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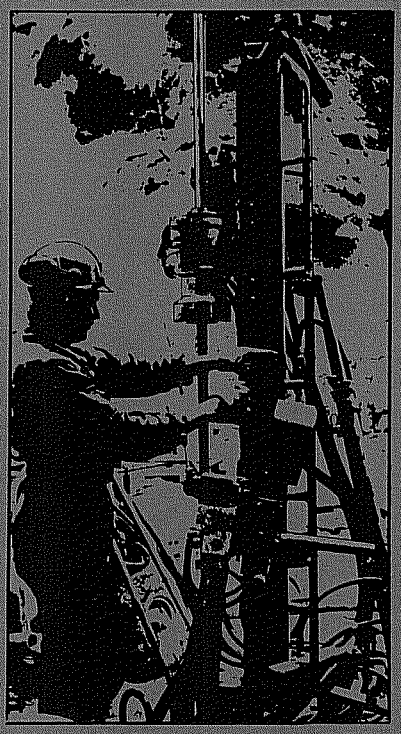
SWEDISH-AMERICAN COOPERATIVE PROGRAM ON RADIOACTIVE WASTE STORAGE IN MINED CAVERNS IN CRYSTALLINE ROCK



Technical Information Report No. 26

I. SOME RESULTS FROM A FIELD INVESTIGATION OF THERMO-MECHANICAL LOADING OF A ROCK MASS WHEN HEATERS ARE EMPLACED IN THE ROCK

Michael Hood
University of California, Berkeley

II. THE APPLICATION OF FIELD DATA FROM HEATER EXPERIMENTS CONDUCTED AT STRIPA, SWEDEN TO PARAMETERS FOR REPOSITORY DESIGN

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July 1979

A Joint Project of

Swedish Nuclear Fuel Supply Co.
Fack 10240 Stockholm, Sweden

Operated for the Swedish
Nuclear Power Utility Industry

Lawrence Berkeley Laboratory
Earth Sciences Division
University of California
Berkeley, California 94720, USA

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

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Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
Price Code: A04

This report is part of a cooperative Swedish-American project supported by the U.S. Department of Energy and/or the Swedish Nuclear Fuel Supply Company. Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory, the Department of Energy, or the Swedish Nuclear Fuel Supply Company.

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I. SOME RESULTS FROM A FIELD INVESTIGATION OF THERMO-MECHANICAL LOADING OF A ROCK MASS WHEN HEATERS ARE EMPLACED IN THE ROCK

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Part I was presented at the 20th U.S. Symposium on Rock Mechanics, Austin, Texas, June 4-6, 1979. Part II was presented at the International Symposium on the Underground Disposal of Radioactive Wastes, Otaniemi, Finland, July 2-6, 1979.

This report was prepared by Lawrence Berkeley Laboratory under the University of California contract W-7405-ENG-48 with the U. S. Department of Energy. Funding for this project is administered by the Office of Nuclear Waste Isolation at Battelle Memorial Institute.

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.

Previous technical reports in this series 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 Lundstrom and Haken 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 H. Carlsson. (LBL-7078, SAC-04).

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9. Theoretical Temperature Fields for the Stripa Heater Project by Tin Chan, Neville G. W. Cook, and Chin-Fu 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 Paul A. Witherspoon. (LBL-7073, SAC-10).

11. Full-Scale and Time-Scale Heating Experiments at Stripa: Preliminary Results by Neville G.W. Cook and Michael Hood. (LBL-7072, SAC-11).

12. Geochemistry and Isotope Hydrology of Groundwaters in the Stripa Granite: Results and Preliminary Interpretation by P. Fritz, J.F. Barker, and J.E. Gale. (LBL-8285, SAC-12).

13. Electrical Heaters for Thermo-mechanical Tests at the Stripa Mine by R. H. Burleigh, E. P. Binnall, A. O. DuBois, D. U. Norgren, and A. R. Oritz. (LBL-7063, SAC-13).

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15. An Approach to the Fracture Hydrology at Stripa: Preliminary Results by J. E. Gale and P. A. Witherspoon. (LBL-7079, SAC-15).

16. Preliminary Report on Geophysical and Mechanical Borehole Measurements at Stripa by P. Nelson, B. Paulsson, R. Rachiele, L. Andersson, T. Schrauf, W. Hustrulid, O. Duran, and K. A. Magnusson. (LBL-8280, SAC-16).

17. Observations of a Potential Size-Effect in Experimental Determination of the Hydraulic Properties of Fractures by P. A. Witherspoon, C. H. Amick, J. E. Gale, and K. Iwai. (LBL-8571, SAC-17).

18. Rock Mass Characterization for Storage of Nuclear Waste in Granite by P. A. Witherspoon, P. Nelson, T. Doe, R. Thorpe, B. Paulsson, J. Gale, and C. Forster (LBL-8570, SAC-18).

19. Fracture Detection in Crystalline Rock Using Shear Waves by K. H. Waters, S. P. Palmer, and W. E. Farrell. (LBL-7051, SAC-19).

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21. Geology and Fracture System at Stripa by A. Olkiewicz, J. E. Gale, R. Thorpe, and B. Paulsson. (LBL-8907, SAC-21).

22. Calculated Thermally Induced Displacements and Stress for Heater Experiments at Stripa by T. Chan and N. G. W. Cook. (LBL-7061, SAC-22).

23. Validity of Cubic Law for Fluid Flow in a Deformable Rock Fracture by P. A. Witherspoon, J. S. Y. Wang, K. Iwai, and J. E. Gale. (LBL-9557, SAC-23).

24. Determination of In-Situ Thermal Properties of Stripa Granite from Temperature Measurements in the Full-Scale Heater Experiments: Method and Preliminary Results by J. A. Jeffry, T. Chan, N. G. W. Cook, and P. A. Witherspoon. (LBL-8423, SAC-24).

25. Instrument Evaluation, Calibration, and Installation for the Heater Experiments at Stripa by T. Schrauf, H. Pratt, E. Simonson, W. Hustrulid, P. Nelson, A. Dubois, E. Binnall, and R. Haught. (LBL-8313, SAC-25).

TABLE OF CONTENTS

Page

LIST OF FIGURES viii

PART I. SOME RESULTS FROM A FIELD INVESTIGATION OF THERMO-MECHANICAL LOADING OF A ROCK MASS WHEN HEATERS ARE EMPLACED IN THE ROCK

ABSTRACT 1

1. INTRODUCTION 2

2. BACKGROUND 2

3. EXPERIMENTAL RESULTS 5

3.1 Temperature Data 5

3.2 Displacement Data as Recorded by Extensometers 9

3.3 Stress Gauges 17

3.4 Decrepitation 17

3.5 Experiment Using Peripheral Heaters 20

4. DISCUSSION 21

PART II. THE APPLICATION OF FIELD DATA FROM HEATER EXPERIMENTS CONDUCTED AT STRIPA, SWEDEN TO PARAMETERS FOR REPOSITORY DESIGN

ABSTRACT 24

1. INTRODUCTION 25

2. REPOSITORY DESIGN CONSIDERATIONS 26

3. RESULTS OF STRIPA EXPERIMENTS 29

3.1 Monitoring of Rock Spalling Along the Borehole Wall 29

3.2 Temperature, Displacement, and Stress Measurements in the Rock Mass 32

4. SUMMARY 36

5. ACKNOWLEDGMENTS 37

REFERENCES 38

LIST OF FIGURES

Page

1. A plan of the test site underground at Stripa showing the time-scale, full-scale, and extensometer drifts 3

2. 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 6

3. 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 6

4. Predicted and measured temperatures plotted as a function of time at a radius of 0.5 m from 5 kW heater at the heater midplane 7

5. Predicted isotherms and measured temperatures in a vertical plane through three of the time-scale heaters, 190 days after heating had started 8

6. Predicted and measured displacements between anchor points 2.25 m below and 2.25 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 11

7. Predicted and measured horizontal displacements between anchor points at the heater midplane at radii of 1.25 m and 2.5 m 13

8. Predicted and measured horizontal displacements between anchor points at the 1-m radius on either side of heater axis in a plane 1.7 m below 5 kW full-scale heater, together with a plot of the ratio of the measured to the predicted displacement between these anchor points as a function of time . 14

9. Predicted and measured vertical displacements between anchor points 3 m above and 3 m below heater midplane for extensometer in time-scale experiment, together with a plot of the ratio of the measured to the predicted displacements between these anchor points as a function of time 16

10. Maximum induced compressive stress at the walls of the 5 kW and the 3.6 kW heater boreholes plotted as a function of time, together with lines denoting the uniaxial compressive strength of the rock 17

List of figures (continued)

Page

11. Predicted temperatures on the heater borehole and measured temperatures on the heater canister plotted as a function of time 20

12. Computed vertical and radial stresses along a vertical line passing through the center of a heated sphere of 250-m radius placed 1000 m below the surface of a half-space (after Hodgkinson, 1978) 28

13. Results of borehole decrepitation around the 5.0 kW full-scale heater 31

14. Ultrasonic velocity measurements between boreholes 4 m apart at the heater midplane elevation in the rock mass adjacent to the 3.6 kW heater 33

15. Predicted and measured stresses from a vibrating wire gauge located 1.5 m radially and 0.85 m above the center of the 5 kW heater H10 35

Part I

ABSTRACT

Results are presented of a field experiment to monitor the response of a rock mass to thermo-mechanical loading from electrically heated canisters emplaced in the rock at a depth of 340 m. Measurements made to date of temperature, displacement, and stress fields indicate that heat is transferred through the rock mainly by conduction; discontinuities within the rock mass have a minimal effect on the heat flow. Displacements within the rock from thermal expansion are shown to be much less than those predicted by linear thermoelastic theory. A plausible, though not complete, reason for these reduced displacements is the absorption of the initial rock expansions into discontinuities within the rock mass. Difficulties have been experienced in obtaining reliable stress measurement data using borehole deformation gauges to monitor changes in rock stress. Some data have been obtained and are being analyzed. Rock decrepitation in the heater boreholes is discussed.

