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INSTRUMENTATION AND COMPUTER BASED DATA ACQUISITION FOR IN-SITU ROCK PROPERTY MEASUREMENTS

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Abstract

This paper discusses instrumentation and computer based data acquisition for in-situ rock property measurements as applied to an experiment conducted at Stripa, Sweden in cooperation with the U. S. Department of Energy and the Swedish government. Electrical heaters were installed in an underground granite mass to simulate thermal loading by canisters of high-level nuclear waste. Extensometers, borehole deformation gages, vibrating wire stress meters, and thermocouples were used to monitor the thermomechanical response of the granite. A computer based data acquisition system recorded data, performed on-line computations and provided graphic output. A summary description is given of the experiment areas, heater systems, data acquisition hardware, and four types of instruments used for the in-situ rock property measurements.

Introduction

A cooperative Swedish-American program is underway to investigate the suitability of granite as a deep underground storage medium for nuclear waste isolation. The experimental program, located in an inactive iron ore mine at Stripa, Sweden, includes three heater experiments to evaluate the thermomechanical response of a granite mass when subjected to the heat load of simulated canisters of high-level nuclear waste.

This report is a compilation and summary of previously reported work[1-4] associated with instrumentation and data acquisition systems for these heater experiments. The authors cited in the first four references are duly recognized as the sources of the material for this tutorial presentation.

The Stripa experiments require the measurement of temperature, rock displacement and stress during one and a half years of heating and cool-down. The first heaters were turned on June 1, 1978, and the last heater was turned off September 26, 1979. Rock cool-down measurements continued through February, 1980. Rock temperatures over 300°C have been measured and the mechanical response of the rock has been measured at temperatures to 150°C. Measured heater canister skin temperatures have approached 500°C.

Few available rock mechanics instruments are designed to meet the accuracy and reliability requirements at the elevated temperatures encountered in this type of experiment. Therefore, available instruments have been modified and tested; and calibration techniques have been developed in an attempt to meet more stringent requirements.[1,2] The modified instruments have produced a wealth of valuable data from the Stripa experiments despite some specific problems and recommendations for further improvements.

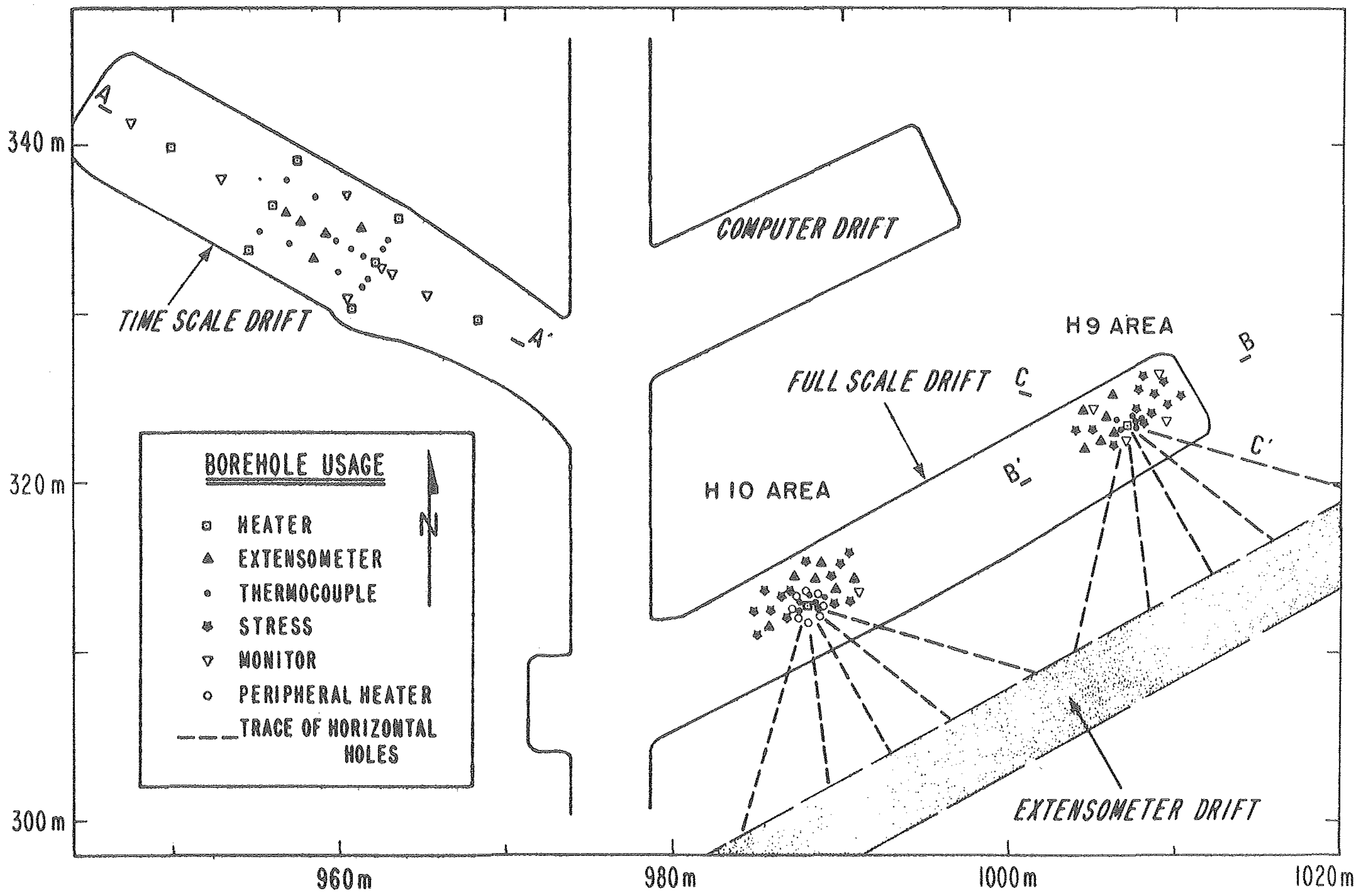

Fig. 1. Plan view of experiment area 340 m underground, showing locations of heater and instrument boreholes.

