Lawrence Berkeley National Laboratory

PREDICTED AND MEASURED TEMPERATURES, DISPLACEMENTS AND STRESSES FROM THE STRIPA HEATER EXPERIMENTS

Author
Chan, T.

Publication Date
1980

Peer reviewed

To be presented at Rockstore '80, Special Session on Nuclear Waste Disposal, Stockholm, Sweden, June 23-29, 1980

LBL-10358

PREDICTED AND MEASURED TEMPERATURES, DISPLACEMENTS AND STRESSES FROM THE STRIPA HEATER EXPERIMENTS

T. Chan, M. Hood and P. A. Witherspoon

January 1980

This project is managed by the Office of Nuclear Waste Isolation, Battelle, Columbus, OH

Prepared for the U.S. Department of Energy under Contract W-7405-ENG-48

PREDICTED AND MEASURED TEMPERATURES, DISPLACEMENTS AND STRESSES FROM THE STRIPA HEATER EXPERIMENTS

T. Chan*, M. Hood** and P. A. Witherspoon*

*Earth Sciences Division, Lawrence Berkeley Laboratory
Berkeley, California 94720
**Department of Materials Science and Mineral Engineering
University of California, Berkeley, California 94720

ABSTRACT

A summary of the results of heater experiments conducted at the Stripa Mine in Sweden is given. These results for the induced temperature, displacement and stress fields, are compared with the original predictions for these parameters which were made using both analytical and finite-element calculations assuming that the material properties of the rock remained temperature independent. Discrepancies between the measured and the predicted results are discussed. Additional calculations, based on a limited amount of laboratory data for the temperature dependence of these material properties, are described. These new predictions are found to agree better with the measured field data.

Un résumé des résultats obtenus lors des expériences de chauffage menées à la mine de Stripa, Suède, est présenté. Ces résultats concernant la température incluide, les champs de déplacements et de contraintes, sont comparés aux prédictions de ces paramètres réalisées par calcul analytique et méthode des éléments finis, avec l'hypothèse que les propriétés des matériaux sont indépendantes de la températures. Les écarts entre les valeurs mesurees et prédites sont discutés. Des calculs supplémentaires, basés sur une quantité limitée de données de laboratoires, concernant la dépendance de ces propriétés des matériaux et de la température sont décrits. Ces nouvelle prédictions sont en meilleur accord avec les données obtenues sur le terrain.

KEYWORDS

Granite, thermomechanical effect, in situ heater test, nuclear waste storage, finite element analysis, Stripa, temperature dependent properties, rock mechanics

INTRODUCTION

Among the many alternatives that have been suggested for isolating nuclear wastes from the biosphere (Department of Energy, 1979) burial in deep underground caverns in a geologically stable formation appears to be the most practicable. The rock in a geological site used for a radioactive waste repository will be subjected to two major types of perturbations: (1) the perturbation due to the excavation of the repository and (2) the thermal loading due to the radioactive decay of the wastes. Civil and mining engineering experience can be relied upon to take into account the mechanical perturbation in the design and construction of the repository (Hoek, 1979). In contrast, there is little experience in the effects of thermomechanical loading of underground structures, especially in hard rock.

Thermally induced stresses are important for repository design in a number of respects. First, high compressive stress may cause borehole decrepitation, thereby reducing the thermal conductivity of the rock and consequently causing increased temperatures in the waste canisters and also complicating waste retrieval should that be necessary. Second, if the waste is to remain retrievable for several decades, an objective that probably will become a policy in the United States (Batch and Heath, 1979), then the thermal stresses must be taken into consideration in the design of the excavations for the repository. Finally, thermally induced tensile stresses will lead to higher fracture permeability either by increasing the aperture or by extending the length of discontinuities. Conversely, compressive thermal stress is likely to reduce the permeability.

In addition to this thermomechanical loading of the rock the heating caused by the decay of the radioactive wastes is likely to cause convection of groundwater which is of concern since this could reduce the time for transport of radionucleides to the biosphere. Chemical reactions, such as corrosion of the canisters by the groundwater also may be accelerated by the heating.

