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CLIMAX GRANITE TEST RESULTS

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Lawrence
Livermore
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INTRODUCTION

The Lawrence Livermore Laboratory (LLL), as part of the Nevada Nuclear Waste Storage Investigations (NNWSI) program, is carrying out *in situ* rock mechanics testing in the Climax granitic stock at the Nevada Test Site (NTS). Although LLL is heavily involved in planning and execution for a test storage of spent reactor fuel in the Climax granite[1] and in the planning and design for a Rock Mechanics Test Facility, this summary will address only those field data taken to date that address thermomechanical modeling for a hardrock repository. The results to be discussed include thermal measurements in a heater test that was conducted from October 1977 through July 1978, and stress and displacement measurements made during and after excavation of the canister storage drift for the Spent Fuel Test (SFT) in the Climax granite. Associated laboratory and field measurements will be summarized.

HEATER TEST RESULTS

Description of Test Layout

Heater Test No. 1 was designed to be a simple temperature measurement test to obtain *in situ* values for thermal conductivity and diffusivity for use in subsequent scoping calculations, and to screen for gross or unexpected effects from the heater. After initial testing, modifications were made to some of the field instrumentation to allow permeability measurement as a function of rock temperature. No stress or displacement measurements were attempted. Figure 1 shows the layout of Heater Test No. 1 and Fig. 2 shows a cross-section along the drift array (identical to the alcove array). This layout was selected such that the two instrumentation lines were oriented parallel and perpendicular to the principal near-vertical fracture orientation at the test location.

The heaters were 16-mm-diam, Inconel-clad, standard-cartridge-type immersion units. The 3-m-long heaters were centralized in 48-mm-diam holes, and were suspended from a 48- to 76-mm-diam step in the heater hole. The mid-point of the heater was 7.5 m below the drift surface, well beyond mining or other

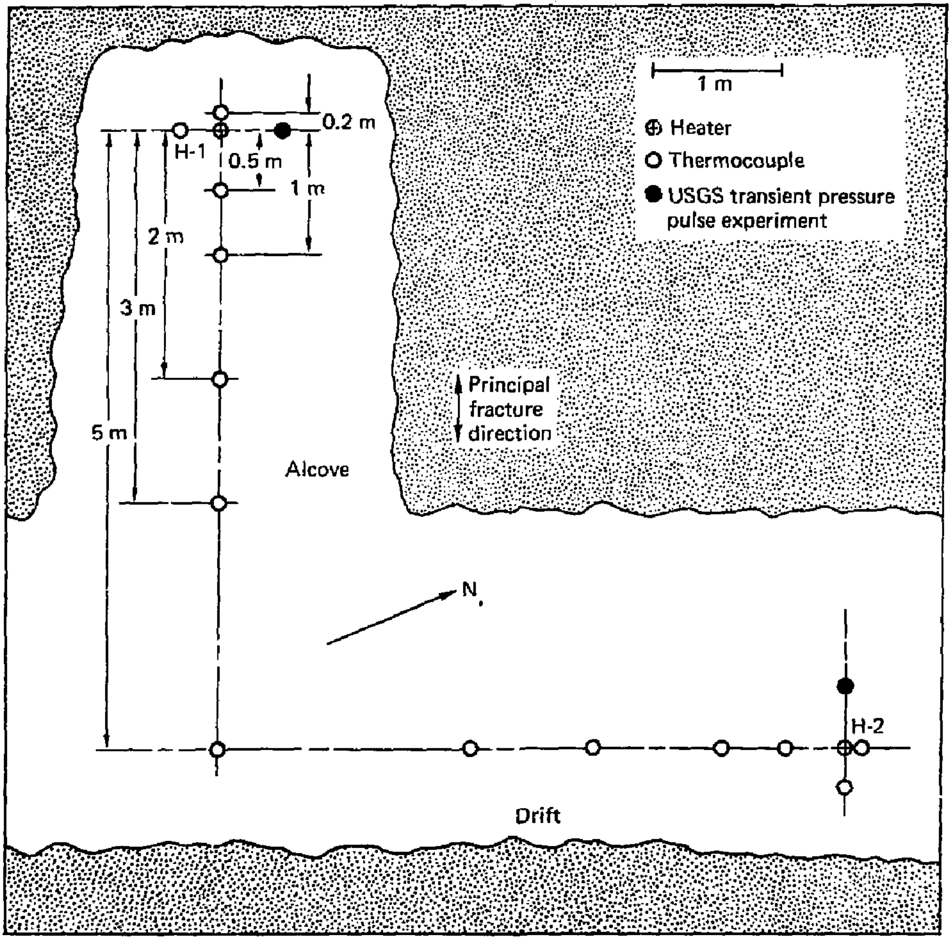


Figure 1. Plan view of Heater Test No. 1 layout, 420 m level, Climax granite (note that location dimensions for drift holes are the same as those for alcove holes).

shock effects and deep enough so that, within the 60- to 70-day time duration of the tests, no significant heat would be lost to the drifts.

The test was planned for initial operation at a constant power level followed by superposed power fluctuations. The test objective was the highest power level consistent with a heater temperature near 600°C at steady state, which turned out to be 3.7 kW. An early power-off cycle was introduced because of an electrical short, so the test plan was adjusted to give a final total average power of 3.7 kW, but with superposed power fluctuations. This allowed a field check on thermal diffusivity, which has a strong effect on temperature for short time periods but not at long time periods.

Thermocouples were mounted on the heaters and in the 48-mm-diam thermocouple holes (Fig. 1). The rock-measuring thermocouples were silver-soldered into copper pins, which in turn were spring-mounted on a stainless steel space frame, fou. to an assembly. For insertion, the copper pins were coated with

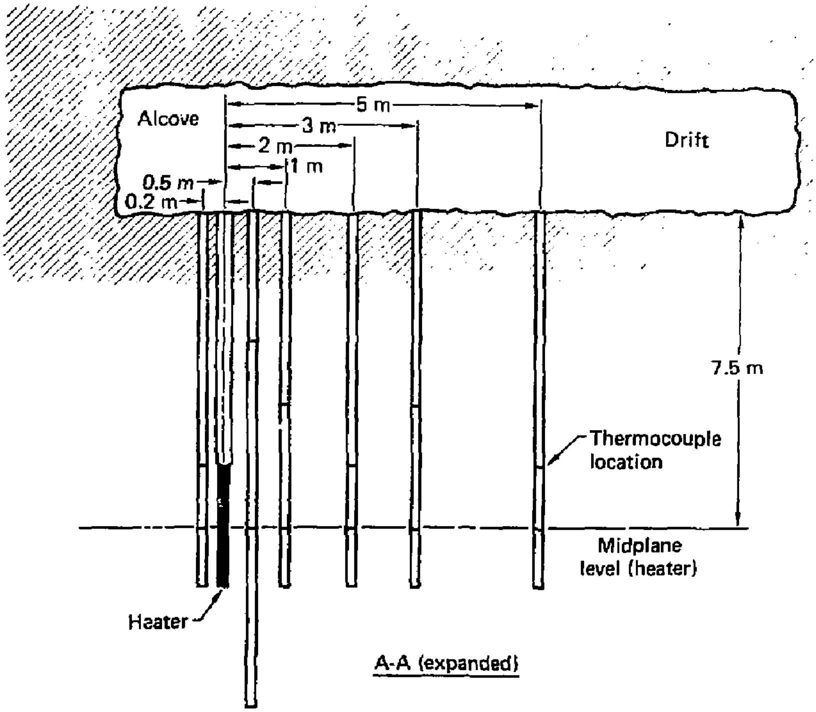


Figure 2. Vertical section along alcove test array, Heater Test No. 1, Climax granite.

thermal-conducting cement, and were then lowered in a withdrawn state and forced into contact with the hole walls once in place. This arrangement worked satisfactorily and allowed us to withdraw the thermocouple assemblies to be reconfigured below packers for the permeability tests.

