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STATUS OF LLNL GRANITE PROJECTS

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ABSTRACT

The status of LLNL Projects dealing with nuclear waste disposal in granitic rocks is reviewed. This review covers work done subsequent to the June 1979 Workshop on Thermomechanical Modeling for a Hardrock Waste Repository[1] and is prepared for the July 1980 Workshop on Thermomechanical-Hydrochemical Modeling for a Hardrock Waste Repository. Topics reviewed include laboratory determination of thermal, mechanical, and transport properties of rocks at conditions simulating a deep geologic repository, and field testing at the Climax granitic stock at the USDOE Nevada Test Site.

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INTRODUCTION

LLNL has two sets of projects relevant to this workshop. We are carrying out laboratory studies of rock behavior under simulated repository conditions, and we are carrying out a series of field tests in the Climax granitic stock at the USDOE Nevada Test Site. Considerable progress has been made in both areas since the workshop on thermomechanical modeling a year ago.[1] This paper summarizes that progress, which is the result of many individuals' efforts, in the context of this workshop.

LABORATORY INVESTIGATIONS

In the area of the laboratory determination of thermal, mechanical and transport properties at conditions simulating those expected in the vicinity of a high-level waste repository at depth, much has been accomplished since the status of the experimental program was last reviewed.[2] Although most emphasis has been placed upon the behavior of granitic rocks, some data has also been taken on other coarse-grained materials, notably gabbro and halite. Measurements undertaken include: thermal conductivity, thermal diffusivity, thermal expansion, bulk modulus, Young's modulus and water permeability. In most cases, these data were determined over the maximum range of confining pressures, pore pressures and temperatures to be expected in a repository constructed at depths ranging to 2000m.

Because of the coarse-grain size (~1 cm) of the suite of rocks selected for the thermal measurements and because of the constraints imposed on the test by the range of pressure and temperature, a new apparatus had to be developed. We have constructed such an apparatus capable of pressures of 100 MPa and 500°C which utilizes a microprocessor for experiment control and data acquisition. In the past year, minor but persistent problems associated with the pressurized electrical leads and with jacketing of the high expansivity halite have been successfully overcome. Duplicate test data have now been determined on 13 cm diameter by 22 cm long samples of the Avery Island salt. Published results[3] indicate that effective pressures (confining pressure minus pore pressure) to 50 MPa have a negligible effect on the thermal conductivity, diffusivity and linear expansion at temperatures from 20° to 200°C. At 20°C and effective pressures increasing from 10 to 50 MPa, thermal conductivity and diffusivity are constant at roughly 7 w/m$^{\circ}$C and [illegible] x [illegible]$^{-6}$ m^2/s, respectively. At 50 MPa and temperature increasing from 20° to 200°C, both conductivity and diffusivity drop by a factor of [illegible]. Thermal linear expansion at 0 MPa matches that at 50 MPa, increasing from roughly 4.2 x 10^{-5}/$^{\circ}$C at 20°C to [illegible] x 10^{-5}/$^{\circ}$C at 200°C. The lack of a pressure effect on all three properties is consistent with previous work. Simple models of microcracking suggest that among common geological materials, the lack of a pressure dependence is unique to halite. This is likely due to combined effects of a low, temperature-sensitive yield strength and a high crystal symmetry.

The coefficient of linear thermal expansion has been determined for Climax Stock quartz monzonite at effective pressures from 0 to 28 MPa and temperatures ranging from 1[illegible]° to 300°C.[4] Data on linear expansion, compressibility and Young's modulus have also been measured but not fully evaluated for the Westerly and Stripa granites to 55 MPa and [illegible]. All samples tested were deliberately chosen to include imperfections such as healed fractures or phenocrysts which could be large compared with the sample dimensions (2.5 cm diameter by [illegible] long). For the two granites, multiple measurements of each property were carried out on [illegible] samples prepared in each of the three orthogonal directions.

Thermal expansion behavior for all [illegible] granitic [illegible] investigated were similar: expansions were neither constant nor a simple function of temperature or pressure. [illegible] was, however, demonstrated in the case of the Stripa granite. In general at [illegible] MPa effective pressure, thermal expansions increase from [illegible] 10^{-6}/°C at [illegible]°C to about [illegible] 10^{-6}/°C at [illegible]. At [illegible] MPa, expansions over an identical temperature range increased from [illegible] 10^{-6}/°C to [illegible] 10^{-6}/°C. These values of expansion are somewhat greater than those expected for an otherwise identical but crack-free rock. Observations of the heated rock indicate that the thermal expansion is accompanied by new microcrack formation. At the temperatures to be expected in the wall rock near a waste canister in granitic rocks, this increase in crack porosity is inferred to increase local permeability by factors ranging up to [illegible].