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Experiment Areas

The heater experiments are located in two drifts 340 meters below the surface. A time-scale experiment is located in one of the drifts and two full-scale experiments in opposite ends of the other drift, as shown in Fig. 1. The time-scale experiment is scaled so that one experimental year represents ten years of waste storage. An extensometer drift runs parallel to the full-scale drift, but at a lower elevation, to provide access for installation of horizontal instrumentation in the rock surrounding the full-scale heaters. Heater power controllers, instrumentation, signal conditioning circuits, data loggers, computer scanners, analog-to-digital converters, and interfacing electronics are housed in sheds located in the two heater drifts. A 2.5 by 8 m instrumentation shed is located against one wall between the two experiments in the full-scale drift. A 3 by 4 m instrumentation shed is located in the back end of the time-scale drift. More than 750 sensor signals are digitized and transmitted to a ModComp IV computer housed in a climate controlled room in a drift a few tens of meters from the heater experiments.

Heaters and Power Controllers

Three styles of electrical heaters were used in the Stripa experiments; full-scale heaters, peripheral heaters, and time-scale heaters.[3]

The full-scale heaters were designed to simulate one of the possible geometries of a single waste canister, and to provide a heat source of up to 5 kW. These heaters were installed in two 406 mm (16 in.) diameter vertical boreholes nominally 5.5 m (18 ft) deep in the floor of the H9 and H10 areas (Fig. 1). Two full-scale heaters are shown in Fig. 2 prior to shipment to Sweden. The dark colorization of the rear canister was caused by testing at temperatures in excess of 600°C. Each stainless steel canister is 2.6 m (8.5 ft) long and 324 mm (12.75 in.) in diameter, and contains four independent heating elements, each capable of 5 kW. Wiring is brought to the borehole surface through a bell-housing attached to the structure at the top of the canister and shown standing just to the left of the canisters. Power is provided by four heater controllers, each also capable of 5 kW. Under normal operation, each heating element and controller combination supplies one-quarter of the canister heating, with the capability of maintaining program power in the event that up to three elements and/or controllers should fail. We have had no failures in Stripa that have required use of this redundancy.

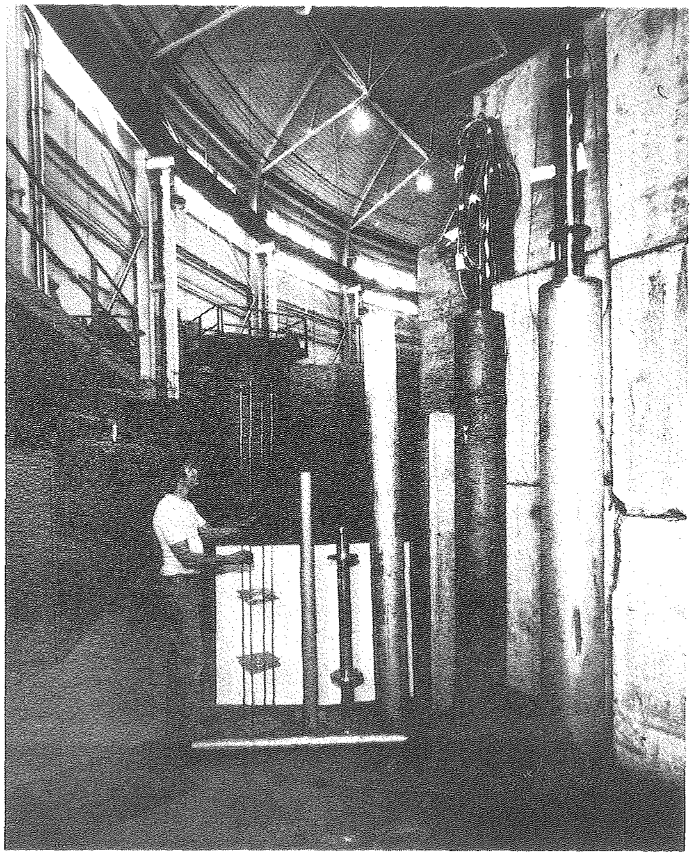

Fig. 2. Full-scale heater canisters.
CBB 7710-10268

The heater in the H9 area was operated as a single unit at a continuous power level of 3.6 kW for nearly 400 days. The H10 heater operated as a heat source at 5 kW for 394 days. After 203 days eight peripheral heaters surrounding H10 were turned on. The 4.3 m (14 ft) long peripheral heaters were installed in 38 mm (1.5 in.) boreholes, approximately 6.4 m (21 ft) in depth and located at a radius of 0.9 m (3 ft) around H10. They were powered at 1 kW each during the first 40 days after their turn on. Power was then reduced to 0.85 kW each until all heaters in the H10 area were turned off. The peripheral heaters each used a single heating element and were powered in parallel groups of four.

Eight time-scaled heaters were arranged in a rectangular array (Fig. 1) to simulate the heat load and distribution of a large field of waste storage canisters. These heaters are approximately one-third the size and power of the full-scale heaters. Modeling laws were used to select a scaling factor and heater spacing that could create a thermomechanical response with a time constant one-tenth that for a full-scale heater. The heaters were installed in 127 mm (5 in.) boreholes at a depth of approximately 11 m (36 ft). Each canister contained two 0.76 m (30 in.) long heating elements, each powered by its own controller. The time-scale controller racks with 16 controllers are shown in Fig. 3. Time-scale canister power levels started at 1.125 kW and were reduced over a one-year period to 0.54 kW, simulating the decrease of power output of high-level radioactive waste over a ten-year period.