To gain a basic understanding of the behavior of a hard rock mass under the special conditions that will arise in an underground repository in the presence of heat-generating, radioactive wastes, a series of heating experiments have been conducted in a granite body at a depth of 338 m in an abandoned iron-ore mine at Stripa, Sweden, about 150 km west of Stockholm. This work is part of a Swedish-American cooperative program of investigations on radioactive waste disposal between the Lawrence Berkeley Laboratory in the U.S. and KBS (the Nuclear Fuel Safety Program) in Sweden. Overviews of the entire project have been published previously by Witherspoon and Degerman (1978) and Witherspoon and coworkers (1980).

In the present paper, a review is given of the current state of understanding of the thermomechanical behavior of a granite rock mass. This is attained by comparison of actual data from the Stripa experiments with numerically modeled temperature, displacement, and stress fields.

THE HEATER EXPERIMENTS

Three heater experiments have been conducted, two full-scale experiments and one time-scaled experiment. The full scale experiments will assess the short-term local thermal and thermomechanical responses of the granite rock mass in the immediate vicinity of an individual nuclear waste canister while the time-scaled experiment will provide field data for the interaction between adjacent waste canisters for two different spacings over a period of time equivalent to about a decade. Details of the objectives and design of these experiments have been given by Cook and Witherspoon (1978) Hood and coworkers (1980) and Hood (1979). A brief summary is given below.

Full-Scale Heater Experiment

Figure 1 illustrates the configuration of the full-scale experiments. In these experiments, electrical heater canisters, 0.32 m in diameter and 2.6 m in height, were placed in vertical 0.406 m diameter drill holes so that the midplane is 4.25 m below the floor of the drift. The two main heaters were operated at constant powers of 3.6 kW and 5 kW, respectively, corresponding to the thermal output of a canister of reprocessed high-level waste from light-water reactors approximately 5 and 3.5 years out of reactor. The 5 kW heater was surrounded by a concentric 0.9 m radius ring of eight peripheral heaters operated at a nominal power of 1 kW each. These peripheral heaters were energized 204 days later than the 5 kW heater to raise the ambient rock temperature by approximately 100°C. Analytical studies of the thermal effects of these peripheral heaters were carried out by Chan and coworkers (1978). Details of the power history for this experiment are given in Chan, Littlestone, and Wan (1980).

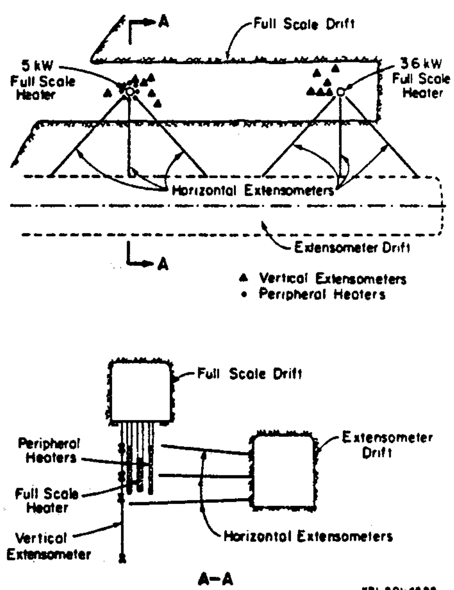

Fig. 1. Geometry of the full-scale heater experiments. Top: plan view; bottom: vertical section.

Time-Scaled Heater Experiment

In this experiment, by reducing the linear dimensions of the experiment by a factor of 3.2, the quadratic relationship between time and distance in linear heat conduction was utilized to compress the time by a factor of 10.2. Eight canisters were emplaced in an array 10 m below the floor of a drift. Spacing between canisters in this array (See Figure 2) was 3 m by 7 m, representing 10 m and 22 m in a full scale array. The power to these heaters was scaled linearly with canister size. At the start of the experiment, the power output of each of these heaters was 1.125 kW, representing 3.6 kW in the full scale. This was reduced during this experiment to represent the decay of reprocessed PWR high-level waste over this time period.

Instrumentation and Data Acquisition

Temperatures and thermally induced displacements and stresses in the rock surrounding the heaters were monitored by numerous thermocouples, multiple-anchor rod extensometers, U.S. Bureau of Mines borehole deformation gauges and IRAD (Creare) vibrating wire "stress-meters" (Binnall and coworkers, 1979). Detailed layout of the instrument boreholes can be found in Kurfurst and coworkers (1978). Data acquisition and display were accomplished using an on-site computer (McEvoy, 1979).