1. INTRODUCTION

Knowledge of the response of a rock mass to thermomechanical loading is a prerequisite to the design of a repository for radioactive waste materials. This topic has been the subject of considerable study in recent years, and much effort has been devoted to the construction of mathematical models to predict the behavior of a rock which is subject to thermomechanical loading. Validation of these models can come only from large-scale field experiments, since the complex nature and geometries of discontinuities within an in-situ rock mass cannot be reproduced in the laboratory. Some field tests have been conducted. The experiments described in this paper were designed, and presently are being conducted, to investigate the response of a granitic rock mass to thermal loading imposed by electrical heaters simulating canisters of nuclear waste.

2. BACKGROUND

A joint American-Swedish program to study the effects of burial of radioactive waste materials in hard rock has been operative since July 1977. As part of this program a suite of experiments, currently in progress, was designed to study the thermomechanical response of a rock mass when canisters, containing electrical heaters to simulate the heat generated by the decay of radioactive materials, were emplaced in the rock at an underground test site. The test facility selected for these experiments is a granitic rock mass adjacent to the underground workings of an abandoned iron ore mine at Stripa in central Sweden. The experimental site is a series of interconnected drifts at a depth of about 340 m below surface (Fig. 1).

The heater canisters are emplaced in boreholes drilled into the floors of these drifts, and the response of the rock mass to the loadings imposed is

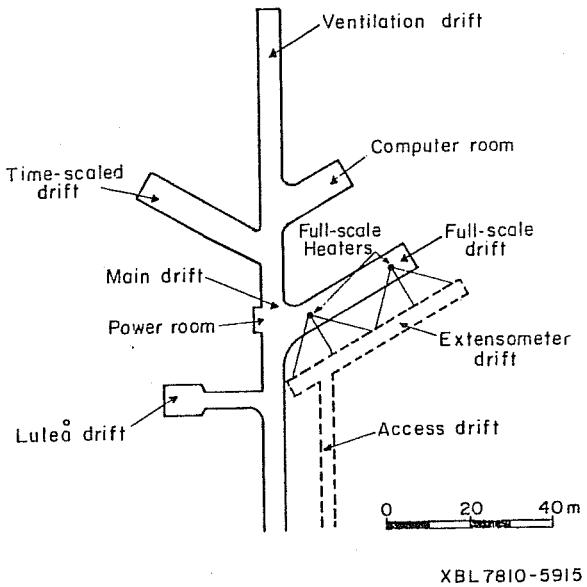

Fig. 1. A plan of the test site underground at Stripa showing the time-scale, full-scale, and extensometer drifts.

measured by instruments which are sited in other boreholes in the rock surrounding these heaters. Thermocouples are used to determine the induced temperature field. Displacements within the rock mass, resulting from thermal expansion, are monitored using multiple anchor rod extensometers. The stresses induced by confinement of the expanding rock mass are inferred from borehole deformation measurements using U. S. Bureau of Mines gauges and vibrating-wire Creare gauges. Approximately 800 channels of instrumentation are used in monitoring, and experimental results are analyzed rapidly using a 512-K byte, 32-bit computer with powerful graphics capability situated underground at the mine test site.

The experimental program comprises four tests: two independent full-scale heater tests, a full-scale test in which the ambient temperature of the rock surrounding the heater is raised to simulate the effects of heating a whole repository, and a time-scale test.

The canisters in the full-scale tests are 2.5 m in length and 0.3 m in diameter, dimensions similar to those proposed by the U. S. Department of Energy for containers holding reprocessed radioactive wastes. The two full-scale heaters are operated at 5 kW and 3.6 kW, representing high-level, radioactive waste canisters buried 3.5 years and 5 years, respectively, after reprocessing (Office of Waste Isolation 1976). These relatively high power levels were selected to study the extent of thermal spalling along the walls of the heater boreholes as a function of canister power levels. This thermal spalling, or decrepitation, will control the maximum acceptable power output (and therefore the age prior to burial) of radioactive waste in canisters for this type of rock.

A second phase of the 5-kW, full-scale heater experiment is to raise the ambient temperature in the surrounding rock by about 100°C, using eight 1-kW heaters in a concentric ring around the full-scale heater. The objective is to simulate the high ambient temperature caused by heat transfer from previously emplaced waste materials.

The objective of the time-scale heater test is to study the effects of thermal interaction between heater canisters on temperature, displacement, and stress fields. Canisters in a waste repository probably would be spaced such that this type of interaction would be negligible during the first few decades of the repository life. The dimensionless time scale factor in the linear heat conduction equation (Rogers and Mayhew 1976) has been used to speed up the time frame of the experiment by reducing all of the linear dimensions of the test apparatus, including canister spacing. An acceleration of the time frame by a factor of 10.2 was selected for this experiment, requiring a reduction in linear dimensions by a factor $1/\sqrt{10.2}$. Scaling in

these proportions does not make the heater canisters unreasonably small compared with the discontinuities in the rock mass, which cannot be scaled. Canister power levels are reduced by the same amount as the linear scale in order to maintain similitude of the temperatures. Eight heater canisters installed in an array of boreholes on centers of 7 m and 3 m are used for this test. Initially the power output of each heater was 1.1 kW, corresponding to 3.6 kW for a full-scale heater. Power to these heaters is reduced continually to simulate the reduction in heat output by radioactive decay over the 20 year period that the experiment represents.

Three of the experiments were started on or soon after June 1, 1978. The fourth experiment, the second phase of the 5 kW full-scale heater test, became operative in January 1979.

3. EXPERIMENTAL RESULTS

3.1 Temperature Data

Temperatures in the time-scale and the two full-scale experiments correspond fairly closely with values predicted by linear heat conduction (Chan, Cook, and Tsang 1978). Representative examples of the temperatures measured at different points in these experiments are given in Figs. 2, 3, and 4. Figure 2 is a plan view of the time-scale experiment taken through the midplane of the heaters. This figure shows the positions of the eight heaters, and plots (a) the predicted temperatures as contours, and (b) the measured temperatures as point measurements, 190 days after the start of the experiment. Figure 3, also a plan view through the heater midplane, illustrates predicted and measured temperatures for the 5 kW, full-scale heater. In Fig. 4, temperature is plotted as a function of time for a single thermocouple positioned at a radius of 0.5 m from the 5-kW heater at the midplane.

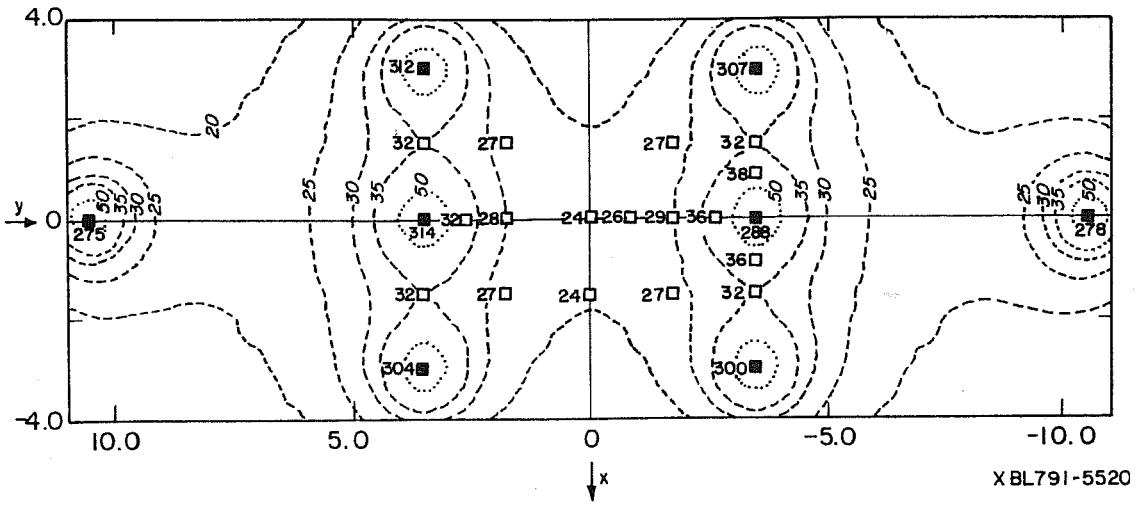

Fig. 2. Predicted isotherms and measured temperatures in a horizontal plane through the center of the time-scale heaters 190 days after the start of the experiment. Heater locations are marked in black. (Scales for both x and y axes are given in meters.)

