26
8-29-80
JPM
2362515
SAND79-1276
Unlimited Release
UC-70

MASTER

In-Situ Tuff Water Migration/Heater Experiment: Experimental Plan

J. Keith Johnstone

Sandia National Laboratories

IN-SITU TUFF WATER MIGRATION/HEATER EXPERIMENT:
EXPERIMENTAL PLAN

J. Keith Johnstone
Geological Projects Division 4537
Sandia National Laboratories
Albuquerque, NM 87185

ABSTRACT

Tuffs on the Nevada Test Site (NTS) are currently under investigation as a potential isolation medium for heat-producing nuclear wastes. The National Academy of Sciences has concurred in our identification of the potentially large water content (≤ 40 vol%) of tuffs as one of the important issues affecting their suitability for a repository. This Experimental Plan describes an in-situ experiment intended as an initial assessment of water generation/migration in response to a thermal input. The experiment will be conducted in the Grouse Canyon Welded Tuff in Tunnel U12g (G-Tunnel) located in the north-central region of the NTS. While the Grouse Canyon Welded Tuff is not a potential repository medium, it has physical, thermal, and mechanical properties very similar to those tuffs currently under consideration and is accessible at depth (~400 m below the surface) in an existing facility. Other goals of the experiment are to support computer-code and instrumentation development, and to measure in-situ thermal properties.

The experimental array consists of a central electrical heater, 1.2 m long x 10.2 cm diameter, surrounded by three holes for measuring water-migration behavior, two holes for measuring temperature profiles, one hole for measuring thermally induced stress in the rock, and one hole perpendicular to the heater to measure displacement with a laser. This Experimental Plan describes the experimental objectives, the technical issues, the site, the experimental array, thermal and thermomechanical modeling results, the instrumentation, the data-acquisition system, posttest characterization, and the organizational details.

DISCLAIMER

This report was prepared as part of work sponsored by the United States Government. Therefore, the United States Government is authorized to reproduce and distribute reprints for government purposes not withstanding any copyright notation that may appear hereon. It is understood that any copyright in any material in this report is owned by the individual author(s) and/or the United States Government. The United States Government is authorized to reproduce and distribute reprints for government purposes not withstanding any copyright notation that may appear hereon. It is understood that any copyright in any material in this report is owned by the individual author(s) and/or the United States Government.

CONTENTS

	<u>Page</u>
Introduction	9
Goals	9
Assess Water Generation/Migration Behavior in Welded Tuff	9
Support of Thermal/Thermomechanical Code Development	11
Support Instrumentation Development	12
Measurement of In-Situ Thermal Conductivity	12
The Requirement for an In-Situ Experiment	13
Relationship to and Interaction With Nevada Nuclear Water Storage Investigations (NNWSIs)	13
Nature of the Experiment	14
Expected Duration	14
Background	14
The Near-Surface Eleana Argillite Heater Experiment	15
At-Depth Climax Granite Heater Experiment	15
Experiment Description	16
The Experiment Site	16
Site Location	16
Geological Properties	16
Site Mineralogy	17
Comparison of the Grouse Canyon Welded Tuff With the Welded Tuffs From Yucca Mountain: Transferability of Results	17
The Experimental Design	20
The Experimental Array	20
Heater Assembly Description	24
Experimental Parameters	26
Instrumentation	29
Power Supply	34
Alcove Design	34
Drilling and Survey Technology	34

CONTENTS (cont)

	<u>Page</u>
Modeling Support	35
Thermal Modeling	35
Thermomechanical Modeling	38
Operation Procedure	39
Responsible Personnel	39
Experiment Sequence	40
Unexpected or Abnormal Behavior	42
The Telephone Alarm	43
Safety	44
Quality Assurance	45
Documentation	45
References	47
APPENDIX A -- Summary of Fracture Analysis of Grouse Canyon Member, Belted Range Tuff at the Tuff Heater Site, U12r Tunnel Complex, Nevada Test Site	48
APPENDIX B -- Recommended Thermocouple Locations for In-Situ Tuff Heater Experiment	55
APPENDIX C -- Thermal Analyses of Tuff In-Situ Heater Experiment	65
APPENDIX D -- Thermomechanical Analyses of Tuff In-Situ Heater Experiment	123

ILLUSTRATIONS

Figure

1	Comparison of the Ambient Pressure Thermal Expansions of Welded-Tuff Samples From G-Tunnel (EV6#3) and Yucca Mountain (Ue25A#1)	18
2	An Example of the Stress-Strain Behavior of Welded Tuff	20
3	Experimental Hole Array	21
4	Schematic Diagram of Symmetrical Orientation of the Experimental Holes Around the Heater Midplane	23
5	Vertical Orientation of the Experimental Holes in Relation to the Alcove and G-Tunnel	23

CONTENTS (cont)

<u>Figure</u>		<u>Page</u>
6	Plan View of the Experimental Array, the Alcove, and G-Tunnel	24
7	Drawing of the Heater Assembly	27
8	Block Diagram of the Data-Acquisition System	33
9	Fielding Activities Schedule	41

IN-SITU TUFF WATER MIGRATION/HEATER EXPERIMENT: EXPERIMENTAL PLAN

Introduction

Goals

The goals of this experiment are to

- Assess water generation/migration behavior in welded tuff
- Support thermal/thermomechanical code development
- Support instrumentation development
- Measure in-situ thermal conductivity

Each of these goals is discussed in detail below.

Assess Water Generation/Migration Behavior in Welded Tuff -- This experiment begins to address issues stemming from the water content of saturated or near-saturated rock. The experiment specifically attempts to assess the in-situ behavior of water in welded tuff as part of the ongoing evaluation of tuff as a potential repository medium.¹

Understanding of water behavior near the heat source (e.g., waste canister of experimental heater) will ultimately be essential to repository design and risk assessment for several reasons:

1. Liquid pathways are postulated as the primary means by which radionuclides might be introduced into the biosphere. The typical reference depth for a repository is 1000 m, well below the water table for most potential sites. Water is well known to attack canisters

and nuclear waste forms (see below). Such an occurrence is probable at some point in the life of a repository located below the water table. The solubilized radionuclides would be carried with the flowing groundwater and could eventually discharge into the biosphere.

2. The presence of hot water implies potential hydrothermal conditions of the type that have been shown to accelerate canister and waste-form degradation.²⁻⁴ Both a heat source and a pressure vessel are required to develop hydrothermal conditions, and both are potentially available in a repository. The heat source is the nuclear waste (spent fuel); the pressure could be applied by the lithostatic load of the rock or the water-table head. The decaying heat content of the waste suggests that such conditions could only exist for the first several hundred years of the repository's lifetime.
3. Water content is known to have a major effect on rock properties such as thermal conductivity, heat capacity, and mineral alteration. Rocks, such as tuffs, that contain reasonably large quantities of water exhibit large decreases in thermal conductivity and heat capacity and increases in compressive strength as the water is driven out (for example, by a nuclear waste heat source). After the thermal period of the waste, the dried-out rock presumably resaturates and the properties approach their initial values. On the other hand, if the water is retained during the thermal period of the waste and a hydrothermal condition develops, then the potential for silicate mineral alteration exists along with potential subsequent changes in thermal and mechanical properties.

4. The means by which the water is released--if it is released--could seriously affect the mechanical integrity of the rock. For example, microcracking (crumbling) may develop as a consequence of rupture of the rock surrounding water-filled pores caused by fluid expansion of vapor overpressurization. Dehydration of the pores because of water migration down the thermal gradient may be followed by rock collapse into the voids because of in-situ stresses and the weakened condition of the rock. The long-range effects of such behavior are unknown.
5. Collection of water in the canister holes could seriously alter the transfer of heat from the canister to the rock mass. Pooling of water in the near-surface full-scale Eleana heater experiment⁵ and the at-depth Climax granite heater experiment⁶ caused significant deviations from predicted thermal behavior. In both cases, the water may have come from outside sources rather than from the rock mass.

The tuff water migration/heater experiment is located in a highly jointed, near-saturated rock mass. Since the rock mass lies well above the water table,⁷ the occluded water is perched. In addition, because the joints for the most part are highly water-transmissive, it appears likely that drilling water will drain away from the experiment site. In view of the foregoing, the experiment should specifically measure the water behavior in rock mass.

Support of Thermal/Thermomechanical Code Development -- Currently, thermal and thermomechanical calculations include relatively simplistic assumptions such as considering the rock mass as a homogeneous medium (joints not considered) and using laboratory-determined properties. Comparison of model predictions obtained by using laboratory-measured properties with the in-situ experiment result serves to validate or improve laboratory methods; e.g., by using confining pressures while making thermal

property measurements. This, combined with careful physical characterization of the rock mass and the deviation from "homogeneity," gradually permits development of more comprehensive codes for describing the medium response. One ultimately hopes to develop a complete constitutive model that includes time-dependent behavior (e.g., dehydration/rehydration, crack generation, crack or joint opening/closing, etc) and that can predict rock behavior based on laboratory-measured properties with a minimum of field tests.

Support Instrumentation Development -- The techniques required to measure in-situ response of a rock mass to various stimuli are not well established. Considerable effort goes into defining what measurements to make and what instruments to use or attempt to improve as well as how to field them. In addition, we must find ways to field the instruments for remote operation, evaluate their long-term durability and stability, and develop methods for in-situ calibration or recalibration--all of which occur in a hostile environment. In this experiment, we attempt to monitor water behavior by using developmental depth and relative humidity gages. In addition, in-situ thermomechanical measurements will be made with a modified stress gage and a laser interferometer.

Measurement of In-Situ Thermal Conductivity -- The thermal field near the heat source depends on the thermal conductivity of the rock mass, which in turn strongly depends on the water content. Drying out the rock in laboratory tests has been shown to decrease the thermal conductivity by as much as a factor of 2. Opening of joints or development of microcracks would decrease the conductivity further, resulting in significantly higher temperatures next to the heat source. The ease with which water is released from the rock depends on the fluid pressure, the in-situ stress field, and the tensile strength of the rock. Inability of the dry rock to support the in-situ loads could result in collapse of the matrix into the newly vacated voids, thereby causing an increase in thermal conductivity. It seems unlikely, however, that the conductivity would assume its original saturated rock value because of the increase in crack frequency.

The Requirement for an In-Situ Experiment

Although the results of laboratory measurement of rock properties are seldom ambiguous, extrapolation of these properties to field conditions is usually difficult. Extraction of test specimens for laboratory tests results in release of the in-situ stress followed by reapplication of a usually isostatic confining pressure in the laboratory. In-situ stresses in a rock mass are seldom isotropic; in some cases, the principal stresses have varied by factors of 3 or more from each other.⁸ In addition, arbitrary, finite boundaries are introduced by extracting the samples from the rock mass, and the potential water behavior is probably severely altered.

Except for the stress-field changes near boreholes or excavations, in-situ experiments measure the natural state response of the rock mass. They include the effects of naturally occurring joints and groundwater. In addition, the sample boundary limitation imposed in laboratory testing is eliminated. Spatial relationships between joints and cracks are undisturbed; i.e., there is no alteration of the joint aperture or translation of opposing joint faces. There is little concern about sample dehydration or chemical changes in the water because of exposure to the air. Even though in-situ experiments are costly and the data often difficult to interpret, they are the only means of validating behavior models and laboratory test methods and results.

Relationship to and Interaction With Nevada Nuclear Waste Storage Investigations (NNWSIs)

This experiment is an integral part of the continuing effort to evaluate various media for nuclear waste storage within the boundaries of the Nevada Test Site (NTS). The experiment specifically addresses the water issue in welded tuff that was originally identified by project participants and later reemphasized by the National Research Council's Committee on Radioactive Waste Management.⁵ The experiment is fundamental in providing an initial evaluation of the thermal response of welded tuff and as a basis for future, more elaborate experiments ultimately leading to large-scale, site-specific tests.

Nature of the Experiment

This experiment, which includes a small heater that is not intentionally scaled in any sense, is primarily generic in a saturated, welded tuff. The experiment is an initial evaluation of the water behavior in a thermal field in which heater power levels are designed to produce a measurable response rather than to simulate a hypothetical waste-canister power output. Certain aspects of the experiment are specific for welded tuffs, as described later in the section on Transferability of Results. The experiment is exploratory, in part, in an attempt to field and evaluate some new or improved instrumentation.

Expected Duration

The heater will be in operation for at least 30 days. This period was selected by noting the near leveling of the predicted thermal profiles and thereby the establishment of a steady-state temperature gradient. However, the actual thermal behavior and the mass-transport kinetics are unknown. The data-acquisition system permits online, real-time analysis of data; consequently, the actual operating time will depend on the response of the tuff. It seems unlikely that operation would continue beyond 4 months.

Background

The in-situ tuff water migration/heater experiment is the latest in a series of in-situ experiments at the NTS designed to address project-related media evaluation. It is the first in-situ experiment to be fielded in welded tuff.

Previous experiments were the Eleana argillite^{10 11} and the Climax granite¹² heater tests. Both of these were designed to test the thermal response of the medium, and both experienced unexpected difficulty because of water intrusion into the heater hole despite the fact that one was a near-surface and the other an at-depth experiment. Neither test was designed to measure water behavior.

The Near-Surface Eleana Argillite Heater Experiment^{10 11}

This experiment at 24 m underground was composed of a series of three tests that were designed to determine the thermal and mechanical responses of argillite to a thermal input representative of a high-level (3.5 to 3.8 kW) waste. Two of the tests used small, scaled heaters and one used a full-scale heater 0.3 m in diameter and 3 m long. The two scaled tests were in support of the full-scale experiment.

Early in the full-scale heater experiment, an unaccountable influx (possibly from the surface) of a small quantity of water collected in the heater hole and caused severe deviations from the expected thermal behavior. This required shutting down the experiment, removing the heater, and providing the heater hole with water drainage. After restart, the experiment ran 250 days without further incident.

In spite of its near-surface nature, the experiment appears to have answered several important questions about argillite stability in a thermal field. In particular, the effects of expandable clay on the thermal response of the argillite were noted.

At-Depth Climax Granite Heater Experiment^{6 12}

These experiments were composed of three scaled heater tests carried out at 425 m below the ground surface. The experiments were designed to test the thermal stability and measure the in-situ thermal conductivity, diffusivity, and permeability at temperature. Test periods ranged from 62 to 83 days.

During the first test, water (possibly drilling water forced into the joint system) migrated into the heater hole and shorted the heater power leads. The short was repaired and the connections isolated from the wet region.

The experiments successfully demonstrated the thermal stability of the Climax granite at high temperature. Good agreement was noted between

the in-situ and laboratory thermal conductivity and diffusivity values. The in-situ permeability was very low, <1 nanodarcy, and decreased with increasing temperature.

Experiment Description

The Experiment Site

Site Location -- The experiment will be placed in the welded portion of the Grouse Canyon Member of the Belted Range tuff. The site is in the U12g tunnel (G-tunnel) complex at a depth of 400 m below Rainier Mesa in the north-central region of the NTS.

Geological Properties -- The welded tuff lies above G-tunnel with only the basal portion partly exposed in the ceiling. Near the experiment, the tuff strikes approximately N30E and dips 7° NW. An alcove 3 m deep x 6 m long was mined in the tunnel wall to house the experiment. The joints intersecting the tunnel and alcove walls were mapped in detail.

Two fully cored, exploratory holes (U12gHEN#1A and #1B) were drilled in the welded tuff at respective depths of 6.7 and 20.7 m. The purpose of these holes was to characterize formations near the experiment and to test drilling capability in order to meet the criteria of hole straightness and wall smoothness for placement of the heater assembly. The exploratory holes also provide pre-experiment test and practice holes for transmissivity testing, practice heater emplacement, and practice packer emplacement and sealing.

Characterization studies included determination of formation thickness (12.5 m), mineralogy, and joint properties for comparison with the wall-mapping result. Joint properties such as frequency, orientation, width, morphology, mineralogy, and predictability were studied. Downhole TV scans were correlated with the core observations; core indices were also determined. The results are summarized briefly here and in more detail in Appendix A.

Four major joint sets were identified. In general, the formation was highly fractured. The joint frequency depended upon the measurement method that increased in the following order: tunnel wall mapping, down-hole TV scan, and core determination. Core indices ranged from 30 to 100. Numerous rubblized zones that varied from 5 to 60 cm long were found in the cores. Many of the joint surfaces were mineralized, and intense argillization was observed in several of the rubblized regions. These zones are apparently water-transmissive.

Site Mineralogy -- The tuff is composed almost entirely of feldspars and silica polymorphs (quartz + cristobalite). Vitric material is noted only occasionally in the basal vitrophyre. Phenocryst phases reported from within the Grouse Canyon include sodic sanidine, anorthoclase, and quartz, with the sanidine dominant. Widespread accessories include fayalite, apatite, zircon, and sodic Fe-pyroxene.¹³ The tuff is rarely zeolitized. Devitrification textures are common, but not masked by growth of authigenic phases. The welded tuff, which lies at least 200 m above the water table,⁷ contains 13% to 17% porosity and is >85% saturated with perched water.