In all cases, heater power, voltage, and current were independently monitored and recorded by the data acquisition system. Voltage and current data were compared with power data as a cross-check.

Dewatering systems were installed in all of the heater boreholes, and desteaming systems were provided for the full-scale and time-scale heaters. The volumes of water removed were logged over the duration of the experiment.

Data Acquisition System

Four types of instruments were used at Stripa to monitor the thermomechanical response of the granite; 389 thermocouples for temperature, 35 extensometers for displacement, 30 US Bureau of Mines (USBM) borehole deformation gages and 26 IRAD (Crearé) vibrating wire stress gages for stress determination. These instruments along with 109 heater power, voltage, and current signals generated more than 750 sensor signals to be recorded. A data acquisition system centered around a ModComp IV computer was used to acquire and digitize data, convert measured values to engineering units, store data for random access, provide on-site graphical data displays, and transfer data to Lawrence Berkeley Laboratory for futher analysis.[4] Duplicate computer peripherals and backup data loggers were used to reduce data losses caused by equipment failures during the life of the experiment.

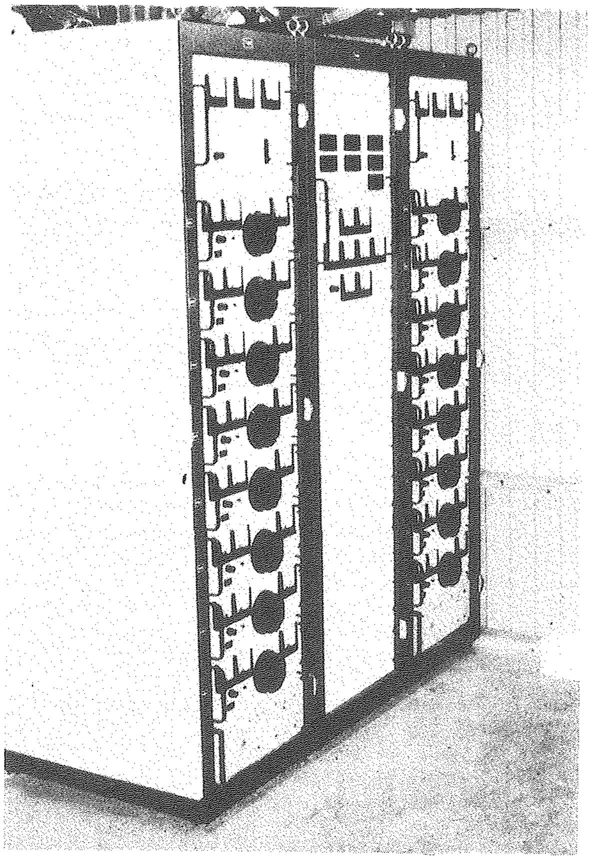
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Fig. 3. Time-scale heater controllers.

A ModComp IV-25 central processor (CPU) was used with a total of 512K bytes of core memory. Peripheral hardware included:

- two 50-million byte disc memory units;
- two nine-track magnetic tape transports;
- a real-time clock;
- two Digital Equipment Corporation DECwriters;
- one Texas Instruments TI-743 printing terminal;
- two Ann Arbor 4080 video terminals;
- two Tektronix 4014 graphics terminals; and
- a Versatec electrostatic printer/plotter.

Alphanumeric and graphic information displayed on Ann Arbor or Tektronix terminals is easily converted to hard copy using the printer/plotter.

Computer remote access (REMAC) of the sensors located in the two heater experiment areas was provided by two ModComp REMAC systems also located in those areas. Wide-range-relay analog-input (WRRAI) subsystems were used in conjunction with the REMACs to sample, multiplex, and digitize the analog instrumentation signals. Digital inputs, such as data from the IRAD gages, were accessed through a ModComp digital input/output interface subsystem (IOIS).

All sensors were also connected to Acurex Autodata Nine, B and F, or IRAD data loggers to backup the computer system. Outputs from these data loggers were recorded on printer paper. The data loggers also proved valuable to cross-check computer data, to aid with instrument calibration, for debug and maintenance, and as a convenient means of reading selected sensors while working in the experiment areas where the data loggers are located.

The Autodata-Nine data loggers are programmed to sense and alarm out-of-tolerance heater voltage, power, and other major and minor alarm conditions. The major alarms along with computer power outages, no central processor response, instrumentation-shed power outage, and smoke detector activation are used to activate audible alarms underground and on the surface. An automatic telephone dialer also sends an alarm to a 24-hour a day answering service.

Before the experiments were started, the computer was used interactively to individually calibrate all USBM gages, extensometers, and low-temperature thermocouples. This was done in the mine after these instruments were wired in their final operating configuration.

During the experiment, all active sensors are sampled at 15-minute intervals. These "raw" data points are time tagged, converted to engineering units (temperature, displacement, and stress), temporarily stored in a 24-hour disc buffer, and logged on magnetic tapes. After raw data points have accumulated for one time-averaging interval, their arithmetic mean is computed to obtain a representative mean data value and associated mean time. These less frequent time-averaged points are stored in a long-term disc file which is maintained on-line for the duration of the experiment.

Predicted temperatures, displacements, and stresses were calculated and stored on disc files for use with the graphic display system. These data are plotted as a function of time and displayed for real-time comparison with time-averaged field data. Predicted temperature contours are also plotted and compared with actual measurements.

ModComp-supplied process input/output software permitted all the applications software to be written in ANSI standard Fortran IV with ModComp supplied real-time extensions.