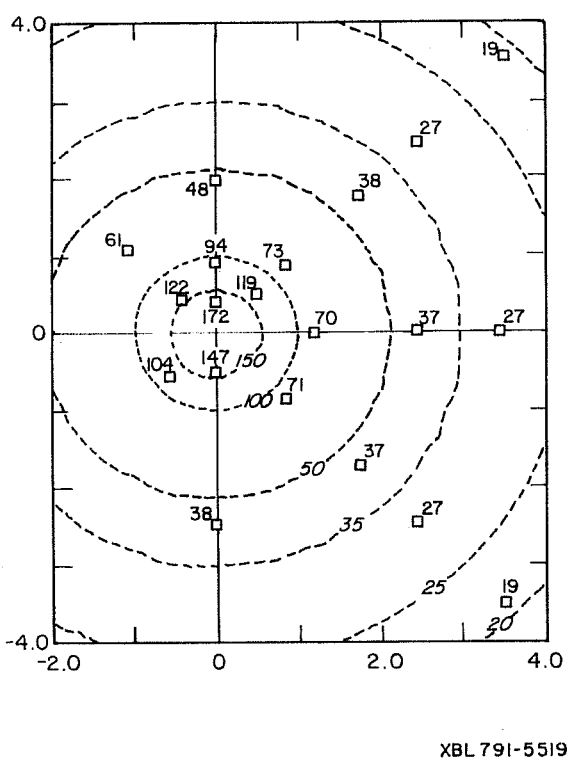

Fig. 3. Predicted isotherms and measured temperatures in a horizontal plane through the center of the 5 kW full-scale heater, 190 days after heating had started. (Scales for both x and y axes are given in meters.)

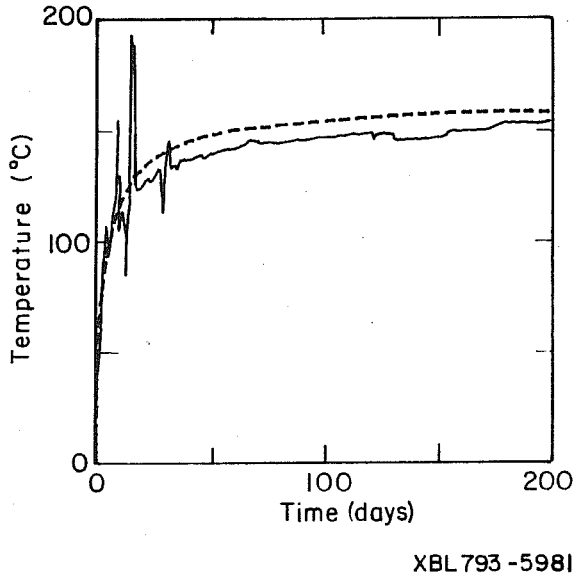

Fig. 4. Predicted (dashed) and measured (solid) temperatures plotted as a function of time at a radius of 0.5 m from 5 kW heater at the heater midplane. Variations in the measured signals at early time periods were caused by corrosion of the thermocouple stainless-steel sheaths. This problem was solved by replacing all of the thermocouples in the full-scale experiments with thermocouples of another type.

These figures illustrate that the measured temperatures correspond fairly closely with the predicted values although, in general, predictions are somewhat higher than measured temperatures. Preliminary calculations (Jeffry et al. 1979) have demonstrated that this discrepancy may be due in part to the difference between the in-situ value for the thermal conductivity of the rock and the value used in the model. Additional work is being performed to check this explanation.

A feature of major interest illustrated by these curves is the symmetry of the induced temperature field, illustrated in the horizontal plane by Figs. 2 and 3 and in the vertical plane by Fig. 5. The symmetry of the temperatures on any horizontal section in Fig. 5 is evident. However, vertical sections in this plot show that temperatures above the heater midplane are somewhat higher than those measured at the same distance below the midplane. This phenomenon, which is observed also in the full-

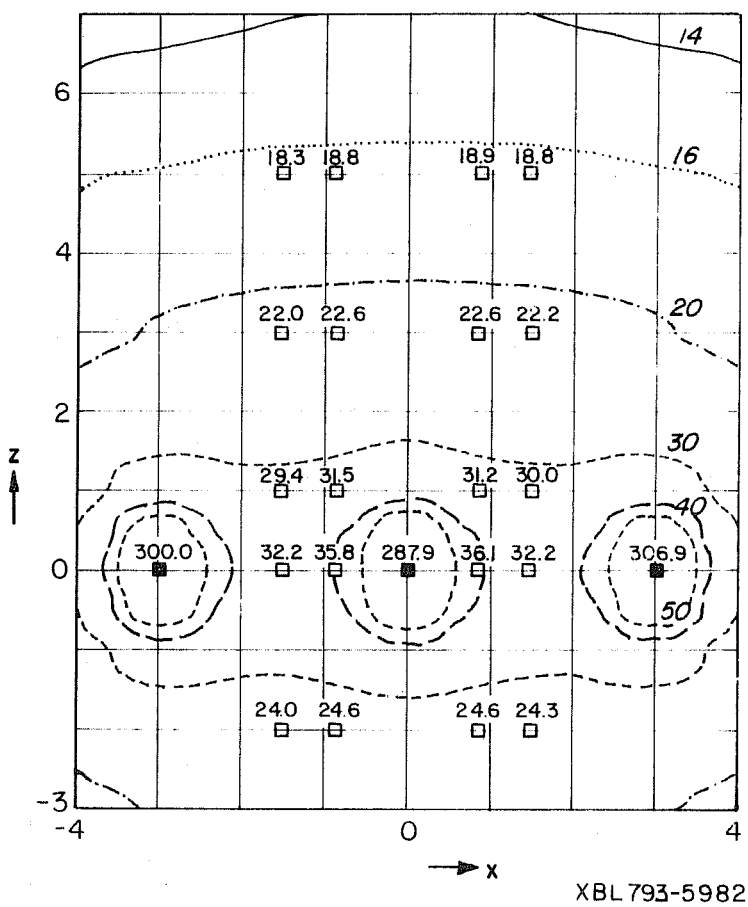

Fig. 5. Predicted (dashed) isotherms and measured (solid) temperatures in a vertical plane through three of the time-scale heaters, 190 days after heating had started. Heater locations are marked in black. (Scales for both x and z axes are given in meters; y = 3.5 m.)

scale experiments, is attributed to convective heat transfer along the borehole wall.

Predictions for the temperature field were based on the assumptions that the rock is a linear, isotropic, homogeneous material, and that heat is transferred only by conduction. The experimental results to date indicate that, for the purposes of determining the induced temperature field, these assumptions are a good approximation.

3.2 Displacement Data as Recorded by Extensometers

Six multiple-rod extensometers, each with four anchor points, are mounted in boreholes adjacent to each full-scale heater. These instruments monitor vertical movements in the rock mass parallel to the axis of the heater. Also associated with each of the full-scale experiments are nine horizontally mounted extensometers of similar type. These extensometers are installed towards the heater from a drift driven parallel to, and slightly below, the full-scale heater drift (Fig. 1). The detailed locations of all instrument and heater boreholes for all of these experiments are given by Kurfurst, Hugo-Persson, and Rudolph (1978).

Measurements from these extensometers show that gross movements within the rock mass as a result of thermal expansions do not agree well with values predicted for these movements. A finite-element numerical code assuming linear thermo-elastic theory is used to calculate displacements within the rock mass adjacent to the heaters (Chan and Cook 1979). In all cases the displacements predicted by this model are greater than the values measured between extensometer anchor points by a factor of at least

two. This result is puzzling: the thermocouple measurements demonstrate that the rock is heated almost in accordance with predicted values, whereas the extensometer measurements show that the expansion of the rock as a result of this heating is far less than predicted. The most likely explanation of these apparently conflicting results is that an error has been made either in the extensometer measurements or in the construction of the theoretical model. In order to investigate this possibility, detailed in-situ calibration checks of selected extensometers have been made and evidence has not been found that would indicate that the readings from these instruments are inaccurate to the extent indicated by these results. Similarly, analytical calculations (using standard equations for the expansion of a linear elastic material adjacent to a heat source) have been made, and close agreement is obtained between these results and the results given by the numerical model.

The least ambiguous of the extensometer measurements are those recorded between anchor points immediately adjacent to a heater, especially when the gauge length between anchor points is across one of the planes of symmetry for the heater. In the case of the vertical extensometers this measurement is given between points 2 to 3 m above and 2 to 3 m below the heater midplane.

A study of rock movements across this plane of symmetry in the two full-scale experiments reveals an interesting trend: for all 12 vertical extensometers the ratio of the measured to the predicted displacement increases from zero to a relatively constant value 10 to 20 days after the start of the experiments. This indicates an initial non-linear, followed by a linear response for these instruments. The mean value of this ratio for these instruments is 0.46 with a standard deviation of 0.05. Graphs showing both

the measured and the predicted displacements, together with the ratio of these two parameters, are plotted as functions of time in Fig. 6 for one of these extensometers.