Comparison of the Grouse Canyon Welded Tuff With the Welded Tuffs From Yucca Mountain: Transferability of Results -- Properties of welded tuffs from the two locations are compared in an attempt to address transferability of results of the G-tunnel test to other welded tuffs--in this case, Yucca Mountain.

Perhaps because of its greater depth, the Bullfrog Member of the Crater Flat tuff (a potential unit in which to locate a repository) appears more varied in general mineralogy than does the Grouse Canyon. In Well J-13 the tuff is fairly biotite-rich (see thermal expansion data, Figure 1), with growth of authigenic silica, K-feldspar, erionite, and analcime at least partially masking primary and devitrified features through overgrowth and coarsening.¹⁴ In the Yucca Mountain hole (Ue25A#1), while growth of authigenic feldspars and silica is apparent,

recrystallization is almost totally absent. The expected effects of relevant mineralogical differences (crystoballite, mica) are discussed below.

Figure 1. Comparison of the Ambient Pressure Thermal Expansions of Welded-Tuff Samples From G-Tunnel (Ev6#3) and Yucca Mountain (Ue25A#1)

Table 1 compares the available physical, thermal, and mechanical properties of the two tuffs. Ranges in porosity and grain density are very similar, though the grain density of the G-tunnel welded tuff is apparently more varied. Measured conductivities at 100°C agree to within 6% of the mean value (1.23 W/m·K). Values obtained by extrapolation to 100% saturation agree almost perfectly.

The interval values for the ambient pressure thermal expansion of the two tuffs are quite similar. Samples from both locations exhibit nearly continuous expansion to at least 500°C. However, differences do exist (Figure 1). The Yucca Mountain welded tuff shows a slight contraction near 75°C not seen in the G-tunnel welded tuff. This is probably because of the presence of a small amount of altered mica in the Yucca Mountain welded tuff. At 250°C and above, the G-tunnel welded tuff exhibits a slight but consistent inflection caused by the α - β transformation of cristobalite, which is not present in the Yucca Mountain welded tuff.

The comparison between strength and moduli of samples from G-Tunnel and Yucca Mountain is less straightforward. Some, but not all, of the differences between the various values may be caused by different test methods used. Other reasons for the differences in values are variations

in the degree of sample saturation and the inherent variability of tuffs in general over distances as small as the length of a test specimen. Variations in mineralogy may also be a factor, but correlation has not yet been established. Preliminary studies have tentatively established an inverse correlation between strength and porosity, which may provide the transferability link from one location to another. In spite of the differences in values, the tuffs exhibit similar stress-strain behavior in that they show an approximately linear central region and a sudden loss of strength at the peak stress (Figure 2).

Table 1
Physical, Thermal, and Mechanical Properties of
Welded Tuffs From G-Tunnel and Yucca Mountain

	G-Tunnel	Yucca Mountain
Porosity (vol%)	13-17 ^{8,15}	13-24 ^{16,17}
Grain density (g/cm ³)	2.52-2.65	2.60-2.64
Thermal conductivity (W/m·K)		
25°C (natural state)	1.5-2.2	2.2-2.6
110°C (dehydrated)	1.0-1.2	1.3-1.7 ¹⁸
Thermal expansion [(K+1) × 10 ⁻⁶ °C ⁻¹] (ambient)		
100°C	6.7	4.0
200°C	7.5	7.3
300°C	10.6	9.9
Ultimate strength (MPa)	114±12 ^a	138 ^b , 130 ^c , 55 ^d
Young's modulus (GPa)	25.6±4 ^a	40.4 ^b , 47.9 ^c , 6.4 ^d

- Average of 4 samples from the Crouse Canyon welded tuff; 1 air-dried and 3 fully saturated porosities ranged from 15 to 20 vol%.
- 1 sample, Topopah Spring welded tuff, air-dried, 13 vol% porosity, depth = 723 ft
- 1 sample, Prosser Pass welded tuff, air-dried, 17 vol% porosity, depth = 2014 ft
- 1 sample, Bull Frog welded tuff, air-dried, 20 vol% porosity, depth = 2452 ft.

Figure 2. An Example of the Stress-Strain Behavior of Welded Tuff

Based on the laboratory-measured properties, the welded tuffs from the two localities are very similar. Virtually all of the properties of one welded tuff lie within the experimental range of the other. Potential differences in the response of a field experiment must be due to the in-situ rock mass properties such as in-situ stresses, joint properties (frequency, width, mineralization, etc), and our ability to characterize them. In view of the limited scale (compared to joint spacing) of this experiment, we expect that the response is representative of other similar welded tuff units. However, since this is a pilot experiment, its real value lies in bounding the various phenomena for larger scale, more sophisticated experiments.

The Experimental Design

The Experimental Array -- The experiment is composed of six satellite holes arranged at three radii concentrically about a central heater hole

as shown schematically in Figure 3. Three holes are designed to measure water behavior, two are for measuring in detail the thermal profiles, and one hole is for measuring thermally induced stress. In addition, a hole aligned as nearly perpendicular to the heater axis and along the midplane as possible is included for a laser interferometer for measuring displacement. The radial distance of the holes from the heater was selected after evaluation of the thermal and thermomechanical modeling and current drilling capabilities. Each hole is located so that it is not shadowed from the heater by another hole. All the holes will be 100% cored during drilling and where possible, visually scanned with a borehole TV camera.

Figure 3. Experimental Hole Array

The nominal diameter of the holes is as follows (in cm):

Heater hole, 12.7

Water migration holes (A), 9.5

Thermocouple holes (B), 7.6

Stress hole (C), 4.8

Laser interferometer hole, 20.3

The hole depth will depend on the local stratigraphy as determined from the core. Preferably, the holes will be >9 m deep to minimize alteration of the in-situ stress at the heater depth by the proximity of the tunnel/alcove. The experimental region in each hole will be located so that the relationship with fractures is known.

The instrument "cavity" in each of the experiment holes is arranged as symmetrically as possible at the midplane of the heater, as shown schematically in Figure 4. One of the water migration holes will be located such that a well-defined joint intersects the water collection cavity, and the other two holes such that joints do not intersect the water collection cavities (if possible). Consequently, the water migration holes may vary from the ideal midplane position shown in Figure 4.

The thermocouple holes will be instrumented with 11 thermocouples arranged as symmetrically as possible about the midplane of the heater. Stratigraphy permitting, the thermocouples will extend to a depth of 2 m beyond each end of the heater. The inner thermocouples in each hole will align with a similar array on the heater and heater hole surface. Every attempt will be made to minimize the free space in the holes, thereby limiting convection currents. Toward this end, care must be taken not to interfere with the water migration behavior or alter the local chemistry. Further details are given in Appendix B.

Since the welded tuff lies in the ceiling over G-tunnel, all of the drill holes except the laser interferometer hole will be oriented at an angle of 20° above horizontal (Figure 5). As a result, the water will drain away from the heater and prevent the refluxing observed in the Eleana and Climax heater tests. Owing to the tunnel arrangement, the laser interferometer hole will be inclined at an angle greater than 20°. The tunnel plan showing the relation between the experimental alcove, the heater array, and the laser interferometer hole is given in Figure 6.

Figure 4. Schematic Diagram of Symmetrical Orientation of the Experimental Holes Around the Heater Midplane

Figure 5. Vertical Orientation of the Experimental Holes in Relation to the Alcove and G-Tunnel

Figure 6. Plan View of the Experimental Array, the Alcove, and G-Tunnel

Heater Assembly Description -- The heater assembly is composed of a heater, insulator, power-leads junction box, instrument bay, packer, and insertion tube coupling. The assembly (Figure 7) is a single unit ~3 m long and is designed for insertion into a hole that is 12.7 cm in diameter.

The heater is composed of two 6 kW hairpin heating elements that are oriented at 90° to each other and enclosed in a 304 stainless-steel, closed-end housing 1.2 m long x 10.2 cm OD. Six equally spaced longitudinal fins are attached to the heater surface to ensure that the heater is centered in the hole and to minimize convection-induced circumferential thermal gradients. Three thermocouples are embedded in the heater surface circumferentially in alternating sections at the midplane and 6 in. from

each end of the heater (for a total of 9 heater thermocouples). Springout thermocouples for measuring the rock wall temperature are located at the same spacing in the remaining sections (also a total of 9). This is shown schematically in Figure 7, Section E-E. Even though one heating element is sufficient to operate the experiment, both will be operated to minimize circumferential thermal gradients. In the unlikely event that one burned out, the power to the other can be increased to compensate for the loss.

The insulator section, shown schematically in Figure 7, Section D-D, is designed to minimize convective heat transfer down the hole toward the power lead junction box and instrument package. The insulating material must be selected such that it will have a minimum effect on the water chemistry or migration behavior. The insulator material should be chemically inert in an aqueous environment or chemically similar to the tuff. The insulator material should also contain as small a surface area as possible to minimize the amount of surface sorbed water. Typically, insulators exhibit large surface areas that can sorb large quantities of water. Ideally, a single block of closed-cell, inert foam would be inserted into the insulator section. Unfortunately, such an approach is impractical because of the large number of thermocouples and the power leads that must pass through the insulator section. The material chosen for the insulator is plus 10 mesh (>2 mm dia) bubbled alumina.* The particles are primarily hollow, closed spheres composed of 99.6% pure alumina. In addition to meeting the above criteria, the spherical particles simplify filling the insulator section. A thermocouple will be located at both the insulator/heater and insulator/junction box interfaces.

The connection between the power leads and the heating elements will be made in the junction box. The box will be filled with high-temperature RTV silicone to prevent water from attacking (shorting) the connections. A thermocouple will also be included in the junction box. The junction box is shown schematically in Figure 7, Section C-C.

*Manufactured by the Norton Company, Worcester, MA.

The instrument bay provides room for mounting the various instruments that monitor the behavior of the water. It also provides an open volume for collecting water. Individual instruments are described in the next section. The instrument bay is shown schematically in Figure 7, Sections A-A and B-B.

The packer is a development device for sealing the heater cavity. It provides for two independent, motor-driven seals. The forward (toward the heater) plate of the packer serves as the platform for mounting the water-monitoring instrumentation.

Attached to the aft plate of the packer is the transition section for coupling the insertion tube to the heater assembly. The transition section contains a leveling device to ensure that the entire assembly is oriented properly during placement. In addition, the transition section contains pressure transducers that could not be mounted in the instrument bay. The transition section is shown schematically in Figure 7, Sections G-G and H-H.

Experimental Parameters -- Water behavior will be monitored in the three water migration holes and the heater hole (Figure 3). Parameters related to the water behavior include temperature, pressure, water-generation rate, relative humidity, and pH. Water and gas sampling capabilities are also included in the design. In the event that water does not collect in the experimental cavities, the best indicator of the water response may be the changes in the relative humidity of the cavity atmosphere. The sampling tubes allow samples to be withdrawn periodically for laboratory analysis. A second water tube allows the cavity to be drained in case the amount of water collected threatens the operation of the other instruments.

The welded tuff thermomechanical behavior will be monitored in the stress and laser interferometer holes. Thermally induced stress and displacements will be measured in these holes, respectively, and temperature will be measured in both holes.

Only two holes are designed specifically to measure the thermal profiles in the rock. However, as noted above, temperature will also be measured in conjunction with the other parameters. Temperature is the fundamental parameter to be measured since all other phenomena depend on it. Temperature measurement is particularly important for determining the thermal conductivity and boiling behavior since neither can be directly measured in-situ in this experiment. The thermal behavior of the heater assembly will also be extensively monitored.

Even though the power input is designed to be constant, it is an important parameter that will also be monitored.

The operating experimental variables can be summarized according to the following classifications:

- Independent Variables - Controlled

- Experiment configuration
 - Thermal source design

- Independent Variables - Uncontrolled
(Ambient Rock Properties)

- Mineralogy
 - Water content
 - Thermal conductivity
 - Heat capacity
 - In-situ stresses
 - Joint characteristics
 - Characteristic water boiling point

- Dependent Variables

- Temperature
 - Pressure
 - Thermal conductivity
 - Thermal-induced stresses
 - Thermal-induced displacements
 - Water migration rate

Instrumentation -- The instruments required to measure the experimental parameters are described below. A commercially available device was selected whenever possible. Nevertheless, there were several

instances where commercial instruments could not survive the test conditions, could not be fielded remotely, or were unavailable.

1. Thermocouples. Standard chromel-constantan (Type E) thermocouples supplied by Gordon Co. will be used. They meet standard limits of error according to ANSI MC 96.1-1975 of $\pm 1.7^{\circ}\text{C}$ from 0° to 340°C and $\pm 0.5\%$ from 340° to 870°C (the upper temperature limit). Those on the heater hole rock wall are 1/16 in. in diameter with Inconel 600 sheaths. All other are 1/8 in. in diameter with 304 stainless-steel sheaths.

As discussed below, accurate measurement of the rock wall temperature in the heater hole is critical. This measurement will be made with thermocouples that spring out from the heater to make contact with the rock wall. The spring force and radiation shield size and material will be determined in a laboratory simulation of the conditions. The correlation between spring thermocouple measured wall temperature and true temperature will also be determined in the laboratory simulation.

2. Pressure Transducers. Two GS series pressure transducers (0 to 15 psi and 0 to 100 psi) supplied by Gulton Industries will be used. The accuracy for both is $\pm 2\%$ of full scale up to 80°C . They incorporate LVDT technology with high-level electrical output and stability. They can be operated in an absolute, gage, or differential mode.
3. pH Measurement. Model S100C pH electrodes supplied by Sorenex will be used. They are sealed reference combination electrodes containing a gel electrolyte. The electrodes operate in the temperature range of 0 to 100°C and up to pressures of 100 psig. The probe will

be connected to a Model NX pH meter supplied by Sargent-Welch. The relative accuracy and repeatability are ± 0.01 pH unit. The pH measurement range is 0 to 14. The temperature compensation accuracy is $\pm 1^\circ\text{C}$. The meter has both analog and binary coded decimal (BCD) output for recording.

4. Relative Humidity Gage (Developmental). A developmental humidity probe, Model BR-101B, supplied by Thunder Scientific will be fielded. The sensor accuracy is $\pm 4\%$ RH ($\pm 2\%$ typical). The upper reliable operating range is 80°C , to which it will be calibrated. The sensor is a solid-state, thin-film, semiconductor. It does not contain any aluminum or other unstable metals that exhibit hysteresis, drift, aging, or instability. The sensor contains a platinum resistance thermometer for temperature measurement. The output is a linearized buffered dc voltage directly proportional to relative humidity.
5. Water Depth Gage (Developmental). The depth gage will measure the rate at which water is collected in the experimental cavities. A market survey was unable to locate a suitable commercial device. Several different approaches are under evaluation and development.
6. Laser Interferometer (Developmental). Laser interferometry is well established but, to the best of our knowledge, it has not been used in an application like this. We are fielding such a device to determine if it can provide a stable, high-resolution displacement measurement in an in-situ environment. A Tropel Model 100 single wavelength continuous wave He-Ne laser will be used. The resolution under ideal conditions is $\lambda/8$ or 80 nm. The output power is ~ 1 nW.

7. Borehole-Inclusion Stress Gage (Developmental). A new strain-gaged stressmeter has been designed by Sandia National Laboratories that should be an improvement over current vibrating-wire types. The extended platen design of the new gage prevents the platen from becoming embedded in the rock during preloading. The strain-gaged transducer permits the use of conventional data-logging techniques rather than the special equipment required by the IRAD-supplied vibrating wire stressmeters. The developmental stressmeter has a sensitivity comparable to that of the IRAD type. It can read to about 200 microstrains. The dynamic range is potentially greater than for the vibrating wire stressmeter, which is limited by excitation harmonics in the wire.

8. Data-Acquisition System (DAS). The DAS is based on a Hewlett-Packard (HP) 9845S fully programmable controller. It will control all instrumentation in addition to collecting and storing data. The DAS is powered by an uninterruptible power supply to protect critical instruments from transient voltage variations and power outages. A block diagram of the system is shown in Figure 8. The basic features of the DAS are

- Enhanced basic language
- 62650 bytes of read/write memory
- Dual tape cartridge drives, 217K byte capacity/cartridge
- Dual flexible disk drives, 500K byte capacity/disk
- IEEE standard 488-1975 interface bus; programmable control of all bus instruments
- 160 (expandable) analog input channels
- Build-in CRT, 310 mm diagonal display; graphics capability
- Interrupt capability
- Real-time clock
- Internal line printer
- Interface for RS-232 and BCD
- ROMs for graphics, mass storage, and I/O.

Figure 8. Block Diagram of the Data-Acquisition System

Data will be collected and stored on paper printout, magnetic tape, and flexible magnetic disks.