Although the heater test has not been formally documented, more details may be found in Refs. 2 and 3.

Initial Scoping Calculations

The initial scoping calculations were done using available literature values of thermal properties for input. The calculation involved superposition and integration in time and space of the analytical solution to the point source equation

$$T = \frac{Q}{4\pi kr} \operatorname{erfc} \sqrt{\frac{r^2}{4\kappa t}} ,$$

where T = temperature; Q = power; k = thermal conductivity; r = distance; κ = thermal diffusivity; and t = time. For most calculations, the 3-m heater was represented as an array of 100 point sources. During the initial scoping calculations, it was always anticipated that two- or three-dimensional finite-difference calculations would be run with a code such as TRUMP,[4] but this was based on an anticipated need to handle variable and nonlinear thermal conductivity and diffusivity. As will be described, we found that the field results could be well approximated using analytic calculations with constant values of thermal conductivity and diffusivity.

The initial scoping calculations (Fig. 3) used a thermal conductivity k of 2.5 W/m·K, a diffusivity κ of 1.0 mm^2/s, and a heater power level of 3 kW. These calculations showed that in four weeks the rock would be approaching steady-state temperature to a distance of 1 m, and that several months would be required for a rise of a few degree Celsius at 5 m. Thus, the test layout was confined to a 5-m distance (Figs. 1 and 2).

Results and Initial Analysis

Thermal profiles in the granite were measured at 52 points at ranges from 0.27 to 5 m from the heaters, although for most of the tests, only about 20

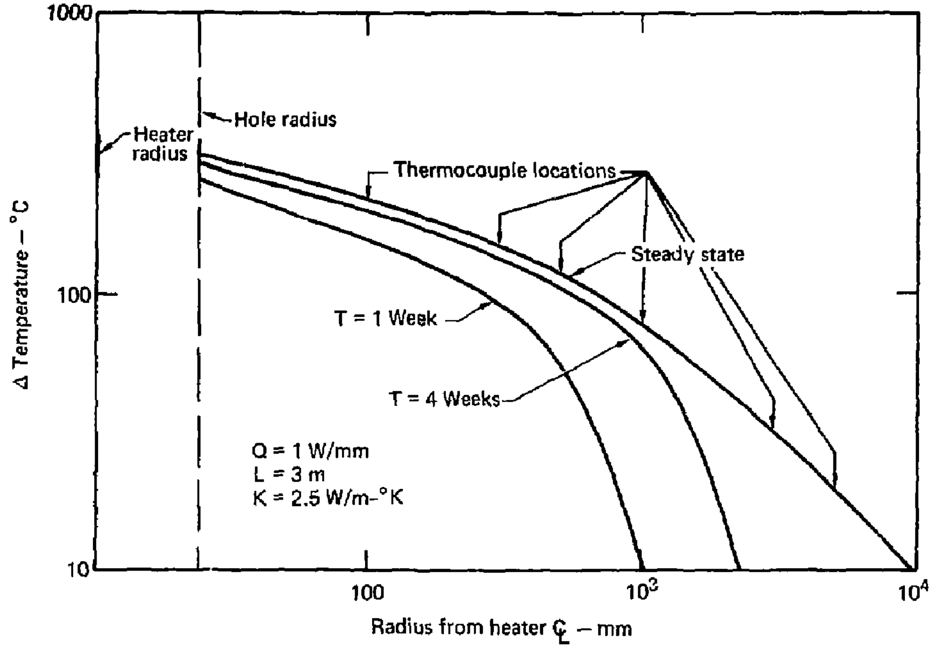


Figure 3. Temperature-distance thermal profiles for various times, Heater Test No. 1 scoping calculations.

channels recorded significant temperature increases. At the time the test was initiated, a two-dimensional, radial-symmetry TRUMP problem had not been set up for several reasons: we had no data on thermal conductivity of Climax granite as a function of temperature, and the set-up of the problem was a complex task. Computational personnel assigned to the task were making numerous analytic calculations to refine projected test times, power histories, and other support to the fielding. Thus, initial data became available without the finite-difference capability, and natural curiosity led us to attempt a match with analytic calculations. An iterative series of simple calculations led to the input parameters $k = 3.05$ W/m•K and $\kappa = 1.23$ mm^2/s for the actual heater length of 2.9 m. These constant values gave good matches both close and far (relatively) from the heater (Figs. 4 and 5). Therefore, throughout the test we continued to use the simpler calculational method for test control and initial analysis.

Posttest Evaluation

After the test, we had access to values of the change in thermal conductivity for Climax granite core samples that were taken during construction of the test.[5] These data showed a decline from about 3.5 to 3.7 W/m•K at ambient temperature to about 3.1 at 200°C (projected). The average slope of these data was input as a linear function starting with an ambient temperature conductivity of 3.0 W/m•K into the TRUMP code in an axisymmetric two-dimensional