The shape of the curves showing ratios of measured to predicted displacements as functions of time (Fig. 6) is indicative of extremely small movements within the rock mass during the initial phase of the experiments. The fact that these curves eventually level out to a constant value shows that a change in the response of the rock mass occurred after some given time period. It is possible that this initial, non-linear behavior is caused by expansions within the rock being taken up in pre-existing fractures and joints. Extensive mapping of these features in the rock (Thorpe 1979) has demonstrated that discontinuities, both major and minor, are so pervasive within this granite that, over gauge lengths equivalent to the minimum

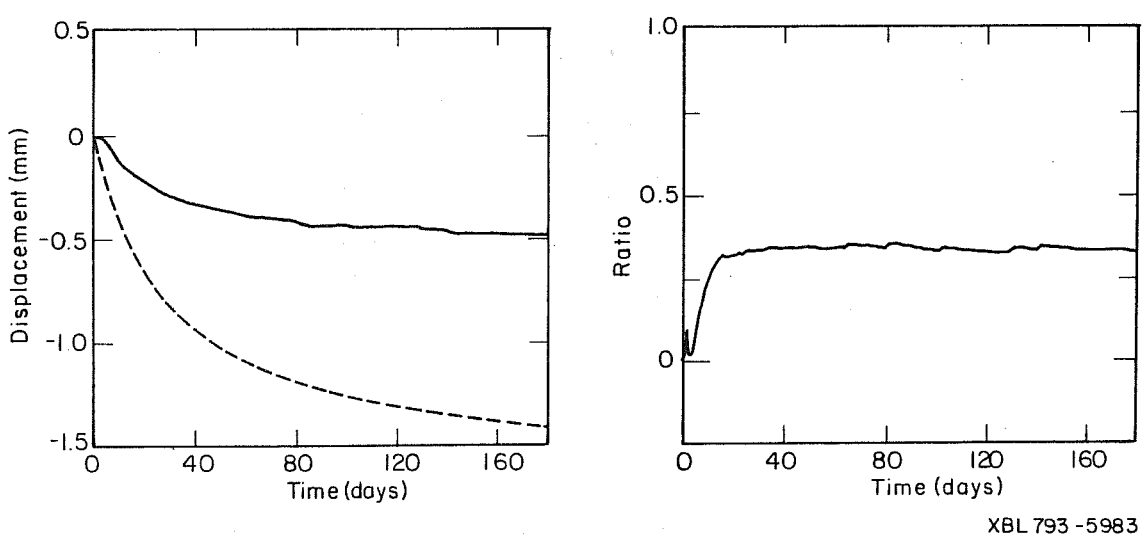

Fig. 6. Predicted (dashed) and measured (solid) displacements between anchor points 2.25 m below and 2.25 m above the midplane of the 5 kW full-scale heater, at radius of 2.0 m from heater, together with plot of ratio of measured to predicted displacement between these anchor points as a function of time

distance between extensometer anchor points, the void spaces introduced by these discontinuities in all cases are more than sufficient to render plausible the explanation of diminution of measured rock displacement by expansion into void spaces. This explanation would apply only to the initial non-linear phase of the displacement curves and does not help to determine the reasons for the ratio plots trending to a value other than unity. Work to gain a better understanding of the observed rock movements is continuing.

Measurements of rock movements using the horizontal extensometers are anomalous, not only when compared with the predicted values, but also when compared with the vertical extensometer measurements from the full-scale experiments. Sixteen of the eighteen instruments that are used to monitor rock movements in the horizontal plane show that the only movements that have occurred have taken place between the anchor points closest to the heater and the extensometer heads. That is, the relative displacements between anchor points along the lengths of these instruments are less than the resolution of the instrument. (The sensitivity of the extensometer readings is still being investigated, but present indications are that it is better than 100 μm.) This is illustrated by a curve in Fig. 7, which is representative of the other experimental results. This result implies that all of the movement has taken place at the extensometer head--a result that is difficult to interpret since this reference point is fixed to the wall of a drift and displacements here will be strongly influenced by this boundary.

In seeking an explanation for this major difference in the observed displacement measured in the vertical and in the horizontal planes it should be noted that predicted rock movements in the horizontal plane are much less than in the vertical plane. Typically, horizontal displacements between

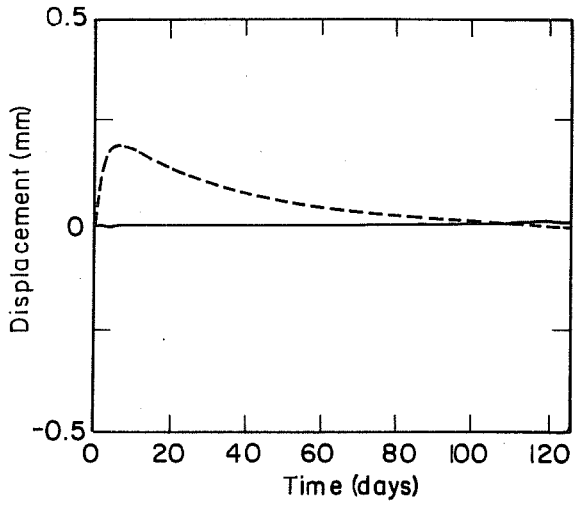

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Fig. 7. Predicted (dashed) and measured (solid) horizontal displacements between anchor points at the heater midplane at radii of 1.25 m and 2.5 m.

anchor points close to the heater at the heater midplane attain a maximum of less than 0.15 mm about 10 days after the heater turn-on. These predicted rock movements compare with predicted movements approaching 1.0 mm between adjacent anchor points for extensometers mounted in the vertical plane. It has been noted already that when predicted rock movements are small, measured displacements are observed to be much less than predicted values. It was postulated that this may be caused by thermal expansions of the rock being absorbed into void spaces. This explanation is consistent with the horizontal extensometer readings.

Two horizontal extensometers, one in each of the full-scale experiments, extend across (and have anchor points on either side of) the plane of symmetry for the heater, namely the heater axis. These instruments are mounted

1.7 m below the heater canisters and have anchor points at a 1-m radius on each side of the axis. Negative (expansion) displacement readings are recorded between these anchor points by both of these extensometers, one of which is illustrated in Fig. 8. The rock movements predicted by the theoretical model between these anchor points for the two extensometers, 120 days after the start of the experiments, are 0.67 mm and 0.92 mm for the 3.6-kW and 5.0-kW heater experiments, respectively. These predicted displacements are greater than the predicted horizontal displacements by adjacent extensometers by a factor of about 5. This finding conforms with the previous observation; namely, that measurable rock movements are non-linear and occur only when the predicted displacements exceed some minimum value.

Five extensometers in the time-scale experiment provide information on the vertical displacements in the rock between this array of heaters. These

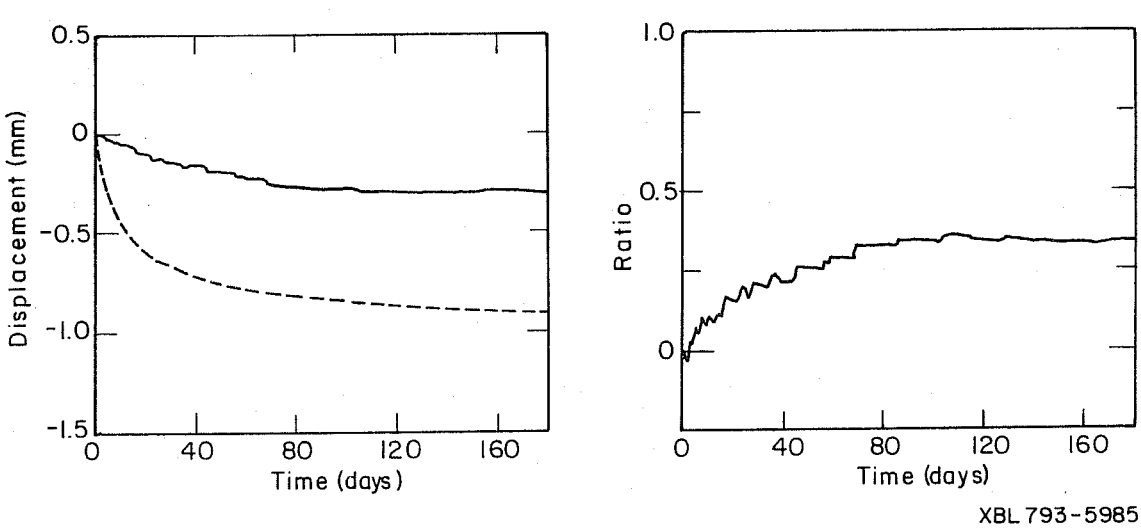

Fig. 8. Predicted (dashed) and measured (solid) horizontal displacements between anchor points at 1 m radius on either side of heater axis in a plane 1.7 m below 5 kW full-scale heater, together with a plot of the ratio of the measured to the predicted displacement between these anchor points as a function of time.

extensometers have anchor points located 3 m above the heater midplane, at the heater midplane, and 3 m below the heater midplane. However, the measurements of rock movements across the heater midplane do not show the consistent trend illustrated by the equivalent anchor points on the full-scale vertical extensometers. Figure 9 plots the measured and the predicted displacements between the anchor points on either side of the heater midplane, as a function of time for two of the time-scale extensometers. These curves are also displayed as a ratio of measured to predicted values.

Comparing the graphs in Fig. 9 with those given previously for vertical rock movements in the full-scale experiments (Fig. 6), two main differences are apparent. First, the time period before any rock movements are observed is long for the time-scale readings. Second, the time-scale displacement/time curves are uneven, with rock movements recorded as step functions. Reasons for these disparities have been investigated and detailed field checks of the instruments have shown that friction between the extensometer rods and the rod supports causes a stick-slip motion of the rods. This produces uneven motion. This problem has been solved by tapping the extensometer heads daily, to release the stuck rods.