Recommendations for future systems include standardizing on one type of data logger for computer backup systems where possible, and the use of the same type of data logger as input multiplexing and digitizing devices for the computer. Nine-track magnetic tape transports to record data from the backup data loggers can also be extremely valuable.

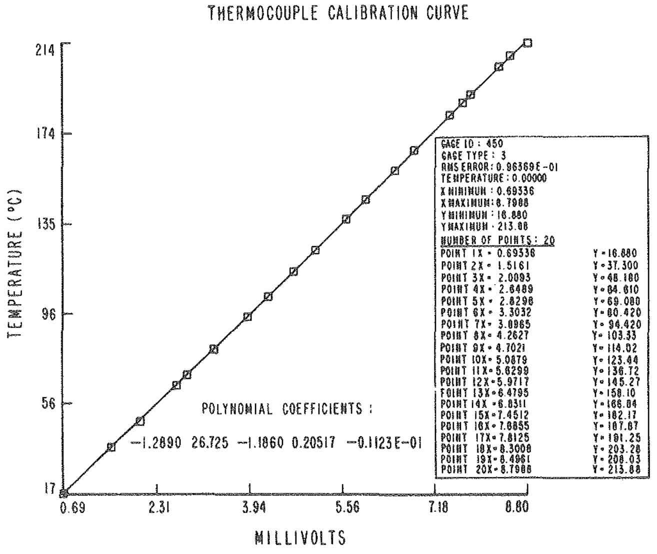
Thermocouples

Temperatures are measured using Chromel-Alumel (ANSI type K) thermocouples connected to ice-point temperature references. Thermocouples are attached to one or more points on each instrument for the dual purpose of rock temperature measurement and thermal compensation of the instrumentation. Others are located in independent thermocouple boreholes and mounted at several locations on each heater canister.

Where possible, thermocouples were obtained from the same Chromel and Alumel melts and from the same wire lots to minimize variability due to differences in metallurgy. Three types of thermocouple wire covering were used:

- TFE Teflon capable of continuous temperatures to 260°C;
- 304 stainless steel sheath for temperatures to 400°C; and
- Inconel 600 sheath capable of temperatures to 1150°C.