Compressibilities have only been fully evaluated for the Stripa granite. Here, the isothermal bulk modulus at 19°C decreases from $8 \cdot 10^{-11}$/Pa to $3 \cdot 10^{-11}$/Pa as pressure is increased from 10 to 50 MPa. At 350°C and over the same pressure interval, the compressibility decreases from $20 \cdot 10^{-11}$/Pa to $4 \cdot 10^{-11}$/Pa. Young's modulus data have not yet been fully evaluated. Elastic property data are not yet available for the Westerly granite.

Permeabilities of White Lake gneissic granite, Westerly granite and Creighton gabbro have been determined at [illegible]°C, at effective pressures ranging to 40 MPa and at deviatoric stresses to 0.85 of the fracture stress.[5] Permeabilities were determined by both the steady-state and the transient methods. The accuracy of this latter method has been assessed by parametric analysis.[6] Sample dimensions were [illegible] diameter by [illegible] cm long and fracture closure, electrical conductance, compressional velocity, and pulse amplitude were determined simultaneously with the permeability.

[illegible] the [illegible] gneissic granite indicated permeabilities of [illegible] to 10^{-24} m² that [illegible] effective pressure [illegible] permeabilities [illegible] that decreased by a factor of two as effective pressure increased to [illegible] MPa and varied by a factor of two as stress was increased to [illegible] of the fracture stress. Permeability of the [illegible] decreased from [illegible] to [illegible] × 10^{-24} m² with effective pressure to [illegible] MPa. Loading of the gabbro up to 0.85 of the fracture stress increased permeability by a factor of seven. The introduction of a throughgoing fracture increased the apparent permeability by 10^{7} to 10^{9} over the intact value in both granite and gabbro.

When compared to the initial value, compressional velocities increased by 5% with pressure to 30 MPa in the gneissic granite. For granite, pressurization from 2 to [illegible] MPa increased the velocity and pulse amplitude by 5 and 30%, respectively, and decreased the conductance by 50%. Velocity, amplitude, and conductance were weakly dependent on pressure in gabbro. The addition of stress decreased velocity and amplitude while increasing conductance markedly in both granite and gabbro. All data on both intact and fractured rock are consistent with crack closure and dilatancy with pressure and stress. Conductance and amplitude exhibit the best potential for monitoring changes in permeability and joint behavior in situ.

In the coming year, we expect to have determined the thermal behavior of at least several granitic rocks to 350°C and 50 MPa effective pressure. Likewise, data on thermal expansion, compressibility and Young's Modulus should be available for the Stripa and Westerly granites, the Climax quartz monzonite and the Creighton gabbro - all determined at pressures to 55 MPa and temperatures to 300° - 350°C. Measurements of permeability on both fractured and unfractured Stripa granite, Climax quartz monzonite and Montello granite should be completed next year. Diagnostic data of velocity, amplitude, conductance and fracture closure will be reported as well.

FIELD TESTING

Spent Fuel Test-Climax

LLNL received authorization for the Spent Fuel Test-Climax (SFT-C) on June 2, 1978 and completed loading the fuel May 28, 1980, less than two years after test authorization. The cost through fuel emplacement was $18.1 million, of which more than half is associated with the use of radioactive waste rather than electric heaters. Therefore, one of the test objectives[7] - the evaluation of the in situ differences in the effects of electrical simulators compared with real waste - could lead to considerable cost savings in future in situ tests. Although the fuel handling system constituted a major part of the effort on the test, it is documented elsewhere[8] and will not be further discussed here.

The original technical concept[7] was revised slightly during test design. A more recent summary has been given.[9] This paper will discuss changes in test design since the original concept and give some very preliminary test results.

The basic layout of the SFT-C has not changed (Figure 1). There are eleven canisters of spent fuel interspersed with six electrical simulators in a canister storage drift. Heater drifts at either side each contain ten electrical heaters. The total array is being operated to produce, within a central 15m × 15m repository model cell, a thermal history which simulates that in the center of a large repository with waste spaced 3m apart in linear arrays which are spaced 15m apart.

Changes in the test layout are mostly additions. The data-acquisition system has expanded from about 700 to 859 channels. The number of thermocouples has increased by 45 from 442 to 487. The number of rod extensometers (116 anchors) and stress meters (18) has remained the same, but 34 wire-extensometers have been added to measure vertical and horizontal convergence in the drifts. We also designed, built, and installed three-directional joint-motion gages electronically monitored at seven stations. There are also a number of manually monitored displacement and convergence pins set at various locations throughout the array.