Other differences between vertical rock movements in the time-scale and full-scale experiments are not explained by instrument behavior. From Fig. 9 it is evident that the ratios of measured to predicted displacements for the two instruments given are very different from each other, and both are much less than the mean value of 0.46 given in the full-scale experiments. These graphs are representative of the readings from the five instruments used to monitor rock movements in this experiment. No explanation for this difference in rock behavior in the two experiments is apparent, but work

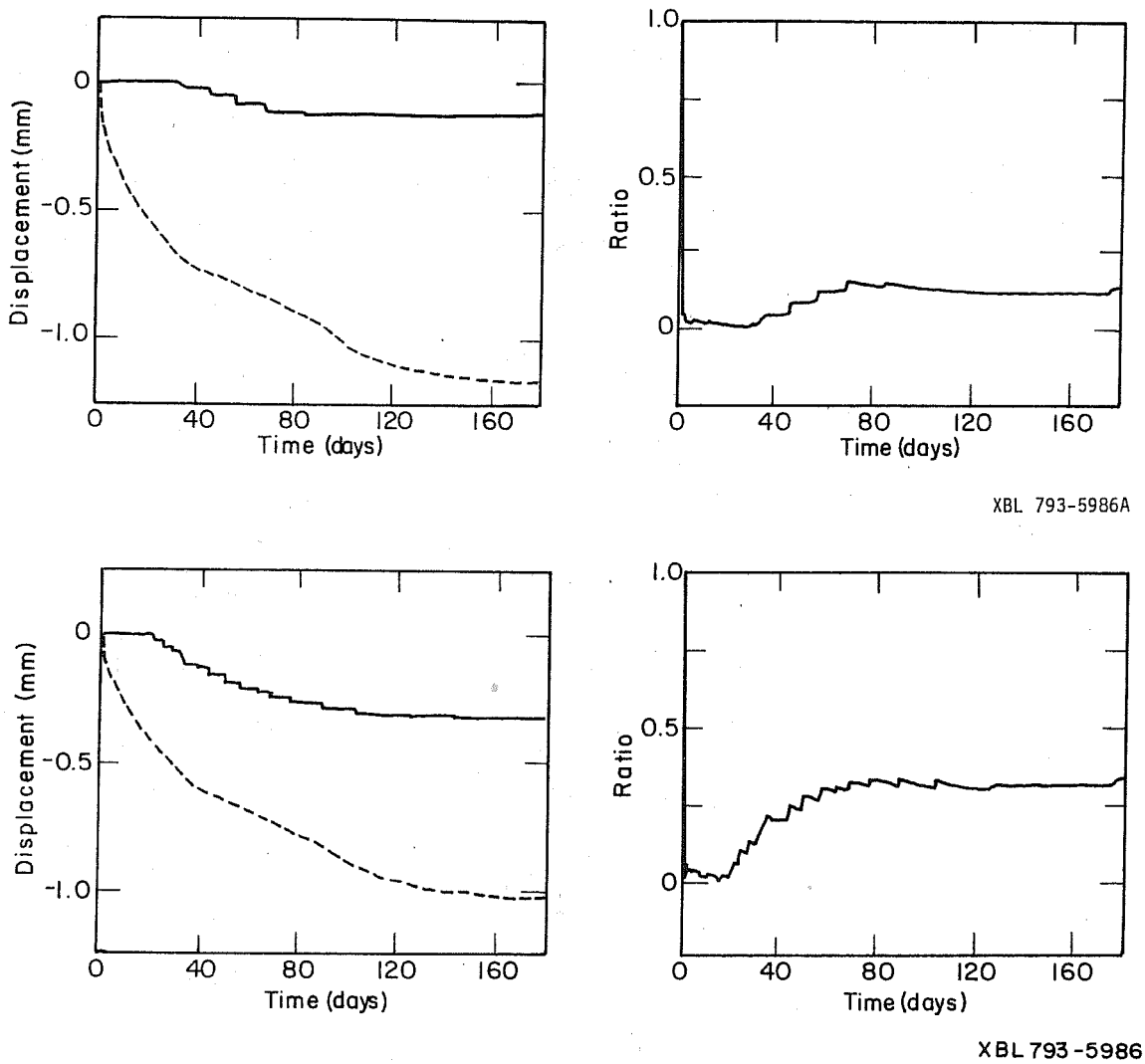

Fig. 9. Predicted (dashed) and measured (solid) vertical displacements between anchor points 3 m above and 3 m below heater midplane for extensometer in time-scale experiment, together with a plot of the ratio of the measured to the predicted displacement between these anchor points as a function of time. A: x = 0.0 m, y = 2.6 m. B: x = -1.5 m, y = 0.0 m.

(Position of the instrument can be obtained from Fig. 2.)

is continuing with special attention being paid to possible differences in the nature of the discontinuities in the different areas accounting for this difference in behavior.

3.3 Stress Gauges

Measurements of rock stress using so-called stress gauges is notoriously difficult, and this experiment has proved no exception. Difficulty has been experienced with interpretation of the readings from both the U.S.B.M. and the Creare gauges; in addition, problems have been experienced with the reliability of the U.S.B.M. gauges operating over long time periods in a hot, wet environment. Some data have been obtained and are being analyzed.

3.4 Decrepitation

The rate of heat generation by decay of radioactive materials falls off rapidly with the age of the materials. This factor is important in burying these materials in rock, since high power output from a waste canister will induce large thermal compressive stresses in directions parallel to the axis of, and tangential to the surface of, the borehole containing the canister (Cook 1978). If these stresses exceed the uniaxial compressive strength of the rock, the borehole wall will fail. While failure of this type is not likely to damage a well-designed canister, its retrieval may be difficult . Thus the strength of the rock is likely to be the factor which limits the canister power output and which therefore determines the minimum age at which these materials should be buried.

The extent of spalling induced in the heater boreholes during these experiments has been observed directly at regular intervals by inserting a borescope in the annulus between the canister and the borehole wall. Decrepitation in the time-scale and in both of the full-scale experiments has been minor. This pattern changed, however, for one of the full-scale experiments after the perturbation induced by the turn-on of the peripheral heaters

to raise the ambient rock temperature. Previously, decrepitation in all holes typically involved slight enlargement of pre-existing fractures and the formation of about 30 small (about 10 mm in diameter and 1 mm thick) rock chips.

Theory predicts that the stresses at the borehole wall assymptote towards a maximum value about 30 days after the start of the experiment; in the case of the 5 kW heater, this maximum stress is tangential and is calculated to be about 215 MPa at the heater midplane (Chan and Cook 1979). This value is in the same range as the mean uniaxial compressive strength of the rock, measured in the laboratory as 208 MPa $\pm$ 31 MPa at room temperature, with only small variations from this mean value at elevated temperatures (Swan 1978). If the borehole were subjected only to a mechanical loading, failure would be expected to occur only when the induced maximum compressive stress exceeded the uniaxial compressive strength of the rock. Also, according to linear thermoelastic theory, failure of the rock under load is a time-independent phenomenon at a given stress level.

These predictions do not agree with the observed results, which are given for both full-scale heater boreholes and for two representative time-scale heater boreholes in Fig. 10. This figure demonstrates that during the first few weeks of these experiments the observed decrepitation of the borehole walls was negligible. As the experiments progressed, the numbers of small cavities observed on the rock walls increased. This was true even when the maximum induced stress was much less than the strength of the rock (Fig. 10b). Another mechanism, such as a change in rock composition as a result of dehydration, or the introduction of thermal strains leading to degradation of mechanical strength (Jaeger and Cook 1976), must be invoked to explain the

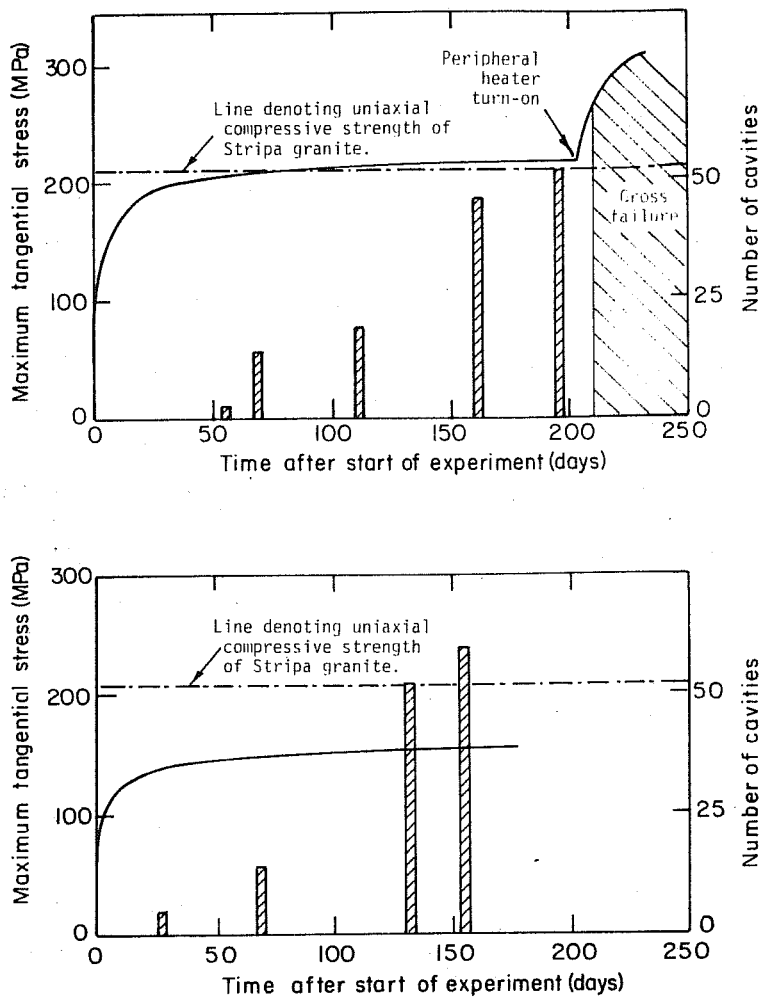

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Fig. 10. Maximum induced compressive stress at the walls of both the 5 kW (upper graph) and the 3.6 kW (lower graph) heater boreholes plotted as a function of time, together with lines denoting the uniaxial compressive strength of the rock. Also plotted are the number of cavities induced in the borehole wall as a result of thermal spalling.

observed spalling. Work in this area is continuing.

