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Author

Chan, T.

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THERMOMECHANICAL MODELING AND DATA ANALYSIS FOR HEATING EXPERIMENTS AT STRIPA, SWEDEN

Tin Chan, Nicholas Littlestone, and Oliver Wan
Earth Sciences Division, Lawrence Berkeley Laboratory
University of California, Berkeley, California 94720

ABSTRACT

Comparisons were made between predicted and measured thermomechanical displacements and stresses for in situ heating experiments at a depth of 340 m in a granite body at Stripa, Sweden. We found that taking into account the temperature dependence of the thermal expansion coefficient and the mechanical properties of the rock substantially improves the agreement between theory and experiment. In general, the displacements calculated using laboratory values of rock properties agree better with field data than in the case of stresses. This may be due to the difference between in situ and laboratory rock modulus. The significance of temperature-dependent rock properties and strength to thermomechanical failure is also discussed.

INTRODUCTION

Deep burial is a likely choice for the long-term storage of nuclear wastes. In estimating the likelihood of any of these wastes returning to the biosphere while still significantly radioactive, account must be taken of the heat generated by their radioactive decay. Effects of this heat include stresses in the rock, groundwater convection, and acceleration of chemical reactions. Thermally induced stresses may alter the flow of groundwater by changing the permeability of the rock. They may also damage boreholes or storage rooms, making it difficult to retrieve the wastes should it become necessary.

One of the rock types being considerd is granite (Department of Energy, 1979). To study the thermal effects in granite, a group of heater experiments has been conducted in a granite body at a depth of approximately 340 m in the Stripa mine in Sweden. These experiments are part of a Swedish-United States cooperative program to study radioactive waste storage (Witherspoon and Degerman, 1978; Witherspoon et al., 1980). Temperatures, displacements, and stresses were measured. In addition, a wide variety of data have been collected, including fracture maps of the sites, laboratory and in situ rock properties, and water flow data.

THE HEATER EXPERIMENTS

Three heater experiments have been conducted. Two "full-scale" experiments have each heated the rock with a heater intended to duplicate in size and power the heat initially given off by a canister of relatively young, reprocessed, high-level waste. Experiment 1 used a 3.6 kW heater and experiment 2 a 5 kW heater, each left on for approximately one year. In addition, to gain more information about the rock behavior at the high temperatures and stresses that might be created by a number of canisters near each other, a series of eight peripheral heaters (1 kW each) was placed in a 0.9 m radius ring around the 5 kW heater of experiment 2 (see Fig. 1). These were turned on 204 days after the 5 kW heater was turned on and their power lowered from 1 kW to .85 kW 40 days later.

Experiment 3 is a time-scaled experiment, that is, assuming linear heat conduction, power and dimensions were scaled to simulate in one year the first ten years of the burial of a waste canister (Cook and Witherspoon, 1978).

Discussion here will center on experiment 2, the highest-powered of the three experiments.

MODELING

Preliminary Model

In this paper, the thermomechanical modeling performed in conjunction with these experiments is discussed.

The model originally used to estimate the results of the full scale experiments consisted of two steps. The first step calculated the temperatures using a

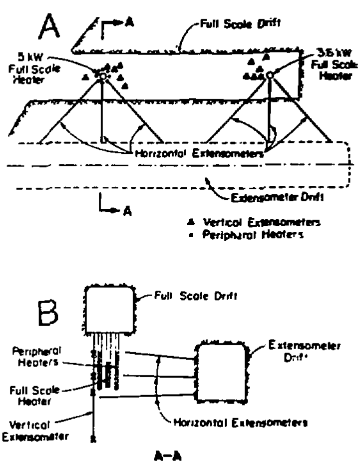

FIG. 1. GEOMETRY OF HEATER EXPERIMENTS. (A) PLAN VIEW OF FULL-SCALE EXPERIMENTS SHOWING LOCATION OF HEATERS AND OF ROD EXTENSOMETERS. (B) VERTICAL SECTION THROUGH FULL-SCALE EXPERIMENT 2.

closed form integral solution of the heat-diffusion equation (Chan et al., 1978). The rock was assumed to be homogeneous and isotropic with constant material properties. The heater was idealized as a finite-length line heater. In calculating the temperatures used as input to the displacement and stress calculations, the rock was assumed to be an infinite medium.