In a nuclear waste repository, as a result of the decay of thermal power from the waste canisters, the rock surrounding the repository will undergo a thermal pulse (St. John, 1978). The behavior of the rock during both the heating and cooling phase will govern the induced stress field, and the rates of groundwater flow through the rock mass. Therefore, temperatures, displacements and stresses were also monitored during the cooling period of the experiments, i.e., after the heaters had been turned off.

PRELIMINARY CALCULATIONS

Prior to conducting the heater experiments, preliminary calculations were made to estimate the expected temperature, displacement, and stress fields in the rock. At the time of these calculations, the thermal and thermomechanical properties of Stripa granite had been determined by laboratory testing using only a very limited number of small intact rock specimens (Pratt and coworkers, 1977). The preliminary models were, therefore, linear thermoelastic calculations in which the rock mass was assumed to be a homogeneous, isotropic and perfectly elastic continuum with temperature-independent material properties.

The thermal field was obtained using a closed form integral solution of the linear heat conduction equation for a finite-length line source (Chan and coworkers, 1978). The thermal field due to arrays of heaters was obtained by superposition. The resulting temperature distribution was then applied as thermal loads to calculate thermoelastic displacements and stresses using a modified version of the finite elements code SAPIV (Bathe and coworkers, 1974). The constant rock properties used in these calculations were: thermal conductivity, $k = 3.2$ W/m°C., thermal diffusivity, $\kappa = 1.47 \times 10^{-6}$ m^2/s, coefficient of linear thermal expansion, $\alpha = 11.1 \times 10^{-6}$/°C, Young's modulus, $E = 51.3$ GPa, and Poisson's ratio, $\nu = 0.23$. Details of the thermoelastic calculations are given by Chan and Cook (1980).

The thermal models were three-dimensional for all heater experiments. For the full scale experiments, the rock medium was either assumed infinite or semi-infinite with the floor of the heater drift idealized as an isothermal plane boundary. For the time-scaled experiment, the heater array was sufficiently far below the heater drift (10 m) that an infinite medium was a satisfactory approximation for the duration of the experiment.

Axisymmetric geometry was assumed in the thermoelastic model for the full-scale experiments with an approximation made to take account of the presence of the drifts, while for the time-scaled experiment a three dimensional model was used.

COMPARISON OF FIELD DATA WITH PRELIMINARY CALCULATIONS

Hood (1979) has compared the preliminary calculations by Chan and coworkers (1978) and Chan and Cook (1980) with field data from Stripa. Temperatures measured in both full-scale and time-scaled experiments are in general agreement with the calculations. An example is given in Figure 2 where the calculated isotherms are shown together with readings of thermocouples in the midplane of the time-scaled heater array. These results imply that linear heat conduction is the predominant heat transfer mechanism. The presence of discontinuities does not seem to affect the gross feature of the thermal field. Furthermore, the *in situ* thermal properties were found by least-squares inversion of the field data (Jeffry and coworkers, 1979) to be quite close to (approximately 10% higher than) small-specimen laboratory values. It was noticed, however, that temperatures measured above the midplane of the time-scaled heater array were slightly higher than those at the same distance below the midplane. This vertical asymmetry was subsequently found to be also present in the 3.6 kW full-scale experiment. Further analysis of temperature data for this full-scale experiment will be discussed below.

