NEAR-SURFACE HEATER EXPERIMENTS

IN

ARGILLACEOUS ROCKS

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Abstract:

Full-scale near-surface heater experiments are presently being conducted by Sandia Laboratories in the Conasauga Formation at Oak Ridge, Tennessee, and in the Eleana Formation on the Nevada Test Site, Nevada. The purposes of these experiments are: 1) to determine if argillaceous media can withstand thermal loads characteristic of high level waste; 2) to provide data for improvement of thermomechanical modeling of argillaceous rocks; 3) to identify instrumentation development needed for further in situ testing; and 4) to identify unexpected general types of behavior, if any.

The basic instrumentation of these tests consists of a heater in a central hole, surrounded by arrays of holes containing various instrumentation. Temperatures, thermal profiles, vertical displacements, volatile pressurization, and changes in in situ stresses are measured in each experiment as a function of time, and compared with pretest modeling results. Results to date, though in general agreement with modeling results assuming conductive heat transfer within the rock, indicate that the presence of even small amounts of water can drasticalley affect heat transfer within the heater hole itself, and that small amounts of upward convection of water may be occurring in the higher temperature areas of the Conasauga experiments.

I. INTRODUCTION

Two near surface heater experiments have been initiated in the Conasauga Formation of Tennessee and one in the Eleana Formation of Nevada, to help in the evaluation of argillaceous rocks as high level waste disposal media. Such experiments provide preliminary media assessment, without expending the time and money required for construction of at-depth experimental facilities.

The basic objectives of these tests are: 1) to determine if argillaceous media can withstand thermal loads characteristic of high level waste; 2) to gather in situ thermomechanical data required to improve modeling accuracy; 3) to identify instrumentation development needs for in situ experimentation; and 4) to identify any unexpected types of general behavior that might result from heating.

The experiments described here consist of a central heater, with dimensions of a nominal waste canister, emplaced at a depth of a few tens of meters. Thermal profiles, vertical displacements, stress, and gas pressure measurements are then made in a series of satellite holes surrounding the heater. Laboratory measurements of material properties and modeling are also being conducted in support of the experiments.

II. SITE GEOLOGY

The two near-surface tests in Tennessee are being conducted at an average depth of 15 m in the Conasauga Formation of Cambrian age. This formation, which at the heater sites occurs within major thrust sheets of the Appalachian Valley and Ridge province, consists of a varied sequence of gray and maroon shales, gray-green siltstones, and thin-bedded limestones. Alternation of rock types occurs on the scale of centimeters. Major minerals within the shales include quartz and "illite", with minor chlorite, kaolinite, and calcite. Due to the thrust faulting, the shale layers at the two heater sites are heavily jointed and folded, and contain numerous shear planes, frequently at spacings of a millimeter or less. Siltstone and limestone interlayers are less disturbed. Ground water recharge rates at the Conasauga experiment sites prior to turn-on of the heaters was approximately 0.01 m^3/hr. in a series of holes 15 meters deep and 0.1 m in diameter. This rate varied over the experimental sites, however, indicating local variability in joint permeability. Since the Conasauga heater holes were pressurized during the experiments, no information is available concerning recharge during the tests.

The near-surface test at the Nevada Test Site is being conducted at a depth of some 23 meters within argillite of the Eleana Formation of Mississippian and Pennsylvanian age. The argillite generally appears to be unlayered in hand specimen, although fine layering is evident in this section. Major minerals within the argillite include quartz, an interlayered "illite" phase, and frequently siderite. Minor phases include kaolinite, pyrophyllite, and chlorite, with possible chamosite. The presence of pyrophyllite indicates metamorphism to temperatures on the order of 200°C. The region near the experiment site has been subjected to both regional thrusting of Mesozoic Age and Basin and Range block faulting, predominately of Tertiary Age. Nonetheless, fracturing is distinctly less prevalent than at the Conasauga sites, with many recovered core lengths of 0.3 m or more. Ground water recharge at the Eleana Site was approximately 0.001 m^3/hr in the 0.4 m diameter heater hole before initiation of the full-scale heater test, though rates varied across the site. Recharge was essentially constant in the early phases of the experiment. Water collection ceased entirely approximately 40 days into the test. Bedding at all three heater sites is inclined at an angle of approximately 30° to the horizontal.

