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The Yucca Mountain Project Drift Scale Test

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ABSTRACT

The Yucca Mountain Project is currently evaluating the coupled thermal-mechanical-hydrological-chemical (TMHC) response of the potential repository host rock through an *in situ* thermal testing program. A Drift Scale Test (DST) was constructed during 1997 and heaters were turned on in December 1997. The DST includes nine canister-sized containers with thirty operating heaters each located within the heated drift (HD) and fifty "wing" heaters located in boreholes in both ribs with a total power output of nominally 210 kW. A total of 147 boreholes (combined length of 3.3 km) houses most of the over 3700 TMHC sensors connected with 201 km of cabling to a central data acquisition system. The DST is located in the Exploratory Studies Facility in a 5-m diameter drift approximately 50 m in length. Heating will last up to four years and cooling will last another four years. The rock mass surrounding the DST will experience a harsh thermal environment with rock surface temperatures expected to reach a maximum of about 200°C.

This paper describes the process of designing the DST. The first 38 m of the 50-m long Heated Drift (HD) is dedicated to collection of data that will lead to a better understanding of the complex coupled TMHC processes in the host rock of the proposed repository. The final 12 m is dedicated to evaluating the interactions between the heated rock mass and cast-in-place (CIP) concrete ground support systems at elevated temperatures. Instrumentation includes thermocouples, resistance temperature devices (RTDs), thermistors, multiple-point borehole extensometers (MPBXs) installed both from within and outside the DST, strain gages installed on the CIP concrete section, cross-drift displacement extensometers, humidity sensors, pressure transducers, electrical resistivity tomography, neutron logging, ground penetrating radar, absorbent pads for water collection, gas sampling ports, acoustic emission/microseismic sensors, an infrared/video camera system, and rapid evaluation of thermal conductivity and diffusivity probe systems. In addition to a description of the DST design, data from site characterization, and a general description of the analyses and analysis approach used to design the test and make pretest predictions are presented.

Test-scoping and pretest numerical predictions of one way thermal-hydrologic, thermal-mechanical, and thermal-chemical behaviors have been completed (TRW, 1997a). These analyses suggest that a dry-out zone will be created around the DST and a 10,000 m³ volume of rock will experience temperatures above 100°C. The HD will experience large stress increases, particularly in the crown of the drift. Thermoelastic displacements of up to about 16 mm are predicted for some thermomechanical gages. Additional analyses using more complex models will be performed during the conduct of the DST and the results compared with measured data.

