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Conceptual Design of Field Experiments for Welded Tuff Rock-Mechanics Program

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Conceptual Design of Field Experiments for Welded Tuff Rock-Mechanics Program

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Abstract

This report furnishes objectives, typical descriptions, and modeling requirements for the conceptual designs of five experiments proposed for testing in welded tuff in G-Tunnel at Nevada Test Site. Two experiments, the Small-Diameter Heater and Unit-Cell Canister Scale, will be designed for model evaluation. Three experiments designed to measure *in situ* geotechnical properties are planned: the Heated Block, Rocha Slot, and Thermal Probe.

Acknowledgments

The author thanks those who have made significant contributions to this effort. L. D. Tyler (Div. 4537) and A. R. Lappin (Div. 4537) from Sandia National Laboratories (SNL), P. F. Gnirk and W. C. McClain from RE/SPEC, and J. E. Russell from Texas A&M University served on a committee to define the technical concepts for the experiments and outline the tasks for developing a test plan for their implementation. W. Barrett (Div. 1116) and C. O. Duimstra (Div. 1124) contributed to the instrumentation definitions; and M. L. Blanford (Div. 5531) defined the models for the Heated-Block Experiment. H. Pratt from SAI prepared much of the input for the Heated-Block Experiment. From RE/SPEC, D. Parrish and H. Waldmen defined the models for the Small-Diameter Heater and Unit-Cell Experiments. Finally, the author acknowledges the helpful suggestions of the reviewers, H. R. MacDougall (Div. 4531) and J. A. Fernandez (Div. 4538).

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Glossary

CHLW	Commercial High-Level Waste
C_L	Centerline
CSIRO	Commonwealth Scientific and Industrial Research Organization
DCDT	Direct-Current Displacement Transducer
GTL	Gross Thermal Loading
HLW	High-Level Waste
MIDES	Mine Design Studies
NTS	Nevada Test Site
SNL	Sandia National Laboratories
TC	Thermocouple
TCD	Technical Concepts Document
USBM	US Bureau of Mines
V_p	Compression Wave Velocity
V_s	Shear Wave Velocity

Conceptual Design of Field Experiments for Welded Tuff Rock-Mechanics Program

Introduction

Background

This document introduces and defines a suite of experiments to be performed in welded tuff in G-Tunnel early in the 1980s so that vital field data can be used as input for the Nevada Nuclear Waste Storage Investigations (NNWSI). These investigations were begun in 1977 to evaluate the suitability of disposing of highly radioactive nuclear wastes on the Nevada Test Site (NTS). Several geologic settings have been examined, including alluvium, granite, argillite, and tuff. After a review of the data for several specific areas, a decision was made to focus exploration on the tuffaceous media of Yucca Mountain as a possible location for a repository and to use existing facilities on the NTS to obtain extensive field data in support of the tuff-materials evaluation.[1]

Sandia National Laboratories (SNL) is responsible for evaluating the thermal, mechanical, and hydrologic suitability of tuffs in a repository environment, and for developing the conceptual repository design for tuff as part of NNWSI. Because a test facility at Yucca Mountain cannot be developed in time to facilitate field testing, an existing underground facility must be used. Preliminary studies have been made in a layer of welded tuff, which has properties similar to those of the welded tuffs in Yucca Mountain, within the G-Tunnel complex at Rainier Mesa on the NTS.[2] Experiments that can be effectively placed in welded tuff are discussed in this report. An additional suite of experiments for nonwelded tuff is to be planned so that field testing can be conducted in G-Tunnel to provide the necessary generic experiments for characterization vital to the consideration of tuffs as emplacement medium.

Objectives

There is a need to provide a technical justification for field experiments in welded tuff. Further, those experiments that could be effectively placed in the tunnel need to be defined. The tunnel exists primarily in a nonwelded-tuff formation at a depth more than 400 m below the surface. Immediately above the tunnel is a relatively thin layer of welded tuff, about 13 m thick, which is suitable for use in the generic testing of welded tuff for the NNWSI. A Rock Mechanics Drift has been driven up through the welded tuff at the end of G-Tunnel and provides access to testing in this medium. For discussion purposes, the G-Tunnel tests in this document refer to tests in the recently exposed welded-tuff layer.

This leads to the objectives of this document. They are

- To define field experiments that resolve issues associated with the use of welded tuff for a host rock
- To provide conceptual designs of each of the experiments proposed for placement in G-Tunnel

Technical Justification

One of the vital technologies incorporated in repository development is rock mechanics. Rock mechanics includes the mechanical behavior of rock in response to both mining and thermal/radiation loading, and the effects of pore, fracture, and mineralogically bound water. Investigations related to waste packages, far-field hydrology, and radionuclide migration are not included.

Many rock-mechanics investigations can be, and are, done in laboratories. The thermal, chemical, and mechanical properties of intact rock samples can be readily determined. There is, however, a problem of scale. Laboratory- and bench-scale tests provide baseline data that must be confirmed in complex, discontinuous, heterogeneous, and possibly anisotropic environments. In particular, field tests emphasize the effects of joints on a rock mass. Thus, field testing under expected repository level conditions is needed.

The SNL program has focused on understanding those issues that must be resolved and then defining a field-testing program for rock mechanics. Activities were coordinated through the Mine Design Studies (MIDES) Working Group. The MIDES Working Group was formed in December 1979 to coordinate research and development programs for tuff. The group was composed of representatives from SNL, Los Alamos National Laboratory, RE/SPEC, Inc., and Texas A&M University. One of its main objectives was to identify issues for a tuff repository and define resultant model and data needs. The group compiled available laboratory and field data into a comprehensive package for this purpose.

Table 1 summarized MIDES issues requiring field experiments in welded tuff. Each of the five major issues identifies phenomena or structural components that have distinctive subissues. These issues and subissues relate to welded tuff in a generic sense and are intended to identify the features that apply to a typical repository setting. Each of these issues is described briefly in the following paragraphs.

Table 1. Summary of MIDES Issues Requiring Field Experiments in Welded Tuff*

1. Very Near-Field Behavior of Water
   - Pore-water migration
   - Variable thermal properties
2. Emplacement-Hole Stability
   - Surface integrity
   - Segment encroachment
   - Pressure effects
3. Joint Behavior
   - Property evaluations
   - Functional stability
4. Floor Performance
   - Surface dislocations
   - Stress concentrations
   - Water migration/transport
5. Room Response
   - Natural geologic influences
   - Thermal mechanical behavior

*Text contains descriptions of subissues

The first issue is the very near-field behavior of water. Welded tuff is inherently porous. For identification purposes, a tuff is considered welded if its porosity is less than 25% by volume. This means that saturated tuff can contain significant amounts of water.

Pore-water content is necessarily site-specific. There are welded-tuff units above and below the static water level at Yucca Mountain. If it is assumed that a repository is located below a water table, there is concern that water might migrate from interstitial voids of the tuff surrounding the canister to the canister surface and change the thermal properties of the surrounding tuff, or increase the corrosion potential of the canister. Water could migrate toward the canister because of thermal loadings or hydrostatic head. Although it is logical to assume that a horizon above the water table would have less water, the more densely welded portion of the Grouse Canyon Member of the Belted Range Tuff in G-Tunnel has a porosity ranging from 15% to 25% and contains pore water up to 95% saturation—even though it is more than 200 m above the water table.[3] The Tuff Water Migration/Heater Experiment in this unit has demonstrated that water migrates towards the heater emplacement hole.[2] Thus, this issue needs further attention and important phenomena need further study.

