MODEL DEVELOPMENT FOR IN SITU TEST RESULTS
IN ARGILLACEOUS ROCK *

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* This work was supported by the U.S. Department of Energy, DOE,
under contract DE-AC04-76DP00789.

** A U.S. DOE facility.

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I. INTRODUCTION

The development and verification of mathematical models of repository performance are essential for risk assessment of geologic disposal of nuclear waste. Two tasks basic to model development are:

1. Define phenomena and develop models for predicting repository behavior
2. Perform tests to evaluate and verify repository models.

The strategy for accomplishing these tasks for determining the thermomechanical effects can be outlined as shown in Figure 1. Laboratory studies can provide data and preliminary phenomenological definition to allow scoping model studies to be conducted. The results of these model studies provide guidance and definition of future investigations by establishing the issues that need to be resolved. The issues may require future laboratory effort or in situ tests. For in situ tests the scoping studies lead to design modeling for such tests. In situ tests may be conducted at shallow depths, of the order of tens of feet below the weathering zone, or at greater depths, a few thousands of feet, which are more representative of a repository. The near surface in situ tests are conducted for two practical reasons: 1) lack of existing at-depth facilities in the rock of interest and 2) cost for development of an at-depth facility. The near surface test does provide the in situ environment for developing constitutive and failure models which can be subsequently verified in at-depth tests. The at-depth

tests not only verify constitutive and failure models but address more specific thermal/structural interaction problems needed for repository design. Finally, the testing of the repository design models are conducted in a vault facility in conjunction with the specific repository site giving verification of the model for predicting repository behavior. To date, the work in argillaceous rock has progressed to the constitutive and failure model phase shown in the strategy of Figure 1. The results of near surface heater experiments in the Conasauga shale and Eleana argillite will be presented showing the resulting model development for the thermomechanical response. These models are then used to predict the at-depth behavior of argillaceous rock.

II. SITE GEOLOGY AND ROCK PROPERTIES

The near surface tests have been conducted in two very different geological settings. The Conasauga experiment was conducted in shales within the Conasauga Formation at Oak Ridge, Tennessee and the Eleana test was conducted in argillite within the Eleana Formation on the Nevada Test Site, Nevada. The geologic description of the two formations are shown in the following table.

GEOLOGIC CHARACTERIZATION OF NEAR SURFACE SITES

	Conasauga	Eleana
Mineralogy	Illite	Mixed Layer Illitic Clay
	Kaolinite	Kaolinite
	Chlorite	Quartz
Structure	Bedding Inclined $\sim 30^{\circ}$	Bedding Inclined $\sim 30^{\circ}$
	Bedding Pronounced	Bedding Obscure
	Lithology Highly Variable	Lithology Uniform
History	Unmetamorphosed	Metamorphosed (Pyrophyllite $\sim 200^{\circ}$)
Fractures	Pervasive ~ 1 mm Spacing	Present ~ 15 cm Spacing
	Numerous Directions	Numerous Directions
Strength	Friable	Well Indurated
Hydrology	Temperate Climate	Desert
	Fractures Facilitate Recharge	Fractures Facilitate Recharge
	Below Water Table	Above Water Table

In reviewing this table a number of observations can be made. The Eleana argillite is much more uniform and competent than the Conasauga shale. In the Eleana Formation the bedding is obscured and fractures are tight, no open fractures were observed in down hole television inspection. The Conasauga formation has highly pronounced bedding with thin interbed siltstones and limestones and fractures were observed to be open. The measured transmissivity of the Eleana formation is an order of magnitude less than that of the Conasauga formation. Also, the Conasauga shale is friable and easily broken where the Eleana argillite is much more competent because

it has not been disrupted by shearing. A very important difference in the sites for the two experiments is the hydrology. The Conasauga test was conducted below the water table in a temperate climate whereas the Eleana test was conducted above the water table in an arid climate.

The properties of the two rocks have been measured in the laboratory and are summarized below.