3.5 Experiment Using Peripheral Heaters

Results from this experiment have not yet been analyzed in detail. One interesting observation, however, is that two significant increases in the temperature measured at the midplane on the skin of the full-scale heater canister were step functions in the temperature:time curve, 12 days and 17 days after the peripheral heaters were turned on (Fig. 11). Also plotted in this figure is a curve showing the predicted temperature rise. Since it is evident from Fig. 10 that the induced compressive strength exceeds the

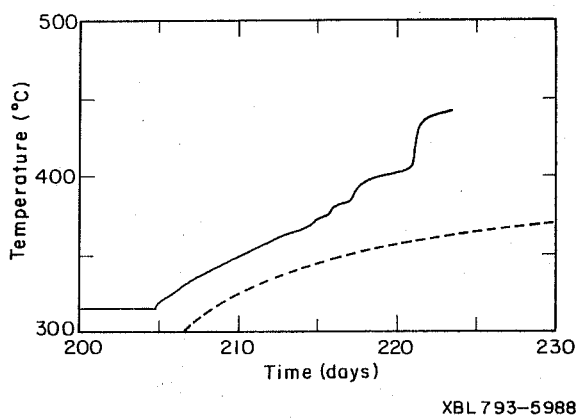

Fig. 11. Predicted (dashed) temperatures on the heater borehole and measured temperatures (solid) on the heater canister plotted as a function of time. Jumps in curve for measured data are a result of decrepitation of borehole following turn-on of the peripheral heaters. The temperature loss by radiation between the canister and the borehole wall is responsible for an approximate 30°C difference between predicted and measured temperatures.

uniaxial strength of the rock over large sections of the borehole wall only a few days after turn-on of the peripheral heaters, gross failure of these walls would be expected.

Observations using the borescope confirm that serious deterioration of the heater borehole occurred within a few days of the peripheral heater turn-on. Initially this spalling was concentrated about the heater midplane and was characterized by the formation of rock chips, 20 to 30 mm in diameter and 2 to 3 mm thick. Following the first step increase in canister skin temperature (Fig. 11), decrepitation of the borehole wall increased severely both in the extent of damage along the length of the borehole and in the size of rock chips. Much larger rock chips were observed, some up to 150 mm in length, and the annulus between the canister and the borehole became blocked with rock fragments.

4. DISCUSSION

The present analysis of the experimental results indicates that:

(a) Heat transfer through an in-situ rock mass is effected mainly by conduction, and the temperature field which is generated as a result of the emplacement of heater canisters within the rock is isotropic and can be predicted using a simple, semi-analytical, mathematical model.

(b) Rock movements caused by thermal expansion are non-linear and consequently are not readily amenable to predictions by simple modeling techniques. Preliminary calculations (Chan 1979) suggest that temperature-dependent parameters for the elastic and thermal properties of the rock, as well as the influence of confining pressure on the coefficient of thermal expansion for the rock, are required for any model to predict rock movements.

Also, the initial response of a rock mass to thermal loading appears to be non-linear in terms of rock movement, especially when the predicted rock movements are small. It is postulated that this phenomenon may be the result of pre-existing void space within the rock mass taking up the expansions. The response becomes linear after this initial phase.

(c) Calculation of the stresses generated within the rock by the applied thermo-mechanical loading are subject to the same considerations as given in (b) above. Further development of instrumentation is required to accurately monitor these stresses in the field.

(d) Decrepitation of the borehole walls appears not to be a significant problem as long as the maximum tangential or axial stress at the wall is less than the uniaxial compressive strength of the rock. In the granite in which these experiments were conducted the calculated stress values indicate that this criterion was not exceeded when a canister with the power output of 5 kW, equivalent to high-level waste materials some 3.5 years old, was emplaced in the granite. Limited spalling of the heater borehole walls is observed at stress levels much less than are given by this criterion. Possibly this is caused by differential expansions of the minerals that comprise the rock.

(e) The stresses induced at the wall of the 5-kW heater borehole, after the turn-on of the peripheral heaters, are artificially high compared with the stresses that would be generated by the emplacement of an equivalent canister in a rock mass which already is at the ambient temperature induced by these additional heaters. Nevertheless, this experiment indicates that the uniaxial compressive strength of the rock may provide a failure criterion for the rock along the borehole wall. The theory of thermo-

elasticity can be used to calculate the stresses that will be induced at this surface by a given heater canister. If these stresses are less than the uniaxial compressive rock strength, then failure of rock on a scale sufficient to impair the ability to retrieve the canister is unlikely.

II The application of Field Data from Heater Experiments Conducted at Stripa, Sweden, To Parameters for Repository Design

Part II

ABSTRACT

Experiments, currently in progress, are designed to yield information about both the near-field and the far-field effects of thermomechanical loading of an in-situ, granitic rock mass. Electrically heated canisters, constructed to represent high-level radioactive waste canisters, are emplaced in boreholes from excavations some 340 m below the surface. Thermally induced spalling along the heater borehole wall, a near-field effect, has been monitored and two types of spalling, one serious and one not serious, have been identified. A suggested failure criterion for the serious type of spalling is $\sigma_{max} \geq C_o$ (where σ_{max} is the maximum induced compressive stress at the borehole wall and C_o is the uniaxial compressive strength of the rock). In one of these experiments this criterion was exceeded, and gross failure at the wall occurred when the equivalent power to the heater was increased beyond 5 kW. The far-field effects of the applied loading are investigated by measuring the temperature, displacement, and stress fields and then comparing the results with predictions which were made based on linear thermoelastic theory. The results show that the dominant mode of heat transfer through the rock is by conduction and, therefore, that predictions of the temperature field are made readily using simple calculations. However, displacements and stresses within the rock mass are measured to be only one-half or less of the values predicted. Two reasons for this major discrepancy are suggested. Work to verify this result is in progress but the implications are profound since, for a given canister power level and canister spacing, the magnitude of the stresses induced in the rock mass would be reduced by at least a factor of two. Alternatively, given a maximum

canister power level, canister spacing within the repository could be halved for the same applied stress loading.

1. INTRODUCTION

The preferred method for disposal of radioactive waste materials is burial in deep underground repositories (National Research Council 1957, American Physical Society 1978). The main requirement for such repositories is that they be capable of isolating these waste materials from the biosphere for very long time periods. Two main prerequisites in the selection of sites for repositories will be that the sites have been, and will remain, geologically stable; and that groundwater flow through the rock, which could act as a transport medium for radionucleides, is low, and will remain low, during a thermal perturbation such as would be induced in the rock by the decay of radioactive wastes. Cook (1978) in an overview summary has examined, from a theoretical viewpoint, the characteristics desirable in a repository in hard rock. Cook recommends that repositories should be sited at depths greater than 0.5 km, but less than 2.0 km below the surface, and that the uniaxial compressive strength of the rock should be of the order of 200 MPa. To obviate the occurrence of faulting and to retard groundwater flow he recommends further that the horizontal component of stress be greater than two-thirds that of the vertical stress, and that the maximum value of this stress difference should be 25 MPa.

This paper focuses on two specific considerations affecting repository design: firstly, the limits on canister power levels in the near field as imposed by decrepitation of the borehole wall and secondly, the ability to predict the thermally induced stresses and their impact upon far-field

effects. Both problems are discussed in terms of recent field results from the experimental program at Stripa.

2. REPOSITORY DESIGN CONSIDERATIONS

a) Borehole Wall. A desirable feature of a repository, and a feature which probably will be a prerequisite for any future repository in the United States, is an assurance of the ability to retrieve canisters from the boreholes in which they are emplaced, should the need arise within a reasonable time after burial. In order to be able to give this assurance, it will probably be necessary to ensure that thermal spalling of the rock at the borehole wall does not occur to any significant extent. This is likely to be a design requirement for the repository regardless of whether the borehole is protected by a liner which could be inserted between the canister and the rock wall.

The main factors tending to cause rock failure at the borehole wall are the induced compressive tangential and axial stresses acting at this surface. These stresses are given by

$$\sigma_z = \sigma_\theta = \frac{\alpha E}{1-\nu} T \times 10^3 \qquad (1)$$

where σ_z = axial component of stress (MPa)

σ_θ = tangential component of stress (MPa)

α = linear coefficient of thermal expansion ($°C^{-1}$)

T = temperature at borehole wall (°C)

ν = Poisson's ratio

E = Young's modulus (GPa).

If these stresses exceed some accepted failure criterion, such as the Mohr-Coulomb criterion, then the rock is likely to fail. Experience with mining in deep-level hard rock formations has shown that a reliable criterion for rock failure around small circular openings is for the induced hoop stress to exceed the uniaxial compressive strength of the rock. Although this experience is derived from situations where the induced stresses are mechanical, there is no reason to expect that thermomechanical stresses would produce a significantly different result.

From Eq. (1), the stresses induced at the canister borehole wall are functions of the rock temperature which, in turn, for a given canister-borehole geometry and rock thermal conductivity and diffusivity, are dependent on the power level of the canister. This power level is a strong function of the age of the material. Thus, prevention of major rock spalling is likely to be the dominant factor in the determination of maximum canister power levels and, therefore, of the minimum age of the wastes prior to burial. The range of heater power levels and geometries used in Stripa experiments was selected to study the spalling phenomenon in detail. The experiments are designed so that the maximum induced compressive stress at the borehole wall is in excess of the uniaxial compressive strength of the rock for at least one of the tests.

b) Far Field. It can be shown using the theory of linear thermoelasticity that as a result of the decay of radioactive materials, a repository will be subjected to a thermal pulse causing the rock surrounding the excavations to reach a maximum temperature within a few decades after burial of the wastes (Hodgkinson 1978, St. John 1978). During the heating phase, thermal expansion of the rock will induce regions of compressive

stress in the heated rock immediately surrounding the repository and tensile stress outside this compressive zone (Fig. 12).