The next issue in Table 1 deals with the stability of emplacement holes (waste-package issues are not included here). Rock might spall or fracture on its surface because of thermal loads or induced pore pressures, and there could also be localized fractures oriented so that segments of tuff might slip and encroach on a canister. Emplacement-hole pressures are related to how effectively the holes are sealed. Pressures might build up from vapors because of heat-induced water migration or from hydrostatic flow created at the closure of a repository.

The third issue is the behavior of joints. Joints are formed in tuffs after the tuffs are deposited and begin to cool and harden. Differential heat losses and the relatively brittle nature of the parent material lead to fracturing. Joints are usually in near-vertical planes, and occur more often near the outside of a geological member. Joints have structural and thermal properties that influence the overall behavior of a rock mass. One concern is the need for evaluating these properties and determining the perturbations that joints have on rock-mass continuum assumptions. Moisture in joints may change bulk thermal properties, and stress and/or temperature fields are expected to affect joint hydrological properties. Another concern is the functional stability of a joint. Joints may alter chemically and the properties may change with time.

The issue dealing with floor performance is identified because this is the region where the effects of thermal loads are first noticed. Thermal loads expand the rock, and the floor can displace upward, possibly influencing emplacement-hole sealing. In room-and-pillar designs under consideration, horizontal stresses can increase in tunnel floors. Floor surfaces are influenced by joint systems created through geological cooling or tunnel excavations. Dislocations may occur as a result of horizontal stress fields. Finally, water migrating in either vapor or liquid form might emerge through the floor and require removal by the tunnel ventilation system, or it may need pumping. This overall phenomenon needs field evaluation.

The last issue in the table deals with room responses to thermal loads. Natural geologic features such as faults, voids, or stratigraphic discontinuities can cause concentrations of stress in rooms that call for corrective actions after excavation and before use. Understanding the thermal mechanical behavior of a room is essential in predicting room stability during startup and operation of a repository. Stress redistributions may occur that can influence pillar behavior. There is also a need to evaluate the thermal unloading of parts of rooms to assess the possible effects of hysteresis.

The formulation of the scope of field experiments to be conducted in G-Tunnel evolved through discussions with representatives of SNL, RE/SPEC, and Texas A&M University. The group reviewed the MIDES issues and the physical testing possibilities available in G-Tunnel. The welded-tuff unit is relatively thin (~13 m), and full-scale room-and-pillar experiments were not considered feasible. This meant that canister-scale experiments should be emphasized. Five experiments have evolved from these discussions into the conceptual design stage.

The resulting aggregation of planned experiments covers two aspects. First, there are the experiments designed for model evaluation. The purpose of these experiments is to use the latest modeling codes to predict responses of the welded tuff to thermal loads and to do detailed posttest evaluations. A small-diameter heater experiment is planned for evaluating thermal models, and a canister-scale/unit-cell experiment is planned for evaluating thermal-mechanical models. The hydrological phenomena are less well-defined and are not included for predictive modeling, but are included for experiment analyses.

The second set of experiments are classified as geotechnical; they are planned to provide field inputs into the overall data base for use in making laboratory-field scale comparisons and in confirming data used in models. Models will be used in the design of these experiments to understand parametric sensitivities; they will also be used in the postexperiment phase.

The first of the geotechnical experiments is a multipurpose experiment designed for measuring field data, such as the modulus of deformation, thermal expansion, etc, and in determining the effects of stress and temperature on these and other properties like hydraulic conductivity. The experiment planned is the heated block. The next two experiments are developmental, defined to bring out the potential anisotropy in the thermal and mechanical properties. The Rocha slot experiment is designed to evaluate the effects of joints on the modulus of deformation, and the thermal probe experiment will evaluate the effects of wet and dry joints on the thermal conductivity of welded tuff. These experiments can be repeated as a function of time, and the functional stability aspects of joints can be evaluated.

All five experiments are directly related to the various subissues that have been identified. Table 2 summarizes these relationships and shows that all the experiments address multiple subissues. The experiments selected reflect state-of-the-art technology. The first three were selected for their demonstrated technical feasibility in other programs; the last two are developmental and relate to special tuff needs.

This suite of experiments is responsive to issues on the use of welded tuff as a host rock for a nuclear-waste repository. The technical justification supporting these experiments stems from a need to establish a firm understanding regarding the behavior of this material. Field data are needed to support site-characterization activities, a process that requires developing baseline information and analyses. Also, there is a need to monitor changes in this information and allow for corrections. The implementation of the proposed experiments during FY82 allows for this.

There is a need for data and phenomenological understanding in support of repository conceptual designs. Behavior of the host rock, pore water, and joints must be understood. There is a need to develop confidence in the predictive capabilities of the models, as well as a need to develop instrumentation and control system experience. Finally, it is useful to evaluate excavation techniques. This can be done in the rock-mechanics field-testing program that is described. Later sections explain the details of these experiments.

Table 2. Issue—Experiment Identification*

Issue	Experiment: Model Evaluation	Experiment: Geotechnical Evaluation
Very Near-Field Behavior of Water		
Pore-Water Migration	1,2	
Variable Thermal Properties	1,2	3,5
Emplacement-Hole Stability		
Surface Integrity	1,2	
Segment Encroachment	1,2	3
Pressure Effects	1,2	
Joint Behavior		
Property Evaluations		3,4,5
Functional Stability		4,5
Floor Performance		
Surface Dislocations	2	
Stress Concentrations	2	4
Water Migration/Transport	2	
Room Response		
Natural Geologic Influences	1,2	
Thermomechanical Behavior	2	3

*Key

No.	Experiment
1	Small-Diameter Heater
2	Unit-Cell Canister Scale
3	Heated Block
4	Rocha Slot
5	Thermal Probe

Outline of the Conceptual Design

Each experiment conceptual design in this report is discussed by a breakdown organized as follows:

- Objectives
- Purpose
  - Rationale
  - Justification
- Experiment description
  - Geometrical configurations
  - Procedure, including potential types of instrumentation
  - Measurement specifics (e.g., numbers and general locations of instruments desired)
  - Proposed operating levels
- Modeling requirements
  - Applications
  - Computer requirements
  - Limitations

The conceptual designs will lead to a preliminary design report. This report will include a more detailed physical layout, performance requirements, a definition of instrumentation and equipment with appropriate installation requirements, and details of the data-acquisition system. Also included will be a definition of the testing facility in G-Tunnel. An experiment implementation schedule and estimated costs will be included in the preliminary design.

The preparation of preliminary designs requires modeling. Modeling requirements are outlined for each experiment, and the last section of this document lists the material properties used in the models. For reference, the modeling codes associated with the experiments are located at SNL and at RE/SPEC. The COYOTE and SANCHO codes are at SNL; SPECTROM is at RE/SPEC.

