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MEASUREMENTS AND CALCULATIONS

T. R. Butkovich
J. L. Yow, Jr.
D. N. Montan

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INFLUENCE OF HEAT FLOW ON DRIFT CLOSURE DURING CLIMAX GRANITE SPENT-FUEL TEST: MEASUREMENTS AND CALCULATIONS

T. R. BUTKOVICH, J. L. YOW, Jr., and D. N. MONTAN
Lawrence Livermore National Laboratory
Livermore, California, 94550

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ABSTRACT

Measurements of drift closure caused by the thermal load have been made routinely during the Fuel Test in Climax granite since about six weeks after emplacement of the fuel. Horizontal and vertical closure was measured with a manually operated tape extensometer at various locations along the lengths of the drifts. Average closures ranged from 0 - 0.6 mm, horizontal and vertical, out to about 2.2 years since the start of the test. At the same time, displacements from the thermal loads were measured with rod extensometers emplaced to measure relative displacements between hole collars and anchor points in holes drilled from two parallel heater drifts.

These data are compared with thermo-elastic finite element calculations which utilized measured properties of the Climax granite. The calculations show that more than half of the closures occur between fuel installation and the first closure measurement. The comparisons show that the results track each other, in that where closure followed by dilation is measured, the calculations also show this effect. The agreement is excellent, considering the averaged measured closures remain within 30% of the total calculated drift closures and the extremely small magnitude of the relative displacements (0.5 mm), measured or calculated.

INTRODUCTION

A generic test to evaluate granite as a medium for deep geologic storage of spent-fuel assemblies from an operating nuclear reactor has been underway since the Spring of 1980. One of the objectives of this test, at the U.S. Department of Energy's Nevada Test Site, is to provide data on the thermal and thermo-mechanical behavior of granite from imposed heat loads.

The installation in Climax stock quartz monzonite was constructed at about 420 m below the surface and 145 m above the existing water table. Figure 1 shows the three parallel drifts excavated on 10 m spacings between centerlines. Seventeen storage holes were

drilled in the floor of the central drift on 3 m centers into which eleven spent fuel canisters and six thermally identical electrical simulators were emplaced. Electrical resistance heaters were also emplaced in vertical holes in the floors of the side drifts on 6 m centers. The thermal outputs of these heaters are being periodically adjusted to simulate the thermal response of a large spent-fuel storage array. Rock and ventilation air temperature are being measured continuously in the drifts and throughout the rock surrounding the excavations.

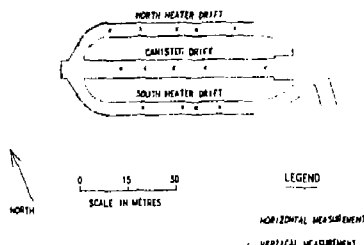


FIGURE 1. PLAN VIEW OF SPENT FUEL DRIFTS SHOWING LOCATIONS OF CLOSURE MEASUREMENTS USED IN COMPARISONS.

MEASUREMENTS, CALCULATIONS AND COMPARISONS

Drift deformation measurements have been made regularly since about 6 weeks following the fuel emplacement. Vertical and horizontal closure readings are being taken with a manually operated tape extensometer at six locations along the central canister drift and at five locations along each heater drift.

Displacements from the thermal load were also measured with rod extensometers emplaced to measure relative displacement between hole collars and anchor points in holes that were drilled from the heater drifts. These instruments were emplaced in the pillars between the drifts in horizontal holes and in holes inclined at 4° and 50° above horizontal.

Finite element calculations were run during the time of fuel emplacement [1]. These calculations were made with measured physical, mechanical, and thermal properties of the Clinax granite [2]. The ADINA [3] structural analysis and the compatible ADINAT [4] heat flow codes were used because of their ability to handle diverse factors such as heat flow by conduction, radiation and convection, thermelasticity, and excavation. ADINAT was adapted to model both internal radiative heat transfer within the drifts and ventilation [5]. For the purpose of the calculations, the start time of the test was assumed to be the date of the installation of the centrally located spent-fuel canister. Electric resistance heaters in the side drifts were energized 0.14 years later and have been periodically adjusted to simulate heat flow in a large repository.

Nearly 500 thermocouples were installed to measure temperature in various positions throughout the test facility. In addition to measurements near the canisters, arrays of thermocouples were emplaced at two locations along the drifts to monitor temperatures in the intermediate field. Figure 2 shows as an example of the measured temperature changes at 1.5 years since the start of the test at various positions in an array approximately 4 m east of the midposition along the drifts, superimposed on the temperature contours calculated with ADINAT. These results are in excellent agreement except in the regions immediately surrounding the drifts where the differences are within about $\pm 2^\circ\text{C}$.