III. FIELD TEST DESIGN

The following section briefly describes the heater design for the near-surface tests, instrumentation and types of data being collected, and data acquisition system being used. Finally, there is a brief discussion of operating conditions at the two sites.

Heater Design

A generalized cross section of the heater emplacement configuration in the Conasauga experiments is given in Fig. 1. The configuration at the Eleana site is similar, except that the heater is at a slightly greater depth, approximately 23 meters.

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. The top 0.6 m of each element has a heavy conductor replacing the nichrome wire, and thus is not heated directly. 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. Each set is wired in a Δ configuration for 3 phase, 240 V operation. If one element of a set of three fails, the other two will suffice until the backup elements are activated.

The heater assembly contains three regions: 1) the heated region; 2) the cold section; and 3) the terminal or junction section. The heated 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. Analysis of the amount of heat conducted directly through the heater to the junction section indicates that only a very small amount of heat is removed from the junction or terminal section, i.e., approximately 50 watts at a total power of 3.8 kW.

As shown in Figure 1, 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, fibre glass insulation is placed as near the top of the heater as practicable.

Measurements made during the heater experiments include heater and rock temperatures, gas pressures, stress, and vertical displacement. Gas transmissivities will be measured before and after the tests. Figure 2 shows the general plan view of the two heater experiments in the Conasauga Formation. The same layout is being used in the Eleana experiment, except that only one heater test is being conducted. Instrumentation of the Eleana experiment holes is essentially the same as that given in the Conasauga layout, though thermocouple spacing in some holes is different. In addition, spring loaded thermocouples are attached to the heater in the Eleana test, and measure heater hole wall temperatures directly. Table 1 describes the instrumentation being used in the full-scale heater tests in some detail.

The data acquisition systems used in the Conasauga and Eleana experiments are identical, and use a Fluke data logger as the central element. Thermocouple data from the experiment flow directly into the logger at preset intervals ranging from minutes to hours. Vertical displacement, pressure, and diagnostic thermocouple data first enter a low level scanner and extender chassis which feeds into the logger. The IR&D-Creare stress data are initially digital and must be converted to analog form before being handled by the Fluke logger. A microprocessor controls the printout terminal so that data for successive printouts of each channel appear in sequence. Data is recorded by a sequential listing of all channels, and by magnetic tape as well.

Despite the similarity of their physical layouts, the procedures followed during operation of the Conasauga and Eleana experiments are quite different. The outer surface at the center plane of the Conasauga heaters was brought up to constant temperature (385°C) within the first week of operation. In order to prevent the heaters from being flooded by ground water, it was necessary to apply external air pressure to the heater holes, approximately equivalent to the hydrostatic head at the hole bottom. The full-scale Eleana experiment, after 21 days at 2.5 kW, is being 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 was drilled to a depth of 35 m in the bottom of the heater hole, and a passageway excavated across to an adjacent hole, S1-3 (see Fig. 2). At this point the heater was again emplaced, and operation at 2.5 kW continued. Water collecting in the sump (S1-1) was pumped out of S1-3 periodically until July 1, at which time water accumulation ceased. Since that time, the Eleana test has been operating in effectively "dry" rock.

As a consequence of the differences in site geology, hydrology, and operating modes of the two tests, thermal modeling efforts for the Eleana and Conasauga experiments have had 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 is being run at constant power, the early-stage transient temperature buildup was and is a primary object of analysis for this test.

Thermal Analysis--Conasauga Formation

The analysis of Conasauga thermal data given here is based on the approximate positions of selected isotherms and the thermal input of the heaters at the two sites, 135 days after starting the tests. Although the heater power decreased slightly in both cases during the time period from thirty to one hundred and fifty days (see Fig. 3), these changes were slow enough to permit use of steady state formulas.