Power Supply -- Power will be supplied by a separate tunnel circuit for heating elements and all instrumentation required for the experiment. A demand-start diesel generator will be placed outside the tunnel to provide backup power in case of a commercial power failure.

Alcove Design -- An instrumentation alcove 3 x 6.1 m has been mined at the experiment location shown in Figure 6. A floor and walls will be added to enclose the alcove for use in data acquisition and experiment control after the necessary drilling has been completed.

Electric power will be provided for heater, instrumentation, and miscellaneous use. An air conditioner will provide climate control including temperature, humidity, and air filtration. Space will be available for instrumentation racks, workbench, power control, and experiment access and operation.

Drilling and Survey Technology -- The requirements for heater hole straightness (<6.4 mm deviation in 3 m) and satellite hole placement (± 5 cm and 20 m) are beyond the capabilities of standard drilling practices. In addition, these difficulties are compounded by the fact that the holes are in a near-horizontal position, which leads to a natural tendency for the hole to drift down and to the right during drilling. State-of-the-art techniques are required to meet the experimental requirements.

Similar comments apply to the survey techniques. Each hole will be surveyed upon completion. The results of the survey will be the primary basis for acceptance or rejection of the hole, although other criteria such as stratigraphy, presence of fractures, voids, etc, and insertion of plug gages will also be important. An as-built survey of the heater hole will be particularly important in locating the laser hole. Upon completion of the drilling activity, an as-built survey of the entire hole array is required.

Modeling Support

Thermal Modeling -- Extensive thermal analysis of the experiment was carried out to

- Determine the appropriate heater power level and locate the experimental effects holes, but remain within the limitations of the heater components and drilling capabilities
- Model the thermal behavior of the heater and the rock for different responses of the rock to the power input
- Determine the sensitivity of the rock response to variations in power input and rock thermal conductivity

Fourteen possible cases were analyzed by assuming two-dimensional, axisymmetric geometry. Temperature solutions for the heater/rock system were obtained numerically through use of the COYOTE computer program for heat conduction. The results of these analyses are presented in detail in Appendix C and summarized here.

Except for the effects of water, the rock was assumed homogeneous. The effects of joints on the thermal behavior were not considered. Heater operation was at constant power for 30 days. Cooldown behavior was also calculated for an additional 30 days.

The variables considered in the analysis were heater power input, boiling temperature of the water in the rock, and thermal conductivity and emissivity of the rock. The power levels considered were 1.25, 1.9, and 2.5 kW. Boiling temperatures of 100° and 235°C were used. Atmospheric boiling (100°C) served as a lower bound. Boiling at 235°C reflects a vapor pressure of 450 psi, the approximate minimum in-situ stress in the G-tunnel welded tuff,⁸ and serves as an upper bound. A hydrostatic boiling point was not considered since such a state does not exist in an unsaturated system.

Thermal conductivity was either held constant or allowed to vary during the experiment. An apparent constant thermal conductivity could

correspond to (1) no water release during the experiment, or (2) pore collapse as the water leaves. The variable case models the change in thermal conductivity that occurs at dryout after boiling. For these analyses, the change was assumed discontinuous. Conductivity for the dried-out rock was $1.2 \text{ W/m}^\circ\text{C}$. Owing to the uncertainties of the conductivity for fully saturated rock, values of 1.7, 2.2, and $2.7 \text{ W/m}^\circ\text{C}$ were used. In all cases, the latent heat of vaporization of water was included in the rock heat capacity.

The results of these analyses are summarized below:

1. The heater power level strongly affects the surface temperature of the heater, the rock wall (heater hole) temperature, and the penetration distance into the rock of the assumed boiling isotherm.
2. The assumed decrease in rock thermal conductivity near the boiling isotherm strongly influences the near (that portion within the boiling isotherm) thermal field. Significant temperature increases at the heater and rock wall surfaces occur for a decrease in thermal conductivity. The location of the boiling isotherm is sensitive to the power level and the initial value of conductivity for saturated rock (1.7, 2.2, or $2.7 \text{ W/m}^\circ\text{C}$), but it is relatively insensitive to the assumed variation in conductivity at dryout. Calculated differences in penetration distances for conductivity variations at dryout were less than 5 cm, which is probably well beyond the resolution capability of the experimental satellite holes. This suggests that (a) measurements of the rock wall temperature in the heater hole during the experiment should provide the most sensitive definition of in-depth boiling in terms of its effect on rock thermal properties, and (b) the rock thermal conductivity has a major effect on the heater operating power.

3. The boiling temperature has a negligible effect on the thermal profiles when the conductivity is constant for a given power level. However, for a variable conductivity, the higher boiling point causes lower near-field temperatures because of the smaller volume of dried-out rock.
4. Variations in the rock emissivity from 0.6 to 0.8 result in negligible differences (~1%) in the maximum surface temperature of the heater.

The final power level to be used during the experiment has not been determined. This decision will be based on materials, instrumentation, and rock mechanical property limitations. In addition, the final calculations will be made by using thermal properties obtained on the core removed from the heater hole at the heater location. Present calculations suggest that there are no material (e.g., heater, packers, RTV) limitations, even at the highest anticipated power level of 2.5 kW.

The instruments that may be affected are the pressure transducers, pH electrodes, relative humidity gages, and water depth gages. The lowest temperature at which problems with any of these instruments might occur is about 80°C. The only holes likely to experience such temperatures in the vicinity of the instruments are the two water migration holes located 41 cm from the heater hole (see Figure 3). Potential instrument difficulties will be evaluated after the final power level/temperature profile calculations.

The potentially most severe difficulties are associated with the heater hole wall stability. Spallation of the rock surface could occur because of thermal shock caused by rapid heating or by steam pressure in closed pores. Rock wall failure could also occur if the thermomechanical stress exceeds the strength of the rock (see the section on Thermomechanical Modeling). Crumbling of the rock wall around the heater would lead to an increase in the near-field temperature because of the decrease in thermal conductivity. Such an occurrence would probably eliminate any

hope of characterizing the water behavior. Consequently, the power level must be selected to maintain the integrity of the rock wall.

The final selection of the power level and the reasons for the selection will be documented separately.

Thermomechanical Modeling -- Thermomechanical analyses of the experiment were carried out to determine the

- Optimum locations for stress meters and laser interferometer displacement gage
- Perturbation of the tunnel opening and the alcove on the in-situ stresses in the experimental region
- Perturbation of in-situ stresses near the heater due to the presence of the heater holes and instrumentation holes

Results of the analyses are given in Appendix D and are briefly summarized here.

The analysis to determine instrument location was carried out consistent with the thermal modeling discussed above. Stresses and displacements were obtained by numerical (finite-element) solution of the MARC computer program. The finite-element mesh and the temperature fields used in these calculations were identical to those used in the thermal analysis. Several cases representing the extremes of power level and boiling temperature were considered. In addition, the rock mass was assumed a homogeneous elastic medium; therefore, the only deviations from in-situ stresses are due to thermoelastic effects. Note then that the instrumentation measures net changes and is independent of initial in-situ stresses.

Stresses and displacements for the two cases at the end of 27 days are given in Appendix D. Calculated results are within a factor of 5 of the measurable ranges at a distance of about 1 m from the heater centerline. The minimum distance from the heater will be determined by the temperature field associated with the input power level selected.

Calculations to determine the effects of the tunnel opening and alcove on the in-situ stresses were done with a closed-form solution that approximates the actual situation. The presence of the heater and satellite holes was neglected. Results show that the perturbations are negligible at the location of the heater.

The perturbation of the in-situ stresses due to the presence of the heater and satellite holes was calculated by using MARC. The thermal effects discussed above were ignored. No attempt was made to account for the 20° angle of inclination of the holes in the orthogonal stress space. Results show virtually no stress interaction between adjacent holes.

The thermal stresses discussed above can be added only to the stress distribution around the heater hole since the thermal calculations are axisymmetric around it. When the stresses are added, they approach the laboratory value for the unconfined compressive strength of the rock. In addition, note that the presence of in-situ fractures would lead to a strength less than that of the laboratory value, while drying out the rock (0% saturation) causes an approximate 30% increase in the laboratory value. The relative importance of these competing effects is not known; consequently, we will monitor the experiment closely as it approaches 30 days of operation.

Operation Procedure

Responsible Personnel

Responsible personnel for this experiment are

L. D. Tyler, Sandia Technical Project Officer for the
Nevada Nuclear Waste Storage Investigations program

J. K. Johnstone, Principal Investigator

D. R. Waymire, Director of Field Activities

Overall responsibility and authority for the experiment lie with the Principal Investigator, although he may be overruled on any decision by the SLA Technical Project Officer. The Principal Investigator is responsible for the conceptual and experimental design. He will coordinate the experimental design and modeling support with the Director of Field Activities to ensure that the experimental objectives are met. The Principal Investigator is responsible for the analysis, interpretation, and reporting of the results. The Director of Field Activities is responsible for instrumentation and heater design, data-acquisition design, coordination of drilling and mining activities, fielding of hardware, and operation of the experiment. Additional staff and staff assistant personnel will support the program as required.

Experiment Sequence

Figure 9 shows the experiment sequence and estimated weeks for completion of individual activities (numbers in circles). The heater will be turned on only after satisfactory instrumentation checkout and calibration and background data have been obtained. The current estimate for heater turnon is January 29, 1980.

The heater will operate for a minimum of 30 days. Thermal and mechanical responses will be continuously compared with the pretest predictions to identify any abnormal behavior. The actual operational time will depend on the experimental response. The data will be continuously evaluated during the experiment, and actual shutdown will occur when the goals of the experiment have been achieved.

Data collection intervals will depend on the phase of the experiment. During initial heatup, every channel could be monitored as often as every 5 min. The channels may be monitored every 15 to 20 min during the transition from heatup to steady-state operation, and every hour during steady-state operation. The actual data collection intervals will depend on the experiment behavior.

Cooldown behavior will be monitored for at least 30 days after the heater has been turned off. Water behavior and expansion and stress subsidence are of particular interest during the cooling period.

Posttest characterization may include permeability measurements, hole examination with the borehole TV camera, and coring the rock surrounding the heater. The visual examination (TV) will be compared with pretest conditions for gross structural changes, and the posttest core will be examined for possible morphological and/or mineralogical alterations. Core samples will also be available for property measurements if desired.

Unexpected or Abnormal Behavior

One of the purposes of any experiment is to determine unforeseen behavior or responses. However, unexpected or abnormal behavior could also be detrimental to the success of the experiment or the safety of attendant personnel. A partial list of unexpected or abnormal behavior follows:

- Thermal runaway
 - Excessive power input
 - Spallation or crumbling of heater hole rock wall
- Loss of heater power
 - Power outage
 - Heater burnout
- Rock wall thermocouples in the heater hole fail to spring out
- Overpressurization in an experimental cavity
- Instrumentation (DAS) malfunction
- Loss of packer seal
- RTV burnup in heater lead junction box
- Large displacements in laser or stress holes.

Most unexpected behavior could be mitigated by altering the heater power; i.e., the power could be decreased, turned off, increased, or left alone. An overpressurized cavity could be corrected by releasing the pressure through a gas or water sampling tube. In general, the impact on the experiment of each of these deviations (or others) must be evaluated at

the time they occur and a course of action determined. Nevertheless, several of the more serious occurrences have been attached to a telephone alarm described below.

The Telephone Alarm

Typically, G-tunnel is open a standard 8 hr shift, 5 days a week. From time to time, it is open longer because of the requirements of various ongoing activities in the tunnel. Except for the heater turnon and heatup, we do not expect to keep the tunnel open except for emergency situations. A telephone alarm will be included in the system to notify appropriate personnel of conditions judged detrimental to the experiment.

Three such conditions have been identified. They are

- Inability of the backup diesel generator to start after a commercial power failure
- Loss of power to the data-acquisition system (DAS)
- Thermal excursion of the heater skin of more than 30°C above the predicted temperature

The backup diesel generator is programmed to attempt startup three times after a commercial power failure. If the generator has not started after the third attempt, the telephone alarm will notify the appropriate personnel.

Even if the diesel generator does not start, the DAS is connected to an uninterruptible power supply (battery pack), which can maintain the DAS but not the heaters for at least 5 hr. However, should there be a loss of power to the DAS for any reason, the telephone alarm will notify the appropriate personnel.

The heater skin was chosen to monitor the thermal behavior in the heater hole for several reasons. First, because the thermocouples are embedded in the skin and covered with welded plates, they are the best protected of all the thermocouples in the heater hole. Secondly, the heater

skin is the most sensitive to both variations in temperature of the heating elements inside the heater or to variations in temperature of the rock wall surrounding the heater. Should the heater skin deviate by about 30°C above the predicted temperature, the telephone alarm system will actuate. If the thermal excursion reaches 100°C before the difficulty is corrected, the heater power is automatically shut off. The 30° and 100°C deviations are at present only estimates of the critical temperature intervals; they may be altered once we have some experience in the thermal behavior of the experiment.

Upon actuation, the telephone alarm system automatically calls a preprogrammed list of people and plays a prerecorded tape that describes the situation. The system is designed to attempt to call each person three times before sequencing to the next on the list. At least five people can be notified, and they may be different people depending on the situation that develops. Personnel will be selected for notification according to their ability to deal with the problem. Note in particular that some conditions may require opening G-tunnel. Under these circumstances, certain mine personnel must be on hand in accordance with Federal mine safety regulations.

Safety

All installation and operational procedures will be consistent with the applicable provisions of the appropriate DOE Manual Chapters and Nevada Test Site Service Organization (NTSSO) Standard Operating Procedures. We have not so far identified any extraordinary hazards associated with this experiment.

One potential hazard is overpressurization of the experiment cavities. Current data suggest this is highly unlikely; however, certain precautions will be taken. The rods used to insert the packer/instrumentation packages will be attached to rock bolts to prevent ejection into the alcove. Should the pressure exceed 15 psig, the DAS will emit an audible beep and a warning will be printed. If overpressurization in excess of 100 psig occurs, a warning light will be activated next to the alcove door

to warn persons entering of the situation. All of the experimental cavities include gas and water sampling tubes that can be used to relieve the pressure.

Quality Assurance

A Quality Program Plan (QPP) has been developed for all of Sandia National Laboratories involvement in NNWSI activities. The experiment will be carried out in accordance with the QPP. The QPP is written in the 18-chapter format prescribed by 10CFR 50, Appendix B, and its provisions comply with AL Chapter and Appendix 08XA.

The QPP addresses only those activities internal to Sandia National Laboratories. Any services performed by NTS support contractors fall under their individual quality assurance plans.

Documentation

A Conceptual Experimental Plan was prepared and submitted to the NNWSI Project Manager for approval. This report, the Experimental Plan, is the second in the series of plan documents prepared subsequent to approval of the Conceptual Experiment Plan. The final pretest thermal calculations used to define the heater operating conditions will be documented upon completion (recall that the final calculations will be based on thermal properties of core removed from the heater hole; see the section entitled "Thermal Modeling"). Barring unforeseen delays, the final report draft of the results of the experiment will be submitted to the NNWSI Project Manager within 6 months after cessation of all activity at the experiment site.

Current status reports will be made orally on a weekly basis to DOE NV NNWSI personnel in accordance with current practice. Written status reports will be submitted on a quarterly basis, also in accordance with current practice. All activities related to the experiment, such as

design studies, inspection, calibration, operational procedures, document control, etc, will be carried out in accordance with the Quality Program Plan described in the previous section.

References

1. Nevada Nuclear Waste Storage Investigations. FY 1979 Project Plan. NVO-196-9 (Las Vegas, NV: US Department of Energy, Nevada Operations Office, March 1979).
2. G. J. McCarty et al, "Interaction Between Nuclear Waste and Surrounding Rock," Nature, 273, 1978, pp 216-217.
3. G. J. McCarty et al, "Hydrothermal Interactions Among Nuclear Wastes, Containment, and Host Rocks in Geologic Repositories," Scientific Basis for Nuclear Waste Management, Vol. I. Proceedings of the Symposium on Science Underlying Radioactive Waste Management (Boston, MA: Materials Research Society, November 1978).
4. J. W. Braithwaite and J. K. Johnstone, "Chemical Durability and Characterization of Nuclear Waste Forms in a Hydrothermal Environment." Proceedings of the Symposium on Ceramics in Nuclear Waste Management (Cincinnati, OH: American Ceramics Society, April 1979).
5. A. R. Lappin, R. K. Thomas, and D. F. McVey, "Present Status of Thermomechanical Modeling of the Response of Argillaceous Rocks to Disposal of High-Level Nuclear Wastes." Spring Meeting of the Society for Experimental Stress Analysis (San Francisco, CA: Society for Experimental Stress Analysis, May 1979).
6. L. D. Ramsdott, ed, Waste Isolation Projects. FY 1978, UCRL-50050-78 (Livermore, CA: Ernest Orlando Lawrence Livermore National Laboratory, January 1979).
7. L. V. Benson, Mass Transport in Vitric Tuffs of Rainier Mesa, Nye County, Nevada, NVO-1253-10 (Reno, NV: Water Resources Center, Desert Research Institute, University of Nevada, October 1979).
8. N. R. Warpinski et al, Hydraulic Fracture Behavior at a Geologic Formation Interface: Pre-Mineback Report, SAND78-1578 (Albuquerque, NM: Sandia National Laboratories, August 1978).
9. Letter from E. F. Gloyna, Chairman of the Committee on Radioactive Waste Management, National Research Council, to S. Meyers, Program Director, Office of Nuclear Waste Management, DOE, April 23, 1979.
10. L. D. Tyler et al, Near-Surface Heater Experiments in Argillaceous Rocks, SAND78-1401C. OECD/NEA Meeting on In-Situ Heating Experiments in the Eleana Formation, Nevada Test Site. Division 4537 (Albuquerque, NM: Sandia National Laboratories).
11. Experiment Design for Near-Surface Experiments in the Eleana Formation, Nevada Test Site. Division 4537, (Albuquerque: Sandia National Laboratories).