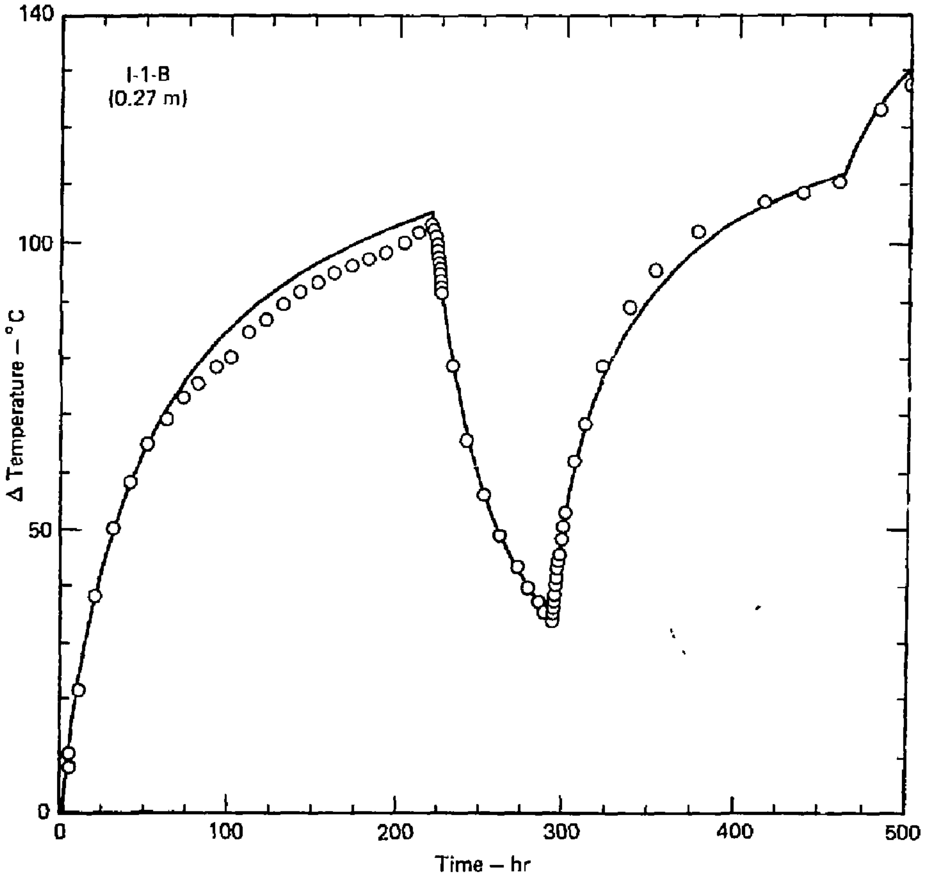


Figure 4. Comparison of calculated (solid line) and measured (circles) temperatures for closest thermocouple (0.27 m) from the H-1 heater.

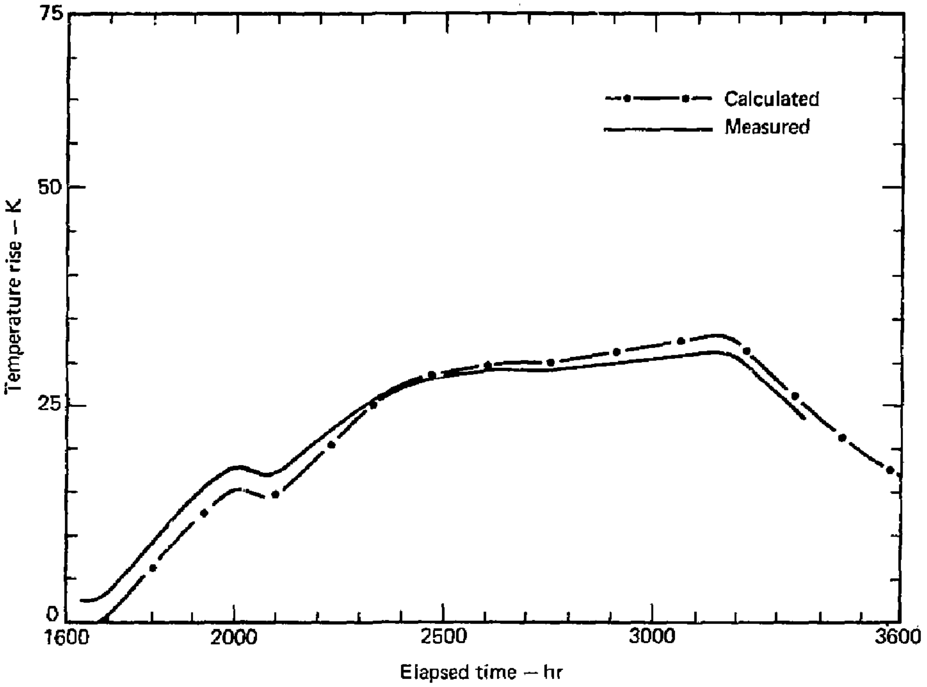


Figure 5. Comparison of calculated with measured temperature rise for moderate (1.79 m) distance thermocouple from the H-2 heater.

calculation. Prior to that, comparative calculations had shown TRUMP to give identical results to the analytic solutions at the scale of the illustrations that follow.

A comparison between a constant k and variable k calculation (both with TRUMP) is shown in Fig. 6. We have no measurements on the borehole rock surface, which is calculated for illustration. However, the maximum difference between the two calculations for 0.27 distance, our closest data point is less than 15°C. And at 1.15 m distance, the two calculations are indistinguishable at this scale.

The original scoping calculations were based on an average value of thermal conductivity of 2.6 W/m•K at 20°C for 14 samples of Climax granite but not from the heater test location.[6] The range of values for these samples was 2.3 to 3.4 W/m•K. Because of the known decline in thermal conductivity with increasing temperature, a constant value of 2.5 was selected for the scoping

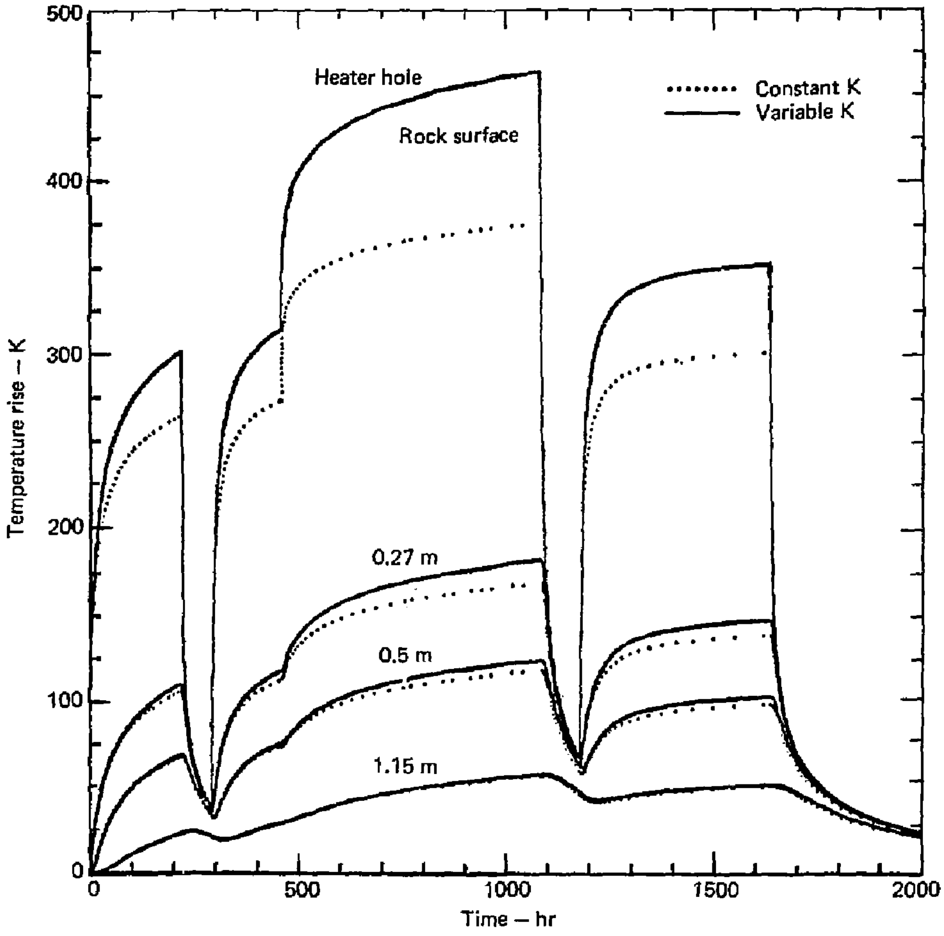


Figure 6. Comparison of TRUMP calculations with constant vs variable thermal conductivity for H-1 test power history.

calculations. Post-test measurements on core taken from the heater test site itself have all given values in the range of 3.4 to 3.7 W/m·K at 20°C, with decline in conductivity to 3.2 at 200°C. As pointed out previously, the best iterative fit to the data used a constant thermal conductivity of 3.05 W/m·K.