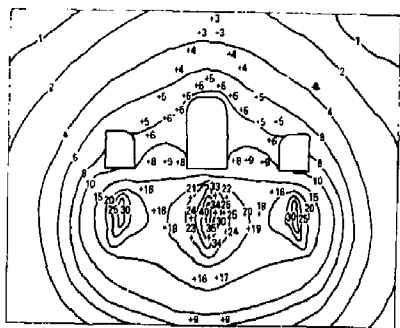


FIGURE 2. COMPARISON BETWEEN MEASURED AND CALCULATED TEMPERATURE CHANGES AT A STATION NEAR THE MIDPOSITION IN THE DRIFTS AT 1.5 YEARS SINCE START OF TEST.

The ADINA calculations were made with an isotropic thermal-elastic model, with laboratory determined temperature dependent expansion coefficients, and using the nodal thermal histories calculated with ADINAT. Separate calculations were run using different elastic moduli for the rock. Averages of laboratory measurements on small samples of granite from the site give a value of 48 GPa, while the average value from field determinations of effective elastic modulus is about 27 GPa. In addition, an explosively damaged 0.5 m thick region around each opening was identified to have an effective elastic modulus of about 13 GPa [6].

Figure 3 shows the calculated nodal vector displacements around the excavations at about 1.5 years since the start of the test. Also shown is the location of the rod extensometers. The rock motion is away from the heat sources beneath the floors of the drifts.

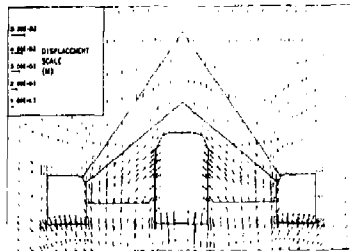


FIGURE 3. CALCULATED NODAL DISPLACEMENTS FROM THE HEAT LOAD IN THE VICINITY OF THE EXCAVATIONS AT 1.5 YEARS SINCE START OF TEST. LOCATIONS OF ROD EXTENSOMETERS ARE SHOWN AS HEAVY LINES.

As expected, the thermally induced drift closures are different for each calculation. Figure 4 shows, as an example, the horizontal closure of the canister drift for each calculation. Values are about a factor of two larger for the field determined modulus than for the laboratory determined modulus, and about 10% still larger when the low-modulus damaged region is included. The calculations show that most of the closure occurs within the first six months for both the canister and heater drifts.

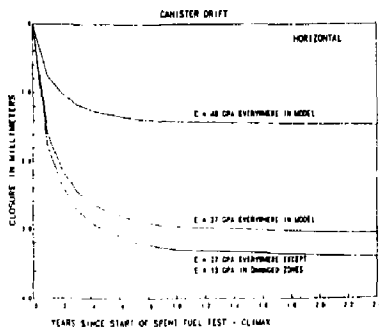


FIGURE 4. CALCULATED HORIZONTAL CLOSURE OF CANISTER DRIFT.

A set of drift closure measurements were made at each location at about one month intervals with a model 51855 Tape Extensometer manufactured by Slope Indicator Co., of Seattle, Washington. Potential sources of error in the reported values include operator influences and thermal correction effects. Variation in results, when measured at the same time by several operators does not exceed ± 0.1 mm [7], while thermal correction errors fall between $\pm 2\%$ of the measured values.

Measurements from five locations in the canister drift, five in the north heater drift and four in the south heater drift were used in the analysis presented here. Temperature corrected results from redundant measurements and different operators were arithmetically averaged to produce a single closure curve for each drift and orientation.

Figure 5 shows as an example horizontal and vertical closures of the north heater drift. Each curve represents results for one of five locations. Variations between locations seem to be random and can be as high as ± 0.2 mm. These five results were averaged to produce single horizontal or vertical closure curves for the north heater drift. Similar procedures were used for both horizontal and vertical closures of south heater and canister drifts.

The single averaged measured closure curves are compared with the calculated results. The calculation chosen for all displacement comparisons was made with a modulus of 27 GPa everywhere in the finite

element mesh, with no explosive damaged region. The reason for this being that prior to the installation of the anchor points, most of the blast damaged region was scaled from the walls. Figures 6a and 6b show the comparison for the horizontal and vertical canister drift closure respectively; Figure 7, for the north heater drift; and Figure 8 for the south heater drift. In each case the total calculated closure since the emplacement of the spent fuel (May 6, 1980) is plotted. Since the first closure measurements were not made until later, the calculation and measurement were assumed to agree at the time of the first reading. It is interesting to note that in each case well over 50% of the closure to 2.2 years occurred in this early time.

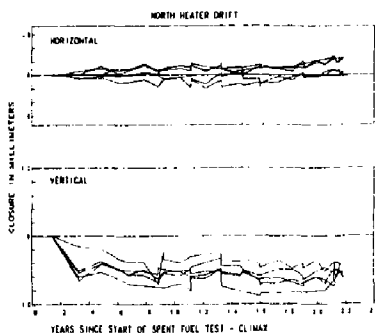


FIGURE 5. MEASURED HORIZONTAL AND VERTICAL CLOSURE OF NORTH HEATER DRAFT AT EACH OF FIVE LOCATIONS.