12. L. D. Ramsport and L. B. Ballou, Experimental Design for the First Heater Test at the Climax Stock, Nevada Test Site, Appendix A in NTS Terminal Waste Storage Program Plan for FY 1978 (Las Vegas, NV: US Department of Energy, March 1978).
13. K. A. Sargent, D. C. Noble, and E. B. Ekren, "Belted Range Tuff of Nye and Lincoln Counties, Nevada," Changes in Stratigraphic Nomenclature, US Geological Survey, US Geol Survey Bull 1224-A, 1964, pp 32-36.
14. G. H. Meiken and M. L. Bevier, Petrology of Tuff Units from the J-13 Drill Site, Jackass Flats, Nevada, LA-7563-MS (Los Alamos, NM: Los Alamos National Scientific Laboratory, 1979).
15. N. B. C. Yelamanchili, Thermal Conductivity and Physical Properties of Rock Cores from G-Tunnel, Report No. 173 (NTS, NV: H&N Materials Test Laboratory, July 1978).
16. N. B. C. Yelamanchili, Physical Properties of Rock Cores Samples from UE25A#1 Drill Hole, Report No. 2458 (NTS, NV: H&N Materials Test Laboratory, April 1979).
17. N. B. C. Yelamanchili, Physical Properties of Rock Cores Drill Hole UE25A#1, Report No. 2068 (NTS, NV: H&N Materials Test Laboratory, December 1978).
18. N. B. C. Yelamanchili, H&N Materials Test Laboratory, NTS, NV, personal communication to A. R. Lappin, Sandia National Laboratories, Albuquerque, NM.

Sandia Laboratories

Albuquerque New Mexico
Livermore California

date: May 17, 1979

to: J. K. Johnstone - 4537

from: G. W. Smith - 4537

subject: Summary of Fracture Analysis of Grouse Canyon Member, Belted Range Tuff at the Tuff Heater Site, U12g Tunnel Complex, Nevada Test Site

Analysis of fracture behavior in the Grouse Canyon Member, Belted Range Tuff was initiated to characterize the near-field geology of the area proximal to the tuff heater experiment planned by Sandia Laboratories. This experiment will be conducted in the U12g tunnel complex located approximately 1400 feet below Rainier Mesa on the north-central Nevada Test Site. Fracture analysis yielded detailed information on the orientation, frequency, morphology, and mineralization of joints in the Grouse Canyon Member.

The Grouse Canyon Member of the Belted Range Tuff is a peralkaline, welded ash-flow tuff extruded from the Silent Canyon Caldera beneath Pahute Mesa approximately 13 to 15 mybp (Noble and others, 1968). Exploratory drilling at the heater site has determined that the Grouse Canyon Member is 41 feet thick in this immediate area. Tunnel Bed #5, an ash-fall tuff, is exposed at the base of the alcove in which the experiment will be run. In sharp contact with Tunnel Bed #5 is the overlying basal vitrophere of the Grouse Canyon Member; the vitrophere is roughly three feet thick. An approximately three feet thick "rubble zone" or zone of large xenoliths occurs above the basal vitrophere. Densely welded ash-flow tuff is exposed above the "rubble zone" at the tunnel back in the alcove area. The strata strike approximately N30E and dip 7°NW in the alcove area.

Detailed mapping of the tunnel drift in and proximal to the alcove revealed four sets of joints: 1) N-S to N20E, 77-90°NW; 2) N50-60W, 75-90°NE; 3) N30-75E, 70-90°SE; and 4) N30E, 70°NW (compaction foliation or bedding plane joints). The N-S to N20E joint set is composed of markedly planar joints which vary in width from closed to .5 inch, occur on a spacing of approximately three feet, and are continuous along strike up to twenty feet. The N50-60W joint set is composed of planar and bifurcating joints which occur on a spacing of four feet, vary in width from 1/8 to 2 inches, and are continuous along strike up to 25 feet. The N30-75E joint set is composed of planar, mostly closed joints which occur on a spacing of less

May 17, 1979

than ten inches and are continuous along strike up to six feet. Bedding plane joints are not observed in abundance.

Measurement of joint orientations in core from the two heater exploratory holes, U12gHEH#1A, #1B, and three other holes (UE12g10#5 and #6, and U12gEV6#3) penetrating the Grouse Canyon member in the area has determined that the four joint sets described above are the major sets in the area.* The most frequently observed joints in the five cores are oriented roughly perpendicular to the orientations of the particular drill hole.

The welded tuff in the area is, in general, a highly fractured rock mass. Frequency of joints varies from none in two feet of core to nine in 1/2 foot of core. The most systematic feature of joint frequency in the area is its variability. For instance, hole U12gHEH#1A averages roughly 3.2 joints per foot while hole U12gHEH#1B, located 2.2 feet away, averages only 1.25 joints per foot. In general, the welded tuff in the cores consists of relatively unjointed sections of one to three foot length separated by intensely jointed sections of less than eight inches in length. Numerous rubblized zones of less than one inch long pieces were found in the cores; these zones vary from two inches to three feet long. In general, there was a substantial increase in the joint frequency in the core above that measured in the alcove and tunnel walls for the existing joint sets.

Mineralization is found along many joint surfaces in the five cores. The most commonly observed mineralization is reflected by an altered tuff groundmass along many joints. Manganese and iron oxides, calcite, clay minerals, and quartz coat other joint surfaces. Joints oriented N40-80W and N-S to N20E are most affected by mineralization. This seems to indicate that these joints possess the greatest water transmissibility. Intense argillization of several zones of rubblized core suggests that these zones also are water transmissive.

Video scans of the heater exploratory holes show several features: 1) most fractures are nonplanar and bifurcating features; 2) zones of rubblized core result from the intersection of many joints at one locality; 3) joints occur in clusters; 4) most joints are open 1/16 to 1/8 inch while several joints are open up to 3/4 inch. Several joints may vary from 1/2 inch wide to closed within 1 inch.

Core indices for the two heater exploratory holes and the three other holes studied are given on Figure 1. Of particular interest are the low core indices from 50 to 70 feet in hole U12gHEH#1B. Also of interest is the fact that core indices for UE12g10#5 and #6, both vertical holes, are generally lower than the indices for U12GHEH#1A, #1B and U12gEV6#3, all low-angle

* No new joint sets were identified.

May 17, 1979

holes. Since most joints in this area have near-vertical attitudes, this relationship can probably be ascribed to the greater probability of intersecting a high-angle joint in a low-angle hole.

The strike of joints found in U12gHEH#1A was projected onto the plane of U12gHEH#1B (and vice versa) to attempt prediction of fracture behavior from core data. Although three rubble zones were predictable, all other rubble zones were not. Most joints do not intersect the other hole at the point projected. These data indicate that either the joints are curvilinear and/or they are not continuous along strike. In conclusion, these results confirm that fracture behavior of the Grouse Canyon Member is both complex and generally unpredictable.

GWS:4537:dsh

Reference

Noble, D. C., Sargent, K. A., Mehnert, H. H., Ekren, E. B., and Byers, F. M., Jr., 1968, Silent Canyon volcanic center, Nye County, Nevada, in Nevada Test Site: Geol. Soc. America Mem. 110, p. 65-75.

Copy to:

4530 R. W. Lynch
4537 L. D. Tyler
4537 A. R. Lappin

UI2g HEH *1A

UI2g HEH *1B

UE12g10 *6

UE12g10 *5

UI2gEV6 *3
(10-foot intervals)

Figure A-1. Core Indices for Several Holes Proximal to Tuff Heater Experiment Site

Sandia Laboratories

date February 15, 1979

Albuquerque, New Mexico
Livermore, California

to A. R. Lappin - 4537

Bulmer or Bulmer

from B. M. Bulmer - 5511

subject Recommended Thermocouple Locations for In-Situ Tuff
Heater Experiment

Ref: Memo, B. M. Bulmer, 5511, to A. R. Lappin, 4537,
dtd 2/14/79, subject, Thermal Analysis of Tuff
In-Situ Heater Experiment

Temperature measurements will be made during the tuff heater experiment at NTS to determine the temperature rise on the heater surface ($R = 2''$), on the rock surface (bore hole, $R = 2.5''$), and in the rock at two indepth locations ($R = 16$ and $24''$). Recommended axial thermocouple locations for this test are symmetric with respect to the heater midplane ($z = 0$):

<u>Measurement</u>	<u>z, inches</u>
1. Heater surface, R = 2"	Same as rock surface
2. Bore hole (rock) surface, R = 2.5"	0 12-18 (as close to 18" as possible)
3. IndePTH, R = 16 and 24"	0 6 12-18 (same as selected for rock surface) 36 60 96

Recommended thermocouple locations are superimposed in Figures 1-8 with computed isotherms at 30 days for each of the eight numerical cases considered in the reference.

Rock and heater surface temperatures will be measured at three circumferential positions at the heater midplane and near each end of the heater (9 measurements total each surface). Computed temperature profiles along the heater

hole (Figure 9) suggest that there will be a significant axial gradient beyond ~12" from the midplane. Thus, a measurement beyond 12" should help to define the axial variation along the hole. However, the measurement should be kept at least 6" from the ends of the heater so as to avoid ill-defined heater end effects.

Proposed thermocouple locations indepth at R = 16 and 24" are positioned axially to provide as much detail as possible within the calculated 50°C isotherm for the range of conditions considered thus far. Temperature profiles at 30 days for the R = 16 and 24" radii are plotted in Figure 10. The locations of the eleven thermocouples proposed for each radius have been selected to best define the axial temperature variation indepth. The location of the second thermocouple from the heater midplane should correspond, if possible, to the axial location selected for the rock and heater surface measurements. As indicated in Figure 10, a measurement 18" from the midplane will provide the best definition of the indepth temperature profile based on computed results.

BMB:5511:ljg

Copy to:

1116 J. D. Plimpton
4530 R. W. Lynch
4537 L. D. Tyler
4537 J. K. Johnstone
4537 D. R. Waymire
5500 O. E. Jones
5510 D. B. Hayes
5511 D. F. McVey
5520 T. B. Lane
5530 W. Herrmann
5531 L. D. Bertholf
5531 W. T. Brown

Figure B-1. Case 1A, Recommended Thermocouple Locations

Figure B-2. Case 1B, Recommended Thermocouple Locations

Figure B-3. Case 1C, Recommended Thermocouple Locations

Figure B-4. Case 1D, Recommended Thermocouple Locations

Figure B-5. Case 2A, Recommended Thermocouple Locations

Figure B-6. Case 2B, Recommended Thermocouple Locations

Figure E-7. Case 2C, Recommended Thermocouple Locations

Figure B-3. Case 2D, Recommended Thermocouple Locations

Figure B-9. Case 2A, Computed Temperature Profiles Along the Heater Hole

Figure B-10. Case 2A, Temperature Profiles at 30 Days for $R = 16$ and 24-In. Radii

APPENDIX C

Thermal Analyses of Tuff In-Situ Heater Experiment

Part I: Thermal Analysis of Tuff In-Situ Heater Experiment

(Memo, B. M. Bulmer, 5511, to A. R. Lappin 4537, dtd 2/14/79)

(Representative plots were selected for inclusion in the Appendix to Part I; therefore, they are not numbered consecutively)

Part II: Additional Thermal Analyses for Tuff Heater Experiment

(Memo, B. M. Bulmer, 5511, to A. R. Lappin, 4537 dtd 2/23/79)

(Representative plots were selected for inclusion in the Appendix to Part II; therefore, they are not numbered consecutively)

Part III: Tuff In-Situ Heater Experiment Rock Thermal Conductivity Sensitivity Study

(Memo, B. M. Bulmer, 5511, to A. R. Lappin, 4537 dtd 3/19/79)

(Representative plots were selected for inclusion in the Appendix to Part III; therefore, they are not numbered consecutively)

Sandia Laboratories

Albuquerque, New Mexico
Livermore, California

date February 14, 1979
to A. R. Lappin - 4537

B. M. Bulmer

from B. M. Bulmer - 5511

subject Thermal Analysis of Tuff In-Situ Heater Experiment

A preliminary scoping analysis has been completed for the tuff heater experiment to be conducted at NTS. Problem definition is given in Reference 1. A total of eight numerical cases were considered for a two-dimensional axisymmetric geometry. The various cases are summarized in Table I.

A schematic of the conceptual heater assembly (as analyzed) is shown in Figure 1. The end of the heater is assumed to be in direct contact with the rock. At the opposite end of the heater is a layer of crushed tuff followed by an air void (containing an experimental package) and a steel plug bonded in place to provide a seal. Thermal properties for each material are presented in Table II. Grout will be pumped in behind the steel plug and is considered in this analysis to have thermal properties identical to the rock.

Heater operation is a constant power level during the first 30 days with cool down after that time. Two power levels were considered in this preliminary study: 1.25 kW and 2.5 kW (see Table I).

Heat transfer between the heater and rock across the 0.5" (1.27 cm) gap is assumed to be by one-dimensional (radial) radiation and molecular conduction through the air. The heater surface will be designed so as to minimize free convection effects within the gap; convection was ignored in the present analysis. Thus,

$$q_{\text{total}} = q_{\text{rad}} + q_{\text{cond}}$$

or,

$$\frac{2\pi k_{eff} l}{\ln(r_o/r_i)} (T_i - T_o) = 2\pi l r_i F_{i-o} \sigma (T_i^4 - T_o^4) + \frac{2\pi k_{air} l}{\ln(r_o/r_i)} (T_i - T_o) ,$$

where,

k_{eff} = gap effective conductivity (combined radiation and conduction)

k_{air} = air conductivity

F_{i-o} = radiation shape factor

σ = Stefan-Boltzmann constant, 4.901×10^{-6}
kJ/day-m²-K⁴

l = heater length

r_i, r_o = heater, bore hole radius, respectively

T_i, T_o = heater, rock surface temperature, respectively.

Solving for the effective conductivity,

$$k_{eff} = \ln(r_o/r_i) r_i F_{i-o} \sigma (T_i^2 + T_o^2) (T_i + T_o) + k_{air} .$$

The radiation shape factor for long, concentric cylinders is assumed, i.e.,

$$F_{i-o} = \frac{1}{\frac{1 - \epsilon_i}{\epsilon_i} + 1 + \frac{r_i(1 - \epsilon_o)}{r_o \epsilon_o}} ,$$

where ϵ_i and ϵ_o are the heater and rock surface emissivities, respectively. The heater emissivity is based on mean values for stainless steel oxidized in air at red heat for 30 min.² A curve fit to these data is,

$$\epsilon_i = 0.1409 e^{0.001283T} ; T \text{ in } ^\circ\text{C} ,$$

and is valid for temperature to approximately 750°C.

The conductivity of air is temperature dependent and is given by the following equation:³

$$k_{\text{air}} = \frac{0.170\sqrt{T}}{1 + \frac{441.7}{T}} 10^{-(21.6/T)} ; k \text{ in } \frac{\text{kJ}}{\text{day-m-}^\circ\text{C}} , T \text{ in } ^\circ\text{R} .$$

Heat transfer in the air void between the crushed tuff and steel plug is assumed to be by molecular conduction only; the preceding expression was used to evaluate this effect.

The boiling of water contained in the tuff may have a significant effect on the rock thermal characteristics as dry-out occurs. A boiling temperature of either 100°C or 235°C was assumed in the analysis.¹ These values assume fully saturated rock with 6 wt% water content. The lower bound, $T_{\text{boil}} = 100^\circ\text{C}$, represents atmospheric boiling, i.e., $P_{\text{fluid}} = 1 \text{ atm}$. The upper bound value of 235°C corresponds to $P_{\text{fluid}} = P_{\text{solid}} \approx 450 \text{ psi}$ (minimum solid stress). During the heater experiment, boiling should occur somewhere between these limits.