KEYWORDS

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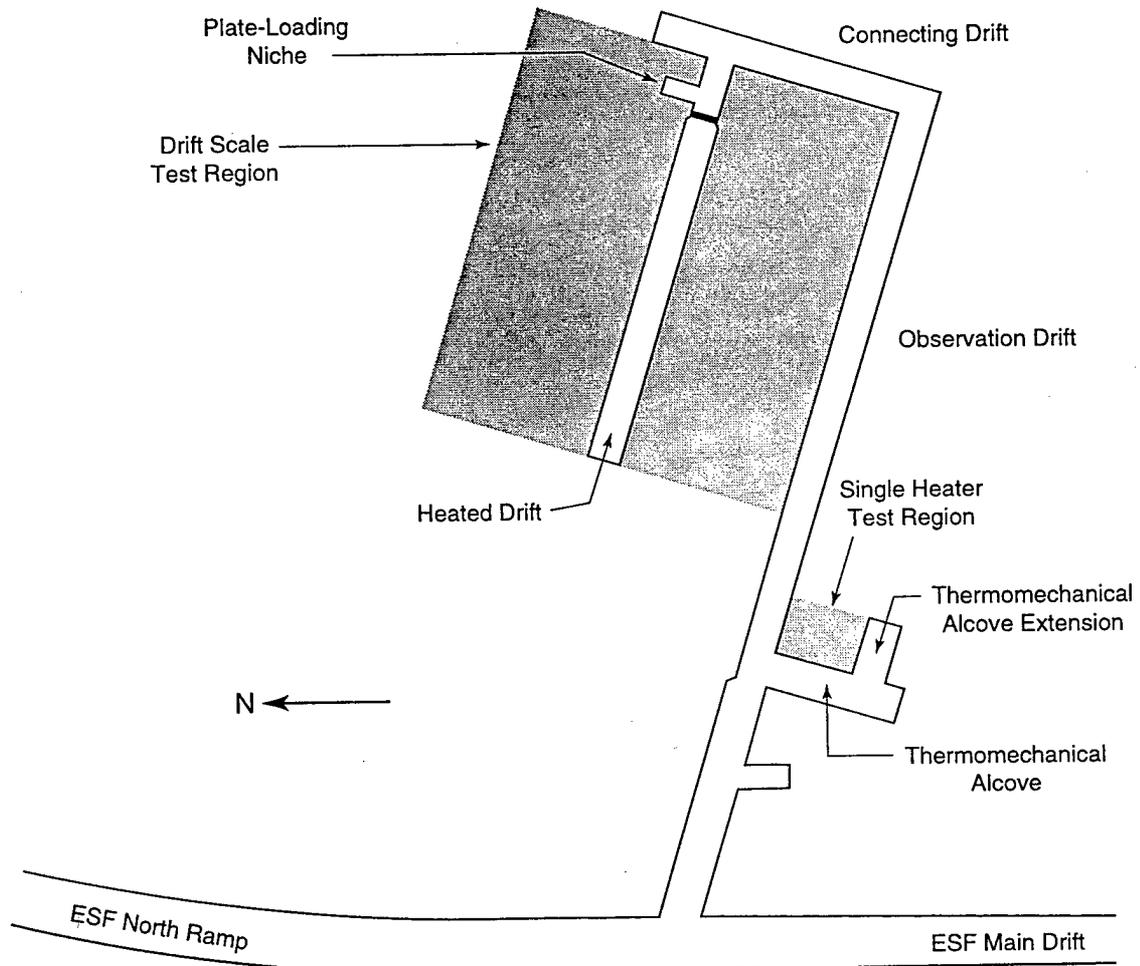
In situ testing, geomechanics, coupled processes thermal testing, numerical modeling.

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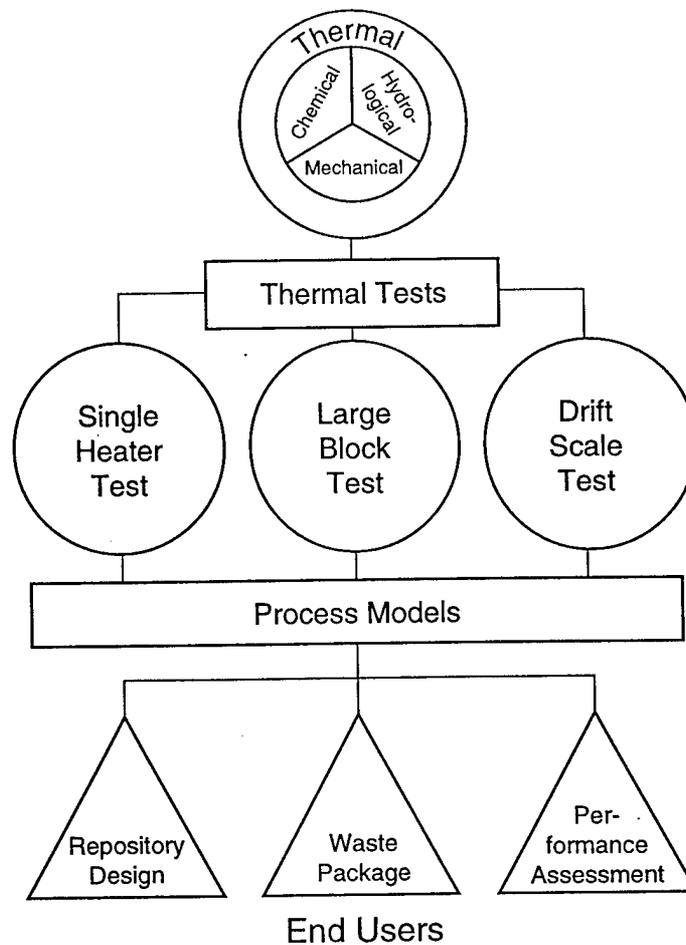
1. INTRODUCTION