In general, heat adsorption and transport by water played only a small role in the thermal profiles. For those locations 0.5 m or less distant from the heater, the rock temperature exceeded the boiling point of water at some time during the test. For those locations, a deflection in the measured temperature-time history curve can be associated with the refluxing of a small amount of water in the thermocouple holes. The subsequent data curves then parallel the slope of the calculated curves. The rock was reheated for the permeability tests with no measurable change in behavior (the heating cycle was closely calculated and monitored using the same 3.05 W/m•K conductivity, with excellent matching).

Permeability Test Data

Following operation of heater test No. 1 for thermal measurements, the layout was modified for *in situ* measurement of permeability as a function of rock temperature.[3] Although these results were not modeled either before or after the test, the rock behavior is reported here for possible relevance to understanding other behavior, such as fracture closure.

By careful control of heater power, plateaus of essentially constant rock temperature were maintained long enough for transient permeability measurements to be made as a function of temperature (Table 1). Consistently, the measured permeability declined with increasing temperature to below the measurement capability of the system and then recovered to about the pretest values.

TABLE 1. *In situ* rock permeability as a function of rock temperature, Climax granite.

		Average permeability (nd)					
		Hole					
Test	Av. Temp., °C	J-02 (0.40m)[a]	I-09 (0.73m)	I-10 (0.37m)	I-11 (0.40m)	I-6 (4.92m)	P-1 (5.23m)
M	32	0.20	0.32	0.67	0.32	--	--
N	52	0.09	0.07	0.15	0.09	--	--
O	76	<0.02	<0.02	<0.02	<0.02	--	--
P	108-60	(Δ)[b]	- - - - - Invalid Test - - - - -			--	--
Q	48	(Δ)	0.47	0.34	0.56	--	--
R	36	(Δ)	0.55	0.57	0.66	--	--
S	28	(Δ)	--	--	0.67	0.50	0.90

[a] Distance from centerline of heater hole.

[b] (Δ) Packer failure following Test O.

Conclusions

The rock temperature for a given applied heat load at a point in time and space can be adequately modeled with simple analytic calculations involving superposition and integration of numerous point source solutions. The input, for locations beyond about a meter from the source, can be a constant thermal conductivity and diffusivity. The value of thermal conductivity required to match the field data is as much as 25% different from laboratory-measured values. Therefore, unless we come to understand the mechanisms for this difference, a simple *in situ* test will be required to obtain a value for final repository design. Some sensitivity calculations have shown that the temperature field is about ten times more sensitive to conductivity than to diffusivity under the test conditions. The orthogonal array was designed to detect anisotropy. After considering all error sources, anisotropic efforts in the thermal field were less than 5 to 10%.

RESPONSE OF CLIMAX GRANITE TO MINING

As noted earlier, LLL is engaged in construction and operation of a Spent Fuel Test in the Climax granite.[1] As a pretest background measurement, stress changes and displacements resulting from mining of the canister storage drift were monitored from the adjacent heater drifts immediately prior to, during, and after mining. There are several reasons for making these measurements. First, stress and displacement measurements will be made throughout the duration of the Spent Fuel Test, and it is desirable to have background data prior to heating of the rock. Second, it has been asserted that the relative magnitudes of stress changes and displacements caused by mining are either large or small compared with heating of the rock. In such a situation, actual field measurements are helpful.

Scoping Calculations

To plan the stress and displacement instrumentation, scoping calculations were made using the ADINA code,[7] a finite-element program for Automatic Dynamic Incremental Nonlinear Analysis. The ADINA code was designed to perform linear and nonlinear analyses in the design of structures. It has one-, two-, and three-dimensional capabilities and can handle nonlinearities that result from large displacements, large strains, or nonlinear material behavior. The material descriptions available include: isotropic or orthotropic linear elastic, isotropic thermal-elastic, elastic-plastic, thermo-elastic-plastic-creep, or a user-specified curve description model. Effectively, the code solves incremental nodal point equilibrium equations for an assemblage of nonlinear finite elements.

The ADINA calculations made for the excavation phase of the spent-fuel test were planar, representing a plane section through the canister and heater drift excavations. The material was assumed to be isotropic and elastic with constant (not temperature or pressure dependent) elastic modulus of 7×10^6 psi (47.63 GPa) and a Poisson's ratio of 0.2. The boundary conditions assumed a preexisting vertical stress of ρgh and a horizontal stress of $0.8\ \rho gh$. The grid used in the calculations has 810 nodal points and 710 four-node elements. This grid is for half of the excavation with a vertical line of symmetry passing through the center of the canister drift.

Figure 7(a) shows the close-in portion of the grid prior to excavation with the outline of the elements that will be removed during the excavation calculations. Figure 7(b) shows the displaced grid following excavation of the side (heater) drifts. The original grid position is shown with the broken lines. The difference between the displaced position and the original position represents the displacement of the material as a result of the mining operation. There are two scales for the figures, one for the grid distance and one for the displacement. From Fig. 7(b), the maximum displacement caused by heater drift excavation is shown to be of the order of one millimeter. Figures 7(c) and 7(d) show the displaced grids following excavation of only the upper level of the canister drift and the total excavation of both levels, respectively. Maximum displacements from all the excavations is about two millimeters. Similar graphs (not included here) show the calculated alteration of the stress field around the excavations.

Instrumentation

Based on these scoping calculations, stress and displacement instrumentation was emplaced from two locations along the heater drifts prior to mining the canister storage drift. Figure 8 is the plan view of this instrumentation