The assumed effect of boiling on the thermal conductivity of the rock is:

Variable k cases

$$k = \text{constant} = 2.2 \text{ W/m}^\circ\text{C} = 190.1 \text{ kJ/day-m-}^\circ\text{C} ; T \leq T_{\text{boil}}$$

$$k = \text{constant} = 1.2 \text{ W/m}^\circ\text{C} = 103.7 \text{ kJ/day-m-}^\circ\text{C} ; T > T_{\text{boil}}$$

Constant k cases

$$k = \text{constant} = 2.2 \text{ W/m}^\circ\text{C} = 190.1 \text{ kJ/day-m-}^\circ\text{C} ; \text{all } T$$

For heat capacitance, the latent heat of water was included in the rock, ρC_p , to account for the energy absorbed during evaporation. This was accomplished by spreading the effect over a 50°C temperature increment in the vicinity of the assumed boiling temperature:

$$\rho C_p = 1975 \text{ kJ/m}^3\text{-}^\circ\text{C} ; T < T_{\text{boil}} - 45^\circ\text{C}$$

$$\rho C_p = \left\{ \begin{array}{l} 8244 \text{ kJ/m}^3\text{-}^\circ\text{C} \quad (T_{\text{boil}} = 100^\circ\text{C}) \\ 6919 \text{ kJ/m}^3\text{-}^\circ\text{C} \quad (T_{\text{boil}} = 235^\circ\text{C}) \end{array} \right\} T = T_{\text{boil}} - 45^\circ\text{C} \text{ to } T_{\text{boil}} + 5^\circ\text{C}$$

$$\rho C_p = 1975 \text{ kJ/m}^3\text{-}^\circ\text{C} ; T > T_{\text{boil}} + 5^\circ\text{C} .$$

These results assume fully saturated rock at 6 wt% water content; latent heat values were taken from Reference 4 for each assumed boiling temperature.

Rock thermal conductivity and heat capacitance variations with temperature are summarized in Figure 2.

The COYOTE finite element heat conduction code⁵ was used to generate time-dependent, two-dimensional axisymmetric temperature solutions in the heater assembly and rock. The thermal model is shown in Figure 3 and contains 465 elements. The indicated physical size of the modeled region insures the validity of the assumed adiabatic boundary conditions for the range of heater powers and problem run times of interest. Thermal model details near the heater are shown in Figure 4; numbered elements for the same region (expanded 5X in the radial dimension) are indicated in Figure 5.

Detailed plotted temperatures are presented in the Appendix for each of the eight cases considered (64 plots total). Locations of plotted temperature histories are indicated schematically in Figure 6. Histories are given for three rays (bottom of heater, midplane of heater, top of heater) at the following 10 radii measured from the heater centerline:

Plot Symbol	R, m,	in.
0	0.0508	2.00 (heater surface)
1	0.0635	2.50 (rock surface)
2	0.076	2.99
3	0.113	4.45
4	0.175	6.89
5	0.262	10.3
6	0.375	14.8
7	0.512	20.2
8	0.675	26.6
9	0.862	33.9

Temperature histories are plotted at eight locations along the centerline (axis) at the following positions measured from the top of the heater:

Plot Symbol	Z, m,	in.
0	0.0	0.0 (heater/rock interface)
1	0.012	0.48
2	0.049	1.94
3	0.11	4.38
4	0.20	7.84
5	0.31	12.3
6	0.45	17.6
7	0.61	24.1

Histories are also provided at the four material interface locations along the centerline of the heater assembly measured from the bottom of the heater:

Plot Symbol	Z, m,	in.
0	0.0	0.0 (heater/crushed tuff)
1	0.36	14.0 (crushed tuff/air void)
2	0.51	20.0 (air void/steel plug)
3	0.61	24.0 (steel plug/grout (rock))

Maximum temperatures are reached at 30 days as the power is assumed to be shut off at that time.

Three contour plots are presented for each case at the following times: 1 day, 10 days and 30 days. Note that the contour plots encompass only the immediate region near the heat assembly: 1m axially from each end of the heater assembly, and 1.5m radially from the centerline. All contour plots are expanded 2X in the radial dimension.

Some significant thermal results are summarized in Table III. These include maximum computed temperatures on the heater and rock surfaces (at the heater midplane) and in the steel plug, and maximum radial and axial penetration distances of the assumed boiling isotherm.

Several conclusions may be drawn from this study:

- (1) Tuff is not as dark as the Eleana argillite and emissivities in the range 0.6-0.8 appear to be reasonable for the present analysis. Variations of ϵ_{rock} (compare cases 1A and 1B) result in relatively small differences (~1%) in the maximum heater surface temperature.
- (2) The heater power level has a strong effect on all important variables (compare Case 1A with 1C, Case 2A with 2B and Case 2C with 2D). All temperatures of interest increase significantly with power, as do the maximum penetration distances of the assumed boiling front into the rock. Thus, it seems reasonable, from the standpoint of test objectives, to operate at the maximum power consistent with the maximum allowable heater operation temperature to achieve the desired extent of boiling in the rock.
- (3) The effect of boiling temperature on the thermal field can have an important "near-field" influence depending on how the rock thermal conductivity is assumed to vary as dry-out occurs. An assumed decrease in k_{rock} at boiling results in a significant temperature rise within

the "near-field" region bounded by the boiling isotherm compared to those cases in which k_{rock} is assumed constant everywhere (compare Cases 1C with 1D, Cases 2A with 2C and Cases 2B with 2D); little temperature change occurs in the region outside of the boiling isotherm. Also, note that the location of the boiling isotherm is relatively insensitive to the assumptions concerning $k(T)_{rock}$. Only a slight increase in penetration distance is evident for cases with an assumed decrease in k_{rock} at boiling compared to the corresponding constant k_{rock} runs.

- (4) For the cases considered, only power has a significant influence on the maximum temperature of the steel plug. However, even for 2.5 kW power, the highest temperature computed for the steel is 75°C, well below the maximum allowable limit of the plug bonding sealant. The ΔT in the steel plug, both radially and axially, is negligibly small.

BMB:5511;ljjg

Copy to:

4530 R. W. Lynch (w/o Appendix)
4537 L. D. Tyler (w/o Appendix)
4537 J. K. Johnstone
4537 D. R. Waymire
5500 O. E. Jones (w/o Appendix)
5510 D. B. Hayes (w/o Appendix)
5511 D. F. McVey (w/o Appendix)
5520 T. B. Lane (w/o Appendix)
5530 W. Herrmann (w/o Appendix)
5531 L. D. Bertholf (w/o Appendix)
5531 W. T. Brown

References

1. Memo, A. R. Lappin, 4537, to B. M. Bulmer, 5511, dtd 12/1/78, subject: COYOTE Thermal Modeling of Tuff Heater Experiment.
2. Y. S. Touloukian and D. P. DeWitt, Thermophysical Properties of Matter, Volume 7, Thermal Radiative Properties, Metallic Elements and Alloys, IFI/Plenum, New York-Washington, 1970, p. 1217.
3. Handbook of Supersonic Aerodynamics, Vol. 5, Bureau of Ordnance, Department of the Navy, Washington, D.C., 1953.
4. J. H. Keenan and F. G. Keyes, Thermodynamic Properties of Steam, Wiley and Sons, New York, 1936.
5. D. K. Gartling, "COYOTE--A Finite Element Computer Program for Non-Linear Heat Conduction Problems," SAND77-1332, Sandia Laboratories, Albuquerque, NM, June 1978.

TABLE I

TUFF HEATER THERMAL ANALYSIS

<u>Case</u>	<u>Description</u>
1A	$T_{\text{boil}} = 235^{\circ}\text{C}$ $\epsilon_{\text{rock}} = 0.6$ $k_{\text{rock}} = \text{VARIABLE}$ $P = 1.25 \text{ kW}$
1B	Same as 1A except $\epsilon_{\text{rock}} = 0.8$
1C	Same as 1A except $P = 2.5 \text{ kW}$
1D	Same as 1C except $k_{\text{rock}} = \text{CONSTANT}$
2A	$T_{\text{boil}} = 100^{\circ}\text{C}$ $\epsilon_{\text{rock}} = 0.6$ $k_{\text{rock}} = \text{VARIABLE}$ $P = 1.25 \text{ kW}$
2B	Same as 2A except $P = 2.5 \text{ kW}$
2C	Same as 2A except $k_{\text{rock}} = \text{CONSTANT}$
2D	Same as 2B except $k_{\text{rock}} = \text{CONSTANT}$

(All cases assume uniform initial temperature of 18°C .)

TABLE II

MATERIAL PROPERTIES

Tuff

$$\rho = 2360 \text{ kg/m}^3$$

$$C_p = 0.2 \text{ cal/g}^\circ\text{C} = 0.837 \text{ kJ/kg}^\circ\text{C} \text{ except in boiling ranges (see text)}$$

$$k = \text{variable (see text)}$$

Crushed Tuff

$$\rho = 0.5 \rho_{\text{tuff}} = 1180/\text{m}^3$$

$$C_p = 0.5 C_{p\text{tuff}} = 0.418 \text{ kJ/kg}^\circ\text{C}$$

$$k = 1 \text{ W/m}^\circ\text{C} = 86.40 \text{ kJ/day-m-}^\circ\text{C}$$

Steel Plug

$$\rho = 7817 \text{ kg/m}^3$$

$$C_p = 0.460 \text{ kJ/kg}^\circ\text{C}$$

$$k = 10 \text{ Btu/hrft}^\circ\text{F (mean value)} = 1494.4 \text{ kJ/day-m-}^\circ\text{C}$$

Heater

$$\rho = 7817 \text{ kg/m}^3 \text{ (based on estimated mass of 44 lbm and total heater volume)}$$

$$C_p = C_{p\text{steel}} = 0.460 \text{ kJ/kg}^\circ\text{C}$$

$$k = k_{\text{steel}} = 1494.4 \text{ kJ/day-m-}^\circ\text{C}$$

Air Gap, Air Void

$$\rho = \rho_{\text{air}} = 1.20 \text{ kg/m}^3$$

$$C_p = C_{p\text{air}} = 1.01 \text{ kJ/kg}^\circ\text{C}$$

$$k = \text{Variable (see text)}$$

TABLE III
TUFF HEATER THERMAL ANALYSIS SUMMARY

	$T_{\text{boil}} = 235^{\circ}\text{C}$				$T_{\text{boil}} = 100^{\circ}\text{C}$			
	<u>1A</u>	<u>1B</u>	<u>1C</u>	<u>1D</u>	<u>2A</u>	<u>2B</u>	<u>2C</u>	<u>2D</u>
Maximum Heater Surface Temperature @ Midplane, $^{\circ}\text{C}$	428	422	662	604	467	744	427	601
Maximum Rock Surface Temperature @ Midplane, $^{\circ}\text{C}$	216	217	530	419	309	655	213	412
Maximum Steel Temperature, $^{\circ}\text{C}$	47	47	75	75	45	68	45	68
Maximum Radial Penetration of Boiling Front @ Midplane, Inches (Measured from Centerline)	N.B.*	N.B.*	10	9	16	29	14	28
Maximum Axial Penetration of Boiling Front Along Axis, Inches (Measured from Top of Heater)	1	1	4	4	7	15	6	14

*No boiling occurs.

(All cases assume uniform initial temperature of 18°C .)

Figure CI-1. Heater Assembly (Conceptual)

Figure CI-2. Tuff Thermal Properties

Figure CI-3. Coyote FE Thermal Model

Figure CI-4. Thermal Model Detail

331	332	333	334	335	336	227
+	+	+	+	+	+	+
316	317	318	319	320	321	
301	302	303	304	305	306	307
+	+	+	+	+	+	+
286	287	288	289	290	291	292
+	+	+	+	+	+	+
271	272	273	274	275	276	277
+	+	+	+	+	+	+
256	257	258	259	260	261	262
+	+	+	+	+	+	+
241	242	243	244	245	246	247
+	+	+	+	+	+	+
226	227	228	229	230	231	232
+	+	+	+	+	+	+
211	212	213	214	215	216	217
+	+	+	+	+	+	+
196	197	198	199	200	201	202
+	+	+	+	+	+	+
181	182	183	184	185	186	187
+	+	+	+	+	+	+
166	167	168	169	170	171	172
+	+	+	+	+	+	+
151	152	153	154	155	156	157
+	+	+	+	+	+	+
136	137	138	139	140	141	142
+	+	+	+	+	+	+
121	122	123	124	125	126	127
+	+	+	+	+	+	+

Figure CI-5. Elements (5X Radial)

Figure CI-6. Temperature History Plot Locations

Figure CIA-2. Case 1A Radial, Midplane of Heater

Figure CIA-4. Case 1A Axial, Top of Heater

Figure C1A-8. Case 1A, 30 Days

Figure C1A-10. Case 1B Radial, Midplane of Heater

Figure CIA-12. Case 1B Axis 1, Top of Reactor

Figure CIA-16. Case 1B, 30 Days

Figure CIA-18. Case 1C Radial, Midplane of Heater

Figure CIA-20. Case 1C Axial, Top of Heater

Figure CIA-24. Case 1C, 30 Days

Figure CIA-26. Case 1D Radial, Midplane of Heater

Figure CIA-28. Case 1D Axial, Top of Heater

Figure CIA-32. Case 1D, 30 Days

Figure CIA-34. Case 2A Radial, Midplane of Heater

Figure CIA-36. Case 2A Axial, Top of Heater

Figure CIA-40. Case 2A, 30 Days

Figure CIA-42. Case 2B Radial, Midplane of Heater

Figure CIA-44. Case 2B Axial, Top of Heater

Figure CIA-48. Case 2B, 30 Days

Figure CIA-50. Case 2C Radial, Midplane of Heater

Figure CIA-52. Case 2C Axial, Top of Heater

Figure CIA-56. Case 2C, 30 Days

Figure CIA-58. Case 2D Radial, Midplane of Heater

Figure CIA-60. Case 2D Axial, Top of Heater

Figure CIA-64. Case 2D, 30 Days

Sandia Laboratories

Albuquerque, New Mexico
Livermore, California

date: February 23, 1979

to: A. R. Lappin - 4537

B. M. Bulmer

from: B. M. Bulmer - 5511

subject: Additional Thermal Analyses for Tuff Heater Experiment

Ref: Memo, B. M. Bulmer, 5511, to A. R. Lappin, 4537
dtd 2/14/79, subject: Thermal Analysis of Tuff
In-Situ Heater Experiment*

Two additional numerical (COYOTE) cases have been run for the tuff in-situ heater experiment at NTS. These correspond to an intermediate power level (1.9 kW) with an assumed boiling temperature in the rock of 100°C. This memo presents the details of these calculations and compares significant results with those reported previously in the reference.

The heater geometrical configuration, material properties, and all calculational procedures are identical to those discussed in the reference. The two individual cases presently considered are:

<u>Case</u>	<u>Description</u>
2E	$T_{\text{boil}} = 100^{\circ}\text{C}$ $\epsilon_{\text{rock}} = 0.6$ $k_{\text{rock}} = \text{VARIABLE}$ $P = 1.9 \text{ kW}$
2F	Same as 2E except $k_{\text{rock}} = \text{CONSTANT}$

Both cases assume a uniform initial temperature of 18°C.

"Variable" rock thermal conductivity refers to a discontinuous change at dry-out from 2.2 to 1.2 W/m°C at the assumed boiling temperature of 100°C, whereas, "constant" implies $k_{\text{rock}} = 2.2 \text{ W/m}^{\circ}\text{C}$ everywhere. The latent heat of water is included in the rock heat capacitance in all cases. The reference contains a more complete description of the assumed variations in k_{rock} and $\rho C_{\text{P rock}}$ near the boiling temperature.

Detailed plotted temperatures for Cases 2E and 2F are contained in the Appendix. Locations of the plotted temperature histories are identical to those presented earlier. As before, all contour plots are expanded 2X in the radial dimension. Significant thermal results are summarized in Table I for Cases 2E and 2F. These include maximum computed temperatures on the heater and rock (bore hole) surfaces at the heater midplane, maximum temperature in the steel plug, and maximum radial and axial penetration distances of the assumed boiling isotherm.

The intermediate power of 1.9 kW considered in this memo permits a direct comparison with previous results (Case 2A-2D, 1.25 or 2.5 kW) in terms of heater power. In Figure 1, maximum computed temperatures on the heater and rock surfaces are compared for all cases with $T_{\text{boil}} = 100^{\circ}\text{C}$ over the range of heater power considered. Figure 2 shows the variation of maximum temperature in the steel plug with power. These maxima occur at 30 days as the heater is assumed to be shut off at that time.

As evidenced by the rock surface temperatures in Figure 1, the assumed variation of $k(T)_{\text{rock}}$ near boiling strongly influences the near thermal field. Measurements of rock surface ($R = 2.5''$) temperature during the experiment should provide the best and most sensitive definition of indepth boiling in terms of its effect on rock thermal properties. Thus, it is imperative that these measurements be made as carefully and as accurately as possible. Other planned measurements at $R = 16$ and $24''$ will be helpful as well, but the surface measurements are the most useful data from this standpoint.