The US Department of Energy (DOE) is evaluating Yucca Mountain, Nevada as a potential site for the emplacement and isolation in a geologic repository of commercial spent nuclear fuel, DOE spent nuclear fuel, and civilian and defense high-level waste. A part of this ongoing evaluation is an extensive characterization program intended to provide data and information on the nature and behavior of the proposed repository host rock. Recently, a thermal testing program has been initiated in the Exploratory Studies Facility (ESF) (Figure 1) at Yucca Mountain to evaluate the important and complex coupled thermal-mechanical-hydrological-chemical (TMHC) behavior expected to occur within and around the proposed repository. The thermal testing program at the Yucca Mountain Project (YMP) includes large- and small-scale field tests, bench and small-scale laboratory tests, and numerical modeling of experiments and designs (DOE, 1988; 1995). The numerical modeling represents an important component of the thermal testing program, as data from the tests will support greater understanding of the coupled processes and the development of conceptual models. The models in turn will be used to support performance assessments of the potential repository behavior. Currently, there are two thermal experiments under way in the ESF: a small Single Heater Test (SHT) and a larger Drift Scale Test (DST). A third thermal test, the Large Block Test, is being conducted in the same rock units exposed on the surface at Fran Ridge, approximately 8 km away. Figure 2 illustrates the coupled processes under investigation at Yucca Mountain and how they are interconnected. Figure 2 also illustrates how the ongoing thermal tests at YMP support the development of process models and shows the YMP customers for the thermal testing data.



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Figure 1: Plan view of the ESF thermal test facility showing the location of the DST



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Figure 2: Interrelationships among coupled processes, ESF thermal tests, process models, and end users

2. OBJECTIVES

The DST is conducted in a thick unsaturated zone in the Topopah Spring Welded Tuff lithologic unit (Tptpmn) (middle-nonlithophysal). The location of the thermal testing facility including the DST is shown schematically in Figure 1. A Plate-Loading niche is located in the northeastern quadrant of the DST. This niche will be used to conduct plate-loading tests to measure the deformability of the rock mass during the heating and cooling of the DST. The overall objectives of the DST are to characterize the TMHC processes that occur around the HD as the temperatures are increased. Specific objectives of the DST are listed below:

- **Thermal** (thermocouples, resistance temperature devices [RTDs], thermistors, rapid evaluation of thermal conductivity and diffusivity [REKA] probe, heater power)
 - Measure the temporal and spatial distribution of temperature.
 - Investigate heat transfer modes and possible formation of heat pipes.
 - Determine rock mass thermal properties.
- **Mechanical** (multiple point borehole extensometers [MPBXs], drift convergence meters, strain gages, plate loading, acoustic emission [AE])
 - Measure rock mass TM properties and response at ambient and elevated temperature.
 - Evaluate ground support response under controlled conditions.
 - Measure drift displacement at elevated temperature.
 - Observe effects of thermal loading on prototypical ground support systems.
- **Hydrological** (electrical resistance tomography [ERT], neutron logging, air-permeability testing, humidity sensors)
 - Measure changes in rock saturation particularly in the drying zone.
 - Monitor the propagation of drying and subsequent re-wetting regions, if any, including potential condensate cap and drainage.