Small-Diameter Heater Experiment

Objectives

- To perform a small-diameter heater experiment in welded tuff and measure the temperature distributions around the heater for purposes of model evaluations.
- To monitor the possible migration of water and/or vapor into the annulus around the heater.
- To use the results of this experiment in the final design of the unit-cell heater experiment.

Purpose

Rationale

The Tuff Water Migration/Heater Experiment[2] demonstrated that pore water migrates toward the heater hole in the heating phase. The experiment was configured to locate the heater near the top of a drillhole, with a +20° inclination; the water collected in a cooler region below the heater. This phenomenon needs to be understood in a typical repository setting, where the potential water-collecting region is heated. A small-scale heater experiment in a vertical borehole satisfies this requirement.

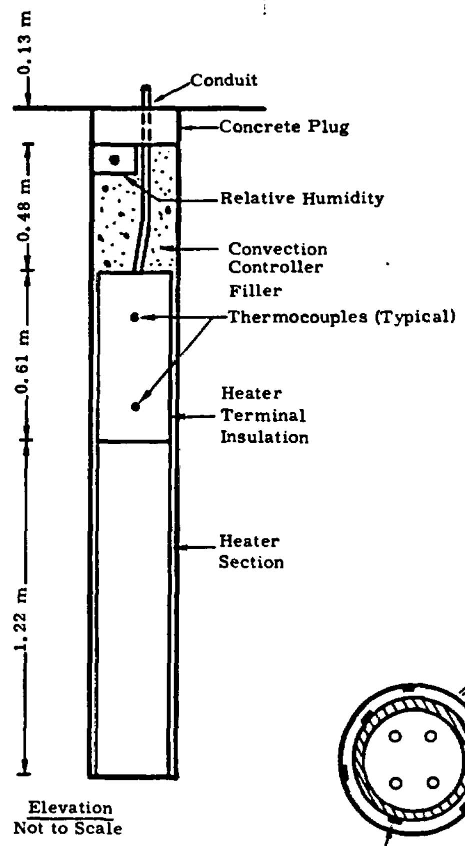
Justification

Water migration needs to be carefully studied on a small scale in an experiment of relatively short duration so that the phenomena can be closely watched and evaluated, and their effects included in the final design of the full-scale experiments. The experiment is to be kept simple by taking measurements only in the heater hole. Temperature measurements are to be predicted with scoping-type modeling calculations. Water will probably migrate to the emplacement hole, possibly saturating the air in the annulus. Some of it could condense and standing water could collect at the bottom of the heater; or vapor pressure could build up in the annulus and pressure relief would be needed. Eventually, a steady-state vapor/liquid boundary could develop somewhere within the emplacement hole, and the thermal conductivities in the air annulus and surrounding rock could be altered.

Experiment Description

Experiment Configuration

See Figure 1.



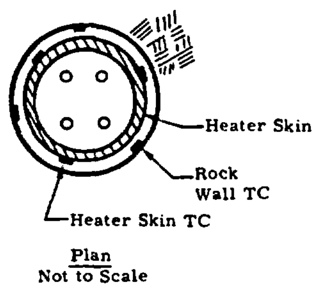


Figure 1. Small-Diameter Heater; Typical Sensor Locations

Experimental Procedure

It is proposed to place a 10-cm heater in a 13-cm-dia emplacement hole. The heater is to be operated at the level used in the Tuff Water Migration/Heater Experiment (~0.8 kW) and the resulting phenomena monitored so that orientation effects upon emplacement holes can be evaluated. Temperatures on the surface of the heater and the surrounding emplacement hole will be monitored by several thermocouples (TCs). Air temperature and relative humidity above the heater, as well as the existence of and level of water in the emplacement hole, will be carefully monitored to determine the evidence of the water migration. A pressure-relief valve will be provided at the surface and any escaping vapor collected. The terminal junction of the heater element is to be insulated so that the temperature of the air above it is near ambient. This should provide maximum condensation and increase the potential for water-phase changes around the heater.

Measurement Specifics

Emplacement Hole (1 hole)

- Heater surface and internal temperatures (20 TCs)
- Emplacement-hole surface temperatures (21 TCs)
- Emplacement-hole bottom temperatures (1 TC)
- Air-space temperatures (2 TCs)
- Air-space relative humidity (1 ea)
- Water-level indicator (1 ea)

Operating Levels

- Heater - 0.8-kW output
- Time - 0 to 30 days continuous operation for a single test

Modeling Requirements

Key Output

- Temperature-Location: Vertical temperature distribution - hole wall - selected time increments
- Temperature-Location: Vertical temperature distribution - heater surface - selected time increments
- Temperature-Time: Emplacement-hole mid-plane distributions
- Isotherms: Selected time increments

Required Inputs (See the section on Material Properties Data)

- Mesh Geometry
- Thermal Properties
  - Thermal conductivity
  - Specific heat
  - Density
- Materials
  - Tuff
  - Air
  - Concrete
  - Bubbled alumina
  - Stainless steel

Computer Requirements

- Finite-Element
- 2-D, R-Z Geometry (axisymmetric)
- Limitations
  - Empirical transformation - boiling phenomena
  - No joints
  - No convection - emplacement hole

Unit-Cell Canister Scale Experiment

Objectives

- To obtain thermal and mechanical measurements in a unit-cell configuration that represent the startup conditions expected during the operation of a repository containing commercial high-level waste (CHLW).
- To verify computer models prepared to predict the thermal and mechanical fields and responses.
- To monitor hydrological behavior in a canister scale setting.

Purpose

Rationale

The unit-cell experiment consists of a central canister-scale heater with surrounding guard heaters for simulation of a repository environment in a sizeable volume of the rock. The experiment is proposed to be operated at an equivalent areal gross thermal loading (GTL) of 100 kW/acre to bring out the complete range of thermal/mechanical/hydrological coupling phenomena.

Justification

The unit-cell experiment provides for thermal and mechanical model validation at the full-canister scale and the very-near field in a repository setting. A significant volume of rock around a heater simulator heats up rapidly after the heat is turned on, and the very-near field in a repository setting can be evaluated for thermal perturbations. Heat is conducted into the rock and most is stored. The high-moisture contents in the relatively porous tuff (~20%) provides a potential for vaporization and a resulting change in thermal properties. Vaporization could reduce the thermal conductivity of the surrounding rock and drive up the temperatures in and around the heater unit. This potential needs field evaluation.