At steady state (i.e., after 150 days) total heater power at Sites One and Two were approximately 5.0 and 6.5 kW, respectively. In situ conductivities computed using these power levels and temperature profiles fall within the range 0.9 to 2.3 W/m°C, which is consistent with values measured in the laboratory prior to the test. Using the temperature gradients at the heater midplane and approximating the 50°C isotherm by a sphere, for purposes of simplicity, the steady state calculations indicate conductivities of approximately 1.3 (Site One) and 1.8 (Site Two) W/m°C. Similar calculations for the approximate volume in the temperature range 100-200°C for Site One imply conductivities of about 1.8 W/m°C. This was an unexpected result because laboratory measurements indicated a sharp decrease in thermal conductivity as samples were heated from room temperature to 100-200°C. Because both choices of isotherm location and temperature gradient are somewhat arbitrary, these numbers should be taken only as an indication of the range of values for the effective in situ conductivity of the Conasauga Formation.

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 when samples were still fresh.

The fact that in situ values lie in the range for the effective conductivities of unheated samples suggests that models using a relatively constant conductivity will account for observed temperature profiles. A parametric study was, therefore, made using the CINDA [1] thermal code, with specified constant conductivities of 1.5, 1.75 and 2.0 W/m°C. Heater temperatures were specified in accordance with those measured at Site One, 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 temperature values and those observed in the field indicates that a constant conductivity of about 2 W/m°C can account for the power input, once the initial transient start-up phase has been concluded (Fig. 3). A comparison between theoretical and actual isotherms shows that for those isotherms below the boiling point of water there is reasonable agreement, which also suggests that a constant effective conductivity of 2 W/m°C is not greatly in error.

There is, however, a consistent slight upward displacement of the higher temperature isotherms in situ compared with those predicted by CINDA. In an attempt to determine if convective circulation could account for this displacement, a second code, SHAFT [2], capable of dealing with two phase flow in a porous medium, was run assuming a heater placed in a uniform isotropic porous medium. 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.

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, and a constant effective in situ conductivity is adequate to describe in situ heat conduction.

Preliminary Analysis--Eleana Experiment

Modeled and measured rock temperatures at the experiment midplane for operation of the Eleana heater test up to 100 days are compared in Fig. 4, with modeled results being based on materials property data listed in Table 2. Preliminary thermal modeling to date includes both temperature-dependent heat capacity and anisotropic effects in thermal conductivity, but assumes radial symmetry for purposes of simplicity. The COYOTE [3] finite element code was used in these calculations, assuming only conduction within the rock, but considering both conduction and radiation in the heater hole.

There is very little difference between modeled and measured temperatures at any point, except for measurements on the wall of the heater hole, which lagged some 30°C behind expected values at early times, but agree remarkably well with modeled results after 50 days. These results indicate good agreement between lab conductivities measured approximately parallel to layering and near-surface in situ conductivity in the Eleana in the same direction. Agreement of results has been improved over earlier results by accounting for volatilization of 3 wt% H_2O between 50 and 100°C by means of temperature-dependent heat capacity. In contrast to the Conasauga results, there is no reason to expect anomalously high in situ conductivities at elevated temperatures, relative to measurements in the lab, since laboratory samples of Eleana are generally more coherent.

A comparison of modeled and measured temperatures at the 0.6-meter radius parallel to strike indicates that there are consistent variations from modeled results that should be noted, though they are generally small, i.e., 10°C or less. Temperatures at depths of 20 m or less exceed modeled temperatures. Temperatures between depths of 20 and 23 m fall slightly below modeled values, while temperatures at a depth of 24 m are consistently slightly higher than modeled. Measured temperatures at the 0.6-meter radius perpendicular to strike lag behind expected temperatures (which assume horizontal layering), by as much as 30°C near the experiment midplane, but exceed modeled values at depths of less than 20 m as is the case parallel to strike. Complete three-dimensional modeling of the Eleana test, including the effects of inclined layering and an estimate of heat transfer in the accessible portion of the heater hole above the heater, is in progress.

Effects of generation or movement of water in the Eleana, while sufficient to depress initial operating temperatures of the heater in the configuration without the sump-hole extension of the heater hole, is not evident in either depressed temperatures or displaced isotherms within the argillite as has been observed in the Conasauga tests. Once care was taken to remove any water that was in the heater hole from the vicinity of the heater, the thermal effects of water generation and/or movement became minimal within the argillite.