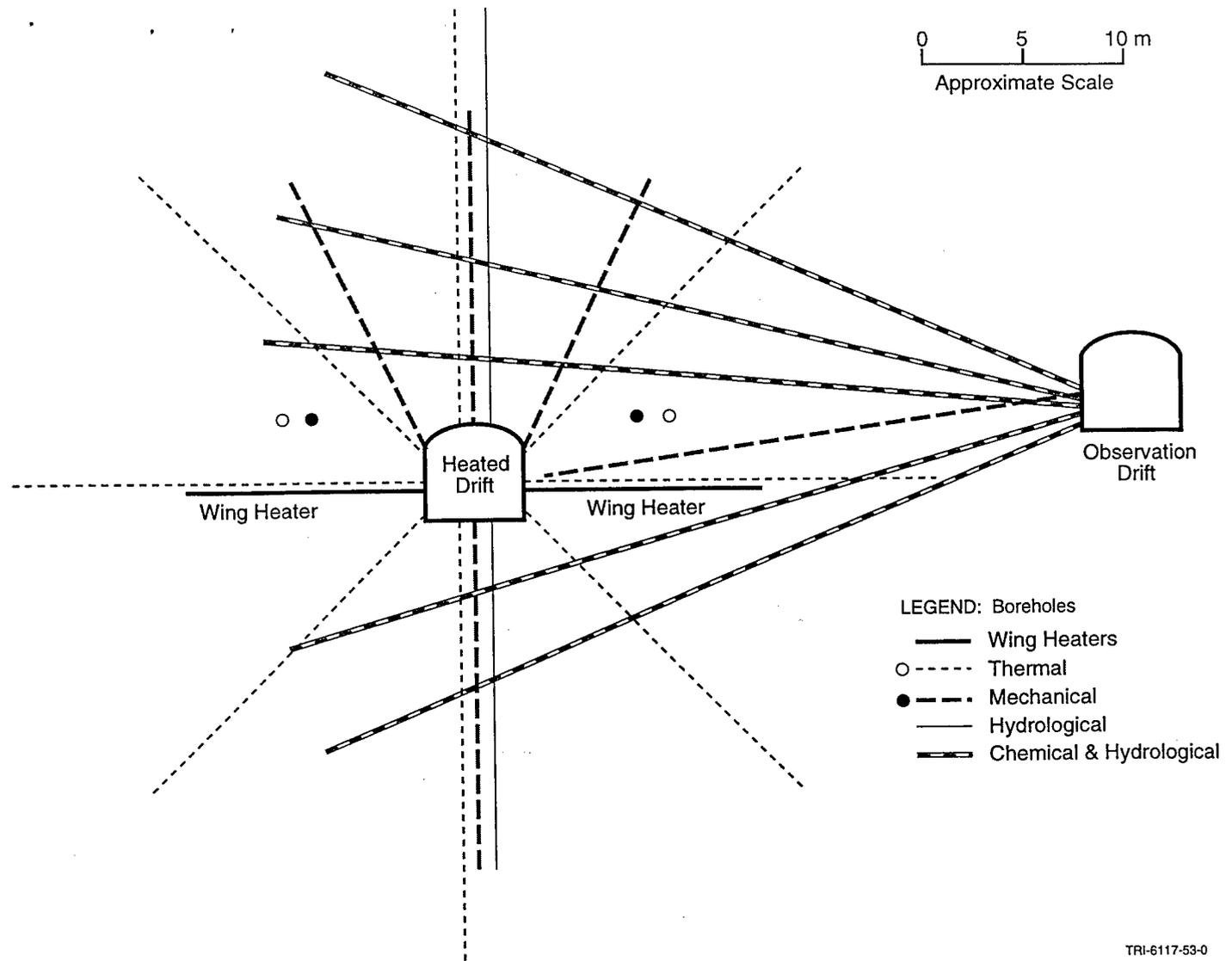
- Measure changes in bulk permeability (pneumatic).
- Measure drift-air humidity, temperature, and pressure.
- **Chemical** (absorbent pads, gas and water sampling ports, waste package coupons)
 - Observe corrosion products on typical waste package materials emplaced in the HD and boreholes.
 - Observe changes in water chemistry, mineralogy, and rock chemistry due to heating and subsequent cooling.
 - Observe impacts of introduced materials (ground support, etc.) on water and rock chemistry.
 - Observe thermal effects on ground support materials.
- **Overall**
 - Evaluate conceptual models that calculate the coupled TMHC behavior such that realistic bounds can be developed for the expected near-field environment.

3. TEST DESIGN

The test objectives are achieved by conducting the following steps, some iteratively: perform pretest numerical analyses of the expected DST behavior, perform pretest characterization of the "ambient" rock mass, install and monitor in situ instrumentation, heat the rock mass, and perform during and posttest numerical analyses of accumulated data. Figure 3 shows a representative instrumentation cross-section for the DST of wing heaters, and thermal, mechanical, hydrological, and chemical sensors installed in boreholes. The CIP section includes additional strain gage instrumentation to assist in evaluations of the CIP concrete performance under extreme thermal conditions as well as cross-drift displacement extensometers installed to measure the horizontal and vertical liner displacements. Heat is generated from 50 wing heaters in the rock mass on either side of the HD and nine floor canister-sized containers with thirty operating heaters each installed in the HD itself. These two types of electrical heaters have an initial combined nominal power output of 210 kW. The wing heaters are perpendicular to the longitudinal axis of the HD and are evenly distributed on 1.83m spacings in horizontal boreholes located on both walls of the HD. Each wing heater has 10m of heated length divided between inner and outer heating elements operated at nominal 1.1 kW and 1.7 kW power for the inner and outer segments, respectively. The TMHC response of the rock mass is measured with over 3700 sensors housed in 147 boreholes. The sensors are connected to an automated Hewlett Packard data acquisition system with an estimated 201 km of wire. The cumulative length of these boreholes is 3300m. The sensors are divided into the following categories with approximate numbers of gages each:

- 3000 thermal (thermocouples, RTDs, and thermistors)
- 128 mechanical (extensometers, resistive strain gages)
- 412 hydrological (humidity, pressure, ERT)
- 130 chemical

Numerous parameters, including temperature, heat flux, heater power, thermal expansion, thermal conductivity, moisture, water flux, water and gas chemistry, displacements, and ground support behavior, are measured and calculated from sensors installed from within the HD and from the Connecting and Observation drifts. Planned durations of the heating and cooling phases are four years apiece. It is expected that the heating phase will elevate temperatures above 100°C in more than 10,000 m³ of rock. The HD walls will not exceed 200°C during heating.



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Figure 3: Drift Scale Test typical instrumentation cross-section

4.0 DST CHARACTERIZATION

The rock mass surrounding the HD was characterized prior to initiating heating the DST. Laboratory tests on rock samples from boreholes in the test bed were conducted. These tests include intact rock laboratory thermal, mechanical, hydrological, and chemical properties. *In situ* characterization activities included: fracture mapping, rock mass classification, air permeability testing, infrared and video imaging, neutron logging, *in situ* thermal conductivity and thermal diffusivity (REKA probe), borehole video logging, and *in situ* stress measurements. Table 1 provides a summary of the *in situ* characterization for the DST area. This table provides only average and ranges of values for various measured parameters.

5.0 SCOPING AND PRETEST ANALYSES

The DST includes data collection, analyses, and evaluation activities. Data collection began prior to heater turn-on during an ambient data collection period. Likewise, analyses were conducted and are planned to be conducted during various phases of DST testing. The temporal relationship between the collection of data and use of data in the numerical modeling of coupled processes is shown in Table 2. Table 2 also lists potential computer codes for each of the four coupled processes expected to be manifested in the DST. A general "time line" is given that shows the relationship between the three stages of data collection and analysis for the DST: test-scoping, pretest, and mid/posttest. A distinction is made between test-scoping and

pretest analyses in that the latter analyses benefit from the characterization data (lab and field) collected prior to turning on the heaters whereas the scoping analyses used the current and best available data at the time. Also, for the DST, more than one combination of conceptual models was evaluated in the pretest analyses. Consequently, the pretest analyses provided more comprehensive and realistic simulations of the expected DST behavior than were provided by the test-scoping analyses.

TABLE 1
SUMMARY OF *IN SITU* CHARACTERIZATION DATA FROM THE ROCK MASS DST (TPTPMN UNIT)

Characterization Parameter	Average Value	Characterization Parameter	Average Value
Laboratory thermal conductivity (saturated, 30°C - T=70°C)	2.1 (W/mK)	<i>In situ</i> stress	$\sigma_h = 1.7$ MPa @ N75°W $\sigma_H = 2.9$ MPa @ N15°E $\sigma_v = 4.7$ MPa
Linear thermal expansion coefficient (heating cycle, 25°C - 325°C)	7.34 - 52.28 ($10^{-6}/^{\circ}\text{C}$)	Air permeability	10^{-13} m ²
Lab mechanical (modulus, Poisson's ratio, unconfined compressive strength)	E = 28.9 - 43.1 GPa v = 0.17 - 0.34 $\sigma_f = 71 - 324$ MPa (unconfined)	Rock mass quality assessment (rock mass rating [RMR], Q)	64.4 = RMR = 97.0 1.7 = Q = 621.9
Lab hydrological (wet drill) (saturation porosity, density, water content)	S = 93% $\phi = 13\%$ $\rho_{\text{bulk}} = 2.20$ $\rho_{\text{particle}} = 2.51$ water content = .053 (g/g)	REKA probe	thermal conductivity = 1.84 (W/mK) thermal diffusivity = 0.99×10^{-6} (m ² /s)
Lab hydrological (dry drill) (saturation porosity, density, water content)	S = 84% $\phi = 11\%$ $\rho_{\text{bulk}} = 2.25$ $\rho_{\text{particle}} = 2.51$ water content = .039 (g/g)	Lab chemistry testing Fracture mapping	water chemistry & min/pet full periphery fracture maps

