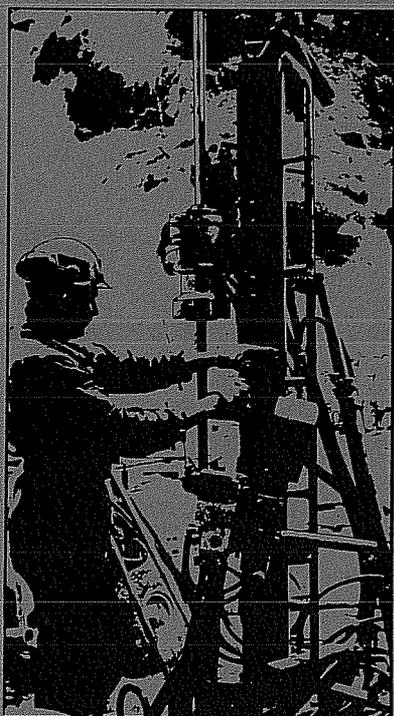


SWEDISH-AMERICAN COOPERATIVE PROGRAM ON RADIOACTIVE WASTE STORAGE IN MINED CAVERNS IN CRYSTALLINE ROCK



Technical Project Report No. 11

FULL-SCALE AND TIME-SCALE HEATING EXPERIMENTS AT STRIPA: PRELIMINARY RESULTS

Neville G. W. Cook and Michael Hood

December 1978

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December, 1978

PREFACE

This report is one of a series documenting the results of the Swedish-American cooperative research program in which the cooperating scientists explore the geological, geophysical, hydrological, geochemical, and structural effects anticipated from the use of a large crystalline rock mass as a geologic repository for nuclear waste. This program has been sponsored by the Swedish Nuclear Power Utilities through the Swedish Nuclear Fuel Supply Company (SKBF), and the U. S. Department of Energy (DOE) through the Lawrence Berkeley Laboratory (LBL).

The principal investigators are L. B. Nilsson and O. Degerman for SKBF, and N. G. W. Cook, P. A. Witherspoon, and J. E. Gale for LBL. Other participants will appear as authors of the individual reports.

Previously published technical reports are listed below.

1. *Swedish-American Cooperative Program on Radioactive Waste Storage in Mined Caverns* by P. A. Witherspoon and O. Degerman. (LBL-7049, SAC-01).
2. *Large Scale Permeability Test of the Granite in the Stripa Mine and Thermal Conductivity Test* by Lars Lundström and Håken Stille. (LBL-7052, SAC-02).
3. *The Mechanical Properties of the Stripa Granite* by Graham Swan. (LBL-7074, SAC-03).
4. *Stress Measurements in the Stripa Granite* by Hans Carlsson. (LBL-7078, SAC-04).
5. *Borehole Drilling and Related Activities at the Stripa Mine* by P. J. Kurfurst, T. Hugo-Persson, and G. Rudolph. (LBL-7080, SAC-05).
6. *A Pilot Heater Test in the Stripa Granite* by Hans Carlsson. (LBL-7078, SAC-06).
7. *An Analysis of Measured Values for the State of Stress in the Earth's Crust* by Dennis B. Jamison and Neville G. W. Cook. (LBL-7071, SAC-07).
8. *Mining Methods Used in the Underground Tunnels and Test Rooms at Stripa* by B. Andersson and P. A. Halén. (LBL-7081, SAC-08).
9. *Theoretical Temperature Fields for the Stripa Heater Project* by T. Chan, Neville G. W. Cook, C. F. Tsang. (LBL-7082, SAC-09).
10. *Mechanical and Thermal Design Considerations for Radioactive Waste Repositories in Hard Rock. Part I: An Appraisal of Hard Rock for Potential Underground Repositories of Radioactive Wastes* by Neville G. W. Cook; *Part II: In Situ Heating Experiments in Hard Rock: Their Objectives and Design* by Neville G. W. Cook and P. A. Witherspoon. (LBL-7073, SAC-10).