IV. CONCLUSIONS

Near-surface heater experiments are an experimental technique used to aid the preliminary evaluation of the suitability of argillaceous rocks for disposal of nuclear wastes. In both the Conasauga Formation of Tennessee and the Eleana Formation of Nevada, results to date indicate: 1) general agreement of laboratory-measured and in situ thermal properties; 2) the marked effects of inclined layering; and 3) that even small amounts of formation or joint-entrained water could have major effects on in situ heat transfer following initial emplacement of nuclear waste. No effects have been found, to date, which would preclude the use of argillaceous rocks for disposal of nuclear wastes.

REFERENCES

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2. Lasseter, T. J.: "Numerical Simulation of Heat and Mass Transfer in Multi-Dimensional Two-Phase Geothermal Reservoirs," ASME Paper n75-WA/HT-71, 13 pp. (1975) (The SHAFT code has been updated, by Sandia, to provide improved modeling).

3. Gartling, D. K.: "COYOTE--A Finite Element Computer Program for Nonlinear Heat Conduction Problems," SAND 77-1332, Sandia Laboratories, Albuquerque, New Mexico (1978).

Table I
Instrumentation Description for Eleana and Conasauga
Near Surface Heater Experiments

Measurement/Transducer	Purpose
Temperature/Thermocouples	
Chromel-Constantan Type-E, in stainless steel sheath; MgO filled. Grouted in satellite holes, strapped to heater surface, or spring-loaded against heater hole wall.	Determine thermal profile in formation; heater diagnostics; measure temperature at surface of heater hole wall.
Temperature/Thermocouples	
Chromel-Alumel Type K, mounted on extensiometer bases	Correct extensiometer data for temperature field
Gas Pressure/Gulton GS613 Diaphram, Type 0	
0-100 psi range, installed at bottom of casing in pressure measurement and heater holes.	Monitor gas generation within formation and in heater holes.
Vertical Displacement/Invar Extensiometers	
Invar rod in thermally affected areas, stainless steel elsewhere. Bottom anchored to hole wall, top attaches to potentiometer at surface.	Measurement of vertical displacement in formation
Stress/IRAD-Creare Vibrating Wire Stress Gauges	
200°C upper limit; gauge is placed in aluminum tubing and potted. Coupled to hole wall with expandable grout.	Estimation of radial and circumferential stresses, thus complementing vertical displacement measurements.
Transmissivity/Geiger-Müller Tubes	
Kr^{85} measurements, using multiple detectors in holes around injection hole; conducter pre- and posttest.	Qualitative data on amount of experiment-induced fracturing

Table II
Material Properties Used in Pretest Modeling of Eleana Argillite

Property	Value
Thermal expansion coefficient	$12 \times 10^{-6}\ {}^{o}C^{-1}$
Heat capacity	$3082 - 2180\ kJ/m^3\ {}^{o}C$
Bulk density	$2600\ kg/m^3$

Thermal Conductivity at Elevated Temperatures
($W/m^{o}C$)

T(°C)	A	C
∿ 25	--	2.43
50	--	2.17
75	1.79	--
100+	1.78	2.06
150	1.53	1.80
200	1.45	1.67
250	1.39	1.69
300	1.36	1.73
350	1.33	1.61
400	1.31	1.46
450	1.29	1.48
500	--	1.27

