Lawrence Berkeley National Laboratory
Lawrence Berkeley National Laboratory

Title
EXPERIMENTAL RESULTS FROM STRIPA

Permalink
https://escholarship.org/uc/item/8zr2m13h

Author
Hood, M.

Publication Date
1979-06-01

Peer reviewed

eScholarship.org Powered by the California Digital Library
University of California

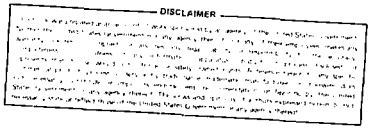
EXPERIMENTAL RESULTS FROM STRIPA

Michael Hood

Assistant Professor of Mining Engineering,
Department of Materials Science and Mineral Engineering,
University of California, Berkeley

June 25-27, 1979

Berkeley, California



DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

EXPERIMENTAL RESULTS FROM STRIPA

Michael Hood*

INTRODUCTION

The behavior of an in-situ granitic rock mass to thermomechanical loading currently is being studied in an experiment at Stripa, Sweden. Electrically heated canisters are used to simulate canisters containing high-level radioactive waste materials and these are emplaced in vertical boreholes drilled in the floor of horizontal drifts in the rock. These drifts are located at a depth of about 340 m below surface.

Four experiments are in progress. Two of these, the "so-called" full-scale experiments, employ canisters 0.3 m in diameter with a heated length of about 2.5 m. The power outputs of these canisters are 5 kW in the one case and 3.6 kW in the other case; these power levels are representative of high-level waste materials 3.5 and 5 years respectively after reprocessing, (OWI, 1976). These two canisters are emplaced in the floor of the same drift underground (Figure 1) but they are separated by a distance of 20 m so that interaction between the temperature and displacement fields for the 2 experiments will be negligible over the 1 year heating phase of the tests. A third experiment, which really is a second phase to the 5 kW heater experiment, involves raising the ambient temperature of the rock surrounding this heater to simulate the emplacement of a canister in a heated rock mass, such as would exist in a repository. The rock immediately adjacent to this canister is heated using 8 x 1 kW peripheral heaters emplaced concentrically around the canister. These 3 experiments are designed to study the near-field effects in the rock of thermomechanical loading by heater canisters.

A fourth experiment, designed to study the far-field effects in the rock

---

*Assistant Professor of Mining Engineering, Department of Materials Science and Mineral Engineering, University of California at Berkeley.

to this loading, utilizes the laws of heat conduction to scale the time by reducing the linear dimensions of the experiment. Eight canisters are emplaced in an array in the floor of a drift in the usual manner (Figure 1), with the physical dimensions of the canisters reduced to $1/\sqrt{10.2}$ the dimensions of the full-scale canisters. Spacing between canisters in this array is 3 m and 7 m, representing 10 m and 22 m in a full scale array. The power to these heaters is scaled linearly with canisters size and at the start of the experiment the power output of each of these heaters was about 1.1 kW, representing 3.6 kW in full-scale. At one year period of the experiment then represents 10.2 years of full-scale heating. Power to these heaters is reduced during this experiment to represent the decay of radioactive waste material over this time period.

Instruments are installed in boreholes in the rock surrounding all of these heaters to monitor the temperature and displacement fields. Cromel-alumel thermocouples are used to monitor rock temperatures, multiple-anchor and rod extensometers are used to monitor gross displacements resulting from thermal expansion of the rock, and U. S. Bureau of Mines and Irad vibrating wire gauges are used to monitor diametral changes within boreholes. Measurements from these borehole deformation gauges are interpreted as changes in the stress field. In the full-scale experiment radial displacement measurements are made using extensometers installed from a drift driven parallel to, and slightly below, the main heater drift (Figure 1). 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. 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. About 800 channels of instrumentation are used to monitor these experiments and analysis and real-time comparison of this field data with theoretical predicted values is available using an on-site computer.