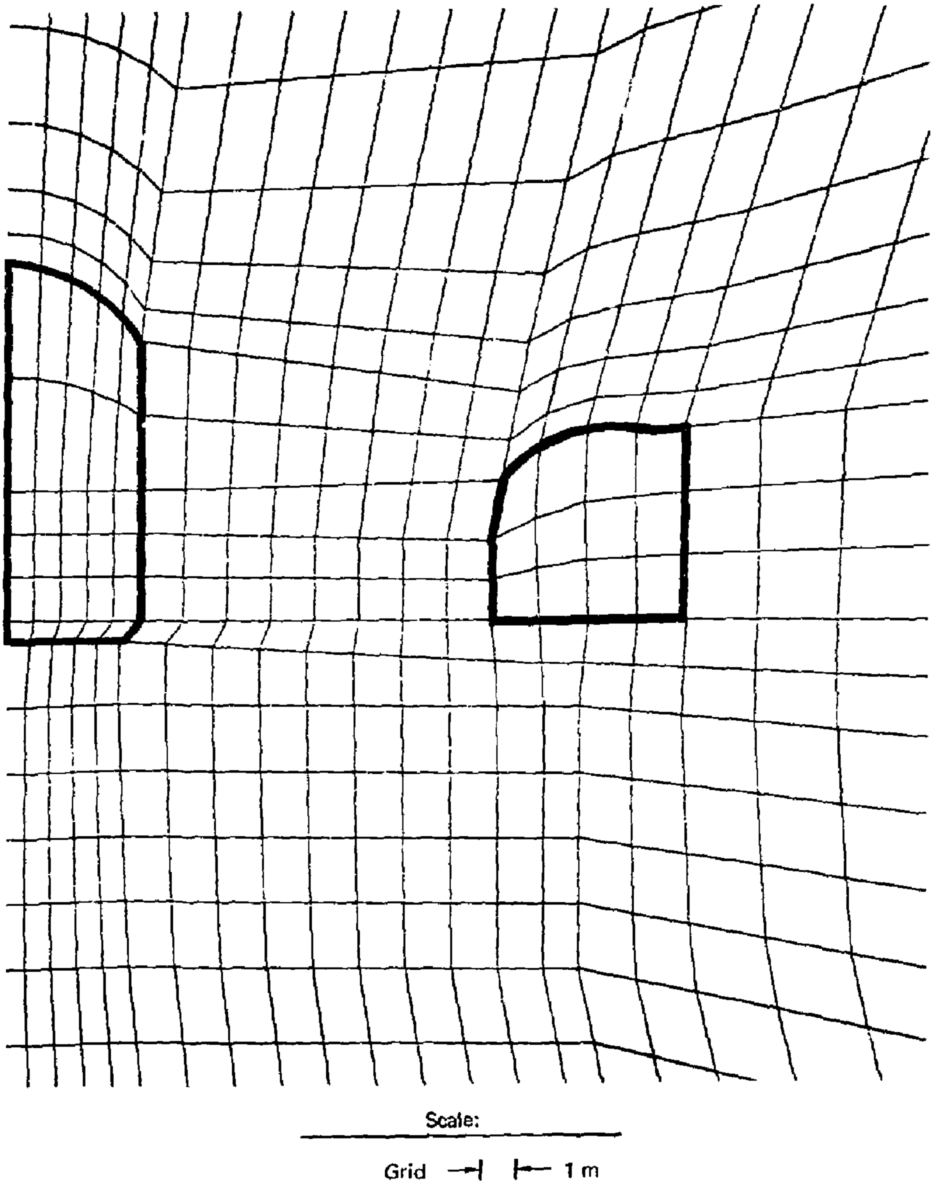


Figure 7(a). Calculational grid before excavation. Bold lines indicate the approximate drift outline.

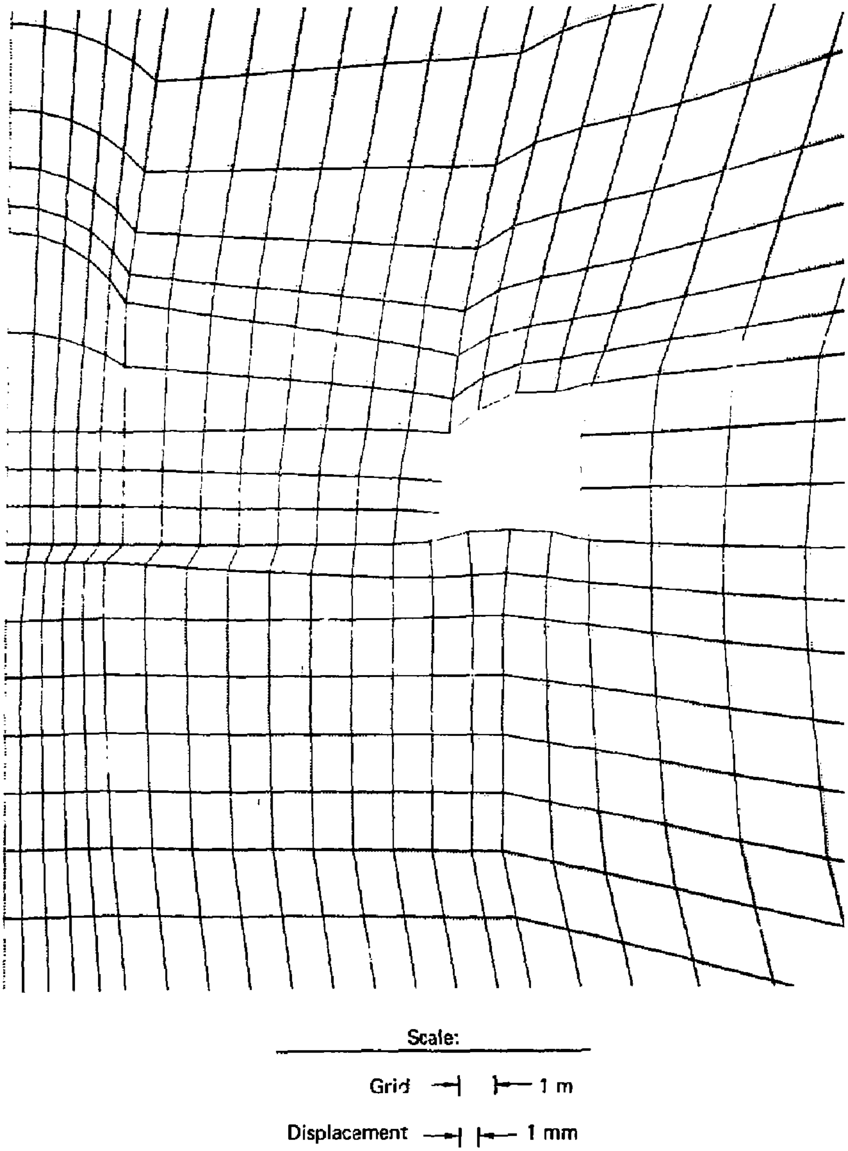


Figure 7(b). Calculational grid following excavation of the side drifts. The dotted lines indicate the position of the original grid [shown in Figure 7(a)].