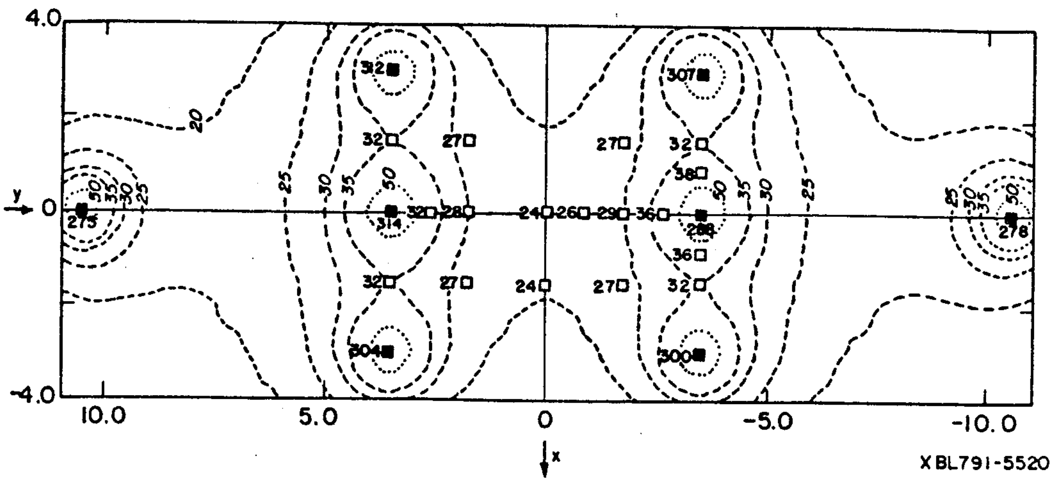

Fig. 2. Horizontal section through midplane of time-scaled heater array, showing predicted isotherms together with actual temperatures recorded by thermocouples (open squares) at 190 days. Heater locations are indicated by solid squares.

Measured displacements and stresses are less than those predicted by a factor of more than two. Displacement readings by the extensometers exhibit two distinct modes of behavior. First, an initial phase is observed immediately after turn-on of the heaters when displacements are very much less than the calculated values. This is followed by a second phase when the measured displacements are less than the predicted values by a constant amount. For many of the instruments, the ratio of the measured to the predicted displacements during this second phase is about 0.4.

The initial, non-linear phase may be caused by absorption of the early expansions of the rock into pre-existing discontinuities within the rock mass. This hypothesis is supported by evidence from an independent experiment where an increase in the velocity of ultrasonic waves through the rock in the vicinity of the heater was observed (Paulsson and King, 1980). The second phase indicates that the rock is responding to the loading in a predictable manner but with a magnitude significantly less than was predicted. Behavior of this kind is consistent with a difference in values for the rock properties for an in situ rock mass and for those in the calculations.

FURTHER CALCULATIONS AND DATA ANALYSES

Temperatures

In an attempt to identify the cause of the asymmetry of the vertical temperature profile, nonlinear numerical thermal analysis was undertaken for the full-scale heater experiments using the finite element code DOT (Polivka and Wilson, 1976). In this finite element model (Chan and Javandel, 1980), the nonuniform initial temperatures measured in the rock, the convective boundary conditions at the surfaces of the heater hole and the heater and extensometer drifts, and the variation of thermal conductivity of Stripa granite with temperature all were taken into account. In addition, when the position of the 3.6 kW heater was re-measured, it was found to have been installed inadvertently 100 mm higher than intended. This correct position was incorporated in the numerical model. Figure 3 illustrates the close agreement between the calculated (lines) and measured (points) temperatures for thermocouples in two boreholes at radial distances 0.4 m and 0.9 m from the 3.6 kW heater. The vertical asymmetry in temperature distribution thus can be explained as primarily a consequence of the operating conditions.

Displacements and Stresses

Sensitivity analysis for temperature-independent rock properties

Because of uncertainties in the material properties of a rock mass, it is of interest to study the sensitivity of the displacements and stresses to changes in rock properties. For a rock medium where the material properties remain independent of temperature, this can be achieved without repeating the numerical calculations using different sets of properties. It can be shown from the theory of linear thermoelasticity that displacements vary proportionally with the thermal expansion coefficient α, vary only slightly with Poisson's ratio ν, and are independent of the value of Young's modulus, E. Stresses are directly proportional to the

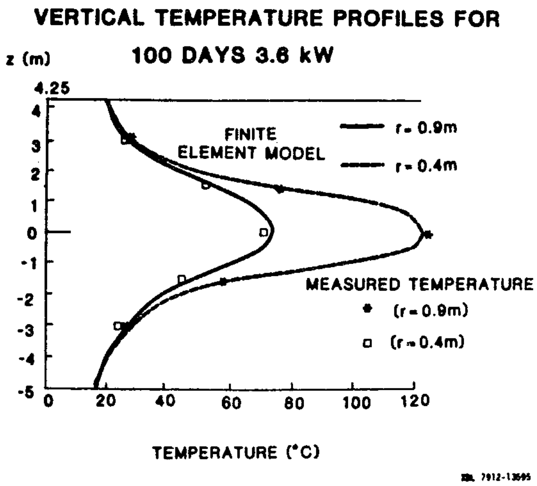

Fig. 3. Predicted and measured vertical temperature profiles in granite at two radial distances from the 3.6 kW full-scale heater at 100 days.

product αE and depend very little on ν. Numerical examples from finite element calculations are given by Chan, Hood and Board (1980) to verify these relations.