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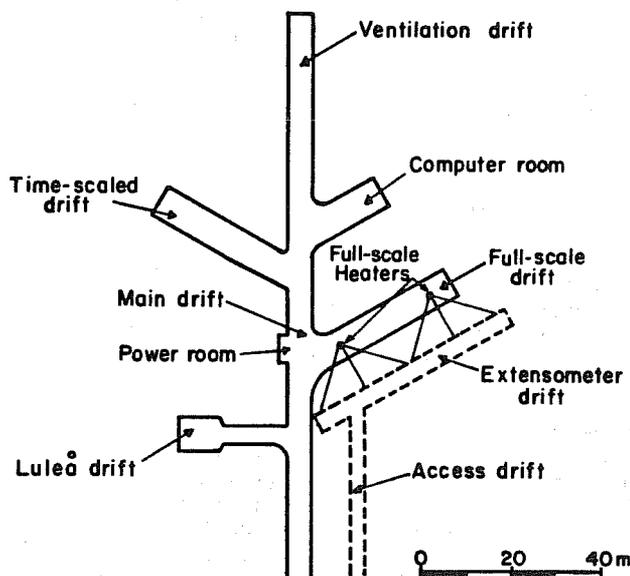
SYNOPSIS

Two full-scale heating experiments and a time-scale heating experiment have recently been started in granite 340 meters below surface. The purpose of the full-scale heating experiments is to assess the near-field effects of thermal loading for the design of an underground repository of nuclear wastes. That of the time-scale heating experiments is to obtain field data of the interaction between heaters and its effect on the rock mass during a period of about two years, which corresponds to about twenty years of full-scale operation. Geological features of the rock around each experiment have been mapped carefully, and temperatures, stresses and displacements induced in the rock by heating have been calculated in advance of the experiments. Some 800 different measurements are recorded at frequent intervals by a computer system situated underground. These data can be compared at any time with predictions made earlier on video display units underground.

** This paper was presented at the OECD Seminar on In Situ Heating Experiments in Geologic Formations, Stripa, Sweden, September 12-15, 1978.*

I. INTRODUCTION

Pursuant to the objectives of *in situ* heater experiments in hard rock as described by Cook and Witherspoon [1], a time-scale and two full-scale heater tests have been designed and installed at a depth of about 340 m below surface in drifts excavated in granitic rock adjacent to an abandoned mine at Stripa, Sweden [2]. The layout of the experimental drifts and associated excavations is as illustrated in Figure 1. Details of this experimental layout were agreed upon in July, 1977; the time-scale experiment was switched on on June 1, 1978, and the full-scale experiments on July 3, 1978, and August 24, 1978. Due largely to the decision to use a digital computer underground to record and present the data on a continuous basis, some preliminary results from the time-scale test and the first full-scale test are already available for study and comparison with theoretical predictions.



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Fig. 1. A plan of the test site underground 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.

II. EXPERIMENTAL LAYOUT

The two full-scale tests comprise electrical heaters with a maximum power output of 20 kW, in simulated high level radioactive waste canisters measuring 0.3 m in diameter and having a heated length of 2.5 m. These heaters have been installed in vertical boreholes 0.4 m in diameter by 5.5 m deep drilled into the floor of the full-scale test drift, and separated by a distance of 22 m.

The first of the full-scale heaters, nearest the entrance of this drift, is operating at a power output of 5 kW, corresponding to that from a canister of reprocessed high-level waste only 3 1/2 years after removal of the fuel from a nuclear reactor [3]. This is considered to be the highest power output of any canister that may be buried. To simulate the effects of interaction between proximate canisters in an underground repository, which would result in a temperature of the rock mass undergoing a thermal pulse as described by Cook and Witherspoon [1], this full-scale heater is surrounded by 8 peripheral heaters on a radius of 0.9 m, each with a length of 4.3 m and a power output of about 1.1 kW. At an appropriate stage in this experiment, these peripheral heaters will be switched on to increase the temperature of the rock around the main heater by about 100°C, so as to measure the response of the rock to the temperature gradient

necessary to enable heat to flow away from the main heater but at a greater absolute temperature.

The second full-scale heater, at the end of this drift, is operating at a power level of 3.6 kW, corresponding to the thermal output of a canister of re-processed high-level waste 5 years after removal of the fuel from a nuclear reactor, [3].

These two full-scale experiments have been designed to assess the near-field thermo-mechanical response of the rock close to these heater canisters to heating in the short-term, and under simulated conditions of rock temperature in the long-term. To facilitate the study of the interaction between adjacent heaters and to measure the response of a larger volume of rock in situ then can be done in these full-scale experiments, a time-scale experiment is also being conducted in a separate drift. Using the quadratic relationship which exists between length and time in solutions to the linear conduction of heat, the linear scale of the time-scale heaters has been reduced to 0.31 of their full-scale counterparts, so that time is accelerated by a factor of 10.2. To maintain similitude of the temperatures, the power output has been reduced by the same amount as the linear scale. The time-scale experiment comprises 8 heaters 0.8 m in length placed in vertical boreholes on centers of 7 m x 3 m drilled to a depth of about 11 m below the floor of the drift (see Figure 3). Initially, the power output of each heater was 1.1 kW corresponding to the 3.6 kW, simulating the reduction in heat output by radioactive decay over a period of 20 years from canisters of high level waste.