PHYSICAL PROPERTIES

	Conasauga Shale	Eleana Argillite
Specific Heat		
(150-400°C)	0.8-1.0 kJ/Kg°C	0.9-1.0 kJ/Kg°C
Thermal Conductivity		
(25°C)	1.1-2.2 W/m°C	2.0-2.6 W/m°C
(125-500°C)	1.1-0.6 W/m°C	2.0-1.3 W/m°C
Bulk Density		
(25°C)	2.6-2.7 gm/cm ³	2.7-2.9 gm/cm ³
Water Content		
(By Weight)	1-3%	1.8-4%
Porosity	0.1-4%	6.8-12%
Thermal Expansion		
(150-450°C)	0.75-1.4 x 10 ⁻⁵ /°C	0.86-1.25 x 10 ⁻⁵ /°C

The properties for the two rocks are very similar except the Eleana has a higher porosity and the Conasauga's thermal conductivity is lower than that of the Eleana. The variation with temperature of the thermal conductivity and thermal expansion are important to note because of the water present in the rocks. This water resides

in the pore space and more importantly in the expandable clays in the "illite" present. The thermal conductivity shown in Figure 2 is for the Conasauga Shale. These data were measured for unconfined samples and show the reduction of conductivity due to water release with increasing temperature. In Figure 3 the thermal expansion as a function of temperature for three Eleana samples is shown. For temperatures above 150°C the three samples show a continuous expansion with temperature as noted in the properties table. Below 150°C, contraction of the rock occurs due to the water released from the expandable clays. The degree of contraction is dependent on the amount of clay present. The general dependence of thermal conductivity and thermal expansion on water release from expandable clays with increase in temperature has been seen for both the Conasauga Shale and the Eleana Argillite.

III. FIELD TEST DESIGN

The following section briefly describes the field test design for the near-surface tests with a brief discussion of operating conditions at the two sites. A generalized cross section of the heater emplacement configuration is shown in Figure 4. The configuration was the same for both sites, with the heater being at a depth of 15 meters for the Conasauga test and 23 meters for the Eleana test.

The heater consists of a sealed, 0.3 m-diameter cylinder of 304 stainless steel containing resistive heating elements, each rated at 6 kW maximum output. Each element is in the form of a

hairpin loop about 3.7 m long, of which 3 m is heated, and consists of a nichrome resistance wire embedded in packed ceramic with an outer stainless steel sheath. Each heater contains six element loops wired in two sets of three, such that three elements are operated simultaneously, with the second set constituting a backup.

The heater assembly contains three regions: 1) the heated region; 2) the cold section; and 3) the terminal or junction section. The heater region contains the 3 m long heated portion of the elements. The cold section contains the unheated (solid conductor) portions of the elements, and is filled with packed vermiculite. The terminal section, which contains the junction between the power leads and the solid conductor portion of the heater elements, is kept cool by air forced down the power lead conduit and up the thermocouple conduit.

As shown in Figure 4, the heaters are emplaced in an open hole and are sealed off near the bottom of the casing by a pneumatic packer. To minimize heat and/or mass transfer in the area between the top of the heater and the bottom of the packer, fiberglass insulation is placed as near the top of the heater as practicable.

Measurements made during the heater experiments include heater and rock temperatures, stress, and vertical displacement. Gas transmissivities were measured before and after the tests. The general plan view for the Eleana heater experiment is shown in Figure 5 and is essentially the same as for the Conasauga experiment. The SI-1 hole is the heater hole and the satellite holes are used for instrumentation. The instrumentation used was thermocouples for temperature, Invar extensometers for displacement, and IRAD-Creare

stress gauges for stress. In addition, spring-loaded thermocouples were attached to the heater in the Eleana test and measured heater hole wall temperatures directly.

The data acquisition systems used in the Conasauga and Eleana experiments were identical and used a Fluke data logger as the central element. Data were recorded by a sequential listing of all channels, and by magnetic tape.

Despite the similarity of their physical layouts, the procedures followed during operation of the Conasauga and Eleana experiments were quite different. The outer surface at the center plane of the Conasauga heater was brought up to constant temperature (385°C) within the first week of operation. In order to prevent the heater from being flooded by groundwater, it was necessary to pressurize the heater hole with air, approximately equivalent to the hydrostatic head at the hole bottom. The full-scale Eleana experiment, after 21 days at 2.5 kW, was run at a constant power level of 3.8 kW. Initial operation of the heater indicated that small amounts of water present in the main heater hole were sufficient to seriously alter the heat transfer to the formation. Consequently, the heater was removed, a sump extension was drilled in the bottom of the heater hole to a total depth of 35 m, and a passageway was excavated across to an adjacent hole, S1-3 (see Figure 5). At this point, the heater was again emplaced, and operation at 2.5 kW was continued. Water collecting in the sump (S1-1) was pumped out of S1-3 periodically for 45 days, at which time the water accumulation ceased. Since that time, the Eleana test has been operating in effectively "dry" rock.