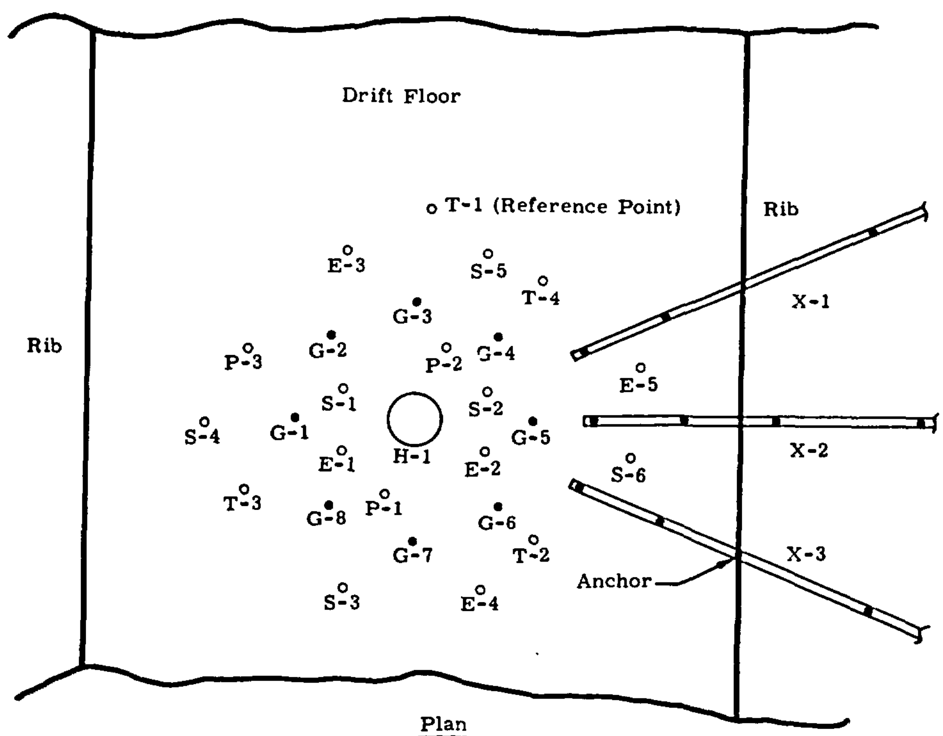
Thermocouples are to be liberally placed in the rock mass to measure the thermal fields resulting from one central and eight surrounding guard heaters. Changes in horizontal stresses as functions of heat loads are to be measured as part of the model evaluation. Horizontal and vertical extensometers will be located around the heaters to monitor and evaluate the displacement changes. Floor displacements will be periodically monitored to assess thermal influences. Internal pore pressures will be monitored to detect moisture phase changes within the intact rock.

Rock-mass thermal and mechanical phenomena are to be observed and results verified with field measurements. Two different modeling efforts are required. The first deals with preparing a set of scoping calculations for use in the preliminary design of the experiment. Appropriate measurement sensitivities are to be predicted through the use of linear elastic models. These can be refined later to provide direction during the early operation under the heater fluxes. The second set of calculations are associated with repository design and development and are the formal calculations to be used in model evaluation. In this case, the full-scale jointed rock model will be used. The models will be correlated by comparing temperature histories at a common reference point, and mechanical histories at convenient measurement points.

Experiment Description

Experiment Configuration

See Figures 2 and 3.



Plan
Scale 1 in. = 1 m

Legend

Symbol	Function	No. Holes	Size Hole
H	Central Heater	1	37cm
G	Guard Heaters	8	EX
S	Stress Measurements	6	EX
P	Pore Pressure Meas.	3	EX
E	Vertical Extensometer	5	NX
X	Horizontal Extensometer	3	NX
T	Thermocouple	4	EX

Figure 2. Unit Cell—Instrumentation and Heater Hole Locations

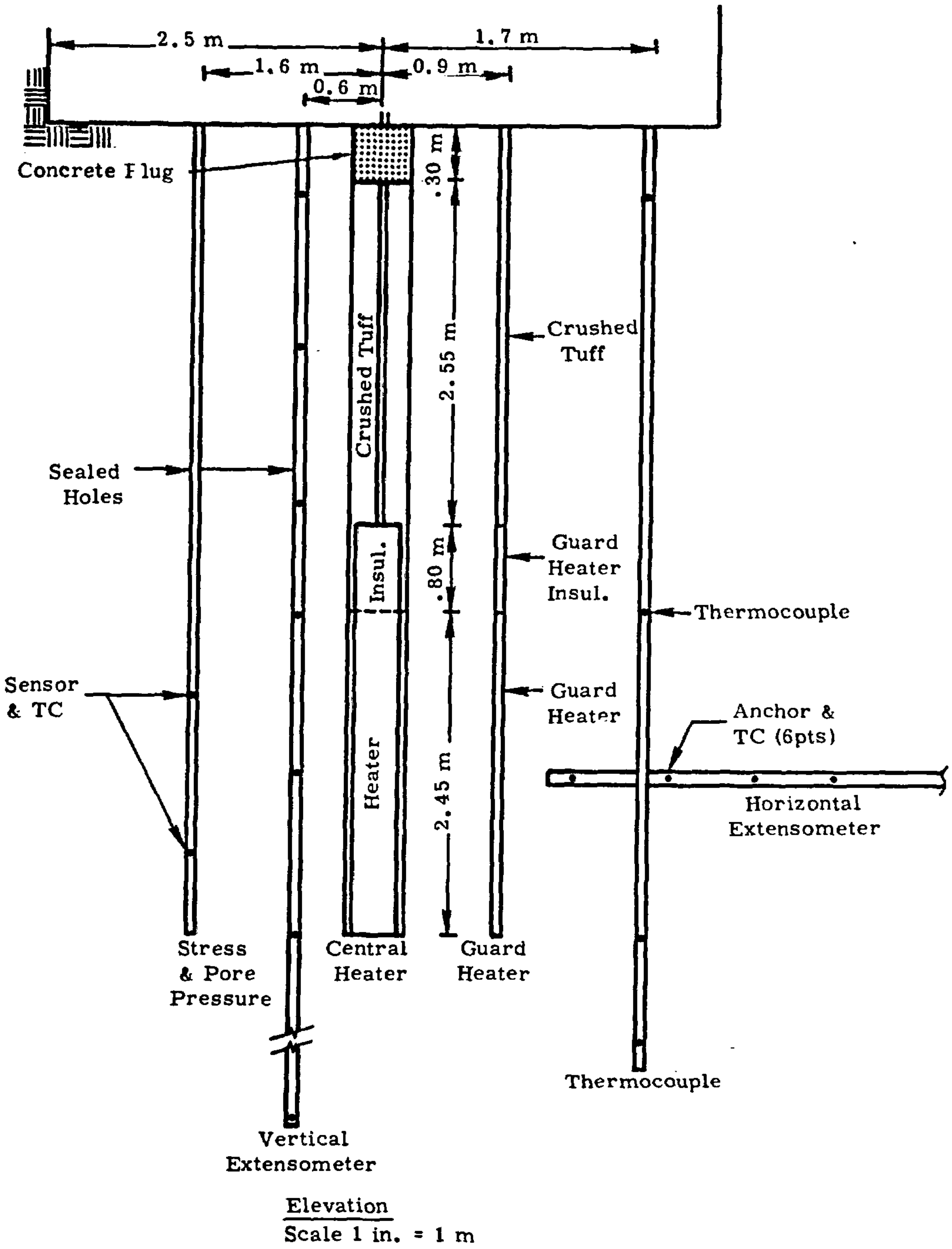


Figure 3. Unit Cell—Typical Instrumentation and Heater Placement

Experimental Procedure

The unit-cell experiment is designed for independent operation of the central heater and surrounding guard heaters. The central canister-scale heater is to be operated at an initial power loading of 2.16 kW and its power decay regulated to simulate a commercial high-level waste (CHLW) canister in service.[4] The surrounding guard heaters are to be regulated so that a reference point in the rock mass around the heaters takes on the temperature history predicted for a similar point in an actual repository. A point close to the central heater will be dominated by that heat source. A point at midpitch in a repository drift would be equally influenced by both heaters for the early years.