PREDICTIVE MODELS

a) Temperature Field

Calculations of the temperature field induced by the emplacement of heater canisters in this rock mass were made prior to the start of the heater experiments. The fundamental assumption for these calculations was that heat is transferred by conduction only. A semi-analytical solution based on the Green's function method was used in these calculations for a time-dependent finite line heater in a semi-infinite medium, (Chan et al., 1978). Three different boundary conditions were considered as solutions (i) infinite medium, (ii) isothermal boundary at the floor of the drift and (iii) adiabatic boundary at the floor of the drift. Comparisons of the results obtained with this method were made with results using a well-known numerical model solution, and excellent agreement was obtained, (Chan et al., 1978). For the full-scale experiments where the heaters are emplaced only 4 m below the drift floor, the drifts are modeled as isothermal boundaries whereas for the time-scale experiment where the heaters are buried 10.5 m below the floor the infinite medium boundary condition is applied.

b) Displacement and Stress Fields

Thermally induced displacements and stresses were calculated using the finite-element program SAP IV (Chan and Cook, 1979). This program is based on linear thermoelastic theory. In these calculations the rock medium is treated as a homogeneous, isotropic continuum. These assumptions were made because of a lack of data on in-situ rock mass properties and conditions and it should be noted that the computer program can handle orthotropic, temperature-dependent material properties.

Because of the different geometries of the experiments, an asymmetrical model was used for the full-scale experiments whereas for the time-scale experiment a three-dimensional model was used, (Chan and Cook, 1979). For

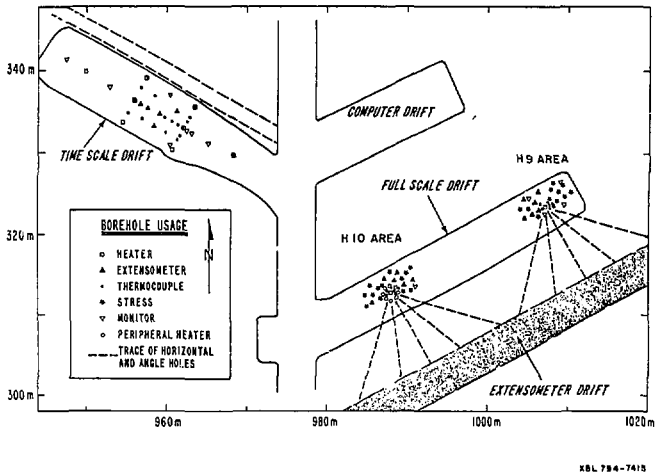


Fig. 1. Plan view of the underground experimental facility showing the drifts where the full scale and time scale experiments are conducted. Also illustrated in this diagram is the drift driven parallel to but at a lower elevation than the full scale drift from which instruments are installed to monitor horizontal movements in the rock.

the full-scale experiments the model was constructed with zero normal displacement boundary conditions with the boundary 100 m from the heater. Comparisons of the results obtained using this model and results from an analytical solution for an infinite cylindrical source showed close agreement for short time periods.

EXPERIMENTAL RESULTS

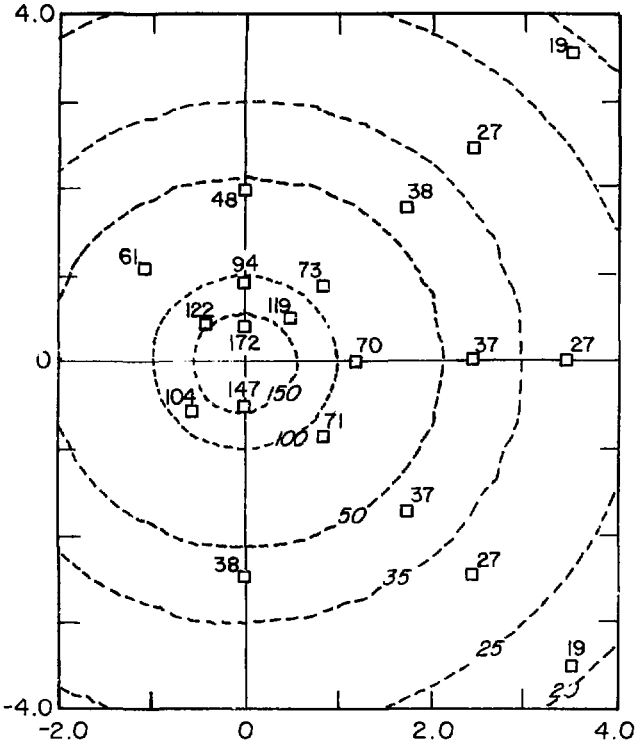
a) Temperature Field

Temperature measurements both in the time-scale and in the full-scale experiments correspond closely to the values predicted (Figures 2 and 3). These results show that linear heat conduction accounts well for changes in temperature although a small, less than 10 percent, difference between predicted and measured values is observed. Preliminary calculations (Jeffrey *et al.*, 1978) have shown that this discrepancy can be attributed to a difference between the values for the rock thermal conductivity obtained by laboratory testing of intact small specimens and the *in-situ* rock mass.

b) Displacement and Stress Fields

Measured values of field displacements and stresses, in all cases, are much less than the values predicted. This result is illustrated by a representative plot of extensometer displacements and by a representative plot of stress measurements using a vibrating-wire Creare gauge in Figure 4 and 5.