To assess the in situ response of the rock to these experiments, three different sets of measurements, each principally dependent upon a different physical property of the rock, are being made as a function of time, namely, measurements of temperature fields, measurements of displacements and measurements of stress.

The instrumentation used for these experiments is summarized in Table I. Details of the instruments are given by Pratt et al., [4], and the exact location of each instrument hole for the different experiments is described by Kurfurst et al. [5]. Similar measurements are made along different, sometimes orthogonal, directions in an endeavor to detect anisotropy in the rock mass. To enable measurements of radial displacement to be made around the full-scale heaters, an extensometer drift has been excavated to the side of, and below the full-scale drift. From this extensometer drift, 3 sets of radial extensometers each at 3 different elevations have been installed in directions perpendicular and at $\pm \pi/4$ to the axis of the drift (see Figure 1). In the time-scale experiment only vertical extensometers have been installed, as this experiment is intended to be virtually unaffected by the proximity of the excavations.

III. THEORETICAL PREDICTIONS

Where heat flow is entirely (or principally) by conduction the development of the temperature field depends upon the diffusivity of the rock and the power and geometry of the heat source.

In a linearly thermo-elastic material, thermally-induced displacements are a function of this temperature field, the boundary conditions and a factor, D, given by

$$D = \frac{1 + \nu}{1 - \nu} \alpha ,$$

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

Similarly, the thermally-induced stresses are a function of the temperature field, the boundary conditions and a thermo-mechanical factor, S, given by

$$S = \frac{\alpha E}{1 - \nu} ,$$

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

TABLE I

INSTRUMENT LAYOUT ADJACENT TO EACH OF THE EXPERIMENTS

a. Instruments Installed Vertically from the Floor of the Full-scale Drift

Instrument type	Number Used	Comments
Temperature measurements: Thermocouples	30	Thermocouples are installed in 6 holes at radii from the heater center varying from 0.4 m to 0.9 m.
Displacement measurements: Extensometers	6	Each extensometer has 4 anchor points varying from 7.5 m below the heater mid-plane to 2.25 m above this plane
Stress measurements: USBM Gauges Irad Gauges	10 2	All of the extensometers, USBM gauges and Irad gauges have thermocouples associated with them which are in addition to the 30 listed above.

b. Instruments Installed Horizontally from the Extensometer Drift

Displacement measurements: Extensometers	9	All of these gauges have thermocouples associated with them.
Stress measurements: USBM Gauges	4	
Irad Gauges	3	

c. Instruments Installed Vertically from the Floor of the Time-scale Drift

Temperature measurements: Thermocouples	60	Installed in an array of the holes.
Displacement measurements: Extensometers	5	All extensometers are vertical with 4 anchor points varying from 3 m below to 7 m above the heater mid-plane.

In principle, suites of such measurements should enable several important properties of the rock mass to be inferred. First, the temperature fields should provide information on the coefficients of thermal diffusivity (from short term data) and conductivity (from long term data) to be derived, and thermal anisotropy and departures from conductive heat flow to be detected. Second, measurements of thermally-induced displacements should provide information on the coefficient of thermal expansion of the rock mass to be derived, making reasonable assumptions about values for Poisson's ratio. The effects of geologic discontinuities on thermally-induced displacements should be evident, especially as the orientation of these discontinuities has been measured and is anisotropic [6]. Finally, measurements of thermally-induced stresses should provide information on the *in situ* value of Young's modulus for the rock mass, although stress is inferred from displacements on a small scale rather than measured direct.

Predictions of the temperature fields, displacements and stresses as a function of time have been made for each experiment, using the linear theory of thermo-elasticity and laboratory values for the thermal and elastic coefficients