The guard heaters can be conveniently located at one-fourth the pitch of canisters specified in the Interim Reference Repository Condition of 100 kW/acre.[4] This will extend the heated zone over an area representative of multiple canisters. A point within the midplane of the heater, midway between the guard heaters and at a radius corresponding to midpitch, should be selected as the reference point.

This point would be sensitive to the thermal gradients of the guard heaters and would represent a point far enough from the central heater to ensure reasonable areal loadings.

It is proposed to regulate the central heater and guard heaters so that the reference point is influenced only by the central heater for the first 3 mo. Then the guard heaters would be turned on and the temperature history of the reference point would assume the profile of the simulated repository. Preliminary calculations indicate that the difference in temperature at the reference point would be <10°C for the first 3 mo, and the radius defining the 100°C isotherm would be ~0.7 m at that time.

Measurement Specifics

Emplacement Hole (1 central heater)

- Heater surface temperature (15 TCs)
- Emplacement-hole surface temperatures (18 TCs) Emplacement-hole bottom temperature (3 TCs)
- Air-space temperatures (2 TCs)
- Air-space relative humidity (if possible)

Guard Heater Holes (8 holes)

- Heater surface temperatures (10 TCs)
- Heater-hole surface temperatures (4 TCs)
- Air-space temperature (2 TCs)

Instrumentation Holes (10 holes minimum)

- Thermocouple (4 TCs/hole plus one for each pore pressure or stress sensor)
- Pore pressures (2 piezometers/hole)
- Stress (2 USBM 3-component or Commonwealth Scientific and Industrial Research Organization (CSIRO) gages/hole)

Extensometer Holes (3 horizontal and 5 vertical holes minimum)

- Displacement (six-point rod extensometer)
- Temperature (TCs with each anchor)

Floor Surface

- Displacements (Direct-Current Displacement Transducer (DCDT))

Operating Levels

- Central Heater - 2.16 kW - CHLW heat decay
- Guard Heaters - Variable power set to provide specific temperature-time history at reference point. Nominal individual guard heater wattage <0.5 kW.
- Time
  - Central Heater - 0 to 2 yr minimum
  - Guard Heater - 0.25 to 2 yr minimum

Modeling Requirements

Key Outputs

- Temperature-Location: vertical temperature distribution - hole wall - selected time increments
- Temperature-Location: vertical temperature distribution - heater surface - selected time increments
- Isotherms: through guard heater centerline (C_L)
- Isotherms: through guard heater midplane
- Isobars: stress - vertical plane through guard heater C_L
- Isobars: stress - vertical plane through guard heater midplane
- Relative Displacements: vertical plane through guard heater midplane
- Relative Displacements: horizontal plane through central heater midplane

Required Inputs (See the section on Material Properties Data)

- Mesh Geometry
- Thermal Properties
  - Thermal conductivity
  - Specific heat
  - Density
- Mechanical Properties
  - Tuff

- Air
- Concrete
- Crushed tuff
- Bubbled alumina
- Stainless steel

Computer Requirements

- Finite-Element
  - 2-D, R-Z Geometry (axisymmetric)
  - 3-D, X-Y-Z Geometry
  - Limitations
    - Empirical transformation - boiling phenomena
    - No joints
    - No convection in emplacement hole
    - Linear elastic mechanical properties

Heated-Block Experiment

Objectives

- To measure the constitutive thermal and mechanical properties of jointed tuff under independent thermal and mechanical loading systems.
- To determine the effects of variable stress and temperature on joint behavior.
- To determine the influences of temperature and stress fields on joint permeabilities.
- To monitor changes in pore-moisture content as a function of thermal loads.

Purpose

Rationale

These geotechnical measurements extend the previous field measurements in welded tuff to include the influence of joints on the properties of rock mass and of the thermal effects on the fundamental thermal/mechanical/hydrological properties. This information is needed to upgrade model parameters and possibly algorithms.

Justification

The Heated-Block Experiment is designed to allow independent controls of heat fluxes and boundary stresses around a sizeable portion of jointed rock with a volume >8 m^3. This instrumentation can be used to monitor intact rock displacements and strains, joint displacements, rock-mass stress, temperatures, and pore pressures. Ultrasonic velocities can be measured. From these measurements, it is possible to measure in-situ thermal conductivity, the thermal expansion coefficient, the static and dynamic moduli of deformations, and joint deformational characteristics. The effects of varying temperatures and boundary stresses can be related to changes in joint permeabilities.

Experiment Description

Experiment Configuration

See Figures 4 and 5.

Experimental Procedure

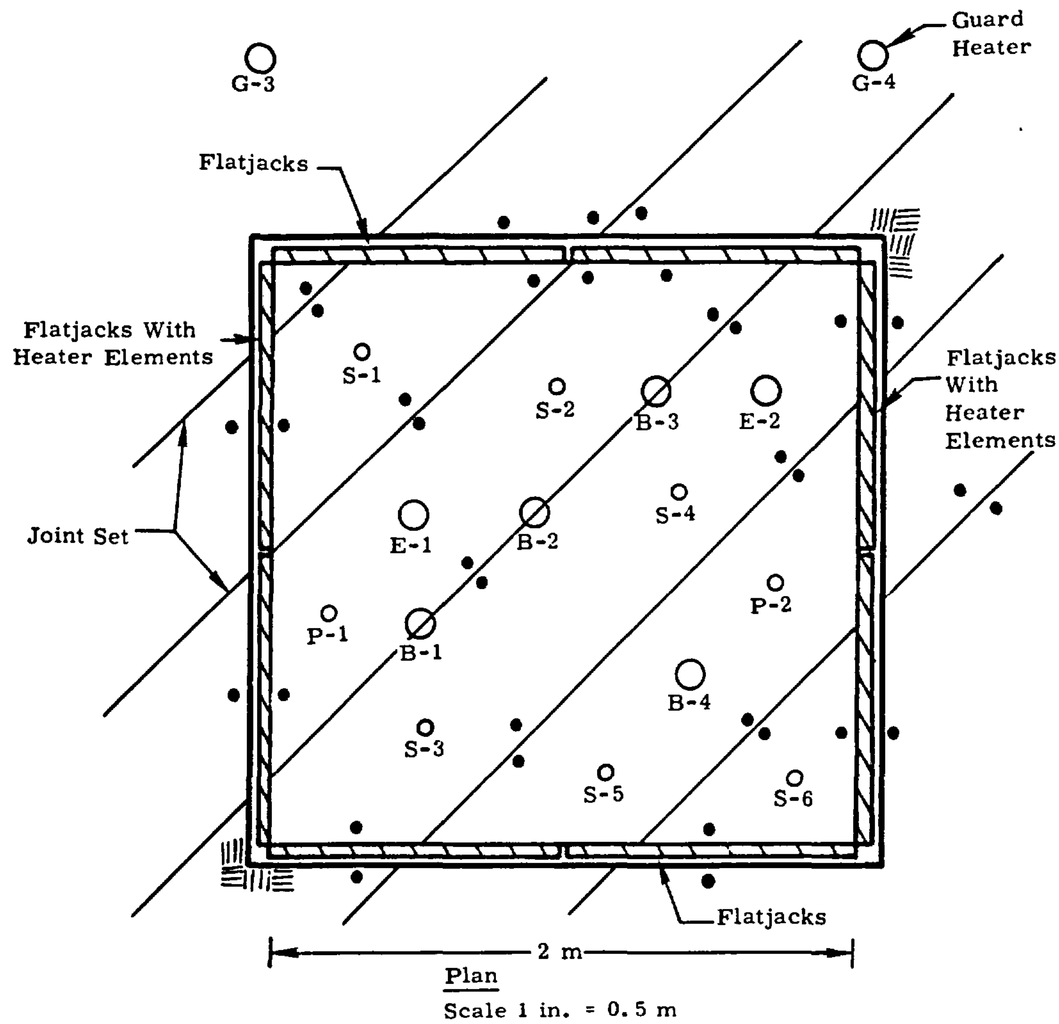
The plan and elevation of the block test in Figures 4 and 5 show that flatjacks and flatheaters are proposed for two parallel faces, and flatjacks for the orthogonal faces. More guard heaters are proposed for the corners to minimize temperature gradients throughout the block. An alternate heater configuration is to place the heaters through the midplane of the block, as at Colorado School of Mines.[5] This is being evaluated with models, and results will be reflected in the preliminary design. The heated-block configuration will allow several tests to be done.