Teflon insulated thermocouples were manufactured with extruded Teflon insulation over the individual wires and a fused Teflon tape wrap over the wire pairs. Junctions were coated with a two component RTV 60 silicone rubber compound. A desired precision of ±0.5°C over a temperature range of 10° to 220°C for these "low temperature" thermocouples necessitated individual calibration. This was done on-site with the thermocouples tightly bundled and inserted into an aluminum mass inside a calibration oven. A platinum resistance temperature probe was used as the standard.[2] A fourth order polynomial curve was fitted to the calibration data, resulting in a set of five coefficients for each thermocouple. These are stored by the computer for online conversion from thermocouple voltages to temperature during the experiment. An illustration of a typical computer output for a thermocouple calibration is shown in Fig. 4.



```
GAGE ID : 450
GAGE TYPE : 3
RMS ERROR: 0.96369E-01
TEMPERATURE: 0.00000
X MINIMUM : 0.69336
X MAXIMUM: 8.7988
Y MINIMUM : 16.880
Y MAXIMUM : 213.88
NUMBER OF POINTS: 20
POINT 1X = 0.69336        Y = 16.880
POINT 2X = 1.5161         Y = 37.300
POINT 3X = 2.0093         Y = 48.180
POINT 4X = 2.6489         Y = 64.610
POINT 5X = 2.8298         Y = 69.080
POINT 6X = 3.3032         Y = 80.420
POINT 7X = 3.8865         Y = 94.420
POINT 8X = 4.2627         Y = 103.33
POINT 9X = 4.7021         Y = 114.02
POINT 10X = 5.0879        Y = 123.44
POINT 11X = 5.6299        Y = 136.72
POINT 12X = 5.9717        Y = 145.27
POINT 13X = 6.4795        Y = 158.10
POINT 14X = 6.8311        Y = 166.84
POINT 15X = 7.4512        Y = 182.17
POINT 16X = 7.6855        Y = 187.87
POINT 17X = 7.8125        Y = 191.25
POINT 18X = 8.3008        Y = 203.28
POINT 19X = 8.4961        Y = 208.03
POINT 20X = 8.7988        Y = 213.88
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XBL 792-7367

Fig. 4. Sample thermocouple calibration curve.

After installation, some thermocouples developed water leakage at the RTV coated junctions causing erroneous readings due to ground currents. This problem was solved by removing all electrical ground points other than those that would occur at the thermocouple junctions. In some of the grouted boreholes, head pressure forced the water along the thermocouple wire between the two layers of Teflon insulation and into the electronics enclosures. This was solved by cutting a short slit in the outer layer of insulation just after the thermocouple wire exited the borehole.

Sheathed thermocouples were used where higher temperatures were expected. Inconel 600 sheath was used for thermocouples attached to heater canisters and 304 stainless steel sheath was used where temperatures might exceed 200°C but remain well below 400°C. All sheathed thermocouples were 1/16 in. outside diameter with magnesium oxide (MgO) electrical insulation and with junctions sheathed but ungrounded. Lengths were selected to allow sheathed wire to exit the boreholes into an ambient temperature environment (10° to 20°C) before entering a transition joint to Teflon insulated type K extension wire.

Due to limitations in the maximum temperature capability of the calibration oven used in Sweden, the medium and high temperature range thermocouples could not be calibrated in the field beyond about 220°C. The five coefficients for a fourth order temperature-voltage polynomial were, therefore, derived from NBS tables.[2]

The sheathed thermocouples were heat treated at just below 600°C for 50 hours to stabilize an upward shift in output voltage that occurs with thermocouples using Chromel at elevated temperatures. This forced an upward but nonrecurring voltage shift equivalent to approximately 0.5°C per 100°C above 0°C. Unfortunately the heat treatment also sensitized the stainless steel sheaths to corrosion,[2,5] subsequently requiring the replacement of over 50 thermocouples. The Inconel sheaths have been trouble-free over the duration of the experiments.

Inconel sheathed thermocouples were inserted down long tubular thermocouple wells attached to the sides of the time-scale heater borehole casings. Closed at the bottom near the heater elements, these wells trapped moisture causing a boiling and condensing cycle within the tubing. The result was erratic temperature readings until the moisture could be removed. Holes in the well bottoms would have avoided this problem.