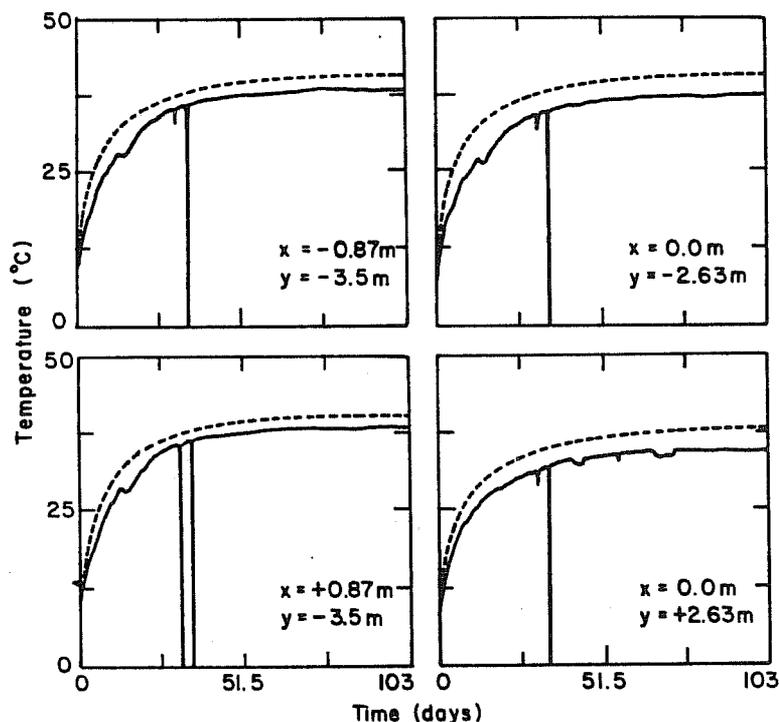
of the granite at Stripa, in advance of the actual experiments [7,8]. The laboratory values used are as follows:

Thermal conductivity	= 3.2 (W/m°C);
Specific heat	= 837 (J/kg°C);
Density	= 2600 kg/m ³ ;
Thermal diffusivity	= 1.47 x 10 ⁻⁶ (m ² /s);
Coefficient of linear thermal expansion	= 11,1 x 10 ⁻⁶ (/°C);
Poisson's ratio	= 0,23;
Young's modulus	= 51,3 (GPa).

IV. PRELIMINARY RESULTS

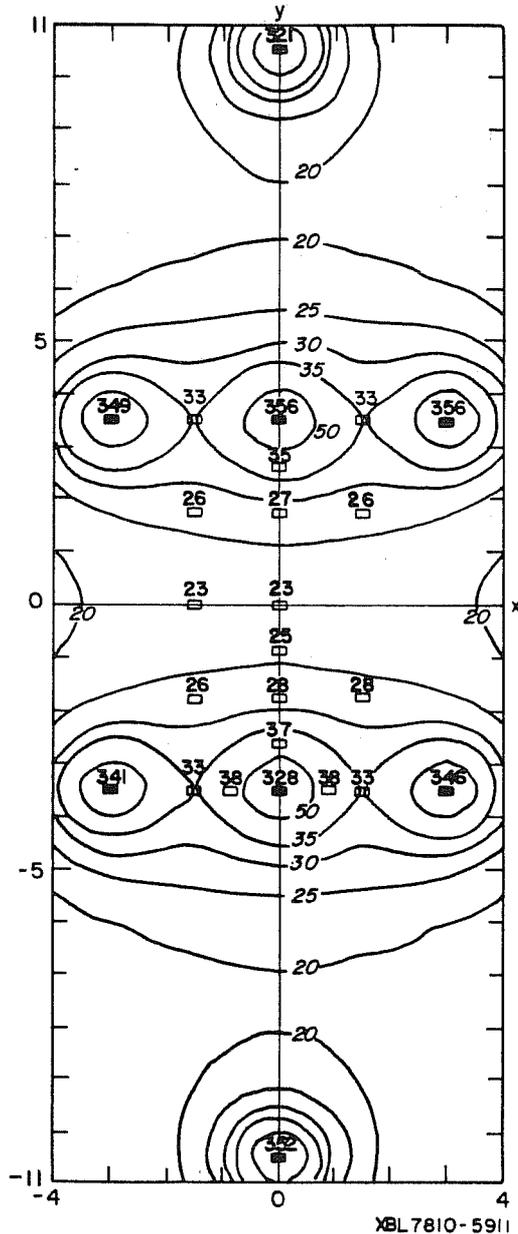
i) Temperature fields:

Predicted and measured temperatures in the mid-plane of the time-scale heaters at a radial distance of 0.87 m along different directions are shown in Figure 2, from the time the heaters were switched on to 103 days. Measured temperatures are slightly lower than those predicted. In part, this is a result of water in the heater holes which causes the heat to be dissipated over a greater length of hole than used in the calculations, by evaporation of water at the heater and condensation further up the hole. In Figures 3 and 4 are plotted predicted isotherms in a horizontal plane through the middle of the time-scale heaters and in a vertical plane across the short axis of the room containing three of these heaters, respectively, together with measured temperatures 90 days after heating had started. Again the comparison between measured and predicted values



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Fig. 2. Curves showing the predicted (dashed) and measured (solid) temperatures as a function of time at a radius of 0.87 m from the mid-points of the two innermost heaters on the y-axis, as shown in Figure 3 from which the hole locations can be found also. The near vertical excursions of the measured values reflect malfunctions in the data collection system.



