alpha E}{1 - \nu} \qquad (3)$$

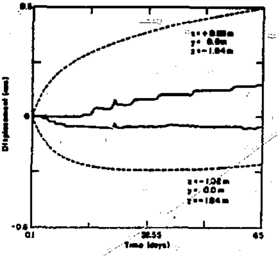

Fig. 4. **Predicted (dashed) and measured (solid) horizontal displacements below the 5 kW full-scale heater at anchor points symmetrically positioned on each side of the heater. Both of these displacements are measured relative to the collar of the hole on the wall of the extensometer drift.**

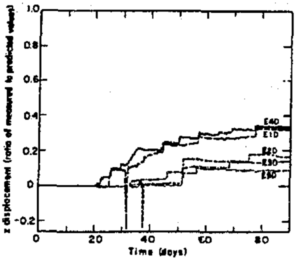

Fig. 5. The ratio between measured and predicted values of displacement for anchor points situated 3 m above and below the mid-plane of the time-scaled heaters as a function of time for each of the 5 extensometers. [The x- and y-coordinates are E1D (0,0), E2D (0,1.75); E3D (0,2.62); E4D (-1.5; 0), and E5D (1.5, -1.75) cf. Fig 3.]

where E = Young's modulus, and the other terms are as defined above.

As usual it has proved difficult to make accurate stress measurements, and calibration of the total stress measuring system has not proved to be completely satisfactory yet, as it has been for temperature and displacement. Accordingly, although the measured values of stress appear to compare well with the predicted values, it would be premature to draw conclusions from these data at this stage.

CONCLUSION

The results of this experiment to date indicate that the temperature fields in a rock mass containing geologic discontinuities can be predicted with accuracy using the simple linear theory of heat conduction.

Geologic discontinuities appear to introduce significant non-linear thermomechanical behavior into the rock mass as a result of which the thermally induced displacements are much less than those predicted by the simple theory of thermoelasticity, using laboratory values for Poisson's ratio and the coefficient of thermal expansion.

The additional compliance introduced into the rock mass by geologic discontinuities affects the thermally induced stresses but to a lesser degree than the displacements.

Further analytical, laboratory and field studies are expected to resolve many of the current uncertainties, especially field data gathered during a planned cooling down period following the switching off of the heaters scheduled in the near future.

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