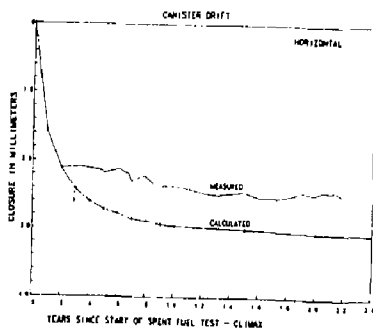


FIGURE 6a. COMPARISON BETWEEN MEASUREMENT AND CALCULATION OF HORIZONTAL CLOSURE OF CANISTER DRIFT.

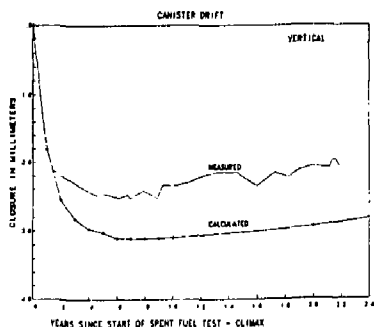


FIGURE 6b. COMPARISON BETWEEN MEASUREMENT AND CALCULATION OF VERTICAL CLOSURE OF CANISTER DRIFT.

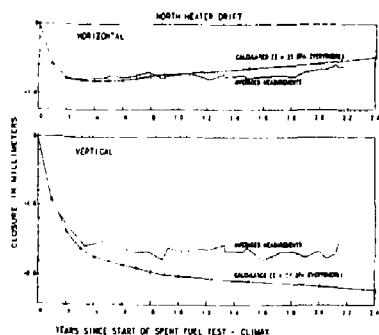


FIGURE 7. COMPARISON BETWEEN MEASUREMENTS AND CALCULATIONS OF HORIZONTAL AND VERTICAL CLOSURES OF NORTH HEATER DRIFT.

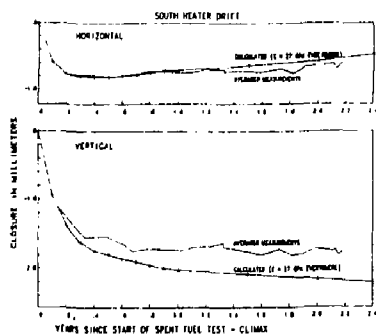


FIGURE 8. COMPARISONS BETWEEN MEASUREMENTS AND CALCULATIONS OF HORIZONTAL AND VERTICAL CLOSURE OF SOUTH HEATER DRIFT.

When the difference between measurements and calculations is being considered, the fractional difference should be based on the total closure. Measurements began after more than half of the calculated closure occurred but at a time when closure rates are still high. A small change from the assumption that both curves are connected at the time of the first measurement can make the agreement between measurement and calculation much better - or worse. Using this assumption however, the greatest difference between measurement and calculations is less than 30%.

Relative displacement measurements from the thermal loads measured with the rod extensometers were available after about 6 months since the start of the test. These measurements were made in holes drilled from the north and south heater drifts at two stations along the drifts. Temperatures were monitored with thermocouples placed near each anchor point in separate holes. Using these data, temperature corrections for the expansion of the rod extensometers were made for each anchor position.

Figure 9 shows as an example a comparison between measurements and calculations for a one year period between about 0.5 years to 1.5 years since the start of the test. This is for the same location as that of the temperature change values shown in Figure 2. Here the upper figure at each anchor point gives the temperature corrected measurement, while the lower figure gives the calculated value. Here again, considering the magnitudes of the displacements, the results are in excellent agreement.

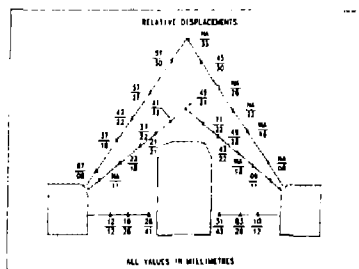


FIGURE 9. RELATIVE ROCK DISPLACEMENTS DURING THE TIME 0.5 TO 1.5 YEARS SINCE START OF THE TEST NEAR THE MID-POSITION IN THE DRIFTS. NA INDICATES MISSING DATA.

SUMMARY AND DISCUSSION

The agreement between measurements and calculation of the drift closures and relative displacements of the rock around the excavation is excellent. Since the calculations were made with an isotropic elastic model, this suggests that the existing jointing in the Climax granite did not appreciably affect the motion of rock during the thermal phase of the experiment.

With respect to tunnel closure comparisons, in each case the measured closure is less than that calculated during the time period where the comparisons were made. This could be the effect of the assumption that the two results are coincident at the time of the first closure result. On the other hand, the elastic modulus of 27 GPa used in the comparison calculation was an average in-situ value. The agreement between measurements and calculation of closure would have been still better if a somewhat larger modulus were used in the calculation.

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