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■ Heater holes; □ Thermocouple holes.

Fig. 3. Predicted isotherms and measured temperatures in a horizontal plane through the middle of the time-scale experiment 90 days after heating had started. (Scale for both x and y axes is given in meters.)

is close, although the effects of heat transfer up the hole by evaporation and condensation can be seen in the higher values of measured temperatures above the heaters.

In Figure 5 are plotted the predicted isotherms in a horizontal plane through the center of the 5 kW full scale heater at 65 days after it had been switched on, together with measured values of temperatures in this plane at various radii and in different directions at that time. In general, measured temperatures are slightly lower than predicted but there is no gross evidence of thermal anisotropy nor of heat transfer other than by conduction.

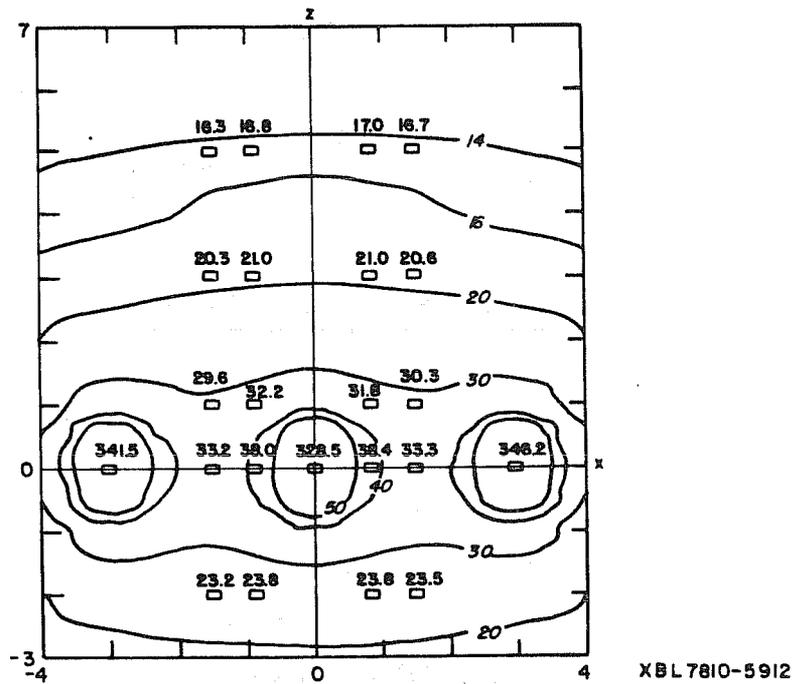


Fig. 4. Predicted isotherms and measured temperatures in a vertical plane ($y = -3.5$ m) containing three of the time-scale heaters, 90 days after heating had started. (Scale for both x and z axes is given in meters.)