Calculations using temperature dependent rock properties

A limited number of laboratory tests of intact small samples of Stripa granite were conducted in parallel with the *in situ* heater experiments. These tests were carried out (by Swan, 1978, for E and ν and by Terratek, Inc. for k and α) to determine the properties of this rock as functions of temperature, and in some cases, confining stress. The results of these tests have been summarized by Chan, Hood and Board (1980).

Since the thermomechanical properties all exhibit significant variations with temperature, finite element calculations were carried out to investigate the influence of these temperature dependent properties on predicted displacements and stresses. The thermal models utilized the nonlinear code DOT referred to above and the thermomechanical model utilized the SAPIV code.

It was found that the weak temperature dependence of thermal conductivity of Stripa granite has only minor effects on the vertical displacements. The temperature dependence of Young's modulus affects the displacements more than the temperature dependence of Poisson's ratio. This is in contrast with the situation for constant rock properties where the magnitude of E does not affect the thermal displacements at all. Finally, the very strong temperature dependence of the thermal expansion coefficient, α, of Stripa granite is reflected in its remarkable effect on the displacements. In Figure 4 the measured vertical rock displacement (negative sign indicates expansion) between two anchor points 2.24 m above and below the heater midplane for a vertical extensometer at a radial distance of 1 m from the 3.6 kW heater is compared with calculated displacement obtained using both constant and temperature dependent rock properties. Evidently, taking into account the temperature dependence of rock properties significantly improves the agreement betwen calculated and measured displacements during both the heating and cooling periods of this experiment. Notice, however, that the displacements calculated with temperature dependent material properties are somewhat smaller in magnitude than the measured displacements.

A similar plot is shown in Figure 5 for relative horizontal rock displacements between two anchor points at 1 m radial distance on opposite sides of the 3.6 kW heater and about 0.6 m below the bottom of the heater. Although the use of temperature dependent rock properties again significantly reduces the magnitude of the calculated displacements, the results are still much higher than the measured values , in contrast to the situation for the vertical displacements. One reason may be that the axisymmetric model used is stiffer in the vertical direction and more flexible in the horizontal direction than the real rock structure. Another possibility is that the measured horizontal displacements are unreliable because of their small values (generally less than 0.2 mm), These values are only slightly larger than the estimated accuracy of the extensometers (laboratory tests have shown that frictional error of up to 0.1 mm can be introduced in these instruments. These tests also indicate that this problem may be greater in the horizontal than in the vertical extensometers).

Comparison of modeled and measured displacements for the 5 kW heater experiment (Chan, Littlestone and Wan, 1980) also reveals trends similar to those noted above, although the predicted horizontal displacements for the 5 kW heater experiment agree better with measured values than that illustrated in Figure 5. This may be due in part to the larger values of displacements in this experiment with the greater heater power.

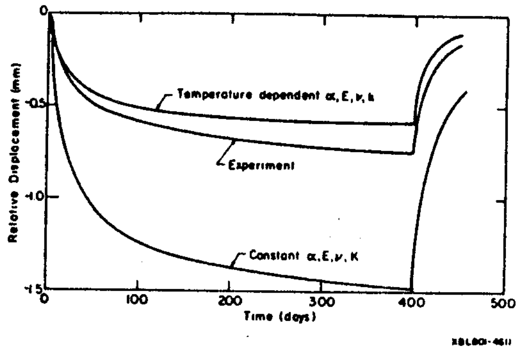

Fig. 4. Predicted and measured relative vertical rock displacements between two anchor points 2.24 cm above and below the heater midplane for a vertical extensometer at a radial distance of 1 m from the 3.6 kW heater. Displacements calculated using both constant and temperature dependent properties are shown.