The extensometer results are displayed in Figure 4 in two plots. In one graph the measured and the predicted data are plotted separately as functions of time. In the second graph the ratio of these two curves is plotted as a function of time. This ratio plot is of interest since it shows two distinct phases in the response of the rock to the loading. During the initial phase, which, in general, is of the order of 20 days for these instruments, the response is non-linear whereas during the subsequent phase the response is linear.



XBL 791-5519

Fig. 2. Predicted isotherms and measured temperatures in a horizontal plane through the center of the 5 kW full-scale heater, 190 days after heating had started. (Scales for both x and y axes are given in meters.)

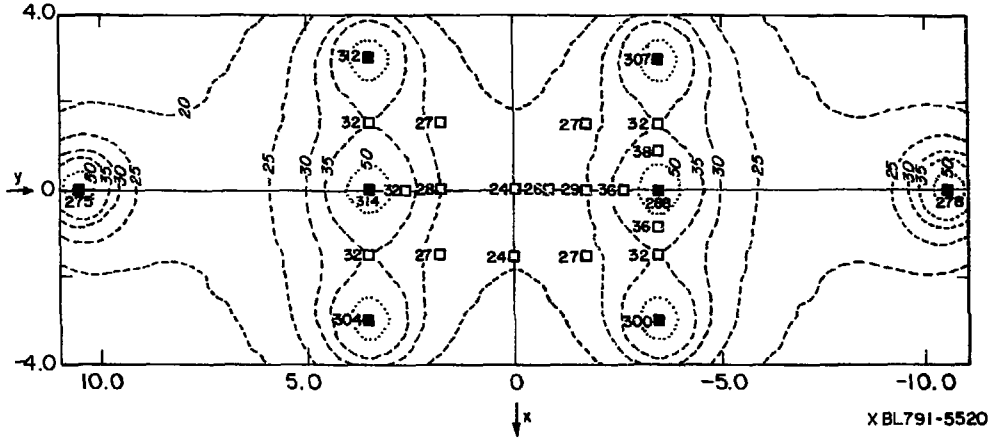


Fig. 3. Predicted isotherms and measured temperatures in a horizontal plane through the center of the time-scale heaters 190 days after the start of the experiment. Heater locations are marked in black. (Scales for both x and y axes are given in meters.)

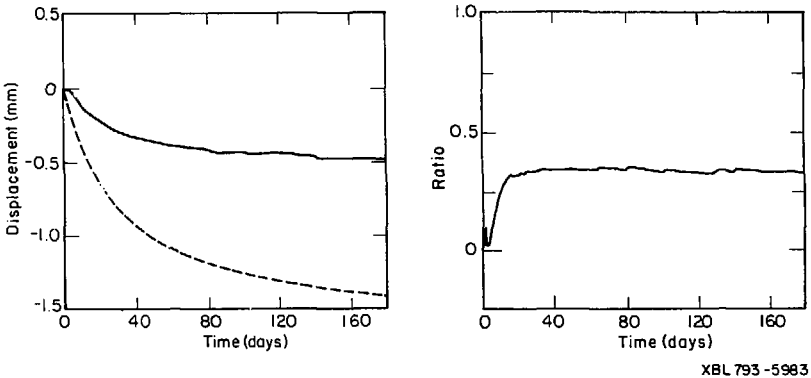


Fig. 4. Predicted (dashed) and measured (solid) displacements between anchor points 3 m below and 3 m above the midplane of the 5 kW full-scale heater, at radius of 2.0 m from heater, together with plot of ratio of measured to predicted displacement between these anchor points as a function of time.