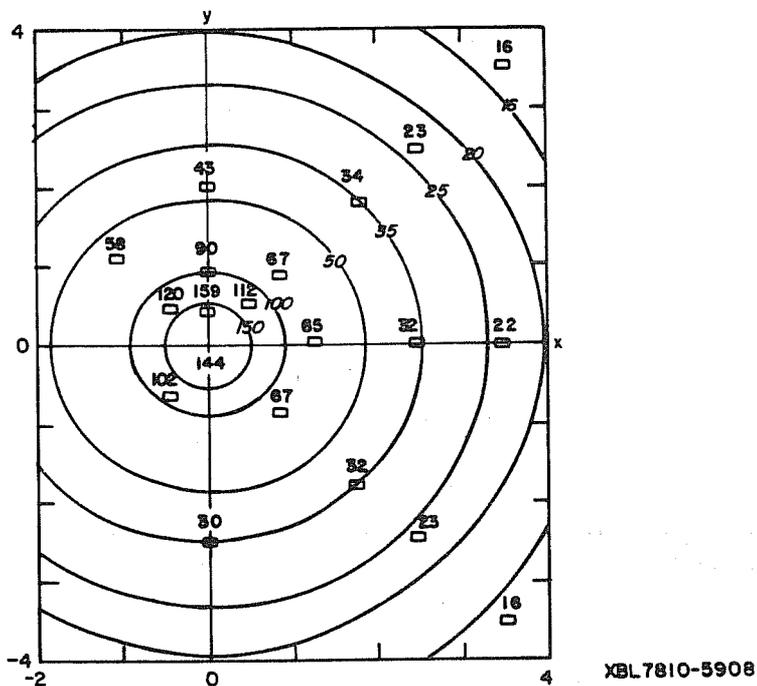
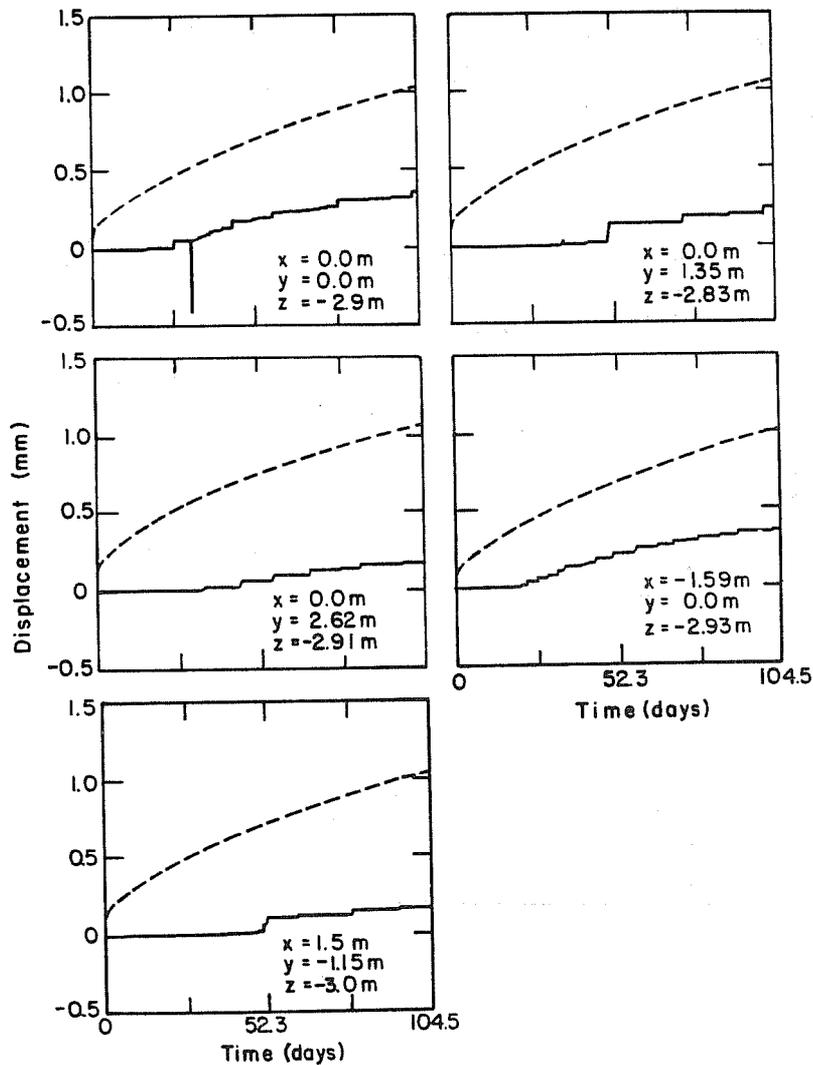


Fig. 5. Predicted isotherms and measured temperatures in a horizontal plane through the middle of the 5 kW full-scale heater, 65 days after heating had started. (Scale for both x and y axes is given in meters.)

ii) Displacements:

In Figure 6 are illustrated plots of rock movements between anchor points 3 m below the heater mid-plane and the hole collars in the time-scale drift. Important features of this Figure which should be noted include: the absence of initial measured displacements, the large disparities between the measured and the predicted values, and the discontinuous nature of these displacements. The differences between the measured and the predicted displacements may be the result of the effects of the floor of the drift. In order to minimize the influence of this boundary, checks have been made of the differential movements between anchor points located 3 m above and 3 m below the heater mid-plane. These checks have shown similar disparities between measured and predicted displacements and that the ratio between the measured and the predicted displacements varies between 1/4 and 1/2. This indicates two points: (i) it appears unlikely that the presence of the drift is affecting the results substantially, and (ii) the