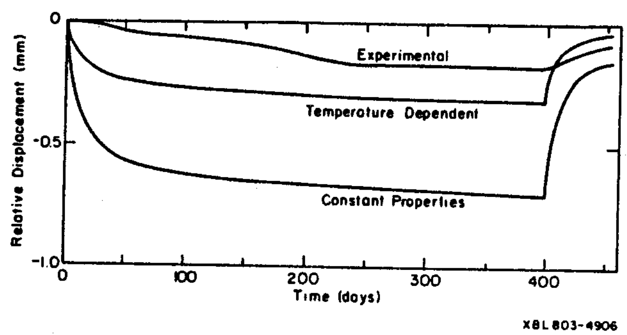

Fig. 5. Predicted and measured relative horizontal rock displacements between two anchor points at 1 m radial distance on opposite sides of the 3.6 kW heater for a horizontal extensometer 0.6 m below the bottom of the heater. Displacements calculated using both constant and temperature dependent properties are shown.

Interpretation of the measurements for changes in rock stress still is in progress. In the field better experience has been achieved with the vibrating-wire Creare gauges than with the Bureau of Mines borehole deformation gauges. For this reason analysis of results from the former is more advanced. Figure 6 illustrates the influence of temperature dependent properties on the calculations for radial stress at a point in the rock at radial distance 1.5 m from the 5 kW heater and 0.85 m above the midplane. From Figure 6A it is seen that, although using temperature dependent rock properties reduces the discrepancy between measured and calculated stresses, the improvement is not as impressive as that for displacements. As a sensitivity analysis, the calculations using temperature dependent rock properties were repeated with a scaled down Young's modulus.

$$E(T) = \frac{37}{69} E_{lab}(T)$$

The rationale for this choice of scaling factor is that a suite of measurements were made of the _in situ_ rock modulus, at the Stripa heater test site using the Colorado School of Mines cell (Hustrulid and Schrauf, 1979). Results of these measurements, which contained considerable scatter, showed a mean value for the modulus of 37 GPa compared to the laboratory value of 69 GPa at 10°C (Swan, 1978). As expected, the calculated radial stress is scaled down by the same ratio, Figure 6B and the predicted stress is now lower than the measured stress. The value of Young's modulus for Stripa granite, determined by various investigators, varies over a wide range (see Chan, Littlestone and Wan, 1980). Obviously, from Figure 6 this factor is of crucial importance in determining the predicted values of the thermally induced stresses.

The main geological features at the Stripa site where the heater experiments are being conducted have been carefully mapped, (Thorpe, 1979; Witherspoon and coworkers, 1979). Whether these have a significant influence on the rock displacements and stresses remains to be determined by further data analysis. For example, if as described earlier, the initial rock expansions are absorbed into pre-existing discontinuities in the rock then both the measured displacements and the measured stresses would be expected to be less than those predicted. On the other hand, if the rock expansions have resulted in slippage along some discontinuities, then the measured displacements would be expected to be greater, and the measured stresses lower than the values calculated using a linear thermoelastic model. If further data analysis indicates that this is indeed what happened in the Stripa heater experiments, the major discontinuities can be modeled as discrete elements of weakness (Goodman, 1976) while the numerous minor discontinuities can perhaps be represented by an equivalent medium (Glynn and coworkers, 1978, Walsh and Grosenbaugh, 1979).

Decrepitation

Serious decrepitation of the wall-rock has been observed in the 5 kW heater borehole shortly after the peripheral heaters were turned on (Hood and coworkers 1980). According to linear thermoelastic calculations using constant rock properties (Chan and Cook, 1980), the highest compressive stress, i.e., the tangential stress at the heater hole would have reached a value of 215 MPa before the peripheral heaters were turned on. This calculated tangential stress increases very rapidly after the turn on of the peripheral heaters. Comparing this stress with the uniaxial compressive strength 208 MPa, of Stripa granite as determined by Swan (1978) at 20°C, Hood and coworkers (1980) suggested that the onset of gross borehole failure may occur when the tangential stress exceeds the compressive strength. Further calculations using temperature dependent properties (Chan, Littlestone and Wan, 1980) have shown that the stress at the wall of borehole is very sensitive to the temperature dependence of the rock properties. Since the strength of Stripa granite (Swan, 1978) was also somewhat temperature dependent and has been measured only to 190°C where it has decreased to a value of 148 MPa, while gross borehole failure occurred at a temperature estimated to be over 300°C, further work is needed to elucidate the mechanism of this thermomechanical failure.