TABLE 2
TEMPORAL RELATIONSHIPS AMONG DATA COLLECTION, NUMERICAL ANALYSES, AND COMPUTER PROGRAMS FOR THE DRIFT SCALE TEST

Time →			
Data	Test Planning YMP General Characterization	Pretest Site-Specific DST Characterization	During Test/Posttest Measurements
Analyses (Models)	Test-Scoping	Pretest Forecast	During Test or Posttest Model Refinement
Codes include:	Thermal	(e.g. V-TOUGH, NUFT, TOUGH2, COYOTE FEHM, ANSYS)	
	Mechanical	(e.g., FLAC, UDEC, DDA, ANSYS, JAC3D, JAS3D)	
	Hydrological	(e.g., FEHM, NUFT, V-TOUGH, TOUGH2, FEMTRAN)	
	Chemical	(e.g., EQ3/6, OS3D, GIMRT, FEHM, NUFT)	

In the broadest sense, the DST is intended to generate site-specific observed data to build confidence in the conceptual models describing the heat-driven processes taking place in the rock mass adjacent to the potential repository openings (the near-field), both during the preclosure and postclosure periods of

performance. The test-scoping analyses, using best available information at the time, are examples of models of the near-field processes.

Scoping analyses provided guidance for the selection of test features such as the size, location, and power output of heaters, and spatial location of the instrumentation. In contrast, the pretest predictions provide baseline predictions of measured parameters such as temperature, displacement, and moisture content. As data from the test become available, synergistic, interpretative evaluations of the agreement between measured and predicted data will help to confirm and/or refine the models, and thereby build confidence in the models and modeling approaches.

Figure 2 presented the possible couplings among the TMHC processes expected to occur during the DST. As indicated in the figure, the couplings have been intuitively but not rigorously divided into primary and secondary relationships. This notion of the TMHC coupled processes represents a more complex relationship than has been considered thus far in modeling. To this point, one-way coupling between thermal and the other three processes has generally been considered. Ultimately, the assessment (and modeling of) TMHC coupled processes will evolve to the extent practical into nearly instantaneous four-way coupling. Naturally, the less complex couplings must first be characterized and understood by the proposed series of data comparisons and model evaluations in the DST.

The scoping and pretest analyses (TRW, 1997) were conducted to guide the DST design and to predict behavior prior to heater activation. One-way coupling of the TMHC processes was employed for these analyses. Thermo-hydrological analyses were first performed, and the resulting temperatures were used as input in the TM and TC analyses of the DST and surrounding rock mass. The thermomechanical analyses provide predictions of stress and displacement in the rock mass surrounding the DST resulting from the induced temperature changes. The predicted stresses and displacements will be compared to the *in situ* measurements during the conduct of the DST. The adequacy of the models to predict observed behavior will be evaluated and alternative modeling approaches will be proposed if necessary. An example of the pretest thermomechanical analyses is presented in Figures 4 and 5. Figure 4 presents a three-dimensional mesh that was used in conjunction with a Sandia National Laboratories structural code (JAC3D) to provide pretest predictions of the rock mass thermomechanical behavior during conduct of the DST (Sobolik *et al.*, 1997). This mesh includes material descriptions for the rock mass, concrete invert segments, and concrete liner. The element death option was used to simulate mining of the HD. Temperatures from TH analyses were input into JAC3D at various time steps and the thermoelastic response of the rock mass was calculated. For these pretest analyses, a range of rock mass properties was used, including high and low bulk permeability (K_b), intact and *in situ* modulus, and intact and *in situ* thermal expansion coefficients. *In situ* values of rock mass modulus and thermal expansion coefficient are derived from SHT data. Figure 5 shows a comparison of the JAC3D results for an MPBX drilled upward from near the midpoint of the HD using a range of parameters. The base case includes low bulk rock mass permeability and laboratory modulus and thermal expansion. For the other cases, parameters were varied to evaluate the model sensitivity to differences in input parameters. Clearly, the selection of material properties can have a significant influence on predicted response. Additional analyses are planned with more complex material models and refined mesh.