IV. MODELING OF TEST RESULTS

As a consequence of the differences in site geology, hydrology, and operating modes of the two tests, modeling efforts for the Eleana and Conasauga experiments have received somewhat different emphasis. The pattern followed in treating Conasauga data was to compare the quasi steady-state isotherms that developed after several months of heater operation with predictions based on simple conduction solutions, assuming constant heater temperature. Having done this, a comparison was made to determine whether or not the deviations noted could be ascribed to fluid convection in the formation. Since the Eleana experiment was run at constant power, the early-stage transient temperature build-up was and is a primary object of analysis of data from this test. Although the displacement data have not been analyzed the thermal behavior coupled with field examination of the heater hole surfaces for a scaled test and the full-scale test in the Eleana formation provide a basis for the thermomechanical modeling of the near surface experiment.

Conasauga Model

The Conasauga thermal data were analyzed by examining the temperature history distributions, isotherms for given times, and the thermal input of the heater. Because the heater boundary condition for this test was a constant heater temperature the first thirty days of operation was at very high and variable heater power inputs to the formation. After thirty days and until the end of the experiment the power input slowly decayed as shown.

in Figure 6. At 240 days the power level has declined to a value of approximately 5.0 kW.* Examination of temperature distribution in the formation showed that only a small region close to the heater was above the boiling point of water and that most of the energy was transferred into saturated rock. Simple analytical models of heat conduction indicated that the energy was being distributed at a constant thermal conductivity of $1.8 \text{ W/m}^\circ\text{C}$. This effective value of conductivity is consistent with the laboratory data at low temperatures as shown in Figure 2.

This effective conductivity at elevated temperature is high with respect to values determined at the same temperature in the laboratory. The fact that in situ values lie in the range for the effective conductivities of unheated samples suggests that the calculated temperature profiles using a relatively constant conductivity should correspond to those profiles observed. A parametric study was, therefore, made using the CINDA thermal code, a two-dimensional transient heat conduction code, with specified constant conductivities of 1.5, 1.75 and $2.0 \text{ W/m}^\circ\text{C}$. Heater temperatures were specified in accordance with those measured, and the void space between the heater top and the packer was assumed to have a constant wall temperature of 100°C . A comparison of the predicted power values and those observed in the field indicates that a constant conductivity of about $2 \text{ W/m}^\circ\text{C}$ can account for the power input, once the initial transient start-up phase has been concluded (Figure 6). A comparison between theoretical and actual isotherms shows that for those isotherms below the boiling point of water there is relatively good agreement (Figure 7) when a constant effective conductivity of $2 \text{ W/m}^\circ\text{C}$ is assumed.

* Approximately $3/4 \text{ kW}$ of the heater power is removed to the air which cools the heater leads.

There is, however, a consistent slight upward displacement of the higher temperature isotherms in situ compared with those predicted by CINDA (Figure 7). In an attempt to determine if convective circulation could account for this displacement, the SHAFT code, a multidimensional porous flow code with two-phase flow capability, was run assuming a heater placed in a uniform isotropic porous media. The result of this modeling effort was a fluid flow and heat transfer pattern which, in a qualitative way, matches the difference inferred from the comparison between the field data and conduction model output. An energy balance comparison between the field data and the heat conduction model showed very good agreement.

To conclude, despite the presence of appreciable ground water and a fractured formation, it would appear that conduction is the principal method of heat transfer through the Conasauga formation in these tests. The fact that the effective in situ conductivity at elevated temperatures is considerably higher than that determined in the laboratory is consistent with the fact that during such lab determinations a sample becomes dried, and in doing so, has cracks open. It is probable that no dessication takes place in situ until temperatures in excess of 100°C are reached, and that even then the weight of the overburden is sufficient to close most small scale cracks. Thus, it is consistent that in situ conductivities would be close to the laboratory values measured for fresh unheated samples.