Recommendations resulting from our experiences at Stripa include:

- Use Inconel sheathed thermocouples exclusively. At least avoid stainless steel sheaths.
- Use grounded junctions in enclosed sheaths.
- Obtain all thermocouple wire from single material melts.
- Retain control samples of thermocouples to check long-term stability.
- Install tubing whenever possible for traveling thermocouples.
- Thermocouples should be removeable for recalibration and/or replacement.
- Provide a means to drain or remove moisture from thermocouple wells.

Rod Extensometers

A rod extensometer is a common device for measuring changes in the axial length of a borehole.[6] Terrametrics, Inc. (Golden, CO) model 4 CSLT(R) extensometers were used at Stripa. Basically these have performed well with interim maintenance and minor field modifications. Each extensometer measures the displacement of four downhole anchor points with respect to the borehole collar over a ranges of ±13 mm. One spring tensioned rod up to 13 m long connects each anchor point to one of four linear variable differential transformer (LVDT) type transducers located at the borehole collar. The major elements of these extensometers (Fig. 5) are: 1) the hydraulic anchor system, 2) the anchor-to-collar rod connection mounted inside a waterproof flexible conduit, 3) a head assembly which includes the rod tensioning system (100 lb per rod) and the displacement transducers, and 4) several thermocouples for sensing the temperature profile along the connecting rods.

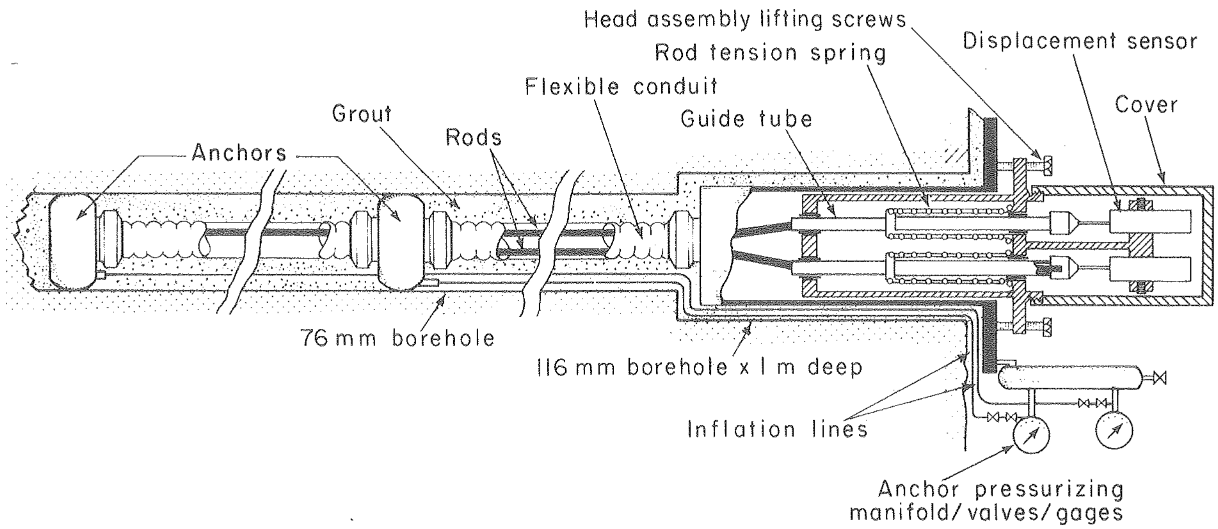

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Fig. 5. Foreshortened illustration of two anchor extensometer.

Each borehole anchor creates a fixed point along the borehole to secure a connecting rod. A hole through the anchor center allows any connecting rods originating at lower anchors to pass through. These anchors (Fig. 6) function by hydraulically inflating, against the borehole wall, a sealed flattened copper tube which has been rolled around a retaining mandrel.

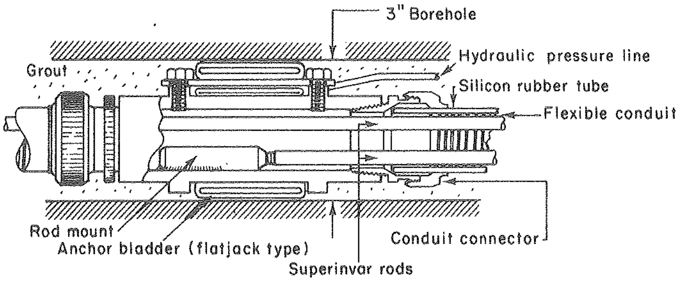

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Fig. 6. Extensometer hydraulic anchor.

On the basis of the anchor system test:[2] 1) Dow Corning X2-1162 silicone fluid was selected as the anchor pressurizing fluid capable of withstanding long term service to 200°C; 2) the hydraulic system was demonstrated to allow control of anchor pressure with changing temperature; 3) anchor creep under a 100-lb axial load at 190°C for 15 days was shown to be less than 2 μm even for an anchor which had been depressurized and where the grout had deteriorated; and 4) common Portland cement grout was demonstrated to maintain adequate strength at temperatures to 200°C.

Thermal expansion measurements were made on seven superinvar rods (Fig. 7), selected at random from the available stock (a single melt). These measurements were found to be reproducible after the stock had been heat treated at 225°C for 5 hours. The average expansion values were utilized in the computer data reduction program to calculate a thermal expansion correction. At stripa this correction was as much as 20% of the gross displacement. The temperature profile along the rods is estimated from the four to six measured values. However, this involved some assumptions, based on the symmetry of the thermal field, which have been found not to be entirely valid. We would, in the future, expect to install a tube down the length of the extensometer to enable a traveling thermocouple to survey the actual thermal profile several times during the experiment.

Extensometer calibrations were in-situ involving both data logger and computer monitoring of LVDT outputs. Calibrations were performed by lifting the head assemblies of the installed extensometers in precise steps of 5.00 mm from 0 to 20 mm.[2] After calibration, heads were positioned near mid-range.