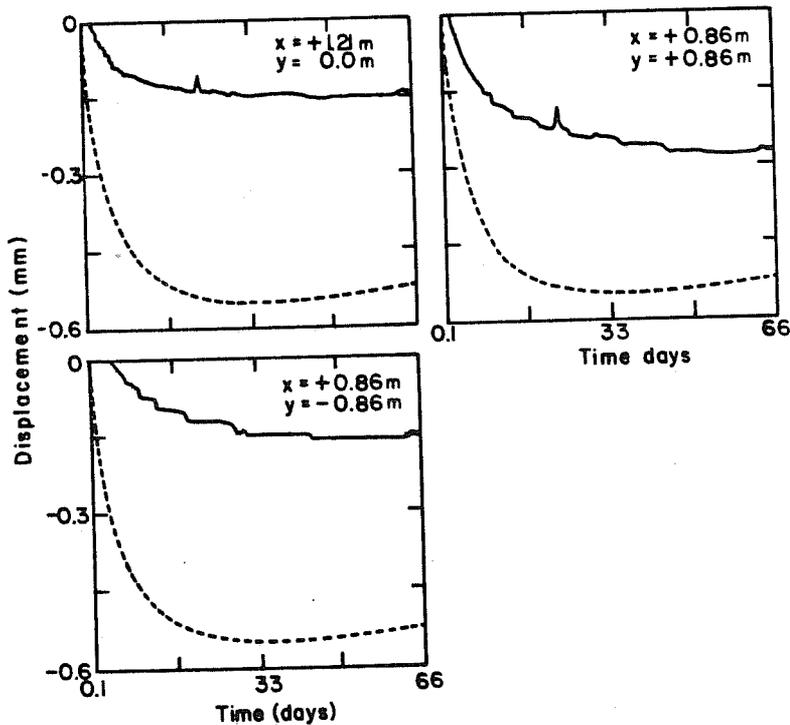
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Fig. 6. Predicted (dashed) and measured (solid) relative displacements between anchor points 3 m below the heater mid-plane and the hole collars in the floor of the time-scale drift, plotted as a function of time.

rock behavior is anisotropic. The discontinuous displacements often occur within a short time period at different anchor positions of the same extensometer and also at different extensometers, suggesting that the rock is behaving as a mass of coupled blocks.

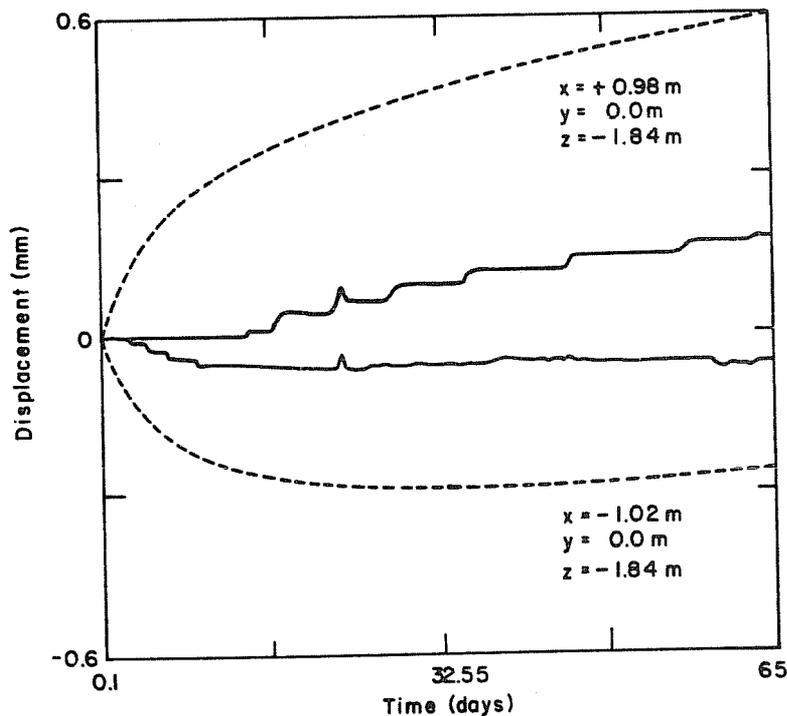
The maximum predicted and measured displacements around the 5kW full-scale heater are illustrated in Figure 7. Note again that the measured values are significantly less than the predicted values but that the shapes of the predicted and measured curves are remarkably similar. Note also that the measurements of rock movements indicate anisotropic behavior. Two sets of readings show displacements that are approximately the same, whilst the third set indicates rock movements about 80 per cent greater, (Figure 7).

In both full scale experiments one horizontal extensometer has anchor points on opposite sides of a diameter below the bottom of the heater. The relative displacement between these two anchor points is the least ambiguous of all the displacement measurements as they are least affected by the boundaries of the drifts. Predicted and measured values for these displacements for the 5 kW full-scale heater are illustrated in Figure 8. Note that they are not symmetrical about the axis of the heater because the displacements at each anchor point have been measured relative to the borehole collar in the extensometer drift. Again measured values of displacement are significantly less than predicted values.