Radial temperature gradients in the rock at 30 days are compared in Figure 3 for the six cases with $T_{\text{boil}} = 100^{\circ}\text{C}$. Locations of the boiling isotherm determined by these plots differ slightly ($\sim 1-2''$) from those interpreted from the temperature contour plots using a variable scale as in the reference (rounded to nearest inch). The boiling isotherm penetration distances derived from the radial gradients are probably more accurate, as the computer-generated contour plots contain inaccuracies owing to code interpolation, plotter distortion, etc., in a region of relatively large radial temperature variations.

As reported in the reference, the location of the boiling isotherm is relatively insensitive to the assumptions concerning $k(T)_{\text{rock}}$, at a given power level (see Figure 4). However, for the situation in which maximum heater temperature is the limiting parameter, the assumed thermal conductivity variation at boiling will influence indirectly the penetration distance through its effect on permissible heater operating power. Consider the following:

Suppose, for example, the upper limit for the heater surface is 550°C. From Figure 1, operating power levels are 1.65 kW ($k_{\text{rock}} = \text{VARIABLE}$) and 2.09 kW ($k_{\text{rock}} = \text{CONSTANT}$). In Figure 4, these power levels correspond to boiling isotherm locations of 18.3 and 22.3", a 20% variation caused by uncertainties in rock conductivity near boiling.

BMB:5511:ljg

Copy to:

4530 R. W. Lynch
4537 L. D. Tyler
4537 J. K. Johnstone
4537 D. R. Waymire
5500 O. E. Jones
5510 D. B. Hayes
5511 D. F. McVey
5520 T. B. Lane
5530 W. Herrmann
5531 L. D. Bertholf
5531 W. T. Brown

TABLE I

TUFF HEATER THERMAL ANALYSIS SUMMARY

	$T_{\text{boil}} = 100^{\circ}\text{C}$	
	<u>2E</u>	<u>2F</u>
Maximum Heater Surface Temperature @ Midplane, $^{\circ}\text{C}$	605	524
Maximum Rock Surface Temperature @ Midplane, $^{\circ}\text{C}$	479	316
Maximum Steel Temperature, $^{\circ}\text{C}$	57	57
Maximum Radial Penetration of Boiling Front Along Axis, inches (measured from centerline)	22 (21)*	21 (20)*
Maximum Axial Penetration of Boiling Front Along Axis, inches (measured from top of heater)	11	10

*Determined from radial temperature gradient; all others from computer contour plots (rounded to nearest inch).

Figure CII-1. Comparison of Maximum Computed Temperature on the Heater and Rock Surfaces for All Cases Over the Range of Heater Power Considered

Figure CII-2. Variation of Maximum Temperature in the Steel Plug with Power

Figure CII-3. Comparison of Radial Temperature Gradients for all Cases at 30 Days

Figure CII-4. Location of the Boiling Isotherm at Given Power Levels

Figure CIIA-2. Case 2E Radial, Midplane of Heater

Figure CIIA-4. Case 2E Axial, Top of Heater

Figure CIIA-8. Case 2E, 30 Days

Figure CIIA-10. Case 2F Radial, Midplane of Heater

Figure C11A-12. Case 2F Axial, Top of Heater

Figure C11A-16. Case 2F, 30 Days

Sandia Laboratories

Date March 19, 1979

To A. R. Lappin - 4537

From A. R. Lappin

From B. M. Bulmer - 5511

Tuff In-Situ Heater Experiment Rock Thermal Conductivity Sensitivity Study

Additional heat conduction (COYOTE) analyses have been performed at your request for several assumed rock thermal conductivity variations for the tuff heater experiment. This study stems from the uncertainty in initial (100% water saturated) rock thermal conductivity in G-tunnel, NTS,¹ and its impact on heater design requirements and experimental test objectives.

The present analysis was conducted with an intermediate heater power level of 1.9 kW and an assumed boiling temperature in the rock of 100°C. The heater geometrical configuration, material properties (with the exception of tuff thermal conductivity), and all calculational procedures are identical to those discussed in Reference 2. Individual cases considered presently are described below:

Case	Description
2G	$T_{\text{boil}} = 100^{\circ}\text{C}$ $\epsilon_{\text{rock}} = 0.6$ $k_{\text{rock}} = \text{VARIABLE} = \begin{cases} 1.7 \text{ W/m}^{\circ}\text{C}; & T \leq T_{\text{boil}} \\ 1.2 \text{ W/m}^{\circ}\text{C}; & T > T_{\text{boil}} \end{cases}$ $P = 1.25 \text{ kW}$
2H	Same as 2G except: $k_{\text{rock}} = \text{VARIABLE} = \begin{cases} 2.7 \text{ W/m}^{\circ}\text{C}; & T \leq T_{\text{boil}} \\ 1.2 \text{ W/m}^{\circ}\text{C}; & T > T_{\text{boil}} \end{cases}$
2I	Same as 2G except: $k_{\text{rock}} = \text{CONSTANT} = 1.7 \text{ W/m}^{\circ}\text{C}$
2J	Same as 2H except: $k_{\text{rock}} = \text{CONSTANT} = 2.7 \text{ W/m}^{\circ}\text{C}$

All cases assume a uniform initial temperature of 18°C. The latent heat of water is included in the rock heat capacitance near boiling (see Reference 2 for a complete description).

Note that in the previous analyses^{2,3} "variable" rock thermal conductivity refers to a discontinuous change at dry-out from 2.2 to 1.2 W/m°C at the assumed boiling temperature, whereas "constant" implies $k_{\text{rock}} = 2.2 \text{ W/m°C}$ everywhere. The present results thus bound (within a reasonable uncertainty) the anticipated total saturation value and provide a basis for comparison with previous results. Assumed variations in $k(T)_{\text{rock}}$ are summarized in Figure 1; included are Cases 2E and 2F for 1.9 kW reported in Reference 3.

Detailed plotted temperatures for Cases 2G-2J are contained in the Appendix. Locations of the plotted temperature histories are identical to those presented earlier, and, as before, all contour plots are expanded 2X in the radial dimension. Significant thermal results are summarized in Table I for Cases 2G-2J. These include maximum computed temperatures on the heater and rock (bore hole) surfaces at the heater midplane, maximum temperature in the steel plug, and maximum radial and axial penetration distances of the assumed boiling isotherm.

The rock thermal conductivities assumed herein permit a direct comparison with previous results (Cases 2E and 2F). In Figures 2 and 3, maximum computed temperatures on the heater and rock surfaces and in the steel plug are compared at 30 days (time of power shutoff) for $T_{\text{boil}} = 100^\circ\text{C}$ and $P = 1.9 \text{ kW}$. For the "variable" k_{rock} runs, the "reference" thermal conductivity used as the abscissa refers to the 100% saturated value assumed for $T \leq T_{\text{boil}}$ (see Figure 1).

Radial temperature gradients in the rock at 30 days are compared in Figure 4; results for Cases 2E and 2F near T_{boil} are included for comparison. As noted in Reference 3, locations of the boiling isotherm determined by these plots differ slightly ($\sim 1\text{--}2^\circ$) from those interpreted from the temperature contour plots using a variable scale. The boiling penetration distances derived from the radial gradients are considered to be more accurate.

The location of the boiling isotherm (Figure 5) is sensitive to the thermal conductivity chosen for saturated rock. However, the assumed variation at dry-out (i.e., "constant" versus "variable") has little effect for a given power level.

A. R. Lappin - 4537

-3-

Copy to:

4530 R. W. Lynch (w/o Appendix)
4537 L. D. Tyler (w/o Appendix)
4537 J. K. Johnstone
4537 D. R. Waymire
5500 O. E. Jones (w/o Appendix)
5510 D. B. Hayes (w/o Appendix)
5511 D. F. McVey (w/o Appendix)
5520 T. B. Lane (w/o Appendix)
5530 W. Herrmann (w/o Appendix)
5531 L. D. Bertholf (w/o Appendix)
5531 W. T. Brown

References

1. Memo, A. R. Lappin, 4537, to B. M. Bulmer, 5511, dtd 3/7/79, subject: Additional Thermal Modeling for Tuff Heater Experiment, Part II.
2. Memo, B. M. Bulmer, 5511, to A. R. Lappin, 4537, dtd 2/14/79, subject: Thermal Analysis of Tuff In-Situ Heater Experiment.
3. Memo, B. M. Bulmer, 5511, to A. R. Lappin, 4537, dtd 2/23/79, subject: Additional Thermal Analyses for Tuff Heater Experiment.

TABLE I

TUFF HEATER THERMAL ANALYSIS SUMMARY

	$T_{\text{boil}} = 100^{\circ}\text{C}$			
	<u>2G</u>	<u>2H</u>	<u>2I</u>	<u>2J</u>
Maximum Heater Surface Temperature @ Midplane, $^{\circ}\text{C}$	627	587	560	504
Maximum Rock Surface Temperature @ Midplane, $^{\circ}\text{C}$	515	448	397	265
Maximum Steel Temperature, $^{\circ}\text{C}$	63	53	63	53
Maximum Radial Penetration of Boiling Front @ Midplane, inches (measured from centerline)	27 (25)*	19 (18)*	26 (24)*	18 (17)*
Maximum Axial Penetration of Boiling Front Along Axis, inches (measured from top of heater)	14	8	13	8

*Determined from radial temperature gradient; all others from computer contour plots (rounded to nearest inch).

Figure CIII-1. Summary of Variations in $k(T)_{\text{rock}}$

Figure CIII-2. A Comparison of Maximum Computed Temperatures on the Heater and Rock Surfaces at 30 Days

Figure CIII-3. A Comparison of Maximum Computed Temperatures on the Steel Plug and the Rock Surfaces at 30 Days

Figure CIII-4. A Comparison of Radial Temperature Gradients for all Rock at 30 Days

$T_{\text{BOIL}} = 100^{\circ}\text{C}$
 MIDPLANE OF HEATER
 $P = 1.9 \text{ kW}$

Figure CIII-5. Sensitivity of the Location of the
 Boiling Isotherm to the Thermal
 Conductivity of Saturated Rock

APPENDIX

Notes:

- (1) See Test of CI for plot locations of temperature histories.
- (2) Contour plots are expanded 2X radial; see Reference 2 for details.

Figure CIIIA-2. Case 2G Radial, Midplane of Heater

Figure CIIIA-4. Case 2G Axial, Top of Heater

Figure CIIIA-8. Case 2G, 30 Days

Figure CIIIA-10. Case 2H Radial, Midplane of Heater

Figure CIIIA-12. Case 2H Axial, Top of Heater

Figure CIIIA-16. Case 2H, 30 Days

Figure CIIIA-18. Case 2I Radial, Midplane of Heater

Figure CIIIA-20. Case 2I Axial, Top of Heater

Figure CIIIA-24. Case 21, 30 Days

Figure CIIIA-26. Case 2J Radial, Midplane of Heater

Figure CIIIA-28. Case 2J Axial, Top of Heater

Figure CIIIA-32. Case 2J, 30 Days

Sandia Laboratories

Albuquerque, New Mexico
Livermore, California

date: JUN 04 1973

to: J. K. Johnstone - 4537

from:
W. T. Brown - 5531

subject: Thermomechanical Analysis of Tuff In-Situ Heater Experiment

The first phase of the thermomechanical analysis of the Tuff In-Situ Heater experiment has been completed. The major objectives of this modeling effort were:

1. To determine optimum locations for stress and displacement instrumentation.
2. To determine the extent to which the presence of the access tunnel and alcove perturbs the in-situ stresses in the experimental region.
3. To determine the perturbation of in-situ stresses in the vicinity of the heater due to the presence of the heater hole and the instrumentation holes.

Only Item 1 is treated in this memo; the other two items will be covered in a later memo.

Several two-dimensional, finite-element calculations were done with MARC to model the response of welded tuff to a heat source. The models represent the best attainable approximations to the situation expected to exist in the planned heater experiment in welded tuff at the Nevada Test Site. The details of the heater configuration are discussed in Reference 1, and the assembly has been represented schematically in Reference 2. That schematic representation has been reproduced in Figure 1 with the basic features of the assembly identified. In the modeling of the mechanical response, the air gap and air void were included in the calculation. The regions containing crushed tuff and the steel plug were not treated in any detail. Their properties were assumed to be identical to those of the welded tuff. This is adequate because the response in those regions will not be important.

The modeling of the mechanical response was done in a manner that is consistent with the thermal response calculations for the same configuration (Reference 2). Those calculations treated a heater operating at a constant power level for 30 days followed by a cool-down period of 30 days. A total of eleven different cases were considered in modeling the thermal behavior. These different cases allowed for variations in power levels, assumed boiling temperatures for in-situ water, variations in rock thermal conductivity (K) and variations in emissivity (ϵ) of the rock. Of these cases,

only two were considered in the mechanical response calculations. The cases, as identified in Table I of Reference 2, were:

Case 1D $T_{\text{boil}} = 235^{\circ}\text{C}$
 $\epsilon_{\text{rock}} = 0.6$
 $K_{\text{rock}} = \text{CONSTANT}$
 $P = 2.5 \text{ kW}$

Case 2A $T_{\text{boil}} = 100^{\circ}\text{C}$
 $\epsilon_{\text{rock}} = 0.6$
 $K_{\text{rock}} = \text{VARIABLE}$
 $P = 1.25 \text{ kW}$

These two calculations considered the two extremes of heater power levels and boiling temperatures that were treated in the thermal calculations. The temperature fields calculated from the thermal modeling were used as input, as a function of time, for the mechanical response calculations.

The planned heater experiment will include two separate sets of instrumentation for measuring stresses and displacements. A hole will be drilled parallel to the heater centerline to allow for stress measurements. The stress gauge, as currently planned, will be situated to obtain the radial stress component and a stress component normal to this. The gauge will be approximately in the heater midplane; the distance of the gauge from the centerline is a parameter to be determined from these calculations. The displacements will be measured with a laser interferometer by placing a mirror in-situ to obtain radial displacements of the rock in a coordinate system which has cylindrical symmetry about the centerline of the heater.

The finite-element mesh used for these calculations is shown in Figure 2. It is identical with the mesh used in the modeling of the thermal response. The boundary conditions are all taken as zero displacement. The experiment will take place at a depth of about 400 meters. The zero displacement conditions on the other boundaries simulate the confining effects of the surrounding rock mass. The actual in-situ stresses due to an overburden and a gravity load on the material in the calculation region were not applied as boundary conditions or body forces. The response of the tuff is purely elastic, and, thus, the only deviations from in-situ stresses are due to thermoelastic effects. The ambient, in-situ stresses will be used as a baseline for the stress gauge; thus, it is adequate to ignore the stresses due to overburdens and body forces.

The properties used for the tuff were values that are appropriate to the depth of the experiment. They were generated at a confining pressure of about 20 MPa. The values used were:

Young's Modulus ³	31.0 GPa
Poisson's Ratio ³	0.25
Thermal Expansion ⁴ Coefficient	$1.2 \times 10^{-5}/^{\circ}\text{C}$
Density ⁴	2360 Kg/m ³

Because of the requirements of the experiment, the important results to be obtained from the calculations are radial stresses, circumferential stresses and radial displacements. The results are presented in two forms. Each of the above quantities are plotted at several radial locations, near the heater midplane, as a function of time. In addition, contours of constant stress have been generated at several selected times during the heating interval of 30 days. The histories of the radial stresses are shown in Figures 3 through 11 for both of the cases considered. Figures 12 through 21 show similar histories for circumferential stresses and the radial displacements are presented in Figures 22 through 29. The jumps that occur in the plots of the various histories are due to the fact that the time axis is not uniform. In addition, the calculation which uses a variable thermal conductivity (Case 2A) shows finite temperature jumps (see Reference 2). The contours are shown at selected times in Figures 30 to 47. When the stresses and displacements are examined, the calculated results are well within measurable ranges within a distance of about 1 meter from the heater centerline. For the cases with the higher power level (Case 1D), the stresses and displacements are measurable beyond 1 meter. The other restriction placed upon instrumentation locations is the temperature field. The gauges should be far enough from the heater to insure that temperatures do not exceed operating temperatures.

Calculations were considered which treated the boundary conditions of the problem with stresses that are more appropriate to the depth of the experiment.⁵ These results are not reported because they show net change in stresses and displacements from their initial values that are the same as reported here. But by assuming the initial values to be zero, it is much easier to determine changes due to thermoelastic effects.

The absolute magnitudes of stresses existing in the medium are important for treating the problem of the balance between pore pressure and in-situ stress. A knowledge of in-situ stress distributions is required to treat this problem. Some aspects of this will be treated in a later memo.