Some measurements need to be made after geologic mapping and before excavation of the test block; these include measurements of modulus of deformation and permeability in boreholes that will ultimately be contained in the block. The in-situ state of stress on the surface can be measured by monitoring the displacements of set pins located on both sides of the slots during excavation unloading and flatjack repressurization phase.

After excavation, the uniaxial tests can begin. Deformation, stress, elastic properties, and permeability can be measured under varying stress fields across two orthogonal directions under ambient temperatures. Since the major joint field is proposed at a 45° angle to the flatjacks, joint-shear behavior can be monitored with surface displacement measurements. Opposite sets of flatjacks can be activated, and measurements made of joint closure and intact-rock modulus of deformation.

The elevated temperature tests can be initiated under a constant biaxial state of stress. Temperatures, displacements, stresses, elastic properties, and fluid-flow characteristics can be monitored under variable thermal fields.

Pore pressures will be monitored throughout the tests. Velocities (V_p and V_s) will be periodically measured to monitor possible changes of moisture in the pores. Various combinations of varying stress and temperature fields can be applied to the block, and the resulting phenomena monitored and evaluated.



Legend

Symbol	Function
G	Guard Heater
S	Stress
P	Pore Press
B	Open Borehole
E	Extensometer
•.	Set Pins

Figure 4. Heated Block—Typical Instrumentation Locations

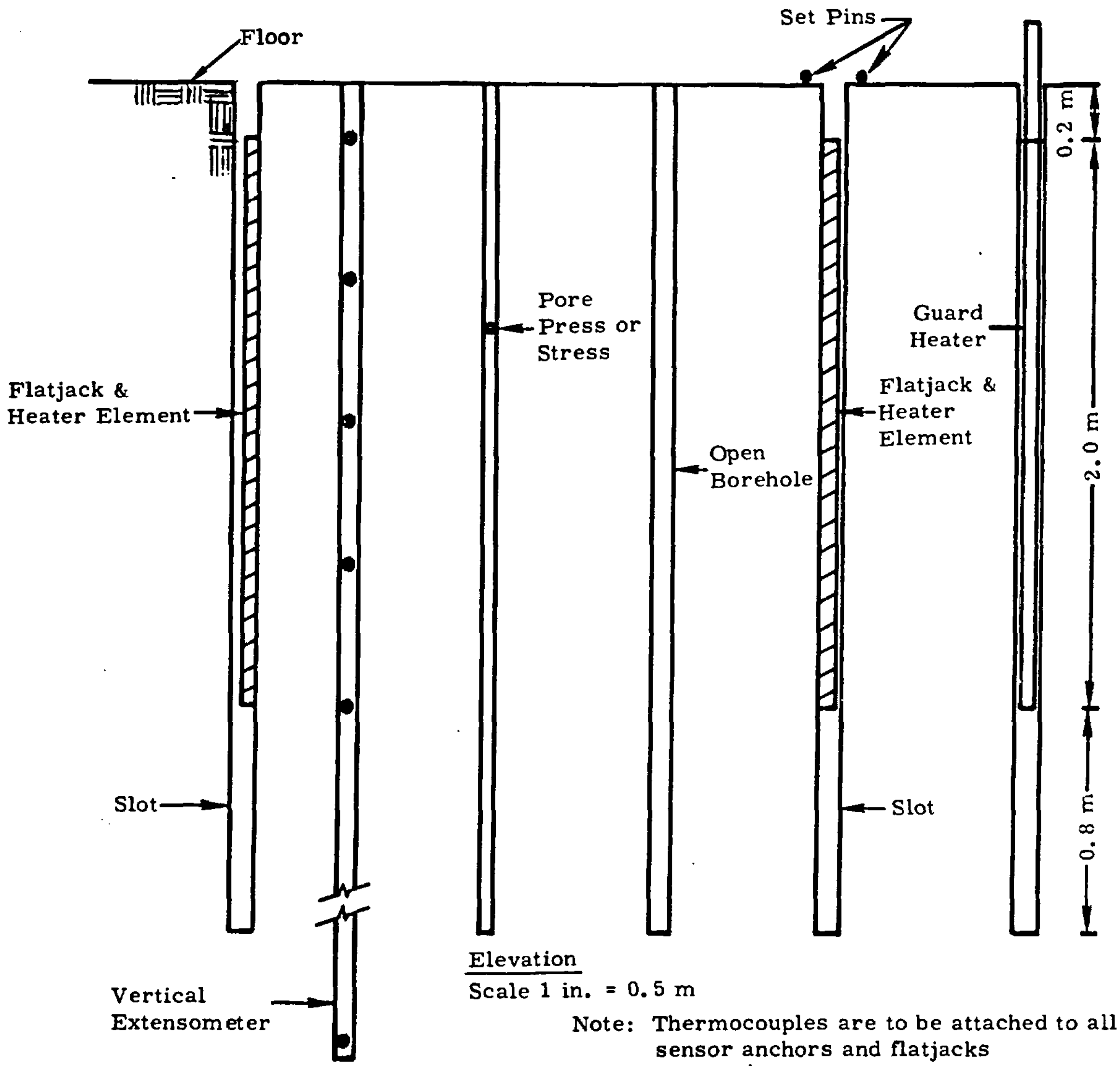


Figure 5. Heated Block—Typical Instrumentation Placement

Measurement Specifics (Numbers in some cases are site-dependent)

Instrumentation Holes (12 holes minimum)