From the standpoint of test design, a significant change has been in the power output of the spent fuel. The original test design was based on a power output of 2kW @ 2.5 years out-of-core.[7] The fuel selected for the test (Ref. 7, Table 7) was calculated to have a power output of 1.85 kW at 2.5 years out-of-core. Although this lower power level resulted in a reduced thermal peak at the rock face of the central storage hole at ∿6 months, this early peak was still in excess of that calculated for the same fuel at 40 to 50 years out-of-core. Thus the basic overtest design was retained.

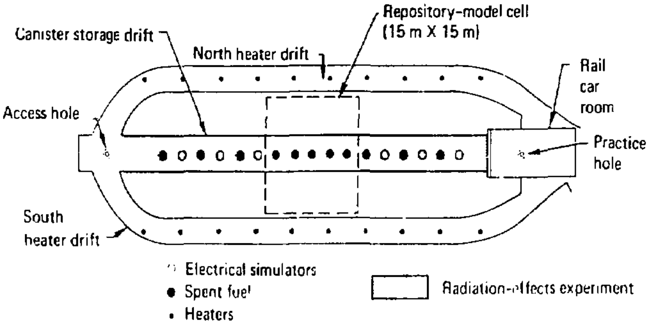

FIG. 1. Plan view of the Climax granite spent-fuel-storage test.

Just prior to fuel emplacement and after most pre-test calculations had been made, a fuel assembly was measured in a boiling water calorimeter. This measurement, since confirmed on a second assembly, gave a power level @ 2.5 years of 1.6kW. This new information required us to make extensive last-minute re-calculations, particularly to select the proper power-decay curves for the electrical simulators and turn-on times for the auxiliary heaters.

With a power output of 1.6kW, the early peak temperature on the borehole wall will be about 4^{0}C greater than that at 40-50 years out-of-core. Therefore, the SFT-C is still an overtest with respect to fuel older than 2.5 years out-of-core. As a result of both the power output change and calculational refinements using TRUMP in the 3-D mode with ventilation considered, the rock-wall peak tem- perature is now expected to be 85^{0}C in about 6 months after the start of the test as compared with slightly more than 100^{0}C in the original concept.

The operation of the guard heaters was originally designed to start 0.3 years after test start-up, and continue at a single power level. For a variety of both operational and test design reasons, those heaters were turned on June 27 at a power level of 925 watts. The power will be increased twice, to 1300W @ 0.6 years and to 1400W @ 1.5 years after test initiation. With the current power history of the guard heaters, an improved match between the repository calculation and the SFT-C calculation has resulted.

The first experiment in the SFT-C test was measurement of the rock response to mining.[1] Following this "mine-by" experiment, some instrumentation was removed for inspection and repair as necessary. Although the stress-meters were in place for only three months, they showed a significant amount of corrosion.[10] Because the SFT-C test duration is 3 to 5 years, some effort was expended in making the stressmeters more likely to survive. In addition the calibration reproducibility has been addressed, as well as the details of installation.[10] With regard to survivability three steps were taken:

1. Nickel-plating of the stressmeter bodies
2. Coating of the stressmeters with plastic film
3. After installation, filling the hole volume around the stressmeters with plastic foam.

The rod extensometer anchors generally performed well during the mine-by experiment. However, there is evidence that one anchor slipped because of premature rupture of the inflation line. These anchors were permanently inflated with a check-value system and are pressurized to the rupture-pressure of a section of inflation-tubing. The cited malfunction, together with the recognition that changes in temperature during the main SFT will cause corresponding changes in anchor-fluid pressure, led to an improved design of the rod extensometer hydraulic system. The design chosen by LLNL is one in which a nearly constant bladder pressure is maintained from the drift level. Changes of bladder pressure are therefore evident, documented, and correctable. Another refinement was to grout the annular space between the instrument and the borehole wall to reduce convection heat transfer within the boreholes. Individual anchors were decoupled from the grout by rings of closed-cell foam fixed above and below each bladder anchor.

Wire extensometers were designed at LLNL to measure vertical and horizontal convergence across the drifts at various locations. Deadweight loading of the wire is employed to eliminate problems associated with changes in wire stress and in catenary associated with spring-loaded systems. Seven sets of LLNL-designed 3-component fracture monitors remotely record displacements along major discrete fractures.

In addition to work specifically covered under SFT-C funding, two other significant areas of study were pursued this year. The first involves an experiment by LBL to determine the location and magnitude of acoustic emissions during the heated phase of the SFT-C. The second area of study is enhanced rock mechanics testing. This work focussed on in situ determinations of rock stress and modulus. Stresses were measured by undercoring and by borehole fracturing. Modulus determinations employed the borehole jack and the "petite seismique" methods.