Displacements and stresses were calculated with a finite-element model using the program SAP4 (Bathe et al., 1974). Constant and uniform rock properties were also used with SAP4 in this preliminary linear thermoelastic model (Chan and Cook, 1980). The geometry was assumed to be axisymmetric about the central heater. The effects of this are: (1) to model the heater drift as a cylindrical cavity; (2) to model the extensometer drift as a torus 10 m from the central heater, and (3) to smooth the eight peripheral heaters into a uniform ring.

Though the calculated temperatures are quite close to the actual temperatures observed, the displacements and stresses predicted by the model are quite different from the measured displacements and stresses (Wood, 1979). They often differ by more than a factor of two, though the time history curves of predicted displacement and stress tend to be of similar shape to the curves for the measurements.

Revised Model

To help determine the source of this difference, the model was revised. The major changes introduced with this model are twofold:

(1) The geometry and boundary conditions are modeled more accurately, both for the temperature calculations and for the displacement and stress calculations. The assumption, made in the preliminary calculations that the heater midplane is a horizontal plane of symmetry was removed. A schematic representation of the finite element model is shown in Fig. 2. Temperatures have been calculated now with the finite-element program DOT (Polivka and Wilson, 1976); this permits the temperature effects of the drifts to be modeled with convective boundary conditions. (A heat transfer coefficient of 3 W/m^2 °C has been used.) It also permits a more accurate approximation to the initial temperatures in the rock. Displacements and stresses have been calculated using this same new mesh.

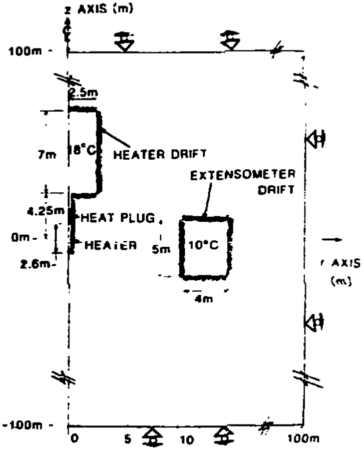

FIG. 2. SCHEMATIC DIAGRAM OF FINITE ELEMENT MODEL. BOUNDARY CONDITIONS ARE SHOWN FOR THE DISPLACEMENT AND STRESS CALCULATIONS. THE OUTSIDE BOUNDARY IS ADIABATIC IN THE TEMPERATURE CALCULATION.

(2) Temperature-dependent material properties have been introduced, both for the temperature calculations and for the displacement and stress calculations. For comparison, calculations with the new mesh have also been made with constant material properties.

Figure 3 shows some of the temperatures calculated with the temperature-dependent model. This will give an idea of the range of temperatures at which the temperature dependence of the material properties is important.

The changes introduced above affect the calculated temperatures only slightly, but significantly change the calculated displacement and stress values. In some cases the new calculations agree quite well with the experiment, and in nearly all cases examined so far they have changed the calculated values in the direction of better agreement.

COMPARISON OF THE MODELS

To illustrate the effect of varying the material properties, calculated and experimental quantities will be compared for two extensometers and two stress gauges in experiment 2.

Summary of the Models Being Compared

The models compared on the plots are labeled A, B, C, and D. Model A is the preliminary calculation (shown only on the extensometer plots). Models B, C, and D are all calculations using the new finite-element mesh and finite-element temperature calculations. The only difference among them is in the material properties used. Model B uses the same constant material properties used in Model A (see Table 1).