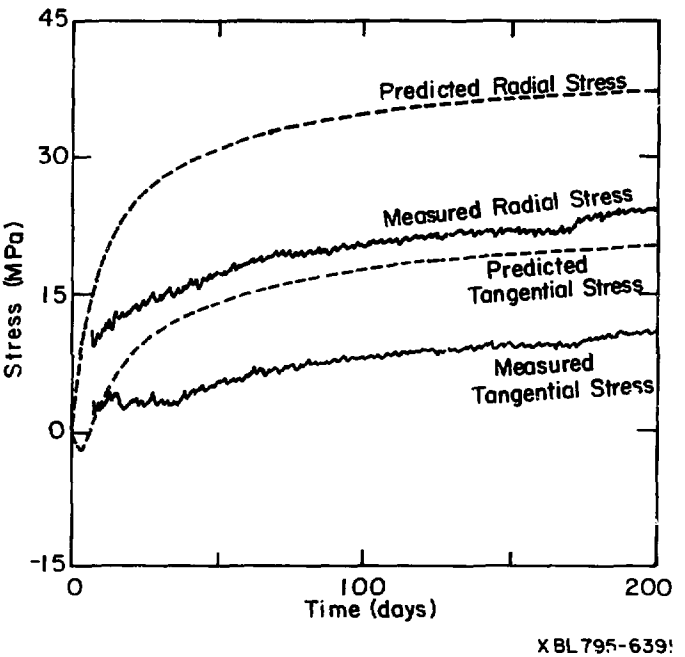


Fig. 5. Predicted (dashed) and measured (solid) radial and tangential stress .085 m above the midplane of the 5 kW heater at a radial distance 1.5 m from this heater. The measured stress values were obtained using a Creare vibrating wire gauge.

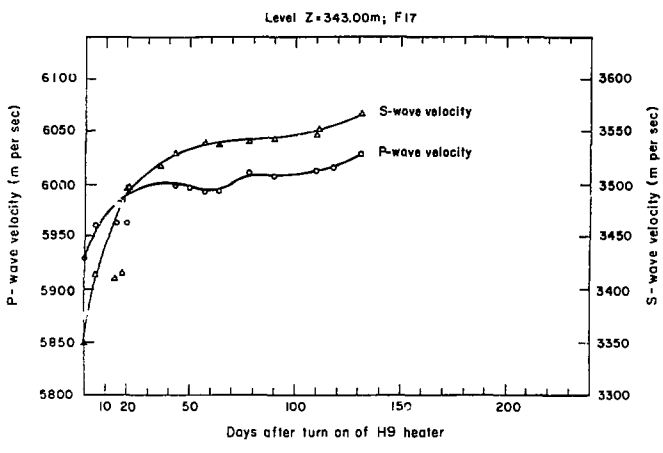


Fig. 6. Ultrasonic velocity measurements between boreholes 4 m apart in the rock mass adjacent to the 3.6 kW heater.

These results are puzzling since from the thermocouple data it is known that the rock mass is subjected to changes in temperature and so consequently thermal expansion of the rock must occur. Detailed checks both of the instruments and of the predictive models have been made and no errors of a nature sufficiently gross to explain these results have been detected.

A plausible explanation for the initial, non-linear rock behavior at early times in the experiment is that the rock expansion were absorbed into pre-existing discontinuities. This argument is supported by cross-hole ultrasonic measurements which were made in the rock adjacent to one of the full-scale heaters. Some of these results are illustrated in Figure 6 from which it can be seen that marked increases in wave velocities were observed during this same time period of the experiment. Further work is needed to justify this explanation and in this regard, it is anticipated that monitoring the rock movements after the heaters are turned off will yield valuable information.

The puzzling feature of the linear portion of the displacement ratio plot (Figure 4) is that this curve trends to a value other than unity. Recent experimental data, (Swan, 1978) has provided some data for the temperature dependence for some of the rock properties. Preliminary calculations using these values in the predictive models indicates that the magnitude of the predicted displacement curve is reduced substantially so that the ratio curve asymptotes to a value close to unity (Chan, 1978). More work is required in the area of laboratory testing in order to determine fully the thermomechanical behavior of specimens of this rock type.

Measurements of changes in stress in the rock mass using the vibrating-wire Creare gauges (Figure 5) show a trend similar to the extensometer measurements, namely that the observed values have a value only about one half or less of the value predicted. Detailed analysis of these results has not yet been made due to

uncertainties in the calibration procedures. Similarly stress measurements obtained using U.S. Bureau of Mines borehole deformation gauges have not been analyzed at all as a result of an error in the original calibration of these gauges.

A more detailed discussion of these results is given in a paper by Hood (1979).

c) Decrepitation

Possible damage to the walls of the boreholes in which the heaters are emplaced as a result of thermally induced spalling, has been monitored from the start of the experiments using a borescope to make visual observation of these surfaces. It should be noted that the power levels selected for the heaters used in these experiments were chosen in an attempt to induce spalling in at least one of these holes in order that a failure criterion for rock by thermo-mechanical loading and an upper limit for canister power levels may be defined.