References

1. Memo, A. R. Lappin, 4537, to B. M. Bulmer, 5511, dtd 12/1/78, subject: COYOTE Thermal Modeling of Tuff Heater Experiment.
2. Memo, B. M. Bulmer, 5511, to A. R. Lappin, 4537, dtd 2/14/79, subject: Thermal Analysis of Tuff In-Situ Heater Experiment.
3. Private Communication, W. A. Olsson, 5532, to W. T. Brown, 5531, dtd 3/7/79.
4. Private Communication, A. R. Lappin, 4537, to W. T. Brown, 5531.
5. Memo, A. R. Lappin, 4537, to W. T. Brown, 5531, dtd 3/7/79, subject: Mechanical Modeling of Tuff Heater Experiment.

WTB:5531:ss

Copy to:

4530 R. W. Lynch (w/o Appendix)
4537 L. D. Tyler (w/o Appendix)
4537 A. R. Lappin
4537 D. R. Waymire
5500 O. E. Jones (w/o Appendix)
5510 D. B. Hayes (w/o Appendix)
5511 D. F. McVey (w/o Appendix)
5511 B. M. Bulmer
5520 T. B. Lane (w/o Appendix)
5530 W. Herrmann (w/o Appendix)
5531 L. D. Bertholf (w/o Appendix)

Figure DI-1. Schematic Representation of Heater Assembly

Figure DI-2. MARC Finite-Element Mesh

Figure DI-3. NTS Heater Simulation Case 1D

Figure DI-4. NTS Heater Simulation Case 1D

Figure D1-5. NTS Heater Simulation Case 1D

Figure D1-6. NTS Heater Simulation Case 1D

Figure DI-7. NTS Heater Simulation Case 2A

Figure DI-8. NTS Heater Simulation Case 2A

Figure DI-9. NTS Heater Simulation Case 2A

Figure DI-10. NTS Heater Simulation Case 2A

Figure DI-11. NTS Heater Simulation Case 2A

Figure DI-12. NTS Heater Simulation Case 1D

Figure DI-13. NTS Heater Simulation Case 1D

Figure DI-14. NTS Heater Simulation Case 1D

Figure D1-15. NTS Heater Simulation Case 1D

Figure D1-16. NTS Heater Simulation Case 1D

Figure DI-17. NTS Heater Simulation Case 2A

Figure DI-18. NTS Heater Simulation Case 2A

Figure DI-19. NTS Heater Simulation Case 2A

Figure DI-20. NTS Heater Simulation Case 2A

Figure DI-21. NTS Heater Simulation Case 2A

Figure DI-22. NTS Heater Simulation Case 1D

Figure DI-23. NTS Heater Simulation Case 1D

Figure DI-24. NTS Heater Simulation Case 1D

Figure DI-25. NTS Heater Simulation Case 1D

Figure DI-26. NTS Heater Simulation Case 2A

Figure DI-27. NTS Heater Simulation Case 2A

Figure DI-28. NTS Heater Simulation Case 2A

Figure DI-29. NTS Heater Simulation Case 2A

Figure DI-30. NTS Heater Simulation Case 1D

Figure DI-31. NTS Heater Simulation Case 1D

Figure DI-32. NTS Heater Simulation Case 1D

Figure DI-33. NTS Heater Simulation Case 2A

Figure DI-34. NTS Heater Simulation Case 2A

Figure DI-35. NTS Heater Simulation Case 2A

Figure DI-36. NTS Heater Simulation Case 1D

Figure DI-37. NTS Heater Simulation Case 1D

Figure DI-38. NTS Heater Simulation Case 1D

Figure DI-39. NTS Heater Simulation Case 2A

Figure DI-40. NTS Heater Simulation Case 2A

Figure DI-41. NTS Heater Simulation Case 2A

Figure DI-42. NTS Heater Simulation Case 1D

Figure DI-43. NTS Heater Simulation Case 1D

Figure DI-44. NTS Heater Simulation Case 1D

Figure DI-45. NTS Heater Simulation Case 2A

Figure DI-46. NTS Heater Simulation Case 2A

Figure DI-47. NTS Heater Simulation Case 2A

Sandia Laboratories

Albuquerque, New Mexico
Livermore, California

date: August 28, 1979

to: J. K. Johnstone - 4537

from: W. T. Brown - 5531

subject: Additional Thermomechanical Modeling of the Tuff In-situ Heater Experiment

Two additional calculations have been run to model the planned heater experiment in welded tuff at the Nevada Test Site. Results from earlier calculations (Reference 1) showed that for power levels of 1.25 kW and 2.5 kW the circumferential stresses near the heater hole would exceed the strength of the welded tuff. Those calculations were done primarily to determine locations for placement of stress and displacement instrumentation; however the calculated circumferential stresses are of concern because they indicate possible failure of the tuff which could prevent removal of the heater.

These current calculations were done in two-dimensional, axisymmetric geometry with the finite-element code MARC. The model is identical with that used for the previous calculations and is discussed in more detail in Reference 1. The elastic properties used in the first set of calculations were obtained at a confining stress of about 20 MPa (Reference 3); however, since the major concern in these calculations is failure near the surface of the heater hole, the unconfined strength of 137.7 MPa (Reference 3) is used.

As with previous calculations, the results of the thermal modeling were supplied by Bruce Bulmer, 5623. The earlier calculations considered extremes of heater power levels as well as different thermal properties for the medium. Because results of both of those calculations indicated stresses that would exceed the unconfined strength, the current calculations considered lower power levels. Table 1, below, compares the properties used in the earlier calculations (cases 1D and 2A) with those used in the latest calculations (cases 2K and 2L).

TABLE 1. Thermal Properties of Tuff and Heater Power Levels.

Case #	Water Boiling Point, °C	Rock Emissivity	Thermal Conductivity	Heater Power, kW
1D	235	0.6	CONSTANT	2.5
2A	100	0.6	VARIABLE	1.25
2K	100	0.6	VARIABLE	1.0
2L	100	0.6	VARIABLE	0.5

Results of these calculations are presented in Figures 1 through 7. Figures 1 and 2 show the variation, near the surface of the heater hole, of the circumferential stress as a function of time for cases 2K and 2L, respectively. Note that in each case the peak value of this component of stress does not exceed the ultimate strength. These locations are taken in the midplane of the heater.

In Figures 3 and 4, the radial component of stress is shown as a function of time at the same location for both case 2K and 2L. Discrete jumps can be seen in the plots in these four figures. As in the earlier calculations, this behavior is due in part to the fact that the time axis is not uniform and in addition, there are discrete jumps in temperature caused by the variable thermal conductivity. This latter effect occurs only for case 2K; in the results of case 2L the temperature rise is not high enough for the variable conductivity to influence the results.

The remaining figures show the spatial behavior of the radial and circumferential stress components and the displacement at 30 days. These values are also in the mid plane of the heater. In each case, the stresses are below the strength of 137.7 MPa and thus no failure should occur. Note that the circumferential (hoop) stress falls off very rapidly with distance from the surface of the hole. It is also clear that the peak value of the radial stress does not occur at the surface of the hole, but after the occurrence of the peak this component also decays rapidly. Unlike the earlier calculations, the initial stresses due to overburden and gravity loads have been included in these present results.

It was concluded from the initial calculations (Reference 1) that the stresses and displacements could be measured within 1 meter of the heater centerline. However, these results show that the magnitudes of stresses and displacements are less than those that were initially calculated. Nevertheless, in each case, the stresses should still be measurable at 1 meter. In the worst case (2L) the radial stress increases by about 5 MPa above the initial in-situ value and this should be within the resolution of the stress instrumentation. The displacements calculated for the 1 kW power level (case 2K) should be measurable by the displacement interferometer, but the displacements calculated for the 0.5 kW power level (case 2L) may be marginal near a radius of 1 meter.

When all of the information is considered, the use of a 1 kW heater should eliminate the concerns regarding failure of the welded tuff and should require no changes in the planned locations for instrumentation.

References

1. Memo, W. T. Brown, 5531, to J. K. Johnstone, 4537, dtd 6/4/79,
Subject: Thermomechanical Analysis of Tuff In-Situ Heater
Experiment
2. Private Communication, W. A. Olsson, 5532, to W. T. Brown, 5531,
dtd 3/7/79
3. Memo, W. A. Olsson, 5532, to J. K. Johnstone, 4537, dtd 8/2/79,
Subject: Mechanical Properties of Tuff from Nevada Test Site

WTB:5531:gs

Copy to:

4530 R. W. Lynch
4537 L. D. Tyler
4537 A. R. Lappin
4537 D. R. Waymire
5500 O. E. Jones
5510 D. B. Hayes
5511 D. F. McVey
5520 T. B. Lane
5530 W. Herrmann
5531 L. D. Bertholf
5532 B. M. Butcher
5532 W. A. Olsson
5623 B. M. Bulmer

Figure DII-1. NTS Heater Simulation Case 2K

Figure DII-2. NTS Heater Simulation Case 2L

Figure DII-3. NTS Heater Simulation Case 2K

Figure DII-4. NTS Heater Simulation Case 2L

Heater Midplane/T = 30 Days

Figure DII-5. Spatial Dependence of Circumferential Stress, with Expanded Scale (Bottom)

Figure DII-6. Spatial Dependence of Radial Stress
With Expanded Scale (Bottom)

Figure DII-7. Spatial Dependence of Radial Displacement with Expanded Scale (Bottom)

Sandia Laboratories

Albuquerque, New Mexico
Livermore, California

date: February 21, 1980

to: J. K. Johnstone - 4537

William T. Brown

from: W. T. Brown - 5531

subject: In Situ Stresses Near G-Tunnel Heater and Instrumentation Holes - Revision

This memo reports the results of calculations that were done to estimate stress distributions in the vicinity of the heater hole and instrumentation holes in the G-tunnel water migration experiment. Because this experiment will measure water migration which can be driven, in part, by stress gradients, it is important to determine the extent to which the stresses encountered in the experimental situation will approximate the actual at depth stress distribution.

Figure 1 represents a map view of the geometry near the instrumentation alcove in the experimental area of G-tunnel. The heater will be inserted into a hole which is drilled into a wall of the alcove at an angle of 20° above horizontal at approximately 3 meters above the floor. The hole has a length of about 20 meters and the heater is approximately 1.2 meters long. Figure 2 is a schematic representation of a cross section of the tunnel containing the heater. In addition to the heater hole there are various instrumentation holes parallel to the axis of the heater. Previous calculations have been reported in which the changes in stress due to thermal effects were determined [1,2]. The purpose of the current calculations is to estimate changes in in situ stresses due to the presence of the various openings.

The calculations have been divided into two distinct parts. In the first set of calculations the presence of the heater hole and of the instrumentation holes is neglected. These calculations are done with a closed-form solution which approximates the actual situation. A second set of finite-element calculations has been done to approximate the stress distribution in the vicinity of the heater hole due to the influence of instrumentation holes. Both of these are discussed below.

Stress Distributions Near Tunnel

To approximate the stress distributions in the vicinity of the tunnel opening, solutions have been obtained for the cross section shown in Figure 2. The method used for these calculations is based on a solution technique developed by Greenspan [3] for obtaining an exact solution for stresses in the vicinity of an opening whose boundary approximates the shape of the actual structure.

The basic techniques used in these calculations come from the mathematical theory of elasticity and were developed for problems other than those

associated with stresses in rocks, but are widely used for such problems [4]. The rock near a tunnel is assumed to be in a homogeneous stress field which is a combination of vertical and horizontal stresses but no gravity field. The tunnel cross section is assumed to have a shape which can be represented in the parametric form

$$\begin{aligned}x &= p \cos \beta + r \cos 3\beta \\y &= q \sin \beta - r \sin 3\beta.\end{aligned}\quad (1)$$

Additionally, the structure is also to be in a state of generalized plane stress with stresses at large distances from the boundary given by the constant normal components $\sigma_x = S_x$, $\sigma_y = S_y$ and shear component $\tau_{xy} = T_{xy}$.

By a proper choice of the parameters p , q and r in Eq. (1), an ovaloid which is a good approximation to the tunnel cross section can be obtained. By using a Cartesian coordinate system, in which the x -axis is parallel to the horizontal direction and the angle β is measured counterclockwise from the x -axis, the tunnel width is $2(p + r)$ and the tunnel height is given by $2(q + r)$. The value for r is obtained from the radius of curvature between the wall and ceiling. The particular values obtained for the cross section in Figure 2 are

$$\begin{aligned}p &= 6.546 \\q &= 2.431 \\r &= -.601\end{aligned}$$

The ovaloid defined by these values is shown in Figure 3 and it compares favorably with the actual cross section.

The method used to obtain stress values is fairly elaborate and is not given here in detail. The essential features of the solution are outlined; details can be found in the paper by Greenspan [3].

Two sets of curves are defined by

$$\begin{aligned}f_1(x,y) &= \alpha, \\f_2(x,y) &= \beta,\end{aligned}\quad (2)$$

and then a pair of values (α, β) defines curvilinear coordinates in the x,y plane which are intersections of these curves. A conformal transformation maps the boundary of the opening into the α, β plane and derivatives of a stress function with respect to α and β are used to calculate the stresses σ_α , σ_β and $\tau_{\alpha\beta}$. These stresses turn out to be rather complicated functions of α and β and of the parameters (p, q, r) describing the opening, but they do not depend on the material parameters. This plane stress solution corresponds to a thin plate with an opening, but the tunnel requires a

plane strain solution in which the displacements parallel to the tunnel axis are zero. The corresponding out-of-plane stress can be obtained from $\sigma_z = \nu(\sigma_\alpha + \sigma_\beta)$, where ν is Poisson's ratio. This out-of-plane stress is not given here but can be calculated easily.

Stress components σ_α , σ_β and $\tau_{\alpha\beta}$ have been calculated for a region which extends about 60 meters vertically and horizontally from the boundary of the tunnel. Two different calculations have been done in which the vertical stress was fixed at

$$S_y = 8.274 \text{ MPa}$$

and the horizontal stress was taken to be

$$S_x = 6.067 \text{ MPa and } S_x = 2.955 \text{ MPa .}$$

These values are meant to represent measured in situ stresses [5]. The variation of stress depends only on the tunnel shape and the ratio of vertical to horizontal initial stresses.

For display purposes, it is more useful to have stresses defined in the x,y coordinate system. This can be done with the transformation

$$\sigma'_{ij} = \sigma_{\mu\nu} \frac{\partial x_\mu}{\partial x'_i} \frac{\partial x_\nu}{\partial x'_j} \quad (3)$$

where $(i,j,\mu,\nu) = 1,2$. The σ' terms are values in the x,y system; for example, $\sigma'_{11} = \sigma_x$, etc. In the α,β system $\sigma'_{11} = \sigma_\alpha$ and the x's have similar interpretations, i.e., $x_1 = \alpha$, $x'_1 = x$. The repeated indices, of course, indicate summation. The Cartesian coordinates (x,y) are defined in terms of (α,β) according to

$$\begin{aligned} x &= (e^\alpha + ab e^{-\alpha}) \cos \beta + ac^3 e^{-3\alpha} \cos 3\beta \\ y &= (e^\alpha - ab e^{-\alpha}) \sin \beta - ac^3 e^{-3\alpha} \sin 3\beta \end{aligned} \quad (4)$$

where a, b, and c are constants depending only on p, q, and r.

Contours of vertical (σ_y) and horizontal stress (σ_x) are displayed in Figures 4, 5, 6, and 7 for the two different values of the horizontal stress. It is clear that in a distance of about two tunnel widths the stress are approximately equal to their applied values. Thus, at the location of the heater, perturbations due to the tunnel are negligible. However, this does not account for stress variations due to the presence of the instrumentation holes. This is addressed below.

There is a small region of tension, for each of these cases, near the corners. This is not shown on the plots.

February 21, 1980

The methods used for these calculations are useful because it requires very little time after the initial programming of the equations. It saves, for example, the time required to generate a new finite element mesh for each calculation. The usefulness is, of course, limited to fairly simple elastic problems in which the structure can be approximated by the simple curves represented by Eq. (1).

Stress Distributions Near Heater and Instrumentation Holes

Figure 8 shows a cross section of a plane which is normal to the axis of the heater, where the heater has the orientation shown in Figure 2. There are various instrumentation holes parallel to the heater axis, with an interferometer hole placed normal to this direction. The major concern is the perturbation in stress at the position of a given hole due to the presence of other holes.

This problem is not reducible to a closed-form solution similar to the one just discussed. Therefore, a finite-element model has been developed to treat this problem in an approximate fashion. In Figure 9, a schematic representation of a finite-element computing region is shown in which only the heater hole and two of the holes at the smallest radius are considered. An elastic solution was done to calculate stress distributions in this plane, but thermal effects were ignored.

The material parameters used were the same as those used in Reference 1. However, the stress variation turns out to be similar to the preceding problem in that these values depend on the shapes and very little on the material parameters. This is only approximately true because of the nature of the boundary conditions. Contours of vertical and horizontal stress are shown for this problem in Figures 10-13 in the same fashion as for the previous problem. There is little stress interaction between adjacent holes in either vertical or horizontal directions. The stresses used as boundary conditions are not the actual values that act on the cross section shown in Figure 8, but the relative magnitudes are approximately correct.