- Thermocouples (4 with each sensor)
- Pore pressures (2 piezometers/hole)
- Stress (2 stress measurements/hole)

Extensometer Holes (3 holes minimum)

- Displacement (6 anchors/hole)
- Temperature (6 TCs/hole - at anchors)

Floor Surface (18 sets minimum)

- Displacements (variable gage length displacement measuring system)

Boreholes (3 holes minimum)

- Sonic velocities (2 transducers)
- Fluid flow (straddle packer system)
- Fluid pressure (pressure gages)

Slots (4 planar slots)

- Flatjack pressures (8 individual jacks)
- Flatjack temperatures (32 TCs)

Operating Levels

- Twin Flatjacks - 0 to 14 MPa at 10 to 15 cycles
- One-Third of Block Above 100°C at 30 days
- Average Maximum Rock Temperature: 85°C
- Time - 0 to 30 days/experiment

Modeling Requirements

Key Output

- Temperature Distribution - Plan
- Temperature Distribution - Elevation
- Stress Distribution - Plan
- Displacement Distribution - Plan

Required Inputs (See the section on Material Properties Data)

- Thermal Properties
  - Thermal conductivity
  - Specific heat
  - Density
- Mechanical Properties
  - Modulus of elasticity
  - Thermal expansion
  - Poisson's ratio
- Materials
  - Tuff
  - Air
  - Stainless steel

Computer Requirements

- Finite-Element
  - 2D, X=Y and R-Z Geometry, Thermal
  - 2D, X-Y and X-Z Geometry, Mechanical
  - Limitation
    - Empirical Transformations - boiling phenomena
    - Discrete Planar Joints
    - Cohesionless Joint Behavior
    - Linear Elastic Mechanical Properties

Rocha Slot Test

Objective

- To measure the modulus of deformation as a function of joint proximity and orientation by using the Rocha slot method.

Purpose

Rationale

The proposed test provides field data about the influences of joints on the mechanical properties used in models. Joint-aperture size and mechanical properties are assumed in models, and the models must reflect the field values. It is known that the slot method activates a larger volume of rock than do borehole methods.[6] Directional properties can be established and anisotropic influences on the bulk mechanical properties determined by locating slots in selected regions of parallel joint sets and orienting them so as to intersect the joint sets at different angles.

Justification

The slot method has been used successfully in subsurface and mine explorations to determine field value for the modulus of deformation.[6] It has not been used to measure the effects of joints on modulus of deformation. Thus, this is a developmental experiment that is technically feasible because tuff has reasonably regular and parallel joint sets.[2] If successful, the technique could be used to define the bulk anisotropic mechanical properties of a jointed-rock mass. A future extension of the experiment would be to make similar measurements in deeper slots, thus minimizing excavation influences; however, this is not planned in this scope of work.

The experiment is to be modeled with general parameters. At the conclusion of the field measurements, the data will then be used to fine-tune or correct the model and accurately describe the phenomena.

Experiment Description

Experiment Configuration

See Figure 6.

Experimental Procedures

Two key factors are associated with the success of this experiment — cutting the slot, and taking actual measurements for computing the modulus of deformation.

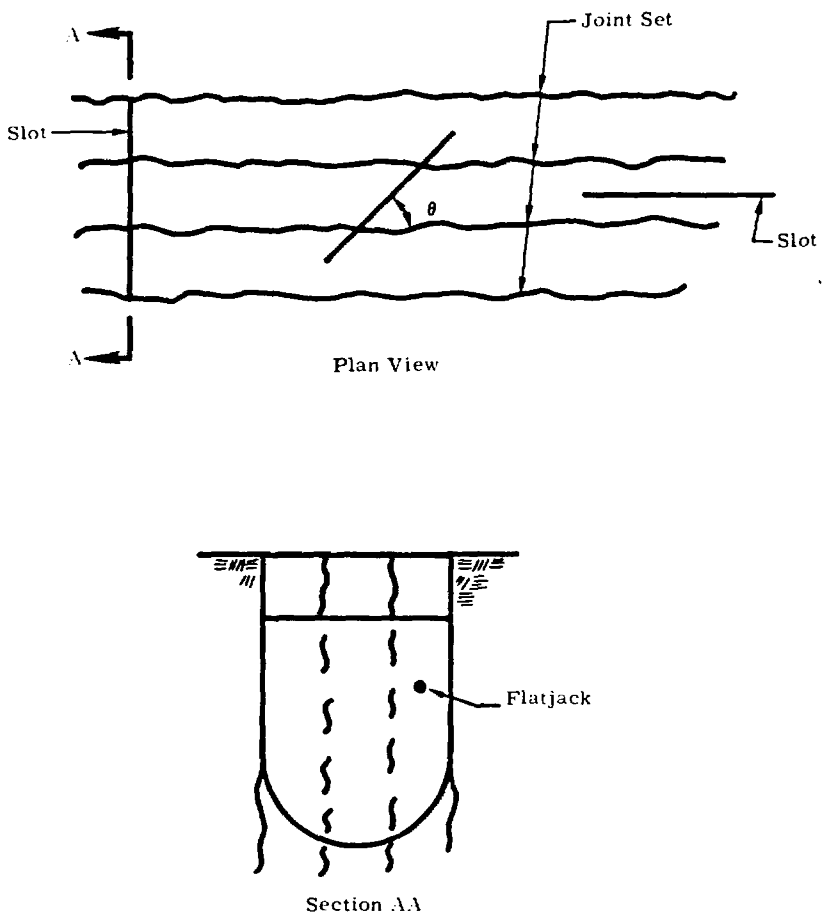


Figure 6. Rocha Slot—Typical Orientations

The method is based on the ability to cut thin, deep slots in rock disturbing only a minimum of the surrounding rock. The most widely used excavation technique is to cut slots with a diamond-disk saw that is 1 m in dia and 7 mm thick. These saws have been used to cut slots up to 2.5 m deep. Thin flatjacks on the order of 1 m wide and 2 m long have been used with pressures >14 MPa. Possibly, a chain saw or wire-rope method can be used to cut these slots in tuff; this would be less expensive. The different excavation methods are being investigated.

The modulus of deformation is calculated from pressure measurements and from strain measurements taken from the flatjack. Electrical strain gages are bonded to the inside of the flatjack-inflating membranes, and deformations are related to these outputs. The process requires careful calibration. Pressure and deformation values are inserted into an equation based on the theory of elasticity, and the resulting modulus of deformation is computed. Measurements are influenced by the tensile strength of the rock at the ends of the slots; better readings are taken if the inflatable flatjack has a smaller lateral dimension than does the slot.

Measurement Specifics

Flatjack

- Pressure
- Deformation

Rock

- Joint orientation
- Joint proximity

Operating Levels

Flatjack

- 0 to 7 MPa

Modeling Requirements

Key Output

- Modulus of Deformation - Joint Angle

Required Inputs (See the section on Material Properties Data)

- Mesh Geometry
- Mechanical Properties
  - Modulus of elasticity
  - Poisson's ratio
  - Tensile strength
- Joint Conditions
  - Dimensions
  - Frequency
  - Orientation
- Slot Conditions
  - Dimensions
  - Pressurized area
  - Material
    - Tuff

Computer Requirements

- Finite-Element
- 2-D Mechanical
- Limitations
  - Discrete Joint Fields
  - Parallel Joints With Uniform Spacing

Thermal-Probe Measurement

Objective

- To measure the thermal conductivity of intact and jointed rock under dry and saturated conditions by using the thermal-probe method.