The results of these observations in the 2 full-scale heater boreholes are given in Figure 7. Also given in this Figure are curves showing the theoretical maximum induced hoop stress at the surface of the holes and the uniaxial compressive strength of the rock (as determined by Swan (1978)). The spalling, prior to turn-on of the peripheral heaters, indicated in Figure 7 was minor, consisting mostly of some enlargement of pre-existing fractures or the formation of small rock chips about 10 mm in diameter and 1 mm thick. It is evident from this Figure that the extent of this minor damage increased as a function of time despite the approximately constant value of the induced stress.

After the peripheral heaters were activated gross failure of the borehole wall was induced. It is of interest to note that this failure is associated with the induced maximum compressive stress exceeding the measured uniaxial compressive rock strength.

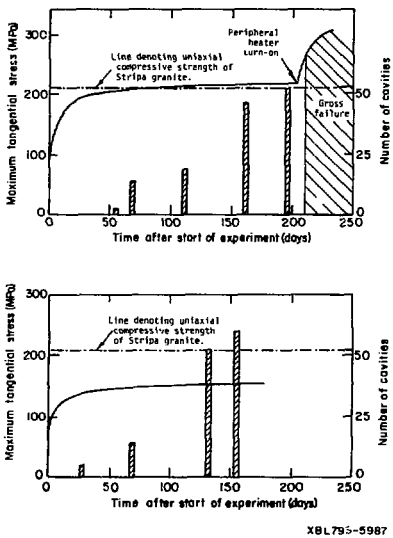


Fig. 7. Maximum induced compressive stress at walls of both the 5 kW (upper graph) and the 3.6 kW (lower graph) heater boreholes plotted as a function of time, together with lines denoting the uniaxial compressive strength of the rock. Also plotted are the number of cavities induced in the borehole wall as a result of thermal spalling.

The results indicate that two different phenomena are involved in decrepitation of the heater boreholes. These observations and their relevance for the design of a repository are discussed in more detail in a paper by Hood et al., (1979).

DISCUSSION

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 theory of heat conduction.

Geologic discontinuities appear to introduce significant non-linear thermomechanical deformation into the rock mass, as a result of which the thermally induced displacements are much less than those predicted by the simple theory of thermo-elasticity. In addition, the assumption that the rock properties are temperature independent appears to increase the values predicted for these displacements significantly. Therefore it is important that the temperature dependence of these properties is known and that these values be used in the calculations.

The onset of significant thermal spalling along the walls of the heater boreholes appears to be related to a conditions where the maximum induced compressive stress exceeds the uniaxial compressive strength of the rock. More work in this area is needed to identify a failure criterion.

The most urgent need, in terms of the development of analytical or numerical models to explain observed rock behavior, is for a model which allows for discontinuities within the rock mass.

ACKNOWLEDGEMENT

This report was prepared for the U. S. Department of Energy under Contract No. W-7405-ENG-48. The contract is administered by the Office of Nuclear Waste Isolation at Battelle Memorial Institute.

REFERENCES

Chan, T. (1978). Private communication.

Chan, T., Cook, N. G. W. and Tsang, C. (1978). "Theoretical temperature fields for Stripa heater project", Vols. 1 and 2, LBL Report #7082, SAC-09, Sept.

Chan, T. and Cook, N. G. W. (1979). "Calculation of thermally induced displacements and stresses for experiments at Stripa" LBL Report #7061.

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 of the 20th U. S. Symposium on Rock Mechanics, Austin, Texas, June.

Hood, M., Nelson, P. H. and Carlsson, H. (1979). "The application of field data from heater experiments conducted at Stripa, Sweden, to parameters for repository design", Proceedings International Atomic Energy Agency/ OECD Nuclear Energy Agency International Symposium on the Underground Disposal of Radioactive Waste, Otaniemi, Finland, July.

Jeffrey, J. A., Chan, T., Cook, N. G. W., Witherspoon, P. A. (1979). "Determination of in-situ thermal properties of Stripa granite from temperature measurements in the full-scale heater experiments", LBL Report #8423.

Office of Waste Isolation, Union Carbide Corporation-Nuclear Division, (1976). "National Waste Terminal Storage Program Progress Report", Y/OWI-8, Oak Ridge, Tennessee 37830, November.

Swan, T. (1978). "The mechanical properties of Stripa granite", LBL Report #7074, SAC-03, August.