In-Situ Migration Test

LLNL is in the process of writing an experimental plan for field tests of radionuclide migration in the Climax granite. During June 1980, construction for natural water collection and preliminary flow tests was started. The basic test concept is to inject radionuclides into a steady-state flow along a natural fracture connecting two drill holes about 2 meters apart. Tritium will be used to define the non-retarded migration, with other nuclides later included to compare field-measured with laboratory-measured retardation factors. Another purpose of this test is to develop and evaluate equipment and experimental techniques to be used in later in situ tests at potential repository sites.

Thermal Modeling

The thermal modeling for the SFT-C is briefly documented in the technical concept report(7) and more thoroughly documented in a draft report(11) Although many of the scoping and design calculations were done using analytic solutions for conductive heat flow, the more detailed calculations were done using the TRUMP finite difference computer program in 2 and 3 - dimensional geometry. This permitted accounting for the small scale details of the as-constructed test geometry, thermal radiation, convective heat transport, and ventilation, in addition to conduction. It has also been necessary to include heat transport by ionizing radiation from the spent fuel.

All of the recent modeling, plus the very early test data, confirm one of the early results of our calculations - that ventilation is a significant factor in reducing the thermal load on the rock and thus should be treated properly in design calculations. We still expect that about a third of the heat introduced into the rock will be removed by the low ventilation rates (1 m^3/s) used in the SFT-C.

All of the thermal measurements to date are tracking within a few degrees of the pre-test calculations. Becauses of the numerous variables in the calculations, this agreement is good. *The variables which need to be addressed* in this test (and are uncertain to 5 - 10%) include:

- o source power level,
- o thermal properties of the rock,
- o fraction of source power in ionizing radiation,
- o emittances of materials (stainless steel canister, carbon steel liner, rock),
- o convective heat transport in the annuli,
- o thermal properties of the many construction materials (e.g., steel, concretes) in the storage holes and the drift floor.

Other perturbing influences include ventilation air temperature and humidity, variations in pre-test ambient temperatures due to high-volume ventilation during the construction phase (up to several ^{0}C at some locations), position in the array, and the six-week sequence of loading fuel.

Thermomechanical Modeling

In order to carry out thermomechanical calculations, it was necessary either to find a thermomechanical code which would handle ventilation or to link a thermal code such as TRUMP to a mechanical code. ADINAT is a heat transfer code compatible to the ADINA displacement and stress analysis code, but does not include the capability to model internal radiation and ventilation. During the past year we have shown[12] that a proper choice of nodes and materials within the drifts can be used to model internal radiation, and that ventilation can be modeled with a boundary convection element. This method has been verified by check calculations against TRUMP.[12] As a result we have been able to use the ADINA-ADINAT codes for our thermomechanical calculations with assurance that the thermal calculations are correct.

Initial mechanical scoping calculations for the SFT-C were documented at last year's symposium[1] and in the technical concept.[7] These calculations were based on a linear elastic continuum model with an unrealistic treatment of overburden stress. It was, therefore, not surprising that discrepancies existed between the field measurements and the calculations for both displacement and stress. During the last year, most project personnel have been constrained to complete work prior to test startup, so that additional analysis of the mine-by data has been at a relatively low priority. However, we have been establishing a capability for modeling both ubiquitous and discrete joints in order to evaluate the effect of jointing on the mine-by data. We have also attempted to improve our knowledge of in situ modulus and state-of-stress.

In addition to purely mechanical calculations, we have improved our thermomechanical modeling capability. At the last symposium we showed that use of temperature dependent thermal conductivities and expansion coefficients could strongly affect modeling results for the 5 kW heater test at Stripa.[13] Subsequent work by LBL has apparently confirmed our results.[14] In our calculations of the SFT-C, we have included temperature dependence of the thermal properties at the appropriate overburden stress levels.[15] Unfortunately these calculations were documented prior to the change from 1.85 to 1.6 kW power level for each canister. Given the numerous uncertainties in input and models, we did not attempt to revise these calculations immediately before fuel insertion. They will be rerun with proper thermal input.

Future Directions

We plan to operate the SFT-C for a period of 3 to 5 years in its present configuration. Although the thermal peak occurs very early on the fuel canister (several months) and on the rock wall (~6 months), the peak temperatures at the edge of the 15 m x 15 m repository model cell (Figure 1) does not occur until about 2 years into the test. Very little cooling will occur at this location before 3 years, so that this seems a minimum test duration.

Although included in the original concept[7], we have only recently begun a serious evaluation of the possibility of refitting the test to include *in situ* studies of annulus backfill in the presence of radiation. We plan to prepare a technical concept for such an annulus backfill test during FY 1981.

During the coming year we plan to improve the thermomechanical calculations in two ways: use of improved input on rock properties, and enhanced code capability for ubiquitous and discrete joints and other parameters. We plan to continue efforts to improve understanding of the rock response to the waste, but foresee no significant changes to the test configuration.

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