Eleana Model

Prior to running the full-scale heater test in the Eleana formation, two scaled heater tests were run to provide assurance

that no major thermomechanical failure of the argillite would occur to prevent a successful full scale, long-term heater test. In the first test, scaled to a heater power of 3.5 kW, computed heater temperatures were within 7% of those measured for the entire 96 hour test. The second test, scaled to 5 kW power as an overtest, showed computed temperatures within 7% of measured for the first 20 hours but the measured temperatures were 15-20% below prediction due to periodic water in-flow at late time in test. Posttest examination of the hole revealed that rock surface spallation had occurred above the heater. Using the thermal output from the finite element thermal code, COYOTE, as an input of the temperature field to the two-dimensional finite element thermal stress code, SASL, and modeling the contraction-expansion behavior for argillite as shown in Figure 3, compressive failure was predicted above and below the scaled heater as observed. Since no major failure occurred in the scaled tests for the scaled power input of 3.5 kW, the full-scale test was conducted. The energy transfer to the formation was modeled as heat conduction with variable thermal conductivity using the finite element thermal code, COYOTE. The comparison of measured and calculated temperatures for different radii from the heater showed good agreement for the first 100 days of operation. After that time the measured values increase above the predictions. Thermomechanical modeling of this test using the finite element code, ADINA, predicted that joint opening would occur in the rock near the heater due to the contraction of the clays as water is released (Figure 8). The opening of joints would cause a reduction in the in situ thermal

conductivity leading to higher temperature than predicted near the heater. Posttest examination of the full heater hole surface revealed an open joint system not present before formation heating.

Summary

The results from the near-surface tests have provided development of thermal and thermomechanical models for argillaceous rock in two distinctly different geologies. The near-surface test results provide:

1. the definition of heat transfer models;
2. the modeling of thermally driven water circulation; and
3. the definition of the joint opening model due to the thermal contraction of argillaceous rock.

V. AT-DEPTH PREDICTIONS

Using the models developed from the near-surface tests, two studies have been made to predict the thermomechanical rock behavior at depth. The first study was an extension of the Eleena heater experiment to depths of approximately 1000 and 2000 meters using a Young's modulus determined from laboratory measurements. The results of the calculations for 1000-meter depth show that the region of joint opening is similar to the near-surface result but was less extensive, only occurring out to 0.7 meter radius instead of 1.1 meter. The results of the calculation for 2000-meter depth show further reduction in the volume of the open-joint region about the heater. However, in this case compressive mechanical failure of the formation in a region above the heater is predicted. If one assumes the in situ Young's modulus is reduced by a factor of 2 to account for the joint system in the rock mass,

the results of the calculations for 1000 m depth show no region in which open joints exist or where compressional failure would occur. Because of these differences in predicted behavior with depth, at-depth experiments are needed to determine the proper in situ properties and check the models. The second study compared the near-surface thermal stress fields with those predicted for a heater 7 meters below a tunnel floor at 425 meters depth. The results of the calculations showed only slight differences in the stress fields; significant differences were noted in the vertical displacement fields above the heater due to the presence of the floor. The tensile strains observed for the near-surface calculation were reduced by the addition of the over-burden stress. This latter result is similar to the behavior observed above when the region of open joints was reduced by the addition of an overburden stress. These predictions made of at-depth behavior are based on near-surface tests results and need to be checked by at-depth experiments. This is particularly important since the near-surface test seems to maximize the open joint effect. Also, experiments are needed to determine if the compressive failure model applies at depths of interest.

VI. CONCLUSIONS

Near-surface heater tests have been conducted in two different geologic settings for argillaceous rocks. The results of these tests have provided the in situ data necessary to develop the thermomechanical models for predicting the response of argillaceous rock to thermal load representative of high-level nuclear

waste. At depth tests would be required before full confidence could be given to the results.

FIGURE 1-- STRATEGY FOR MODEL VERIFICATION

FIGURE 2
THERMAL CONDUCTIVITY - CONASAUGA SHALE

LINEAR THERMAL EXPANSION MEASUREMENTS OF ELEANA ARGILLITE
FIGURE 3

FIGURE 4
HEATER SCHEMATIC

FIGURE 5--ELEANA HEATER EXPERIMENT SCHEMATIC

FIGURE 6--POWER DATA COMPARED WITH CINDA CALCULATIONS FOR CONASAUGA HEATER EXPERIMENT

— Actual Isotherms - Site One
--- Computed Isotherms - CINDA

FIGURE 7
COMPARISON OF ACTUAL AND COMPUTED ISOOTHERMS FOR THE CONASAUGA
EXPERIMENT AT 135 DAYS

FIGURE 8
MECHANICAL MODELING RESULTS
ELEANA FULL-SCALE HEATER