6. SUMMARY

The DST is under way at Yucca Mountain; the heaters were turned on December 3, 1997. The test is currently planned to continue for up to four years of heating and four years of cooling. The DST includes nine large canister-sized containers with thirty operating heaters each, located within the drift and fifty "wing" heaters located in boreholes in both ribs with a total nominal power output of 210 kW. A total of 147 boreholes (combined length of 3.3 km) house most of the over 3700 TMHC sensors connected with 201 km of cabling to a central data acquisition system. Test-scoping and pretest numerical predictions of one way thermal-hydrological, thermal-mechanical, and thermal-chemical behaviors have been completed (TRW, 1997). These analyses suggest that a dry-out zone will be created around the DST and a 10,000 m³ volume of rock will experience temperatures above 100°C. The HD will experience large stress increases,

particularly in the crown of the drift. Thermoelastic displacements of up to about 16 mm are predicted for some thermomechanical gages. Additional analyses using more complex models will be performed during the conduct of the DST and the results compared with measured data.

Data will continue to be collected and periodically reported. A series of comparative analyses will be performed during and after the DST to evaluate the various coupled TMHC processes observed during the test. Constitutive models of the DST behavior will be evaluated, developed, and compared with the acquired data. The net result of the entire thermal testing efforts at Yucca Mountain will lead to a greater understanding of the effects of temperature on repository behavior. This understanding will be used to support upcoming performance assessments of potential repository behavior.