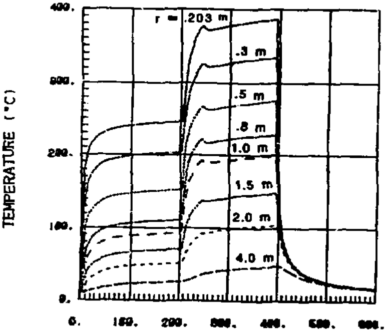

FIG. 3. ROCK TEMPERATURES IN THE MIDPLANE OF EXPERIMENT 2 ACCORDING TO MODEL C (OR D) AS A FUNCTION OF TIME FOR VARIOUS RADIAL DISTANCES.

TABLE 1.

Material property	Symbol	Value	Units
Thermal conductivity	k	3.2	W/m°C
Coefficient of linear thermal expansion	α	11.1×10^{-6}	°C
Young's modulus	E	51.3	GPa
Poisson's ratio	ν	.23	
Specific heat	c	837	J/kg°C
Density	ρ	2600	kg/m^3

Models C and D both use temperature-dependent values for thermal conductivity (k), thermal expansion coefficient (α), Young's modulus (E), and Poisson's ratio (ν). These values are shown in Fig. 4 as dashed lines superposed on plots of experimental measurements of the various properties. The values for density and specific heat in all models are the constant values shown in Table 1.

The only difference between models C and D is in the temperature dependence of α. In model C, the curve for α at high temperatures was linearly extrapolated when few measurements were available at high temperatures. Also, the measurements that were available then were primarily at low confining pressures where α seems to climb much more rapidly with temperature than at higher pressure. The model C curve for α climbs very rapidly above 200°C. This is probably a very extreme (upper) limiting case. In model D, α follows closely the lower side of the existing measurements.

Displacement

The vertical displacements plotted (Fig. 5) are for the relative rock displacement for a pair of anchor points, one above the heater midplane and one below the midplane. The curves split clearly into three sections. The first is before the turn-on of the peripheral heaters; the temperatures here are probably closer to those expected in an actual repository than are the high temperatures in the middle period

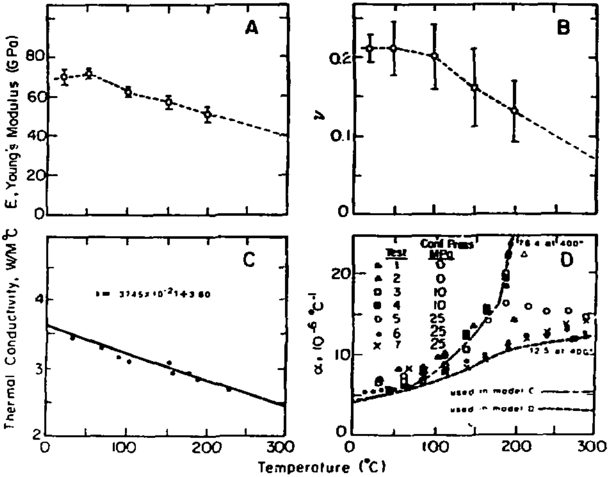

FIG. 4. MATERIAL PROPERTIES OF STRIPA GRANITE. THE DASHED LINES SHOW THE TEMPERATURE DEPENDENT PROPERTIES USED IN MODELS C AND D. THE POINTS PLOTTED SHOW THE EXPERIMENTAL RESULTS UPON WHICH THESE WERE BASED. EXPERIMENTAL RESULTS GIVEN IN PLOTS A AND B ARE AFTER SWAN (1978); THOSE IN PLOT C ARE AFTER PRATT ET AL. (1977); TESTS 1 THROUGH 5 IN PLOT D ARE REPORTED IN CHAN, HOOD, AND BOARD (1980), TESTS 6 AND 7 IN BOARD (1980).