Only one of the displacement transducers has failed during operation; however, internal rod friction has caused the displacement output to move in a stepwise fashion. We conclude that most of this friction effect resides in the spring tensioning and guiding elements of the head since up to 80 μm of stored

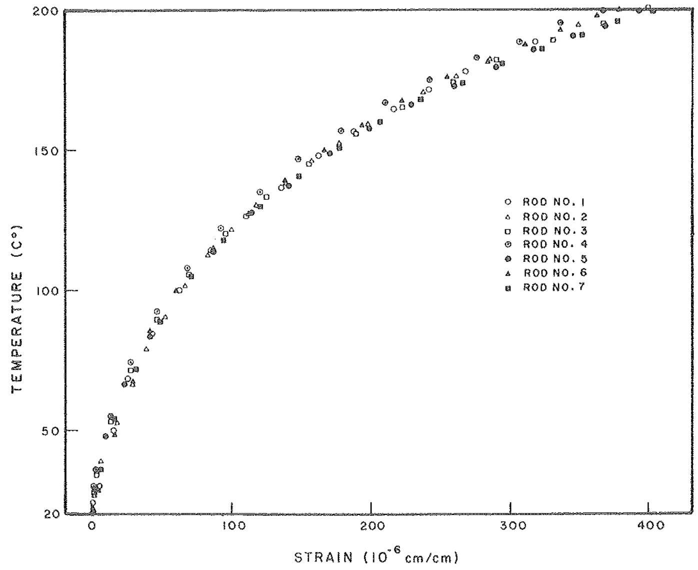

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Fig. 7. Thermal expansion measurements made on seven superinvar extensometer rods.

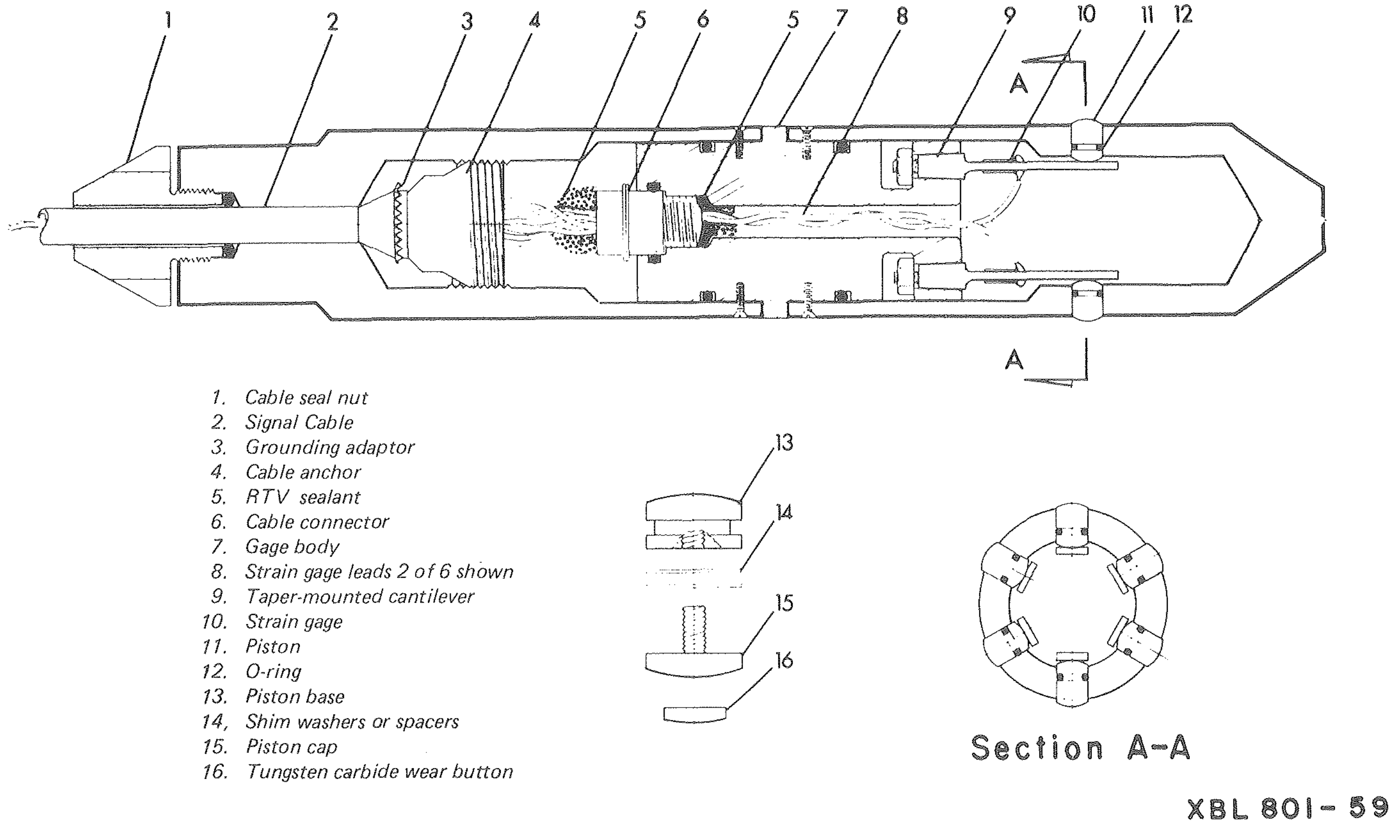

Fig. 8. Sectional view of USBM borehole deformation gage.

rod displacement was released when the heads of the extensometers were rapped with a screwdriver handle. A routine has been instituted to rap each instrument head in this fashion several times per week to continuously release the friction. Some design changes such as modifying the rod spacings and the bushing materials can reduce the friction, and vibrators can be added to the head to periodically release the stored energy.

In spite of the existence of a flexible metal conduit with a silicone rubber outer sleeve to protect the rods and thermocouples, water has accumulated in many of the horizontal extensometers and is probably also present in the vertical units. Water may corrode the rods and thermocouples, and create deposits inside the rod guide bushings. Electrical connections at screw-type terminal strips within the extensometer heads have caused trouble due to oxidation and corrosion. These have been replaced with solder connections and were waterproofed where necessary. The head covers have been drilled to allow leakage water to drain.

USBM Gages

The US Bureau of Mines "soft" borehole-inclusion gage utilizes three pairs of opposed cantilever beams to sense diameter changes of a 38 mm borehole (Fig. 8). These measurements across three diameters at 60° separation allow the principal stress changes in one plain in the rock to be calculated. Strain gages are mounted on the top and bottom of each cantilever. The four strain gages on opposing cantilevers make up one bridge circuit.

The gage was developed to measure in-situ stresses by the overcoring technique at ambient temperature.[7] For the Stripa application, the gage data reduction scheme was adapted for operation over a long time period at elevate temperatures, and several gage modifications have been made by the manufacturer, Rogers Arms and Machine Co. (Grand Junction, CO).2

USBM gage responses to temperature and strain were determined during laboratory tests at temperatures up to 200°C. The gage output was found to include voltage offset at constant displacement which was proportional to temperature and different for each cantilever pair.[2] There was also a linear change in slope (voltage versus displacement) of 6% from 23° to 200°C as indicated in Fig. 9.

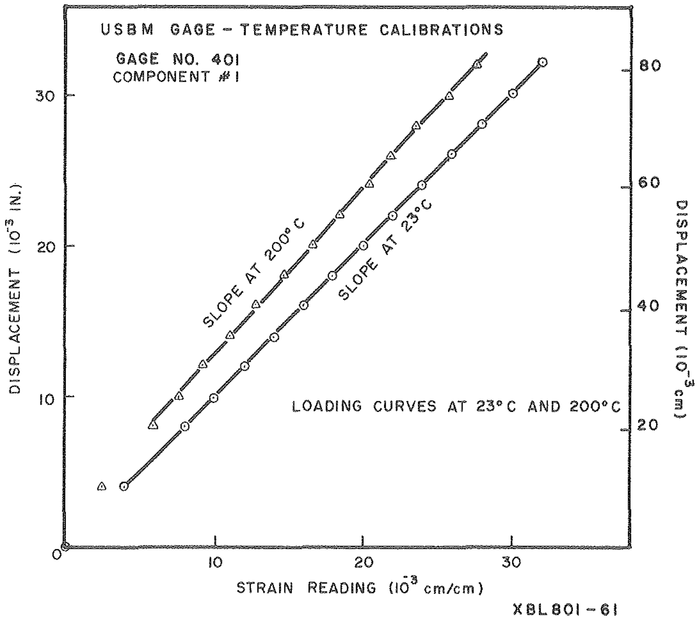

Fig. 9. USBM gage calibration curve.

Each USBM gage was calibrated on-site at ambient temperature just prior to insertion into a borehole. A thermocouple was installed with each gage to provide data for temperature corrections. Conversion of borehole deformations to stress, with an assumption of plain strain, utilizes input of values for Young's modulus and Poisson's ratio of the rock medium.[2]

The USBM gages have experienced numerous failures in service at Stripa. Sixteen of the twenty gages installed in vertical holes and two of the ten installed in horizontal holes have failed, some several times. The failures have been caused by water entering the gage housing, probably through or around the electrical cable. These failures occurred as either a short circuit at a strain gage or open circuit due to extensive corrosion of the pins in the connector joining the cable to a strain gage. The leaks occurred in spite of a regular dewatering operation which assured that the water level in any borehole was always below the gage.

To correct these problems, the gages were removed, rebuilt, recalibrated, and leak tested before reinstallation. The rebuilt gages incorporated several design changes to improve the integrity of the hermetic seal at the cable connection and to replace the pin connections with soldered connections. The gages passed a leak test procedure which subjected them to several days of immersion in water at 20 psig and 100°C. Those gages reinstalled in vertical boreholes were filled with a silicone fluid to prevent moisture from collecting in critical areas.