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Fig. 7. Predicted (dashed) and measured (solid) horizontal displacements of the rock in the mid-plane of the 5 kW full-scale heater taken along different directions. These curves show relative displacements between anchor points at a radial distance of 1.2 m from the heater and the collar of the hole on the wall of the extensometer drift.



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Fig. 8. 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.

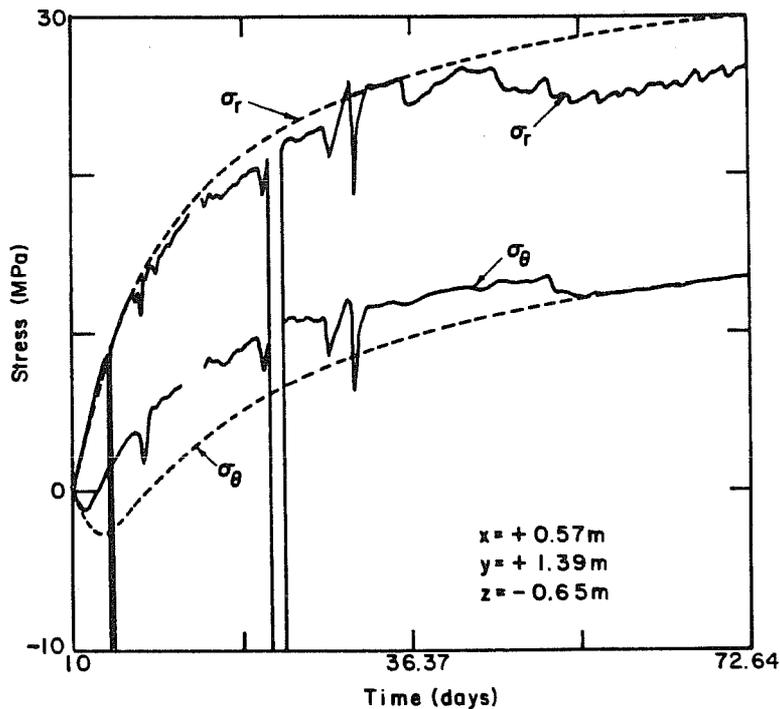
All these data suggest that the thermally-induced displacements in the rock mass are indeed less than those predicted by theory. This result may be expected because the rock mass is jointed and expansion may take place into joint spaces. If this were so, the values of the thermally-induced stresses should be less than the predicted values. Stress measurements are notoriously difficult to make but readings obtained from a number of instruments, such as that illustrated in Figure 9 suggest that the measured values of the thermally-induced stresses are similar to the predicted values!

V. DISCUSSION

These data are not yet adequate nor have they been studied in sufficient detail for other than tentative conclusions to be drawn.

Nevertheless, the temperature measurements suggest that heat flow in the rock mass is predominantly by conduction and that theoretical calculations using laboratory values of thermal coefficients can be used to predict rock temperatures reasonably well.

To date, displacement measurements have yielded puzzling results. Measured values of displacement are all from 1/2 to 1/4 of predicted values, even as both change with time. Predicted and measured values have been checked for any consistent error which would explain this disparity most readily; both appear to be accurate. It seems most unlikely that the values of Poisson's ratio and the coefficient of thermal expansion for the rock mass *in situ* could differ from those used in the calculations by an amount sufficient to account for the observed disparity. Thermal expansion of the rock mass into open joints would explain the disparity. Measurements of such displacements may be expected to differ from those predicted by theory in several ways. Initially they may be very small, as



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Fig. 9. Predicted (dashed) and measured (solid) radial, σ_r , and tangential, σ_θ , stresses in the vicinity of the 5 kW heater. Stress readings were computed from borehole displacements measured using a USBM borehole deformation gauge. Excursions of the measured curves reflect malfunctions of the data collection system.

the thermal expansion of the rock is taken up by spaces between joint surfaces. Thereafter, as stresses are generated across these surfaces, the displacements would become increasingly linear. The relative disparities between measured and predicted displacements may be expected to vary with the direction in which they are made because of the anisotropy of jointing. Displacements may tend to be discontinuous because of stick-slip caused by friction across joints [9]. Although evidence for each of these kinds of deviation of measured displacement from predicted displacement can be found, there are exceptions. If displacement into spaces between joints were as important as the disparity between predicted and measured values suggests, the compliance of the rock mass that is, the value of its Young's modulus would be much less than that of laboratory specimens. From this it would follow that the magnitudes of the thermally-induced stress would be correspondingly smaller. Although difficulties have been experienced in making stress measurements, many of them (c.f. Figure 9) indicate that this is not always the case.

VI. ACKNOWLEDGEMENT

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