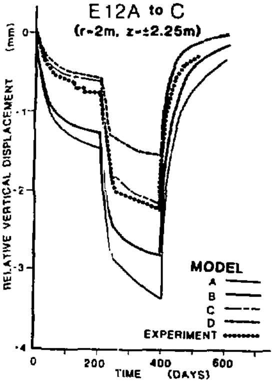

FIG. 5. RELATIVE VERTICAL DISPLACEMENT BETWEEN A PAIR OF ANCHOR POINTS IN EXPERIMENT 2. THESE ANCHOR POINTS ARE LOCATED 2.24 m ABOVE AND BELOW THE HEATER MIDPLANE, ON A VERTICAL EXTENSOMETER AT 2 m RADIUS FROM THE 5 kW HEATER.

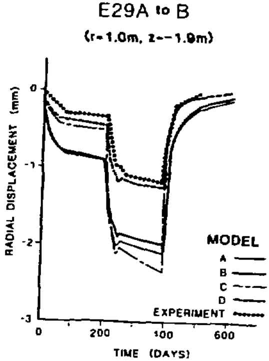

FIG. 6. RELATIVE HORIZONTAL DISPLACEMENT BETWEEN A PAIR OF ANCHOR POINTS LOCATED 0.6 m BELOW AND 1 m HORIZONTALLY ON OPPOSITE SIDES OF THE 5 kW HEATER.

when both the central and peripheral heaters are on. However, the middle period clearly demonstrates the effect of the temperature dependence of the rock properties. Data at these high temperatures may be particularly important in predicting the effects in the rock immediately surrounding a waste canister. This information will be useful for establishing an upper limit for the thermal power of a waste canister for a particular potential site. The final period is the cool-down period, when all heaters have been shut off.

Before the peripheral heaters have been turned on, the difference between models A and B (both of which use constant properties) is fairly small. Models C and D (the temperature-dependent models) are quite close to each other and give much better agreement than A and B with the experiment.

After the peripheral heaters have been turned on, the difference between the displacements calculated by models A and B becomes significant. Since these two models differ in several ways in their assumptions and approximations, further sensitivity analysis is necessary to isolate the separate effects of the several differences.

Although the temperature dependence of α in model D seems much more reasonable than that in model C, here model C follows the experiment much more closely. This is not true for the horizontal displacement to be discussed next and seems to be fortuitous. The discrepancies between model D and the field data suggest that further improvement of the model is necessary.

Note that during the cool-down phase, unlike during the initial heating-up phase, temperatures are generally low and models C and D (differing only in high temperature values of α) give essentially identical results. The model C and D values are less than the experimental values by a greater margin during cool-down than they were during the heating period. Inelastic response may be indicated here, but this cannot be concluded without more definitive determination of rock properties.

Results for the horizontal extensometer (Fig. 6) are somewhat different. The plot shows relative displacement betweem two anchor points on opposite sides of the central heater, each at a radius of 1 m from the heater and 0.6 m below the bottom of the heater. Models A and B are close to each other. Model D, the one currently considered best, agrees quite well with the experiment. Model C predicts very large relative displacement when the peripherals are turned on, a result expected from the very large thermal-expansion coefficient used for the high temperature zone between the two anchor points.

For the vertical extensometer previously discussed model D calculated less expansion than was observed. Here model D gives greater expansion than the experiment. The reason for this is not yet clear. One possibility may be the geometrical approximation in the axisymmetric model which tends to predict too low a vertical displacement. There is also some question about the accuracy of the horizontal measurements because of the length of the extensometer rods and their horizontal orientation.

Stress

Thermally induced stress changes are presented in Fig. 7 (compressive stress is positive) for two IRAD (Creare) vibrating wire gauges. One is at a radius of 1.75 m from the heater and .65 m below the midplane; the other is 1.5 m out and .82 below. Gauge C14 is in a horizontal hole and gauge C3 is in a vertical hole. Both measure the tangential stress. In addition, C14 measures axial stress and C3 the radial stress.

