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ROCK INSTRUMENTATION PROBLEMS
EXPERIENCED DURING IN-SITU HEATER TESTS
E. Binnall¹, A. DuBois¹, and R. Lingle²

October, 1979

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Four types of instruments were used at Stripa; 389 thermocouples for temperature, 35 rod extensometers for displacement, 30 US Bureau of Mines (USBM) borehole deformation gages and 26 IRAD

(Crearé) vibrating wire stress gages for stress determination. These sensors are installed in vertical and horizontal instrumentation boreholes strategically located around vertical heater boreholes.¹

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. A third drift provides access for horizontal instrumentation. All signal conditioning circuits, data loggers, computer scanners, analog-to-digital converters and interfacing hardware are housed in sheds located in the two heater drifts. More than 750 sensor signals are digitized and transmitted to a ModComp IV computer² located a few tens of meters from the heater experiments.

Selected samples of IRAD gages and of medium and high temperature thermocouples were laboratory calibrated. All USBM gages, extensometers and low temperature thermocouples were calibrated in the field. The field calibrations were performed on-line with the instruments integrated into the computerized data acquisition system.

THERMOCOUPLES

Rock, instrument and heater canister temperatures are measured using Chromel-Alumel (ANSI type K) thermocouples connected to ice-point temperature references manufactured by Kaye Instruments. Thermocouples were purchased from Omega Engineering and, where possible, were obtained from the same wire lot 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
- . 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 $\pm 0.5^\circ\text{C}$ over a temperature range of 10° to 220°C for these "low temperature" thermocouples necessitated individual calibration. A fourth order polynomial curve was fitted to the calibration data, resulting in a set of five coefficients for each thermocouple. These were stored by the computer for on-line conversion from thermocouple voltage to temperature during the experiment.

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 could 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" 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 (10–20°C) before entering a transition joint to Teflon insulated type K extension wire.

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, subsequently requiring the replacement of over 50 thermocouples. The Inconel sheaths have been trouble free.

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 for future experiments include:

- . Use Inconel sheathed thermocouples exclusively. At least avoid stainless steel sheath.
- . Use grounded junctions in enclosed sheaths.
- . Obtain all thermocouple wire from single material melts.
- . Retain control samples to check long term stability.
- . Install tubing for traveling thermocouples.
- . Thermocouples removable for recalibration or replacement.
- . Avoid closed thermocouple wells that can capture water.

ROD EXTENSOMETERS

A rod extensometer is a common device for measuring changes in the axial length of a borehole.³ Terrametrics Inc. (Golden, CO) model 4CSLT extensometers were used. 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 range of ± 13 mm. One spring tensioned rod up to 13 meters long connects each anchor point to one of the four linear variable differential transformer (LVDT) type sensors located at the borehole collar. The major elements of these extensometers (Fig. 1) are: 1) the anchor system; 2) the anchor-to-collar rod connection mounted inside of a waterproof flexible conduit; 3) a head assembly which includes the rod tensioning system (100 lbs/rod) and the displacement sensors; and 4) several thermocouples for sensing the temperature profile along the connecting rods.

On the basis of anchor system tests: 1) Dow Corning X2-1162 silicone fluid was selected as the anchor pressurizing fluid capable of withstanding long time 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 pound axial load at 190°C for fifteen days was shown to be less than 2 microns 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 several superinvar rods, 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 averaged 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 by using a cubic spline curve fitting procedure. However, this involves some assumptions, based on the symmetry of the thermal field, which have been found not to be entirely valid. We would, in the

Fig. 1. Sectional view of extensometer, two anchor version.

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.

Only one of the displacement sensors 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 microns of stored rod displacement was released when the heads of the extensometers were rapped with a screw driver handle. A routine has been instituted to rap each instrument head in this fashion several times per week to continuously release the friction. No technique has been devised for evaluating any possible downhole friction effects, other than to observe that the indicated displacements no longer include significant stepwise movements. Some design changes such as modifying the rod spacings and the bushing materials can reduce the friction, and a vibrator 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 most of the horizontal extensometers and is probably also present in the vertical units. Water may corrode the rods and thermocouples, and create deposits inside of 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 any leakage water to drain. We will investigate the source of these water leaks at the conclusion of the heater experiments.

VIBRATING WIRE STRESSMETERS

Vibrating wire stressmeters⁴ manufactured by IRAD GAGE Inc. (Lebanon, NH) have been installed in 38 mm diameter boreholes surrounding the full scale electrical heaters at Stripa. 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.

The vibrating wire stressmeter (Fig. 3) operates on the principle 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. 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

A plot of $\Delta\sigma = C_1(T) \times (R + \Delta R)^{-2} + C_2(T)$ for two different temperatures. $C_1(T)$, $C_2(T)$ and ΔR are functions of temperature (T) and of the room temperature calibration values.

$\Delta\sigma_{1-2}$ = the change in stress between the time and temperature at installation (subscript 1) and some later time (subscript 2).

Fig. 2. IRAD gage data reduction method.

Fig. 3. IRAD gage cross-section. Fig. 4 USBM gage calibration curve.

measured by exciting the wire and measuring its period of vibration (160 to 400 microseconds).

Preliminary tests demonstrated that the IRAD gages require individual calibration and that these calibrations are temperature dependent. Laboratory calibration in a sample of Stripa granite at ambient and at elevated temperatures provided a method for calculating (Fig. 2) the rock stress changes as a function of measured gage temperature (T) and period of vibration (R).

Note that R_1 (Fig. 2) is the gage reading after the gage has been preloaded, by wedging it into the hole, and allowed to reach thermal equilibrium. The gage cannot measure the state of stress then existing in the rock unless that stress is released by over-coring. At Stripa the IRAD gage senses only stress changes subsequent to its installation.

Most of the IRAD gages have operated reliably for approximately one and a half years. Three gages have failed and one of these

was sectioned, revealing a severely 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 coefficient 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.

USBM GAGES

The US Bureau of Mines "soft" borehole-inclusion gage utilizes three pairs of opposed cantilever beams to sense changes in the dimensions of a borehole. These measurements across three diameters at 60° separation allow the principal stresses 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.⁵

For the Stripa application the gage data reduction scheme was adapted for operation over a long time period at elevated temperatures, and several modifications have been made in the gage (manufactured by Rogers Arms and Machine Co., Grand Junction, CO):

1. The cantilever arm was changed to 17-4 Ph stainless steel;
2. High temperature strain gages and solder, and Teflon-insulated wire were used;
3. Individual excitation was provided for each bridge;
4. A thermocouple was mounted on each USBM gage.

The 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 a voltage offset at constant displacement which was proportional to temperature and different for each cantilever pair. There was also a linear change in slope (voltage versus displacement) of 6% from 20° to 200°C as indicated in Fig. 4.

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. 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 an 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. It is still too early to assess their performance.

CONCLUSION

A large amount of valid data has been obtained from the Stripa experiments by the use of modified and calibrated off-the-shelf rock instrumentation. The elevated temperatures and the need for long time integrity in a wet environment revealed unsolved problems. The identification and solution of these problems would greatly benefit future experiments. Obviously more effort should be applied to the development of instruments to meet the environmental, reliability and accuracy requirements for test site observations.

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