A. Axial thermal conductivity, one sample. Nearly perpendicular to layering.

C. Average of radial conductivities of 4 samples. Nearly parallel to layering.

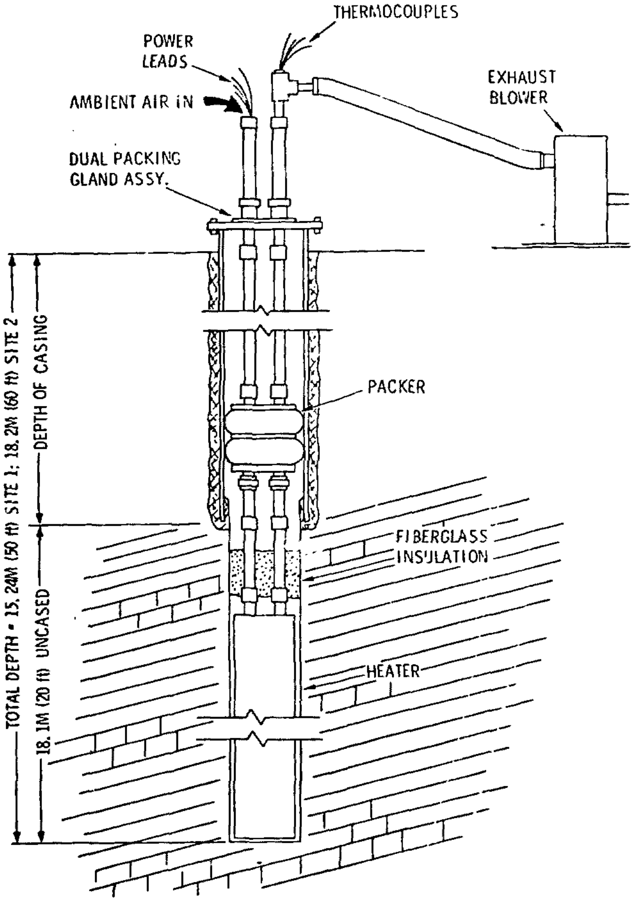

Figure 1: Generalized cross section of full-scale near surface heater configurations, Conasauga tests 1 and 2.

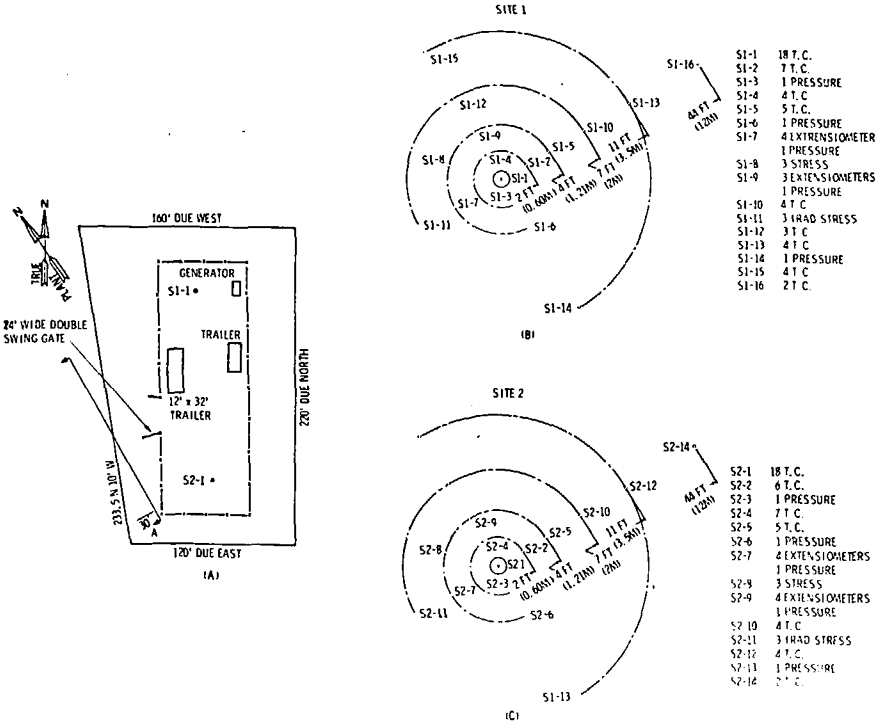

Figure 2: Generalized plan view of full-scale near-surface heater sites in the Conasauga Formation, including usage of instrumentation holes. T.C. = thermocouple.