As in the case of the extensometers, model B values are much larger than the experimental values. For these gauges, model D is consistently an improvement over model B, though it remains far from the experimental values. Some questions remain regarding the interpretation of the readings of these gauges. For example, the gauges were calibrated under uniaxial stress whereas the thermally induced stress is three-dimensional. Field calibration under biaxial stress is now in progress.

During cool-down, rather high tensile stresses are recorded by these two IRAD gauges. This is predicted by none of the models. It could perhaps be caused by some error in the measurements.

IMPLICATIONS OF COMPARISONS

Possible Improvements to the Model

Though Model D seems to be giving reasonable results in general, there is still much room for

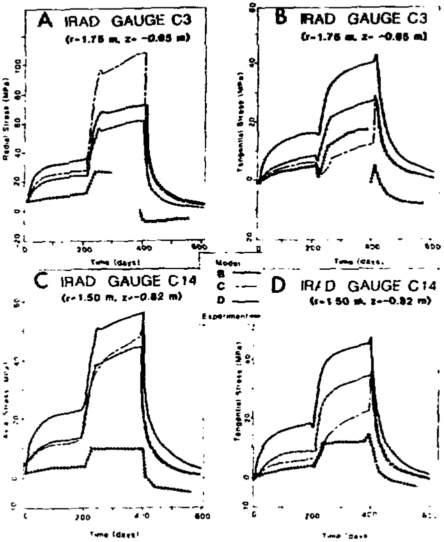

FIG. 7. STRESS MEASURED BY IRAD (CREARE) GAUGES C3 AND C14 IN EXPERIMENT 2.
A. RADIAL STRESS, GAUGE C3
B. TANGENTIAL STRESS, GAUGE C3
C. AXIAL STRESS, GAUGE C14
D. TANGENTIAL STRESS, GAUGE C14

improvement in the model. Improvement can be made at two levels:

(1) measuring the material properties more accurately as a function of temperature and incorporating the knowledge in the model;

(2) modifying the model to more accurately reflect the complexities of the real situation.

A number of modifications suggest themselves:

(a) Model the combined dependence of one or more of the material properties on stress as well as on temperature. This would require more detailed measurement of the material properties, using a nonlinear numerical code, and knowing the in situ state of stress.

(b) Use a three-dimensional finite-element mesh to more accurately model the geometry. This will be inevitably expensive.

(c) Attempt to incorporate the effect of fractures (e.g., as discrete joint elements, Goodman, 1976), inclusions, and other inhomogeneities in the model. As a first approximation this might be accomplished by suitable modifications to E (i.e., deriving an equivalent medium, e.g., Glynn et al., 1978, Walsh and Grosenbaugh, 1979), particularly if a stress-dependent E is modeled.

The most straightforward changes would seem to be those involving improved modeling of the temperature dependence. The above comparisons indicate that changes in rock properties within the measured range can produce significant changes in the calculated results.

Examination of Rock Properties

It is of interest to examine which material properties seem to affect the results most when changed within reasonable ranges. The theory of linear thermoelasticity sheds some light on what to expect when comparing thermomechanical effects in rocks with different sets of constant material properties. Displacements depend proportionally on α, weakly on ν, and are independent of changes in E from one constant value to another. Stresses depend proportionally on the product of α and E, with a weak dependence on ν (Chan, Hood, and Board, 1980).

A number of finite element calculations using a version of model B with various values of constant material properties produced results in agreement with the theoretical relationships noted above. In addition, exploratory calculations were made with versions of models B and C in which one property at a time was changed from a constant to a temperature-dependent value. These indicate that within the range of material properties considered here, displacement is most significantly affected by changing from constant to temperature-dependent α while individual changes in the other material properties produce much smaller effects (Chan, Hood, and Board, 1980). Though one could argue that the large effect of changing α from the constant to the temperature-dependent value occurred only because the original constant value was unrealistically high, the value is within the range of values measured for α at temperatures occurring in the experiment. A lower constant value for α would presumably give bad results in the high temperature parts of the experiment; if one would like to use a constant value for α it is not at all clear what value one should choose.