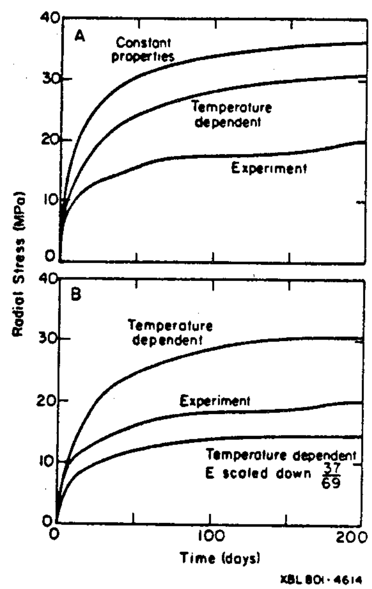

Fig. 6. Predicted and measured (using Creare gauge) radial stress at radial distance 1.5 m from the 5 kW heater and 0.85 m above the midplane, illustrating the influence on calculated stress of the temperature dependency of rock properties (A) and of scaling down the Young's modulus to approximate more closely the <u>in situ</u> rock modulus (B).

CONCLUSIONS

The results demonstrate that the dominant mode of heat transfer through the granite rock mass at Stripa is conduction in spite of the presence of discontinuities. The measured displacements within the rock mass, caused by thermal expansion of the rock, are much less than predicted by the original models which assumed temperature independent material properties. Although at the present time only a limited amount of data from laboratory tests exists to describe these properties as functions of temperature and confining pressure, it is shown that the temperature dependence of the coefficient of expansion has the greatest influence in predicting values for displacements. The temperature dependence of the Young's modulus also affects these predictions significantly whereas the temperature dependence of both the Poisson's ratio, and the thermal conductivity, only have a small influence. Predictions for thermally induced stresses are not affected as significantly by the temperature dependence of these properties, but it is shown that these stresses, as expected from thermoelastic theory, are directly proportional to the value for the in-situ Young's modulus. Unfortunately this modulus is difficult to determine and wide scatter has been obtained in many of the measurements that have been made. Additional work is needed to determine the failure mechanisms for decrepitation along the walls of the heater boreholes.

REFERENCES

Bathe, K. J., E. L. Wilson and F. E. Peterson. (1973, 1974). SAP IV, A structural analysis program for static and dynamic response of linear systems. Report EERC 73-11, College of Engineering, University of California, Berkeley.

E. Binnall, A. DuBois, R. Lingle (1979). Rock instrumentation problems experienced during in-situ heater tests. Paper presented at International Symposium on the Scientific Bases for Nuclear Waste Management, Materials Research Society, Boston, Ma., November 26-30.

Chan, T., N. G. W. Cook and C-F. Tsang (1978). Theoretical temperature fields for the Stripa heater project. Report No. LBL 7082, SAC-09, Lawrence Berkeley Laboratory, Berkeley, Ca.

Chan, T. and N. G. W. Cook (1980). Calculation of thermally induced displacements and stresses for experiments at Stripa. Report No. LBL 7061, SAC-22, Lawrence Berkeley Laboratory, Berkeley, Ca.

Chan, T., N. Littlestone and O. Wan (1980). Thermomechanical modeling and data analysis for heating experiments at Stripa, Sweden. Proc. 21st U. S. Rock Mech. Symposium, Rolla, Mo., May.

Chan, T. and I. Javandel (1980). Heat transfer in granite as inferred from temperature analysis for heater experiments at Stripa, Sweden, to be presented at ASME Winter Conference, Chicago, Illinois, November. See also Javandel, I. and T. Chan (1979). EOS (Trans. Amer. Geophys. Union), Tectonophysics Abstract T96, 60, No. 46, November 13.

Chan, T., M. Hood and M. Board (1980). Rock properties and their effect on thermally-induced displacements and stresses. Presented at ASME 1980 Energy Technology Conference and Exhibition, New Orleans, February, submitted to ASME Journal of Energy Resources Technology.

Cook, N. G. W. and P. A. Witherspoon (1978). Part II: In-Situ heating experiments in hard rock: Their objectives and design. Report No. LBL 7073, SAC 10, Lawrence Berkeley Laboratory.

Draft Environmental Impact Statement (1979). Management of commercially generated radioactive waste. U. S. Department of Energy, April. DOE/EIS-0046-D.

Glynn, E. F., D. Veneziano, H. H. Einstein (1978). The probabilistic model for shearing resistance of jointed rock. Proceedings of the 18th U. S. Symposium on Rock Mechanics, Reno, Nev.