These problems have ignored the presence of a temperature field but this presents no major difficulty. At locations distant from the holes the thermal stress add to the purely elastic terms. Since the original thermal stress calculated [1,2] did not include the presence of instrumentation holes, the stresses are not correct at those locations. However, the perturbations are fairly small because of the hole sizes.

References

1. Memo, W. T. Brown, 5531, to J. K. Johnstone, 4537, dtd 6/4/79, subject: Thermomechanical Analysis of Tuff In-Situ Heater Experiment.
2. Memo, W. T. Brown, 5531, to J. K. Johnstone, 4537, dtd 8/28/79, subject: Additional Thermomechanical Modeling of the Tuff In-Situ Heater Experiment.

February 21, 1980

3. Greenspan, Martin, "Effect of a Small Hole on the Stresses in a Uniformly Loaded Plate," Quarterly Appl. Math., 2, pp. 60-71 (1974).
4. Terzaghi, Karl and Richart, F. E., "Stresses in Rock Cavities," Geotechnique--The International Journal of Soil Mechanics, III. No. 2, pp. 57-90 (1952).
5. J. K. Johnstone, personal communication.

WTB:5531:ls

Distribution:

4530 R. W. Lynch
4537 L. D. Tyler
4537 A. R. Lappin
4537 D. R. Waymire
5500 O. E. Jones
5510 D. B. Hayes
5511 D. F. McVey
5520 T. B. Lane
5530 W. Herrmann
5531 L. D. Bertholf
5532 B. M. Butcher
5532 W. A. Olsson
5533 A. J. Chabai
5534 J. R. Assay
5531 W. T. Brown

Figure DIII-1. Map View of G-Tunnel Test Area (Not to Scale)

Not to Scale

Figure DIII-2. Schematic Representation of Tunnel Cross Section Near Heater Location Parameters Used Represent Dimension at Widest Location (Tunnel + Alcove)

Figure DIII-3. Ovaloid Approximating Tunnel Cross Section, Shape is Symmetry about x-axis and y-axis

Figure DIII-4. Vertical Stress Contours Near Tunnel. Stress Distribution is Symmetric about x-axis and y-axis. $S_x = 6.067$ MPa, $S_y = 8.274$ MPa

Figure DIII-5. Horizontal Stress Contours Near Tunnel. Stress Distribution is Symmetric about x-axis and y-axis. $S_x = 6.067$ MPa, $S_y = 8.274$ MPa

Figure DIII-6. Vertical Stress Contours Near Tunnel. Stress Distribution is Symmetric about x-axis and y-axis. $S_x = 2.955$ MPa, $S_y = 8.274$ MPa

Figure DIII-7. Horizontal Stress Contours Near Tunnel. Stress Distribution is Symmetric about x-axis and y-axis. $S_x = 2.955$ MPa, $S_y = 8.274$ MPa

Figure DIII-8. Conceptual Experimental Array for Tuff Water Migration/Heater Experiment

Figure DIII-9. Finite-Element Mesh for Representation of Heater and Instrumentation Holes

Figure DIII-10. Vertical Stress Near Holes.
 $S_y = 8.274$ MPa, $S_x = 6.067$ MPa

Figure DIII-11. Horizontal Stress Near Holes. $S_y = 8.274$ MPa, $S_x = 6.067$ MPa.

Figure DIII-12. Horizontal Stress Near Holes. $S_y = 8.274$ MPa, $S_x = 2.964$ MPa.

Figure DIII-13. Vertical Stress Near Holes.
 $S_y = 8.274 \text{ MPa}$, $S_x = 2.964 \text{ MPa}$

DISTRIBUTION:

US Department of Energy
Asst Secretary for Def. Programs
Mail Stop SF-066
Washington, DC 20545
Attn: D. C. Sewell (DP-1)

US Department of Energy
Asst Sec. for Nuclear Energy
Mail Stop 6E-095
Washington, DC 20545
Attn: G. W. Cunningham (NE-1)

US Department of Energy (7)
Office of Nucl Waste Management
Mail Stop B-107
Washington, DC 20545
Attn: S. Meyers, NE-30
R. G. Romatowski, NE-30
C. A. Heath, NE-30
D. L. Vieth, NE-30
R. Stein, OW, NE-30
C. R. Cooley, NE-30
M. W. Frei, NE-30

US Department of Energy (2)
Richland Operations Office
PO Box 550
Richland, WA 99352
Attn: F. Standerfer
D. J. Squires

US Department of Energy
Albuquerque Operations Office
PO Box 5400
Albuquerque, NM 87185
Attn: D. T. Schueler, Jr.

US Department of Energy
San Francisco Operations Office
1333 Broadway, Wells Fargo Bldg
Oakland, CA 94612
Attn: L. Lanni

Rockwell International (2)
Atomics International Division
Rockwell Hanford Operations
Richland, WA 99352
Attn: R. Deju
B. Dietz

US Department of Energy (24)
Nevada Operations Office
PO Box 14100
Las Vegas, NV 89114
Attn: M. E. Gates
R. W. Taft
R. W. Newman
J. B. Cotter
M. P. Kunich
H. L. Melancon
A. J. Roberts
R. M. Nelson
D. G. Jackson
P. J. Mudra
R. H. Marks, CP-1
S. R. Elliott
B. W. Church
T. H. Blankenship
R. R. Loux (10)

US Department of Energy (3)
NTS Support Office
PO Box 435
Mercury, NV 89023
Attn: J. H. Dryden
F. Huckabee
L. P. Skousen

DOE Region 9
Director of External Affairs
111 Pine Street, 3rd Floor
San Francisco, CA 94111
Attn: D. J. Cook

US Department of Energy
Columbus Program
Richland Operations Office
505 King Avenue
Columbus, OH 43201
Attn: J. O. Neff

Nuclear Regulatory Commission (2)
Washington, DC 20555
Attn: J. C. Malaro, M/S SS674
R. Boyle, M/S P-522

Holmes & Narver, Inc.
PO Box 14340
Las Vegas, NV 89114
Attn: A. E. Gurrola

DISTRIBUTION (cont):

University of California
Lawrence Livermore National Laboratory (7)
PO Box 808

Livermore, CA 94550
Attn: L. D. Ramsdott, L-204
A. Holzer, L-209
L. B. Ballou, L-204
J. S. Kahn, L-49
K. Street, L-209
R. C. Carlson, L-204
A. B. Miller, L-204

Los Alamos National Scientific Laboratory (6)
PO Box 1663

Los Alamos, NM 87545
Attn: K. Wolfsberg (2)
L. S. Germain, M/S 570
L. Lanham, M/S 755
B. M. Crowe, M/S 978
J. R. Smyth, M/S 978

Westinghouse (7)
PO Box 708
Mercury, NV 89023
Attn: D. C. Durrill

Westinghouse - AESD (1)
PO Box 10864
Pittsburgh, PA 15236
Attn: J. B. Wright (6)
W. R. Morris
T. E. Cross
R. J. Bahorich
C. R. Bolmgren
W. A. Henninger

University of Arizona
Nuclear Fuel Cycle Research
Tucson, AZ 85721
Attn: J. G. McCray

US Geologic Survey (3)
National Center
Reston, VA 22092
Attn: G. D. DeBucharanne, M/S 410
P. R. Stevens, M/S 410
D. B. Stewart, M/S 959

US Geologic Survey (2)
PO Box 25046
Federal Center
Denver, CO 80225
Attn: G. L. Dixon, M/S 954
W. S. Twenhofel, M/S 954

Geologic Society of America
3300 Penrose Place
Boulder, CO 80302
Attn: J. C. Frye

University of Kansas
Kansas Geological Survey
Lawrence, KS 66044
Attn: W. W. Hanblaton

Battelle Memorial Institute (10)
Office of Nucl Waste Isolation
505 King Avenue
Columbus, OH 43201
Attn: N. E. Carter
S. Basham
J. Carr
ONWI Library (5)
R. A. Robinson
W. Carbiener

State of Nevada
Governor's Office of Planning
Coordination
Capitol Complex
Carson City, NV 89710
Attn: R. Hill, State
Planning Coordinator

Fenix & Scisson, Inc.
PO Box 498
Mercury, NV 89203
Attn: F. D. Waltman

State of Nevada
Capitol Complex
Carson City, NV 89710
Attn: N. Clark
Dept of Energy

Woodward-Clyde Consultants
Western Region Library
No. 3 Embarcadero Center
San Francisco, CA 94111

DISTRIBUTION (cont):

Computer Sciences Corp.
6565 Arlington Blvd
Falls Church, VA 22046
Attn: J. Lahoud

John A. Blume Engineers
Sheraton Palace Hotel
1340 Jessie Street
San Francisco, CA 94105
Attn: P. Yanev

Harvard University (2)
Dept of Earth Sciences
Cambridge, MA 02138
Attn: R. Siever

Dartmouth College
Dept of Earth Sciences
Hanover, NH 03755
Attn: J. Lyons

Internatl Atomic Energy Agency
Div of Nucl Power & Reactors
Karntner Ring 11
PO Box 590, A-1011
Vienna, Austria
Attn: J. P. Colton

Fenix & Scisson, Inc.
PO Box 15408
Las Vegas, NV 89114
Attn: G. Pinder

California Energy Resources
Conservation & Devel Ccm
1111 Howe Avenue
Sacramento, CA 95825
Attn: A. Soinski

University of California
Lawrence Berkeley Laboratory
Energy & Environment Division
Berkeley, CA 94720
Attn: P. Witherspoon

Hanford Eng Development Lab
PO Box 1970
Richland, WA 99352
Attn: D. Cantley

Arthur D. Little, Inc.
Acorn Park
Cambridge, MA 02140
Attn: C. R. Hadlock

Brown University
Dept of Geological Sciences
Providence, RI 02912
Attn: B. Giletti

Texas A&M University
Center for Tectonophysics
College Station, TX 77840
Attn: J. Handin

Law Engineering Testing Co
2749 Delk Road, SE
Marietta, GA 30067
Attn: B. Woodward

Holmes & Narver, Inc.
PO Box 1
Mercury, NV 89023
Attn: G. E. Christensen

Subcommittee on Energy
Research & Production
Room B-374
Rayburn House Office Bldg
Washington, DC 20575
Attn: S. Lanes, Staff Dir.

Dept of Health and Environment
Bureau of Radiation Control
Forbes Field
Topeka, KS 66620
Attn: G. W. Allen, Director

State of Connecticut
Energy Research and Policy
80 Washington Street
Hartford, CT 06115
Attn: F. N. Brennehan

Executive Office
Lansing, MI 48909
Attn: W. C. Taylor
Science Advisor

Dir for Policy and Planning
325 West Adams St - Room 300
Springfield, IL 62706
Attn: A. Liberatore

DISTRIBUTION (cont):

Nuclear Energy Division
Nucl Projects Coordinator
PO Box 14690
Baton Rouge, LA 70808
Attn: L. H. Bohlinger

Oregon Dept of Energy
Labor & Industries Bldg
Room 111
Salem, OR 97310
Attn: D. W. Godard

Radiation Protection Div
1000 Northeast 10th Street
PO Box 53551
Oklahoma City, OK 73152
Attn: R. L. Craig, Dir

Reynolds Elect & Eng Co., Inc. (6)
PO Box 14400
Las Vegas, NV 89114
Attn: H. D. Cunningham
W. G. Flangas
C. W. Adair
V. M. Milligan
C. W. Dunnam
E. J. Beecher

Radiation Health Info Project
Environmental Policy Inst
317 Pennsylvania Ave, SE
Washington, DC 20003
Attn: E. Walters

State of South Carolina
Div of Energy Resources
Edgar A. Brown Bldg
1205 Pendleton Street
Columbia, SC 29201
Attn: L. E. Priester, Jr.

Federal Agency Relations
1050 17th St, NW
Washington, DC 20036
Attn: O. H. Davis, Dir

Environmental Program Supvr
903 Ninth Street Office Bldg
Richmond, VA 23219
Attn: K. J. Buttleman

Energy Administration
Dept of Natural Resources
Tawes State Office Bldg
Annapolis, MD 21401
Attn: P. Massicot, Actg Dir

State of Ohio Environmental
Protection Agency
361 E. Broad St - Box 1049
Columbus, OH 43216
Attn: J. F. McAvoy, Dir

State of Connecticut
House of Representatives
One Hundred and Sixth District
24 Rock Ridge Road
Newtown, CT 06470
Attn: J. W. Anderson

Missouri Dept of Natural Resources
PO Box 176
Jefferson City, MO 65102
Attn: T. D. Davis

Mississippi Dept of Natural Resources
Suite 228, Barefield Complex
455 North Lamar Street
Jackson, MS 39201
Attn: P. T. Bankston

Tennessee Energy Authority
Suite 708 Capitol Blvd Bldg
Nashville, TN 37219
Attn: J. A. Thomas, Assoc Dir

Council Member
374 South Rock River Drive
Berea, OH 44017
Attn: G. A. Brown

Public Law Utilities Group
One American Pl, Suite 1601
Baton Rouge, LA 70825
Attn: D. Falkenheier, Asst Dir

Energy Facility Site Eval Council
820 East Fifth Ave
Olympia, WA 98504
Attn: N. D. Lewis

DISTRIBUTION (cont):

University of Texas at Austin
University Station, Box X
Austin, TX 78712
Attn: E. G. Wermund

Dept for Human Resources
Commonwealth of Kentucky
Frankfort, KY 40601
Attn: R. M. Fry

Office of Energy Resources
73 Tremont Street
Boston, MA 02108
Attn: L. Morgenstern

Dept of Environmental Regulation
Twin Towers Office Bldg
2600 Blair Stone Road
Tallahassee, FL 32301
Attn: D. S. Kell

1417 F. L. McFarling
1417 G. F. Rudolfo
4413 F. Donath
4500 E. H. Beckner
4510 W. D. Weart
4512 T. O. Hunter
4530 R. W. Lynch
4537 L. D. Tyler (5)
4537 B. S. Langkopf
4537 A. R. Lappin (10)
4537 J. K. Johnstone
4537 D. R. Waymire
4538 R. C. Lincoln
4541 H. C. Shefelbine
4732 A. R. Sattler
5500 O. E. Jones
5510 D. B. Hayes
5512 D. F. McVey (2)
5520 T. B. Lane
5521 L. W. Davison
5521 R. K. Thomas
5530 W. Herrmann
5541 W. C. Luth
5623 B. M. Bulmer
8266 E. A. Aas
3141 T. L. Werner (5)
3151 W. L. Garner (3)
For DOE/TIC (Unlimited Release)
DOE/TIC (25)
(R. P., Campbell, 3154-3)

SECTION C-C

SECTION D-D

SECTION A-A

SECTION B-B

7. MAY BE OBTAINED FROM:
SENSOREX
9711 DOLSA AVE.
WEST MINSTER, CAL. 92683

8. MAY BE OBTAINED FROM:
THUNDER SCIENTIFIC CORP.
623 WYOMING N.E.
ALBUQUERQUE, N.M.

INSULATION TO BE DETERMINED BY SANDIA
ORG. 4537.

SENSORS 28 AND 29, THERMOCOUPLES TO BE
FURNISHED AND INSTALLED BY ONE 124.
WELD WELD AT DISCRETION OF
ENGINEER.

ITEM 31 MAY BE USED IN PLACE OF ITEM
3 AT THE DISCRETION OF THE ENGINEER

NOTES:

1. FOR GENERAL REQUIREMENT
2. WELD & INSPECT PER 98121
1300 ELECTRODES PER AMS
ELECTRODES OR RODS PER
SANDIA ORG. 4537.
3. POTTING MATERIAL TO BE
SANDIA ORG. 4537.
4. CONNECTORS TO BE SUPPLI
ORG. 1123.
5. MAY BE OBTAINED FROM:
HAMLIN INC.
LAKE & GROVE ST.
LAKE MILLS, WISC. 53551
6. MAY BE OBTAINED FROM:
CULTON INDUSTRIES
1844 WHITTIER AVE.
COSTA MESA, CAL. 92627

Figure 7. Drawing of the Heater Assembly

GULTON INDUSTRIES
1644 WHITTIER AVE.
COSTA MESA, CAL. 92622

IN PLACE OF ITEM
"1" OF THE ENGINEER.

[Redacted]					
CLASSIFICATION AUTHORITY [Redacted] DATE OF REVIEW [Redacted]					
AGENCY APPROVALS:					
DATE	SIGNATURE	TITLE	DATE	SIGNATURE	TITLE
10/15/97	[Signature]	[Title]			
UNCLASSIFIED			ASSEMBLY, WELDED TUFF HEATER EXP.		
DECLASSIFY ON:			EXEMPT FROM GDS		
UNCLASSIFIED			EXEMPTION CODE: 25X(1)		