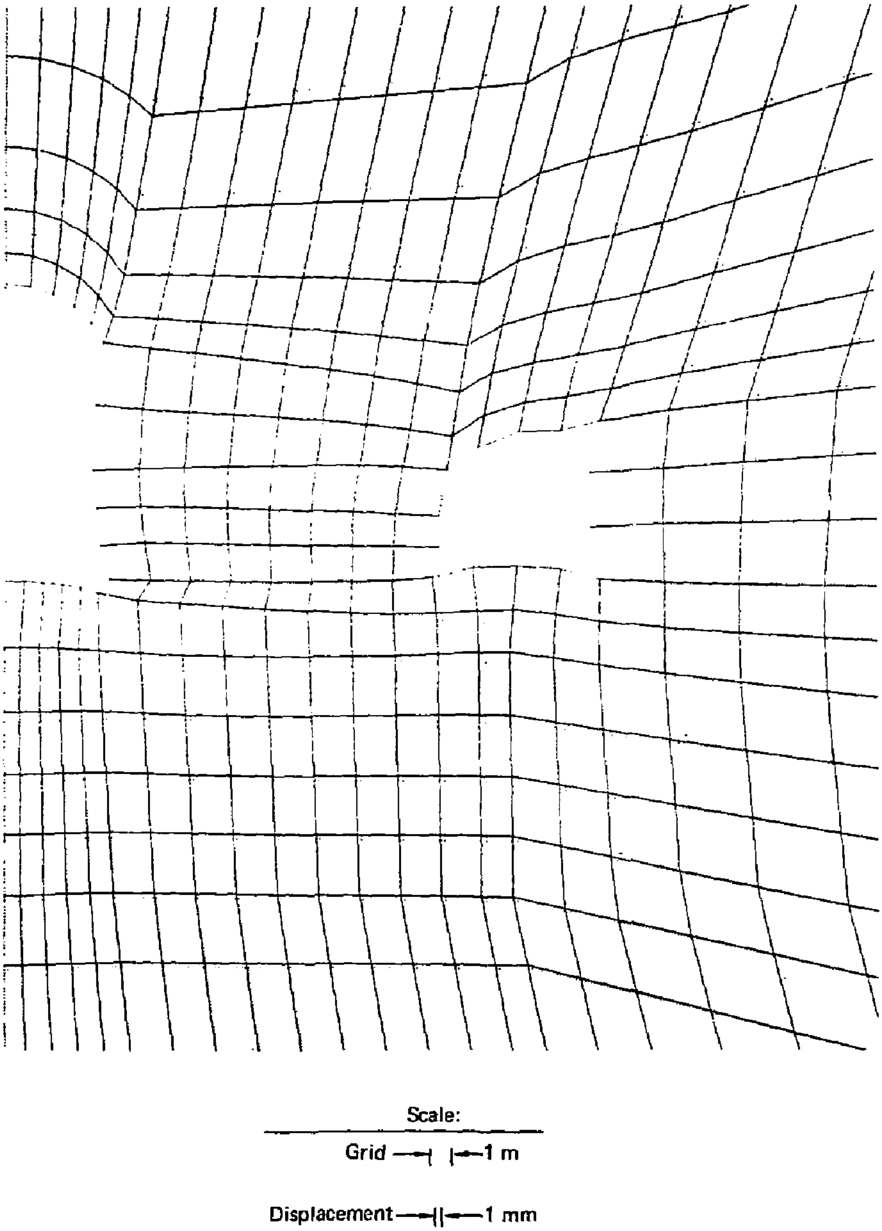
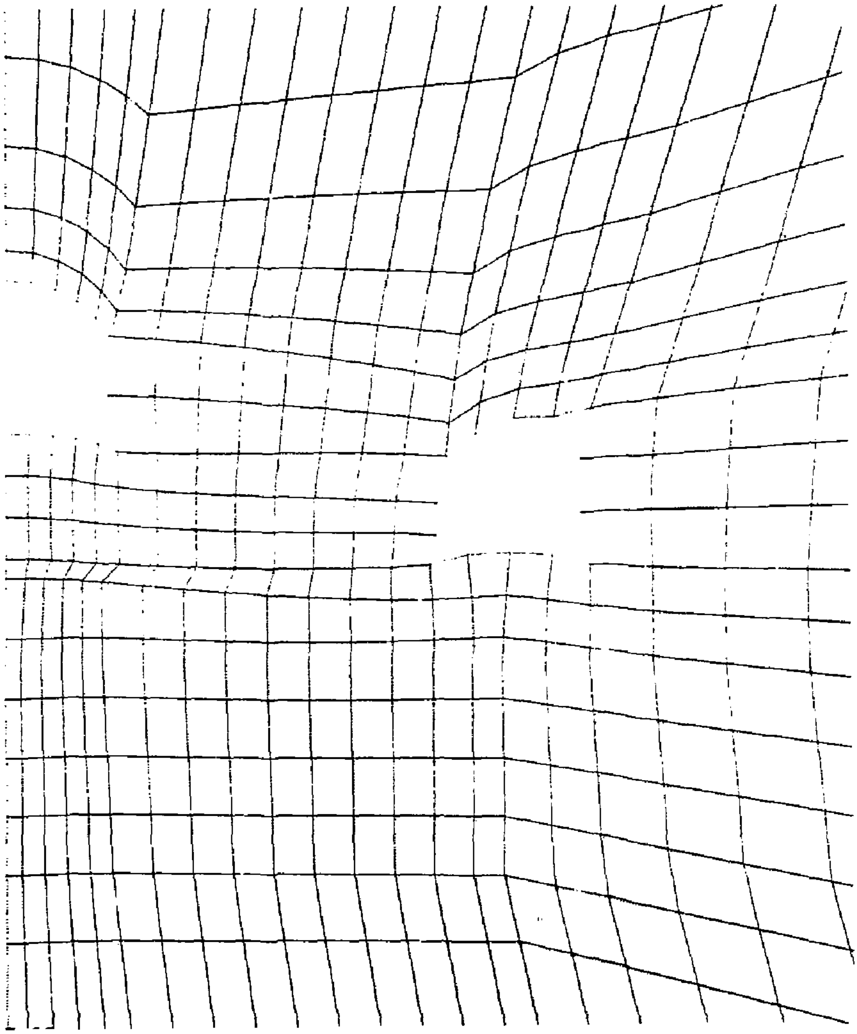


Figure 7(c). Displaced grid following excavation of the upper and lower levels of the canister drift and the side drift. The dotted lines indicate the position of the original grid [shown in Figure 7(a)].



Scale:

Grid ⟶| |⟵ 1 m

Displacement ⟶||⟵ 1 mm

Figure 7(d). Displaced grid following excavation of the canister drift and the side drift. The dotted lines indicate the position of the original grid [shown in Figure 7(a)].

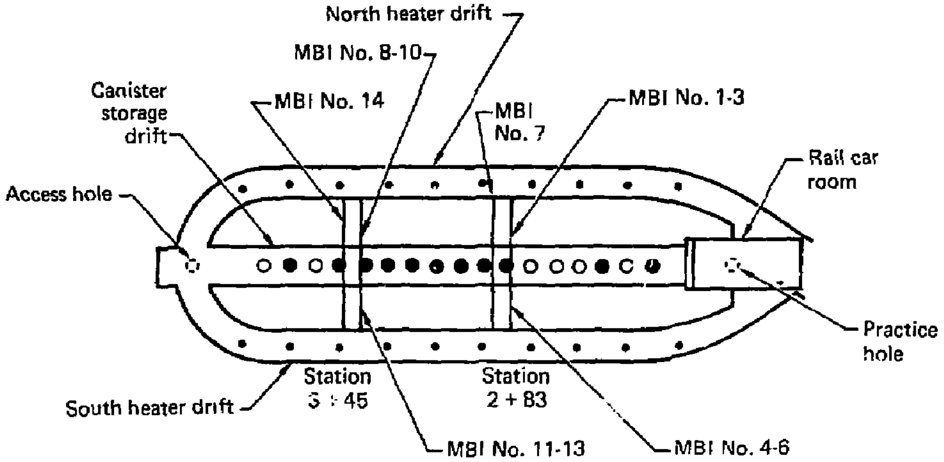


Figure 8. Plan view of mine-by experiment, Climax granite spent fuel tests, NTS.

and Fig. 9 shows a schematic cross-section. The specific locations of each anchor point or stress meter were selected based on analysis of core from the drill holes. Convergence was also measured by taping through MBI 7 and MBI 14, which are horizontal holes connecting the heater drifts (Fig. 8). The *in situ* state of stress in the rock was measured southward from the South Heater Drift near station 3+00, between the two instrumentation clusters. U.S. Geological Survey personnel used the rock overcore method for these measurements.