The strong dependence of the calculated displacements and stresses on the values used for α and E and the wide variation in the values measured for these properties suggest that α and E be looked at carefully. There remains considerable uncertainty in these material properties. There is considerable scatter in the values for α and there is little data concerning the dependence of α on stress.

To give an idea of the variation in measured values for E, some values are summarized in Table 2.

TABLE 2. Young's modulus, E, for Stripa Granite from various sources.

Temp. (°C)	Confining pressure (MPa)	E* (GPa)	Comments**	Source
		51.3		Pratt et al. (1977)
		59.4		Carlson (1978)
		55		Thorpe et al. (1979)
20°		69.4	uniaxial	Swan (1978)
50°		71.2		
100°		62.4		
150°		57.2		
190°		50.8		
	5	75.4	triaxial	Swan (1978)
	10	77.2		
	20	82.2		
	30	83.2		
23°		64.8	***	Schrauf et al. (1978)
88°		59.3		
	5.5	48	using CSM cell	Hustrulid and Schrauf (1979); Schrauf et al. (1978)
	10.3	61		
		36.8	in situ using CSM cell	
		69.6	ultrasonic velocity	Pratt et al. (1977)
	10	78	ultrasonic velocity	Nelson et al. (1979)
		74.5	in situ ultrasonic velocity	Nelson et al. (1979)

* There is wide variation in the number of samples used to make these measurements.

** All values are laboratory values unless marked "in situ."

*** Measurements made in conjunction with IRAD gauge calibration.

Laboratory measurements of E have been somewhat consistent, though even here there is quite a lot of scatter. The two in situ measurements so far made produce different results. One of these is a value deduced from cross-hole ultrasonic velocity measurements. This is slightly higher than most of the laboratory values. Furthermore, a limited examination of the data (Paulsson and King, 1980) indicates that these velocities rose during the first few weeks of the experiment and then remained roughly constant until the heater was turned off (measurements were made for experiment 1, with no peripheral heaters). This could perhaps be due to a closing of fractures; this has not been unambiguously confirmed. A straightforward substitution into the equations relating E to P- and S-wave velocities (using velocities read from a graph presented in Witherspoon, Cook, and Gale, 1980) gives an increase in E from 75 GPa to 82 GPa during the first 100 days of the experiment (this is a rough calculation based on one set of values only). This is opposite to the laboratory-measured decrease in E with rising temperatures. It could, however, be consistent with a model in which the rock is assumed to get stiffer (E increasing) as fractures close or as confining stress increases (see Table 2), or it could perhaps suggest that for some other reason the laboratory measurements do not properly reflect the in situ temperature dependence.

The other in situ measurement of E shown in the table was made with CSM (Colorado School of Mines) cells. The mean value of E obtained was considerably lower than any other measurement. It is not yet clear how to interpret this measurement - whether it is a reflection of the in situ modulus in general, of the local modulus around the measurement holes, or of some problem in measurement.

DECREPITATION

An accurate knowledge of material properties at high temperatures is particularly important in attempting to understand the conditions under which borehole decrepitation will occur. One of the objectives of this experiment was to study these conditions. Massive decrepitation occurred at the central heater hole of experiment 2 shortly after the peripheral heaters were turned on. However, without a model which can accurately predict stress at high temperature, it is not clear at what stress level this decrepitation occurred. Hood et al., (1979) suggested that gross thermomechanical failure of the borehole occurred when the thermally induced hoop stress just exceeded the uniaxial compressive strength of intact samples of Stripa granite. (This was based on a comparison of results from the constant-materials property model, i.e., model A, with the room temperature compressive strength. The uniaxial compressive strength of the rock decreases from 208 MPa at 20°C to about 150 MPa at 190°C according to measurements by Swan (1978). The strength has not been measured at the temperature of the rock around the borehole when the decrepitation occurred (over 300°C). Fig. 8 shows calculated values for the largest (compressive) normal stress at the 5 kW heater hole; this is the tangential stress. In the latest model (model D) these reach 150-175 MPa long before the decrepitation occurs; there is another slight rise in value at the time of the decrepitation. However, there remains too much uncertainty both in the accuracy of the stress calculations (e.g., due to lack of Young's modulus measurement at high temperature) and in the measurements of strength to interpret these figures as of yet.