Purpose

Rationale

There is a need to measure in-situ thermal properties across joints. Some joints in welded tuff have apertures on the order of 1 mm. Thermal models ordinarily assume that thermal conductivities are related to the intact rock and its state of interstitial moisture. These codes assume isotropy in the thermal fields. There is reason to believe that parallel joint sets will cause the thermal conductivities to be anisotropic; this needs confirmation.

Justification

Experiments are needed on intact and jointed rock under variable moisture conditions to evaluate the full spectrum of variables. The experiments can best be performed in the field, where excavation and transportation influences on the joints can be minimized.

The basic theory for the thermal probe applies to a homogeneous isotropic material.[7] Field applications to date have been on intact rock; applications of the thermal probe to jointed rock will require some development. The transient line source thermal conductivity measurement technique will have to be modified for an anisotropic medium. The initial thinking is to try to measure the conductivity by inserting a small thermal probe in the plane of the joint. Modeling difficulties may dictate insertion of the probe perpendicular to the joint plane or the need for developing miniature heater experiments. This needs to be resolved before completing final modeling and experimental efforts. The next section is written with the assumption that the probe is parallel to the plane of the joint.

Field methods need to be developed to estimate moisture content in the rock and joints before thermal-probe testing.

Experiment Description

Experiment Configuration

See Figure 7.

Experimental Configuration

Close-fitting ceramic probes are inserted in small-diameter holes, nominally <2 mm, that are ~15 cm deep. The probe contains heater elements and a TC. The technique is to monitor the thermal response of the TC as a function of time as the heaters are activated. The construction of the thermal probe allows application of line source transient theory, and the thermal conductivity can be measured.[7]

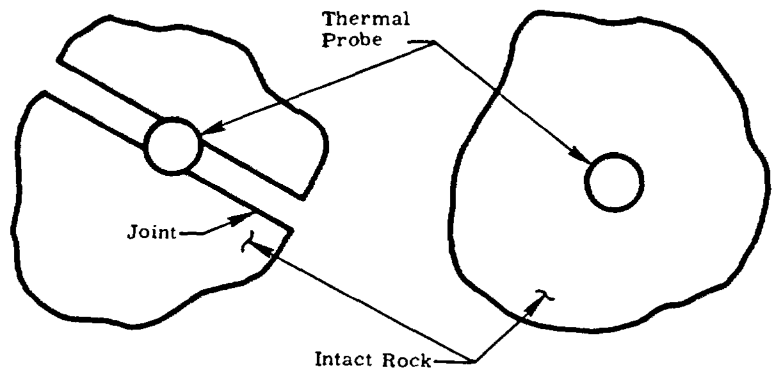


Figure 7. Thermal Probe—Typical Placement

Measurement Specifics

- Temperature rise
- Time
- Orientation to joint
- Moisture content

Operating Levels

- 0° to 90°C temperature increase of rock

Modeling Requirements

Key Output

- Thermal conductivity - joint conditions

Required Inputs (See the section on Material Properties Data)

- Thermal Properties
  - Thermal conductivity
  - Specific heat
  - Density
- Joint
  - Dimensions
  - Moisture content
- Probe
  - Dimensions
- Materials
  - Tuff
  - Air
  - Water

Computer Requirements

- Finite-Element
- 2-D, Thermal-Anisotropic
- Limitations
  - Minimum Joint Size
  - Minimum Probe Size

Material Properties

There are little data describing the thermal and mechanical properties of the welded tuff in G-Tunnel. Until recently, the tunnel was located in nonwelded tuff, and material-properties measurements were concentrated there. A Rock Mechanics Drift has been mined up through the welded tuff. That area is being characterized both geologically and analytically in parallel with design preparation. These new data will be factored into the final Test Plan covering this work.

Preliminary design data are incorporated into this document so that realistic data will be available to make design calculations. Principal sources are references 2 and 3. Table 3 summarizes this data for the Grouse Canyon Tuff and Table 4 summarizes it for other materials included in the modeling.

Table 3. Preliminary Design Properties of Grouse Canyon Tuff

Bulk Properties

Bulk Density	ρb	$= 2.3$ g/cm^3
Grain Density	ρg	$= 2.6$ g/cm^3
Porosity	ϕ	$= 16\%$
Saturation	s	$= 95\%$

Table 4. Preliminary Design Properties of Other Materials

Thermal Properties

Thermal Conductivity - $K = 35.8$ W/m·K air in tunnel

$K = 1.12$ W/m·K concrete

$K = 1.00$ W/m·K crushed tuff

K (kJ/day·m·K) = 0.0251 (T) + 4.29
where T is in Kelvin, bubbled alumina

$K = 20$ W/m·K stainless steel

Heat Capacity

$\rho C_\rho = 1.02$ kJ/m^3·K air
$= 1835$ kJ/m^3·K concrete
$= 4.94$ kJ/m^3·K crushed tuff
$= 971$ kJ/m^3·K bubbled alumina
$= 4016$ kJ/m^3·K stainless steel

Mechanical Properties

Modulus of Elasticity
$E = 26$ GPa

Poisson's Ratio
$\upsilon = 0.21$

Ultimate Strength
$\sigma_{compressive} = 110$ MPa (saturated)
$\sigma_{tensile} = 4$ MPa

Initial Conditions

In-Situ Stress $\sigma_{vertical} = 8.3$ MPa
$\sigma_{horizontal} = 3.0$ MPa

Temperature $T_o = 18°C$

Hydrologic

Intact-Rock Permeability
$K_i = 1 \times 10^{-17}$ m^2

Jointed-Rock Permeability
$K_j = 1 \times 10^{-12}$ to 1×10^{-10} m^2

Thermal Properties

Thermal Conductivity
$K_{sat} = 1.49$ W/m·K T <70°C
$K_{dry} = 1.11$ W/m·K T >120°C

Heat Capacity
$\rho C_{\rho sat} = 2674$ kJ/m^3·K T <70°C
$\rho C_{\rho dry} = 1641$ kJ/m^3·K T >120°C

Heat of Vaporization
$(\rho C_\rho)_T = 95°C = 6990$ kJ/m^3·K ($\phi = 16\%$)

Thermal Expansion
$\alpha = 9.5 \times 10^{-6}$ C^{-1} (T <200°C)

Emissivity
$\epsilon_{rock} = 0.6$

Summary

The purpose of this document is to introduce the concepts leading to the formulation of field experiments to be performed in G-Tunnel on the Nevada Test Site in order to address issues regarding the use of welded tuff as a host rock for a nuclear-waste repository. The issues have been defined and the technical justification for the experiments presented. Conceptual designs for five experiments that can be reasonably and economically conducted are outlined. These designs include modeling requirements and preliminary design material properties so that this document can serve as a reference for a detailed preliminary design and a later Test Plan.

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