Preliminary Data

One of the simplest methods of displaying the large amount of data taken is to compare calculated and measured values for the data stations. Figures 10 and 11 show such a comparison for the electronically read extensometers at stations 2+83 and 3+45. The values in parentheses are calculated; all others are measured. Negative values indicate shortening between the anchors and the extensometer head; positive values indicate lengthening.

Figures 12 and 13 show data from manually read tape-extensometer measurements. The same conventions are used as for Figs. 10 and 11.

Table 2 shows a comparison of measured and calculated changes in vertical stress as a result of mining. VSM 1 and VSM 2 are both located in the same drill hole; VSM 3 is in a nearby drill hole. Although the calculations differ

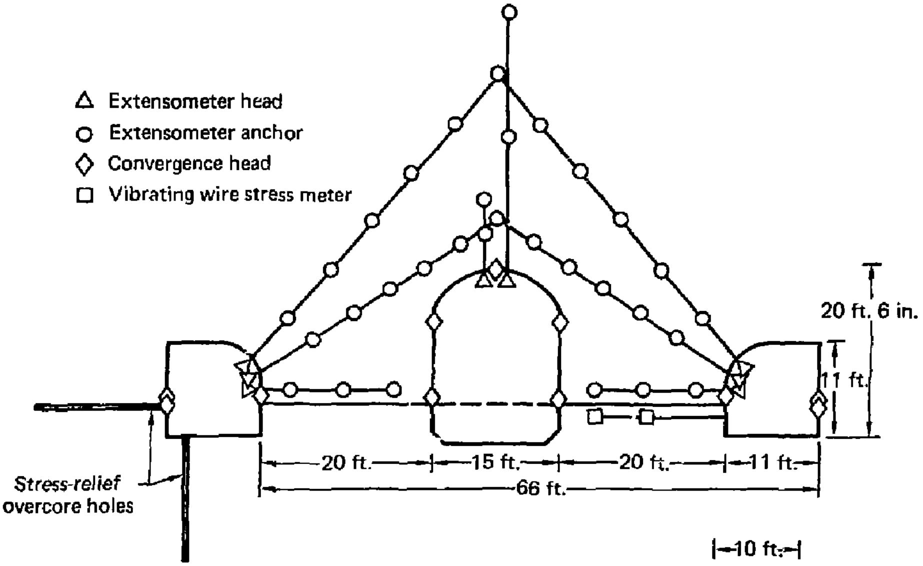


Figure 9. Schematic cross-section of spent fuel test showing relative locations of mine-by instruments.

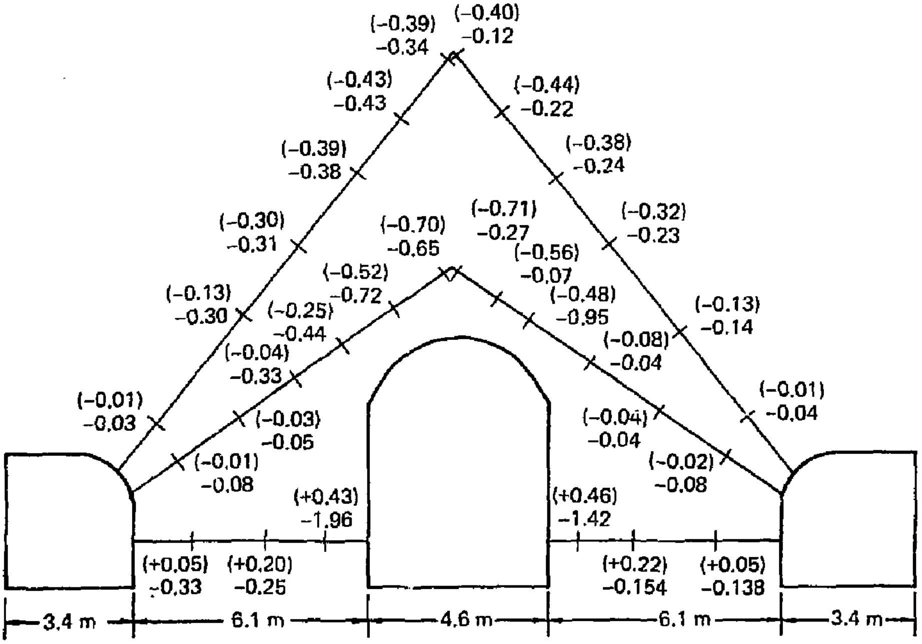


Figure 10. Mining-induced relative displacements (mm) in the less-jointed rock (~2 r 83).

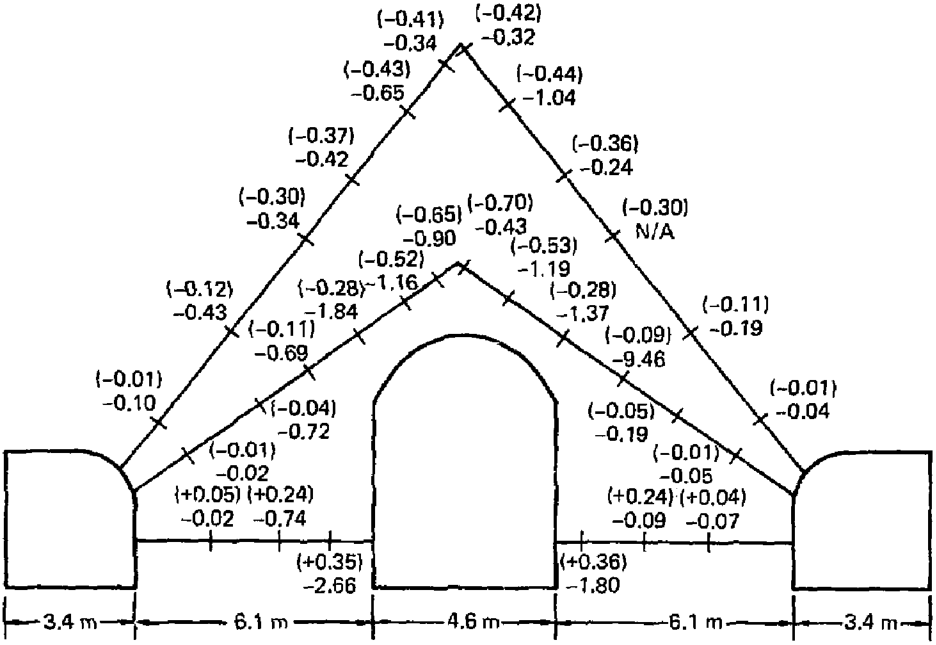


Figure 11. Mining-induced relative displacements (mm) in the more-jointed rock (~3 + 45).