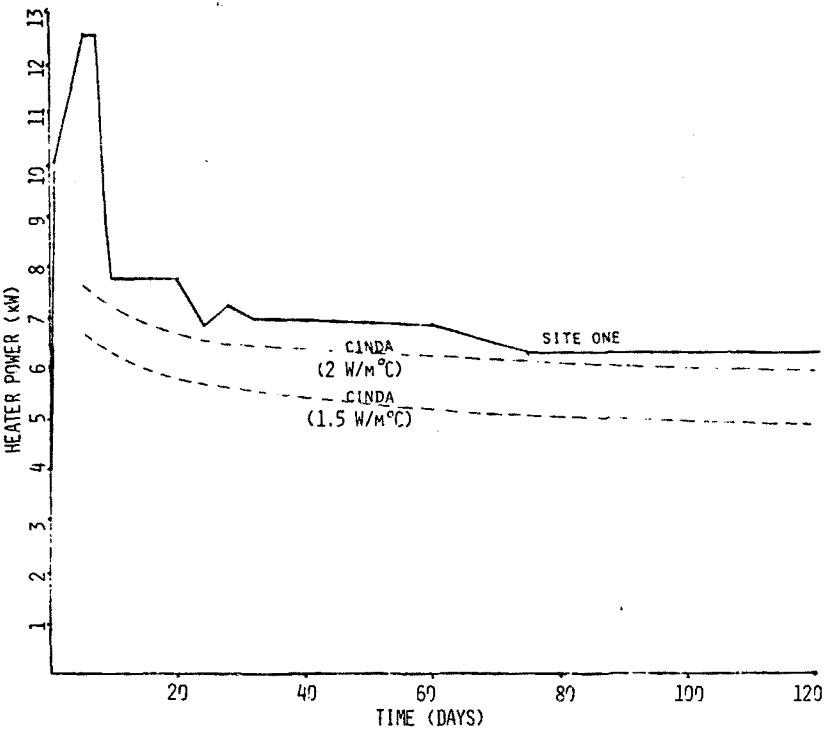

Figure 3: Comparison of modeled and measured heater powers as a function of time and in situ effective thermal conductivity; Conasauga full-scale near-surface heater tests.

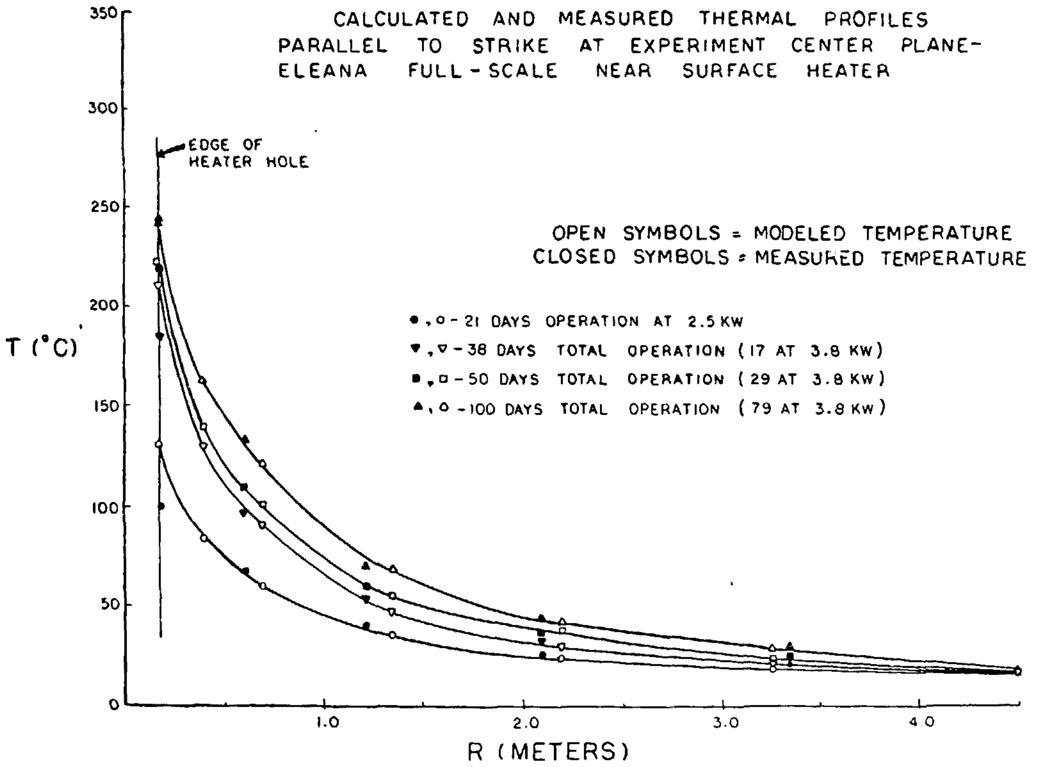

Figure 4: Comparison of modeled and measured thermal profiles, Eleana full-scale near-surface heater test. Profiles measured parallel to strike at the depth of the heater center plane.