Vibrating Wire Stressmeters

Vibrating wire stressmeters[8] manufactured by IRAD Gage, Inc. (Lebanon, NH) have been installed in 38 mm diameter boreholes surrounding the full-scale heaters. Two stress meters oriented at 90° to each other are wedged into each of eight horizontal holes and five vertical holes to measure the principal stress changes in the rock resulting from the thermal gradients. A thermocouple is installed with each orthogonal pair of gages, and borehole dewatering is provided.

The vibrating wire stressmeter (Figs. 10 and 11) operates on the principal that a change in the tension on a wire causes a change in its fundamental period of vibration. The IRAD stress meter consists of a hollow steel cylinder with a highly stressed steel wire stretched across a diameter of that cylinder. When installed in a borehole, the cylinder is preloaded across the borehole, in the direction of the wire axis, by means of a sliding wedge and platen assembly.

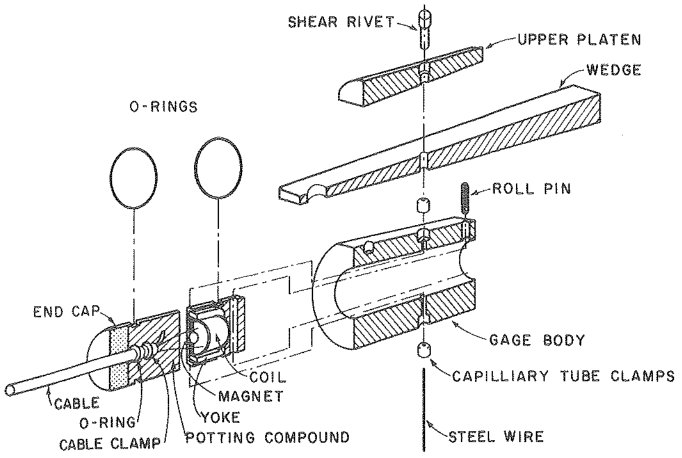

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Fig. 10. Vibrating wire stressmeter, sectioned view.

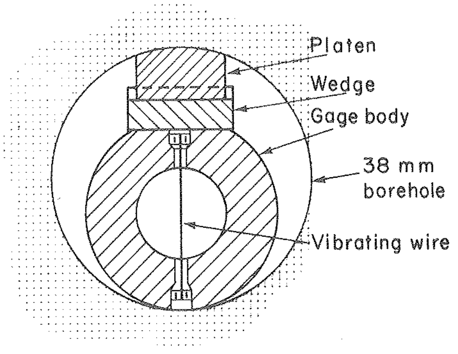

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Fig. 11. Sectional view of vibrating wire stressmeter wedged in borehole.

In this way the gage becomes a "hard" inclusion and the wire undergoes a change in tension as the steel cylinder deforms from stress changes in the surrounding rock. This change in wire stress is measured by exciting the wire and measuring its period of vibration (160 to 400 μsec).

Laboratory calibration in a sample of Stripa granite at ambient and at elevated temperatures provided a method for calculating the rock stress changes as a function of measured gage temperature (T) and period of vibration (R). A plot of R as a function of rock stress change ($\Delta\sigma_r$) for two temperatures is shown in Fig. 12. These curves fit the equation

$$\Delta\sigma_r = \frac{C_1(T)}{(R+\Delta R)^2} + C_2(T)$$

where $C_1(T)$, $C_2(T)$ and ΔR are functions of temperature (T) and of ambient temperature calibration values.[2] As an approximation, these values can be considered linear with temperature; however, additional studies are needed to determine their true variations as a function of temperature.

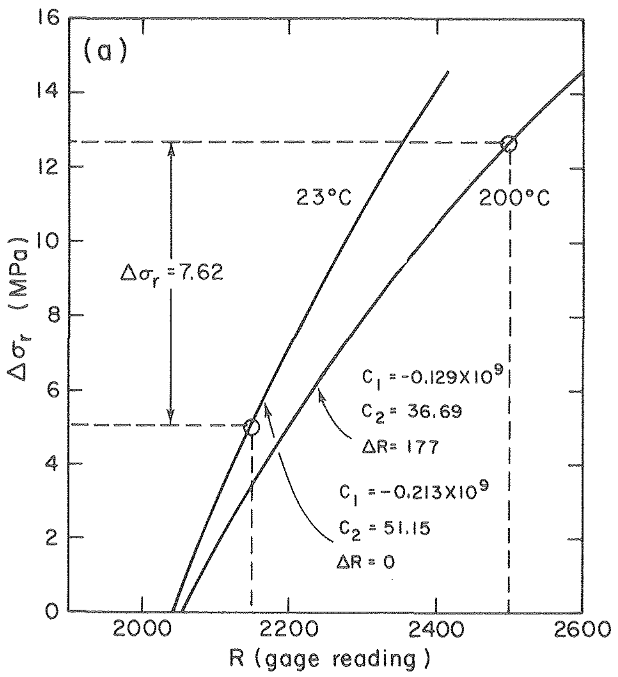

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Fig. 12. Vibrating wire stressmeter calibration curves

Note that the initial value of R (Fig. 12) is the gage reading after the gage has been preloaded, by wedging it in the hole, and allowing it to reach thermal equilibrium. At Stripa the IRAD and USBM gages sense only stress changes subsequent to their installation.

Most of the IRAD gages have operated reliably for aproximately one and half years. Three gages have failed and one of these was sectioned, revealing a severly rusted wire. Other gage failures will be investigated at the conclusion of the experiment. The principal problem with these gages is in the uncertainties of the data reduction. The gage calibration "constants" are sensitive to rock modulus and coefficients of expansion as well as to the exact seating of the preloading wedge system. In spite of calibration in a uniaxially loaded sample of the host rock, considerable uncertainties remain in the calculated stress change, particularly under conditions of varying temperature and cyclic loading.

Conclusion

A large amount of valuable data has been obtained from the Stripa experiments. The heater systems have been highly reliable. The data acquisition system has also functioned reliably underground, maintenance being consistant with a system the size of the Stripa installation. Off-the-shelf instruments have been modified and calibrated to perform beyond their original design requirements. Elevated temperatures and the need for long-term integrity in a wet environment have revealed additional unsolved problems--their identification and solution would greatly benefit future experiments.

Acknowledgements

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