Goodman, R. E. (1976). Methods in Geological Engineering in Discontinuous Rocks, West Publishing Co., St. Paul, Minn.

Batch, J. M. and C. A. Heath (1979). U. S. program for the disposal of radioactive waste. Proceedings International Symposium on the Underground Disposal of radioactive Wastes, Otaniemi, Finland, July 2-6.

E. Hoek (1979). The role of modeling in the design of nuclear waste repositories - The design engineer's viewpoint. Proceedings of workshop on thermomechanical mdoeling for a hardrock waste repository, UCAR-10043, Berkeley, Ca., pp. 33-43, July 25-27.

Hood, M. (1979). Some results from a field investigation of thermo-mechanical loading of a rock mass when heater canisters are emplaced in the rock, Proceedings 20th U. S. Symposium Rock Mechanics, Austin, Texas, pp. 429-435, June.

Hood, M., H. Carlsson, and P. H. Nelson (1980). The application of field data from heater experiments conducted at Stripa, Sweden to parameters for repository design. Report No. LBL-9392, Part 2, Lawrence Berkeley Laboratory, Berkeley, Ca., March.

Hustrulid, W. A. and T. Schrauf (1979). Borehole modulus measurements with the CSM cell in Swedish granite. Proc. 20th U. S. Symp. Rock Mech., Austin, pp. 509-515, June.

Jeffry, J. A., T. Chan, N. G. W. Cook and P. A. Witherspoon (1979). Determination of in-situ thermal properties of Stripa Granite from temperature measurements in the full-scale heater experiments - Methods and preliminary results. LBL-8423, SAC-24, Lawrence Berkeley Laboratory, Berkeley, Ca.

Kurfurst, P. J., T. Hugo-Persson and G. Rudolph (1978). Borehole drilling and related activities at the Stripa Mine. Report No. LBL-7080, SAC-05, Lawrence Berkeley Laboratory, Berkeley, Ca.

McEvoy, M. B. (1979). Data acquisition, handling, and display for the heater experiments at Stripa. Report No.LBL-7062, SAC-14, Lawrence Berkeley Laboratory, Berkeley, Ca.

Paulsson, B. and M. King (1980). Monitoring and investigation of a rock mass with a cross-hole seismic technique. Rockstore - Special Session on Nuclear Waste Disposal, this conference.

Polivka, R. M. and E. L. Wilson (1976). Finite element analysis of nonlinear heat transfer problems. Report No. UC SESM 76-2, Department of Civil Engineering, University of California Berkeley, Ca.

Pratt, H. R., T. A. Schrauf, L. A. Bills and W. A. Hustrulid (1977). Thermal and mechanical properties of granite, Stripa, Sweden. Terra Tek Report TR-77-92, Salt Lake City, Utah.

St. John, C. N. (1978). Computer models and the design of underground radioactive waste repositories. prepared for special Summer Session Current Developments in Rock Engineering, Massachusetts Institute of Technology, June 26-30.

Swan, G. (1978). The mechanical properties of Stripa granite. LBL-7074, SAC-03, Lawrence Berkeley Laboratory, Berkeley, Ca.

Thorpe, R. (1979). Characterization of discontinuities in the Stripa granite - Time-scaled experiment, LBL-7083, SAC-20, Lawrence Berkeley Laboratory, Berkeley, Ca.

Walsh, J. B. and M. A. Grosenbaugh (1979). A new model for analyzing the effects of fractures on compressibility. Journal Geophysical Research, 84, pp. 3532-3536.

Witherspoon, P. A. and O. Degerman (1978). Swedish-American Cooperative Program on radioactive waste storage in mined caverns. Report No. LBL-7049, SAC-01, Lawrence Berkeley Laboratory, Berkeley, Ca.

Witherspoon, P. A., P. Nelson, T. Doe, R. Thorpe, B. Paulsson, J. E Gale, C. Forster (1979). Rock mass chacterization for storage of nuclear waste in granite. Report No. LBL-8570, SAC-18, Lawrence Berkeley Laboratory, Berkeley, Ca.

Witherspoon, P.A., N. G. W. Cook and J. E. Gale (1980). Geologic storage of radioactive waste--Results from field investigations at Stripa, Sweden. Proceedings State of Waste Disposal Tech., Mill Tailings, and Risk Analysis Models, University of Arizona, March 10-14, Tuscon.