The relationship between the stress at which decrepitation is expected to occur and the uniaxial strength has not yet been established. From the limited amount of field experience in rock heating, it appears that there are three different modes of fracturing: (1) formation of powdery fragments, (2) progressive flake-like spalling, and (3) gross thermomechanical failure.

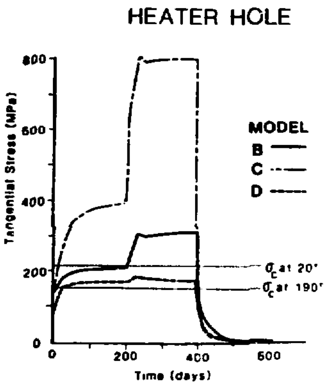

FIG. 8. TANGENTIAL STRESS AT THE BOREHOLE WALL MID-PLANE LEVEL OF THE 5 kW HEATER OF EXPERIMENT 2, AS CALCULATED BY THREE OF THE MODELS. ALSO SHOWN ARE VALUES FOR UNIAXIAL COMPRESSIVE STRENGTH, σ_c, OF STRIPA GRANITE (SWAN, 1978).

Powdery fragmentation has been observed (Bourke, 1980) in a heating experiment at Cornwall when the rock wall of a borehole in granite reached a temperature around 300°C. Microscopic mechanisms, e.g., thermal expansion of water inclusions in quartz or differential thermal expansion of different grains, have been suggested to be responsible for this kind of fragmentation. Hood et al. (1979) reported progressive flake-like decrepitation in Stripa experiments prior to the failure at the time of the peripheral heater turn-on. This type of spalls might have been formed by coalition of microcracks that arose from microscopic effects.

Gray (1965) studied thermal spalling in a 2m x 2m tunnel and a 0.9 m x 0.9 m test passage in gneiss due to heating by exhaust gases from a diesel-powered electric generator and an oil furnace, respectively. Massive spalling occurred in both openings at rather moderate temperatures: less than 110°C (estimated) in the 2 m tunnel and 61°C (measured) in the 0.9 m test passage. The spalls were plate-like in appearance with lengths ranging from one-sixth to one-third the width of the tunnel. Gray suggested that the size and shape of the spalls reflected the pattern of macroscopic thermal stress. He also attempted to produce spalls in a 15 cm-diameter borehole near the 0.9 m test passage but was not successful, although the surface temperature was increased by about 195°C. This may be related to the so-called "size effect" in the mechanical strength of rocks.

Further work is clearly necessary to study the thermomechanical decrepitation mechanisms.

CONCLUSIONS

Significant improvement in the numerical model for the displacement and stress has been obtained by taking the temperature dependence of the material properties into account. Further research on the dependence of the properties on temperature and stress is needed to determine whether the current model can be modified to adequately predict the observed results merely by accurately incorporating these dependencies into the model. It is possible that more complex modifications, such as using a three-dimensional mesh or modeling the discontinuities of the rock (either by discrete joint elements or by an equivalent medium) may be necessary before good agreement between the experiment and theory can be achieved.

Knowledge of the temperature dependence of the material properties is particularly important in attempting to understand and predict decrepitation in waste canister boreholes, since temperatures are particularly high at the canister boreholes.

ACKNOWLEDGMENTS

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