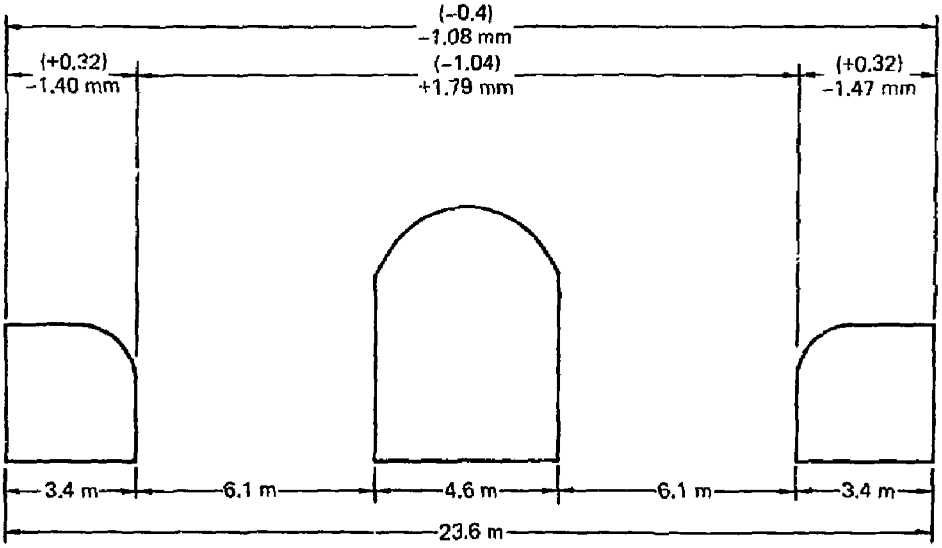


Figure 12. Mining-induced horizontal relative displacements in the less-jointed rock (~2 + 83).

widely, all calculated values are different in sign and widely separated in magnitude from the measured values.

It should be emphasized that these are very preliminary results. We present these unevaluated data in the hope that they will be of some benefit to this workshop.

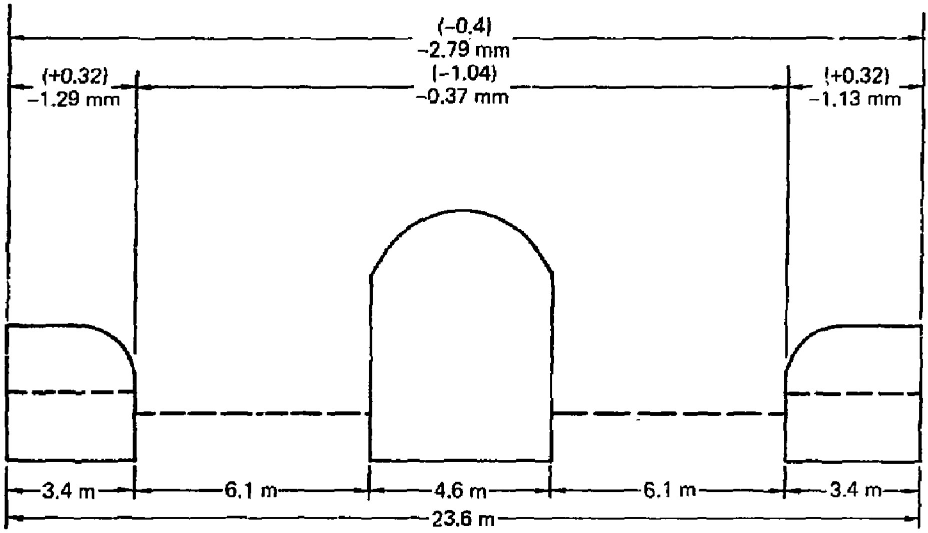


Figure 13. Mining-induced horizontal relative displacements in the more-jointed rock (~3 + 45).

TABLE 2. Comparison of measured and calculated changes in vertical stress as a result of mining, SFT-C.

Stress meter number	Dist. from canister drift, ft	VSM reading, psi	Calc. #1, psi	Calc. #2, psi	Calc. #3, psi	Calc. #4, psi
VSM 1	3	-1405	292	514	630	792
VSM 2	10	-196	396	697	390	490
VSM 3	3	-1020	292	514	630	792

Note: E = 8.8 × 10^6 psi for VSM calculation
Calc. #1 assumes E = 5.0 × 10^6 psi
Calc. #2 converts Calc. #1 to E = 8.8 × 10^6 psi
Calc. #3 assumes E = 7.0 × 10^6 psi
Calc. #4 converts Calc. #3 to E = 8.8 × 10^6 psi

TABLE 3. Summary of USGS overcore stress values.

Orientation	Assumed stress for calculations, psi	Calculated from measured stress, psi
Parallel to tunnels	1264	563
Perpendicular to tunnels	1264	1279
Vertical	1580	1148

As noted above, the scoping calculations assumed a vertical stress equal to overburden load, and a horizontal stress equal to 0.8 of overburden. The USGS overcore stress determinations gave different values, as summarized in Table 3. All of the other input data were taken from measurements on intact core and therefore do not represent the rock mass properties. Given the unrealistic input, the fact that rock is known not to be a continuum, and the fact that the calculational mesh did not represent the as-built drift geometry, one would not expect these calculations to predict rock behavior. Before publishing the results, we intend to improve the calculations by using the as-built geometry and more realistic input, although we currently plan to use the continuum code.

Conclusions

Lawrence Livermore Laboratory has documented the response of the Climax granite to mining and has made a preliminary comparison with the instrumentation scoping calculations. These data will form a baseline for analysis and evaluation of measurements during the thermal phase of the Climax granite Spent Fuel Test.

REFERENCES

1. L. D. Ramspott, L. B. Ballou, R. C. Carlson, D. N. Montan, T. R. Butkovich, J. E. Duncan, W. C. Patrick, D. G. Wilder, W. G. Brough, and M. C. Mayr, *Technical Concept for Test of Geologic Storage of Spent Reactor Fuel in the Climax Granite, Nevada Test Site*, Lawrence Livermore Laboratory, Rept. UCRL-52796 (1979).

2. L. D. Ramspott, Technical Editor, *Waste Isolation Projects--FY 1977*, Lawrence Livermore Laboratory, Rept. UCRL-50050-77 (1978).
3. L. D. Ramspott, Scientific Editor, *Waste Isolation Projects--FY 1978*, Lawrence Livermore Laboratory, Rept. UCRL-50050-78 (1979).
4. A. L. Edwards, *TRUMP: A Computer Program for Transient and Steady-State Temperature Distributions in Multidimensional Systems*, Lawrence Livermore Laboratory, Rept. UCRL-14754, Rev. 3 (1972).
5. R. Lingle and H. Pratt, *Laboratory Measured Material Properties of Granodiorite, Climax Stock, Nevada Test Site*, Terra-Tek informal report TR 78-47 (August 1978).
6. F. Maldonado, *Summary of the Geology and Physical Properties of the Climax Stock, Nevada Test Site*, U.S. Geological Survey Open-File Report 77-356 (1977).
7. K. J. Bathe, *ADINA, A Finite Element Program for Automatic Dynamic Incremental Nonlinear Analysis*, Massachusetts Institute of Technology, Cambridge, Mass., Rept. 82448-1 (September, 1975, reissued May, 1976).