This induced tension is of concern because it will produce reductions in the compressions across joints in this zone. Since the permeability of crystalline rocks such as granite arises mainly from the hydraulic conductivity of joints and fractures, the induced tension will result in increased groundwater flow throughout this portion of the rock mass.

The factors which influence the magnitudes of these induced stresses are (after Hodgkinson 1978):

(i) Size and shape of the repository

(ii) Depth of the repository

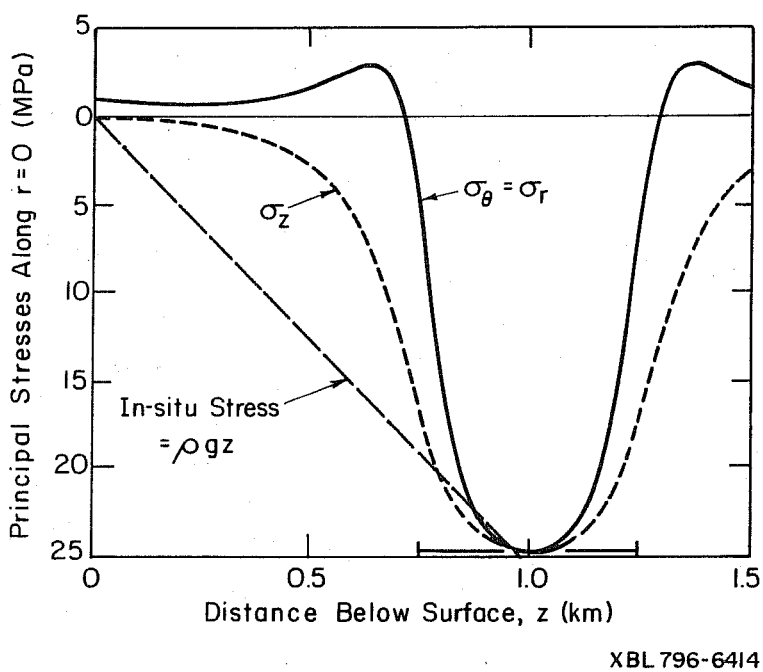

Fig. 12. Computed vertical and radial stresses along a vertical line passing through the center of a heated sphere of 250-m radius placed 1000 m below the surface of a half-space (after Hodgkinson 1978).

(iii) Thermal conductivity of the rock

(iv) Total heat load of the repository.

In general all of these factors are controllable and, at any given site, all factors except (iii) are controllable. These then form design criteria for the repository.

3. RESULTS OF STRIPA EXPERIMENTS

3.1 Monitoring of Rock Spalling Along the Borehole Wall

With a borescope designed to withstand high temperatures, the rock walls along the boreholes where the heaters are emplaced have been periodically observed and the extent of decrepitation recorded. The results of these observations in the two full-scale heater holes are given in Fig. 10 (Part I).

This graph illustrates a number of interesting points. First, the predicted induced compressive stress, which is a hoop stress, asymptotes to a maximum value within 10 to 20 days after the start of the experiment. Second, small cavities appeared on the wall surface after several weeks of heating; the number of cavities increased as a function of time, apparently independent of the induced stresses until the additional, peripheral heaters were activated. Third, after turn-on of these peripheral heaters, gross failure of the rock occurred along the length of the borehole.

The curves of stresses as a function of time illustrated in Fig. 10 are calculated using Eq. (1), with temperature-independent values for the elastic properties of the rock. Spalling along the borehole walls was extremely limited, and may be considered insignificant, before turn-on of the peripheral heaters. After this event, when the induced compressive stresses at the surface were caused to increase, gross failure of the wall occurred.

The nature of the spalling phenomenon before and after the perturbation caused by the peripheral heaters is illustrated diagrammatically in Fig. 13. Deterioration of the rock wall immediately after the start of the experiment was very limited, and was characterized by the enlargement of pre-existing fractures intersecting the borehole and the formation of small rock chips, typically 10 mm in diameter and 1 mm thick along this surface. This type of damage increased with time but, even after continuous heating for more than 200 days, only 50 to 60 of these minor spalls could be observed along the complete length of the borehole. This amount of damage can be regarded as negligible. After activation of the peripheral heaters, gross failure of the wall occurred rapidly. Within a few days, the annulus between the canister and the borehole became filled with debris, preventing further observation.

These results indicate that two distinct mechanisms are involved in this spalling phenomenon. First is the time-dependent behavior, which obviously is not explained by thermoelastic theory, and which is not well understood. Cook (1978) has suggested other possible mechanisms for thermal deterioration of rock, including (a) dehydration of clay minerals and (b) differential thermal expansion of individual crystals within the rock. Second is the gross failure, which appears to be stress related; further work is required to determine positively the stress criterion beyond which the rock will fail.

Finally, note that the increased stresses induced at the heater borehole wall by turn-on of the peripheral heaters could be reproduced simply by increased power in the main heater. The equivalent full-scale heater power to generate these same stress levels at the rock wall is about 7 kW (Chan 1978). With heater power levels of 5 kW, in this rock type, borehole wall

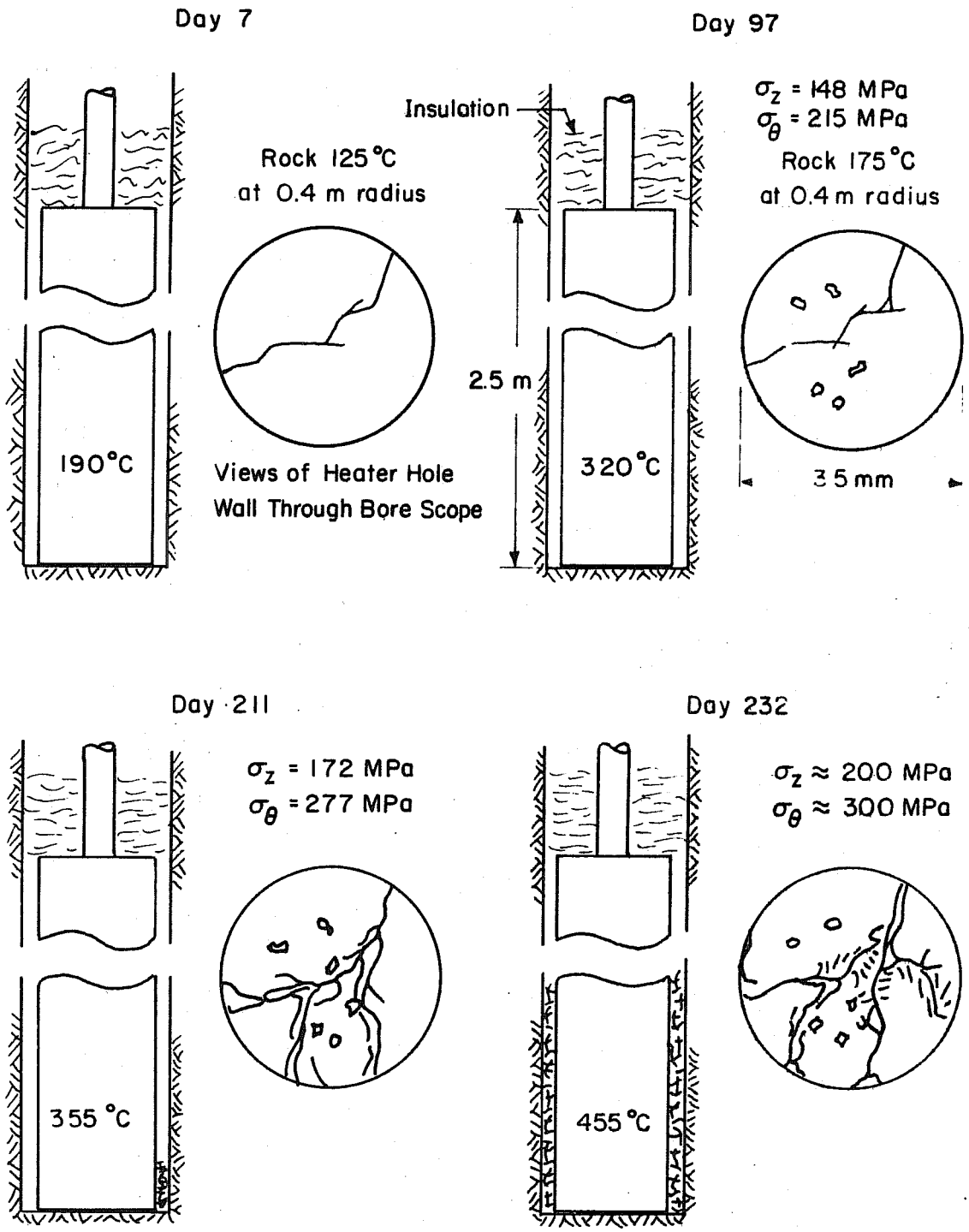

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Fig. 13. Results of borehole decrepitation around the 5.0 kW full-scale heater. Peripheral heaters were started at day 204.

decrepitation is negligible; at levels of 7 kW, gross failure of the borehole is induced. Therefore, about 5 kW is the maximum acceptable power level for canisters of this geometry in this rock type.

3.2 Temperature, Displacement, and Stress Measurements in the Rock Mass

Thermocouple readings show that rock temperatures are symmetrical about the heater midplanes and heater axes; that is, the heat flow is not affected by discontinuities in the rock mass. Since conduction is the dominant mode of heat transfer, the temperature field is amenable to prediction using relatively simple semi-analytical or finite-element methods (Chan, Cook, and Tsang 1978).