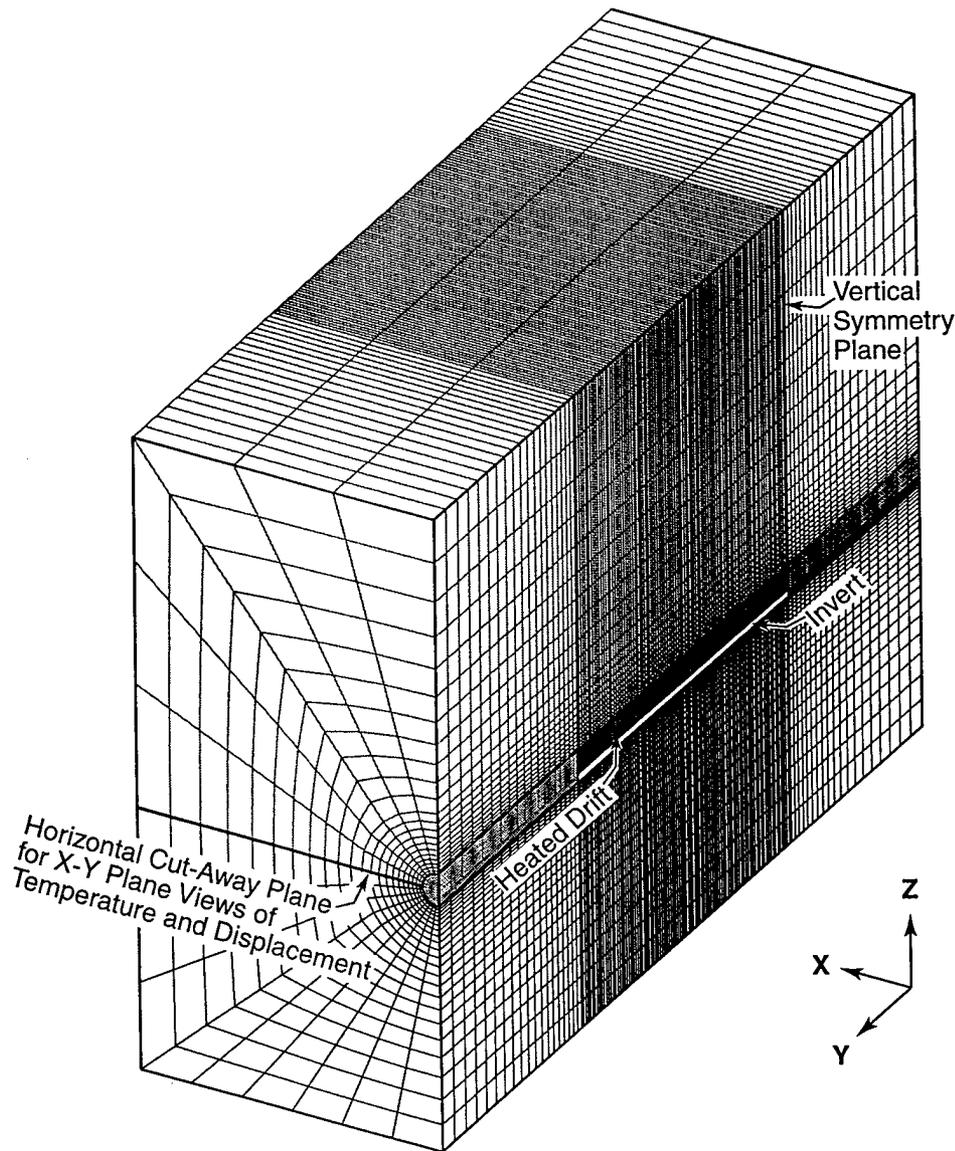


Figure 4: Three-dimensional mesh of the heated drift used for the JAC3D thermomechanical pretest analyses

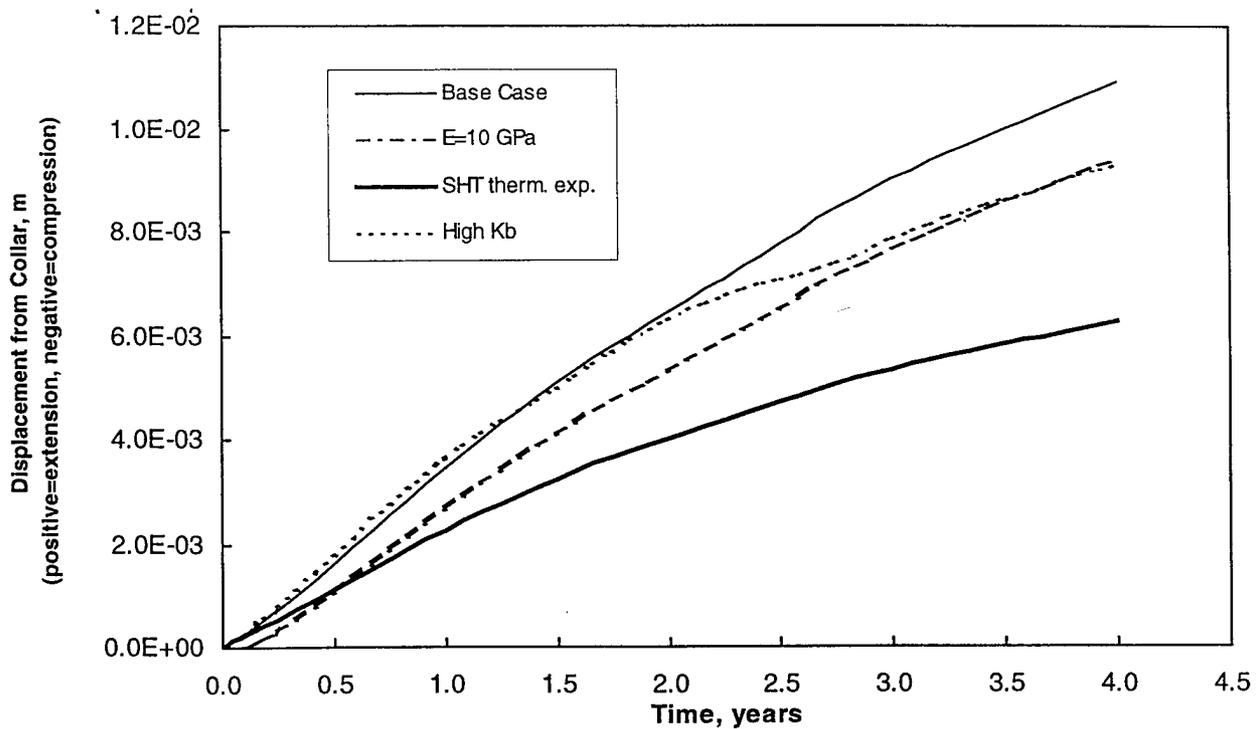


Figure 5: Comparison of predicted displacement for an MPBX drilled upward from near the midpoint of the HD for various thermomechanical pretest analyses

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