Unlike temperature, displacement measurements are not consistent with values predicted (Chan and Cook 1979) for each of the extensometer and stress gauge locations using linear thermo-elastic theory. The extensometer readings, which are the easiest to interpret since displacement is measured directly, show two distinct types of behavior. Soon after the turn-on of the heaters, displacements are very much less than those predicted.

Later, displacements increase uniformly, but at one-half or less of the predicted rate. The ratio of the measured displacements to the predicted displacements as a function of time is given in Fig. 6 (Part I). These non-linear initial portions and subsequent linear portions of the curves are puzzling, since the thermocouple data indicate that the rock mass is subjected to changes in temperature and, therefore, to thermal expansion. Detailed checks of both the instruments and the predictive models have revealed no errors sufficiently gross to explain these results.

A plausible explanation for the initial, non-linear rock behavior is that the rock expansion is absorbed into pre-existing discontinuities. This argument is supported by independent experimental evidence using cross-hole ultrasonic measurements in the rock adjacent to one of the full-scale heaters. Some of these results are illustrated in Fig. 14, which shows marked increases in wave velocities during this same time period of the experiment, probably indicating closure of fractures in the rock between the transducer and the receiver.

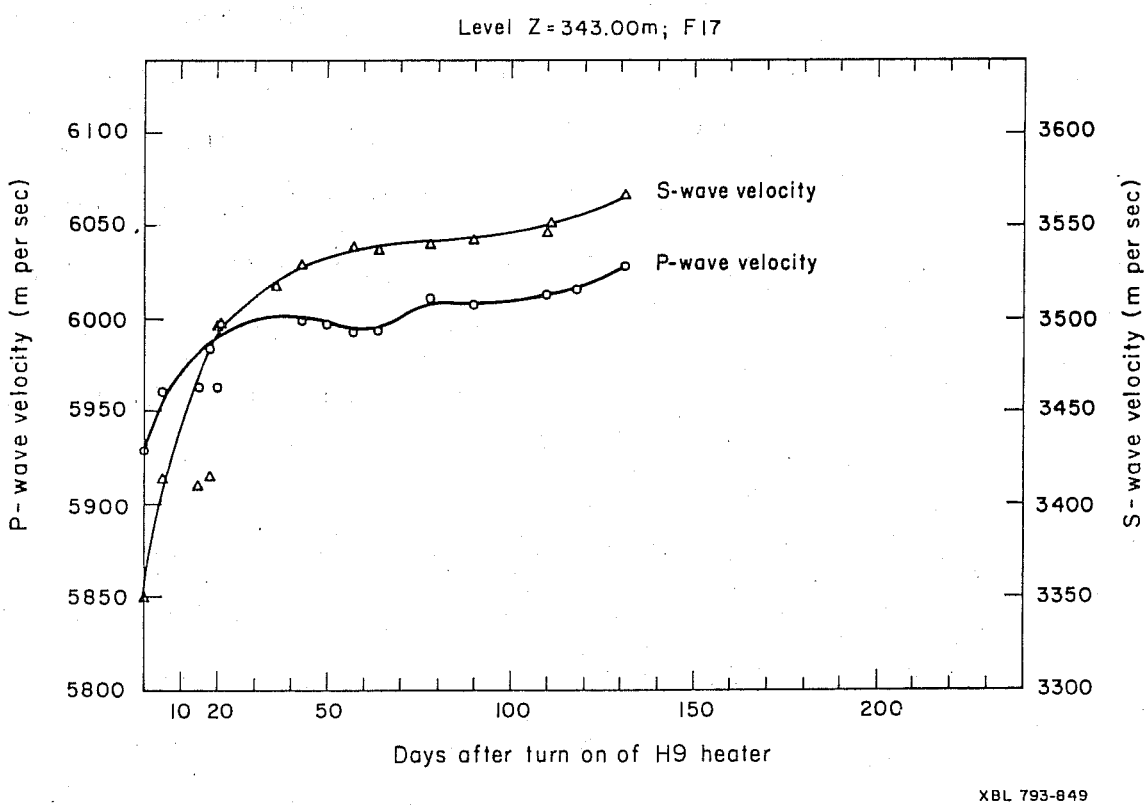

Fig. 14. Ultrasonic velocity measurements between boreholes 4 m apart at the heater midplane elevation in the rock mass adjacent to the 3.6 kW heater.

The puzzling feature of the linear portion of the displacement ratio plot (Fig. 6) is that this curve trends to a constant value other than unity. Recent experimental data (Swan 1978) have shown that some rock properties are temperature dependent. Preliminary calculations using these values in the predictive models indicate 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 laboratory testing is needed 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 (Fig. 15) show a trend similar to the extensometer measurements; namely, the observed results have a value only about one-half or less of the values predicted. Here, again, the induced far-field stresses appear to have values much less than the values that are predicted by thermoelastic theory. These results are still being analyzed. Stress measurements obtained using U.S. Bureau of Mines borehole deformation gauges have not been analyzed because the gauges were incorrectly calibrated.

If rock expansions are indeed reduced by the presence of pre-existing discontinuities, the stress induced in the rock mass by the thermomechanical loading will be reduced substantially, and calculations made using linear thermoelastic theory of the stress field surrounding a repository (for example, the predictions illustrated in Fig. 12) will be overly conservative. This implies that the disturbance to the groundwater flow regime in the regions outside the heated rock mass, where the compression across joints is reduced, will be less than predicted. Another effect will be that during the first few decades, when the rock surrounding the repository is undergoing the

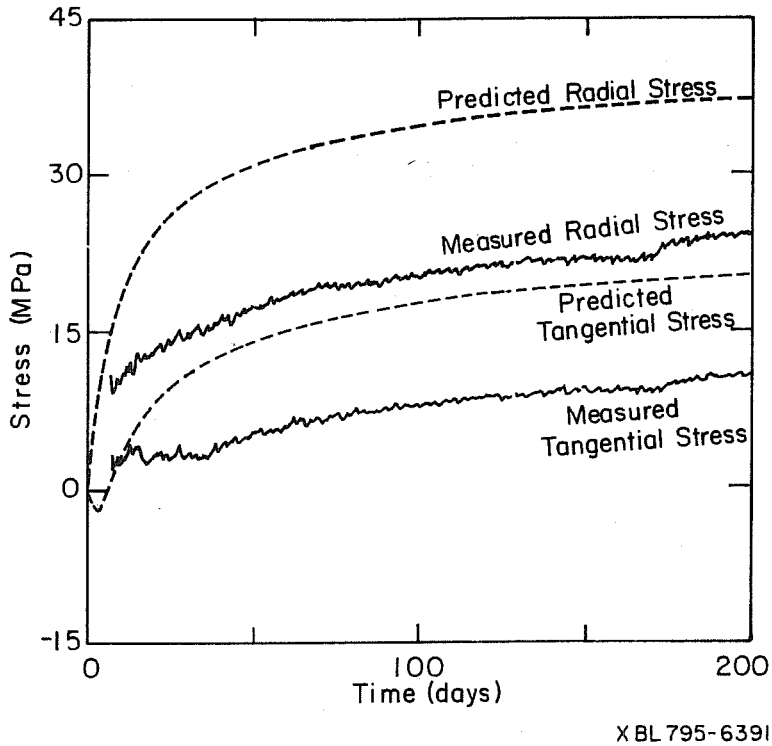

Fig. 15. Predicted and measured stresses from a vibrating wire gauge located 1.5 m radially and 0.85 m above the center of the 5 kW heater H10. Stress components are directed along and tangential to a radial line from H10 to the gauge position.

heating part of the pulse cycle, groundwater flow through this heated rock mass will be reduced, since the rock discontinuities are compressed. This second point may not be of long-term importance because after the maximum temperature has been reached in the rock surrounding the repository and as this rock begins to cool, the joints and fractures which had been closed by the heating may reopen causing the groundwater flows to return to, or even to increase beyond, their original levels. The experimental program at Stripa will monitor rock behavior and groundwater flow through the rock for a minimum period of 6 months after the heaters are turned off, so that questions of this kind can be answered quantitatively.

4. SUMMARY

The results of the field experiments, to the extent that they have been analyzed at the present time, and the impact of these results on the design of a repository in hard rock are as follows:

a) The maximum power level for proposed radioactive waste canisters, one of the near-field design criteria for a repository, has been determined within close limits. For the Stripa granite rock type this power limit is between 5 kW and 7 kW, probably closer to the former. It is suggested that a failure criterion for the onset of gross decrepitation of the heater borehole wall may be $\sigma_\theta = \sigma_z \geqslant C_o$. Further work is required to confirm this as a failure criterion.

b) Displacements and stresses induced by thermomechanical loading generally are less than the values predicted by linear thermoelastic theory. Reasons for these lower measured stress values, including instrument calibration, are still the subject of investigation but it is postulated that two mechanisms may be responsible. First, time lags in the displacements (as measured by extensometers and by ultrasonic wave velocity measurements) indicate that during the initial phase of the experiments rock expansions may be absorbed into pre-existing fractures. Second, if temperature-dependent rock properties are used in the predictive numerical codes, the magnitudes of the theoretical displacements and stresses are reduced substantially. Further work in this important area is required, and it is anticipated that the data gathered during the monitoring of the cool-down period after the heaters are turned off will be crucial.

It follows that if the stresses induced in the rock surrounding the repository are significantly less than those predicted by linear thermo-elastic theory, then the concerns regarding the increased permeability of the rock will be reduced.

5. ACKNOWLEDGMENTS

B. Paulsson provided the ultrasonic velocity data, and L. Andersson assisted with the borehole decrepitation observations. The observations of T. Schrauf (Terra Tek, Inc.) concerning the stress measurements were useful for this analysis.

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