In Situ Thermomechanical Properties Study Plan 8.3.1.15.1.6

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ABSTRACT

The In Situ Thermomechanical Properties Study Plan describes a set of thermal experiments to be conducted in the Exploratory Studies Facility (ESF), along with a detailed rationale for conducting the tests. The information to be obtained from these experiments will be used: (1) to determine in situ rock-mass thermal, mechanical and thermomechanical properties; (2) to evaluate drift stability under thermal loading; (3) to evaluate the interaction of ground support in underground openings with the surrounding rock-mass under thermal loading; and (4) to examine the near-field thermal-mechanical-hydrologic environment. Three complementary tests, along with alternative configurations, are proposed: Single Element Heater Tests, Plate-Source Thermal Tests, and an Emplacement Drift Thermal Test. A Single Element Heater Test consists of emplacing a long heater rod into the wall or roof of an alcove, instrumenting the surrounding rock-mass, and measuring the thermal response. A Plate-Source Thermal Test consists of emplacing a row of long heater rods into the wall of an alcove, instrumenting the surrounding rock mass, and measuring the thermal response. Plate-loading apparatus will also be installed in the test alcove as part of this test. The Emplacement Drift Thermal Test simulates an underground waste emplacement drift.

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1.0 PURPOSE AND OBJECTIVES

The experiments in the In Situ Thermomechanical Properties study are designed to provide a set of data for use in determining site suitability, for direct input into repository design, for model development and validation, and for assessments of preclosure safety and postclosure performance. These data consist of rock-mass properties over a range of temperature, information on drift response and stability under thermal loading, information on the interaction of ground support with the rock mass at elevated temperatures, and information on the near field thermal-mechanical-hydrologic-chemical environment.

In Chapter 1, the purpose and objectives of the In Situ Thermomechanical Properties study are discussed. Chapter 2 describes a suite of experiments intended to span the possible test designs required to satisfy the objectives of the study. Chapter 3, Application of Results, discusses how the data to be obtained from the tests will be used. The tests described in this study, in addition to the supplying the data to meet the objective of this study, will also provide data to support other studies, particularly studies that investigate other coupled thermal processes.

Thermomechanical data needs and conceptual designs of thermomechanical tests were presented in the Site Characterization Plan (SCP) (U.S. DOE, 1988). Since that time, a number of events have occurred which have caused the tests planned under the thermomechanical study to be changed. In Section 1.1, the thermomechanical data needs that were identified in the SCP are presented. In Section 1.2, events in the Yucca Mountain Site Characterization Program (YMP) that have occurred since the SCP was issued which impact the in situ thermomechanical tests are discussed. In Section 1.3, the re-evaluation of data needs that was conducted in response to the events occurring in the YMP program is discussed. In Section 1.4, the results of the re-evaluation of data needs is presented. In Section 1.5, the strategies that led to the current conceptual thermomechanical test designs are discussed.

1.1 SCP Approach

The design of the repository system cannot be accomplished without close coordination between the site characterization program and performance assessment. The ability to demonstrate that the design meets the regulatory requirements relies heavily on performance assessments performed at the system and subsystem levels, using data and parameters developed from the site characterization program. The SCP laid out a strategy of assuring compliance with the regulatory requirements by embodying those requirements in a set of *issues*. The SCP issues hierarchy contains four key issues, leading to a second level of issues, then to a level of information needs. The issues that form the second level are grouped as performance assessment and design issues under each key issue. Regulatory and functional requirements imposed on the repository system are embodied in these issues. The third level consists of information needs, which are groupings of activities and data needs appropriate to the resolution of an issue. The information needs are to be addressed by the site characterization program and by specific performance analyses and subsystem designs, as necessary for resolution of each issue. Issues would then be resolved by using the related information and performance analyses to demonstrate that the design meets the performance needed to resolve the issue. The needed performance was established through the

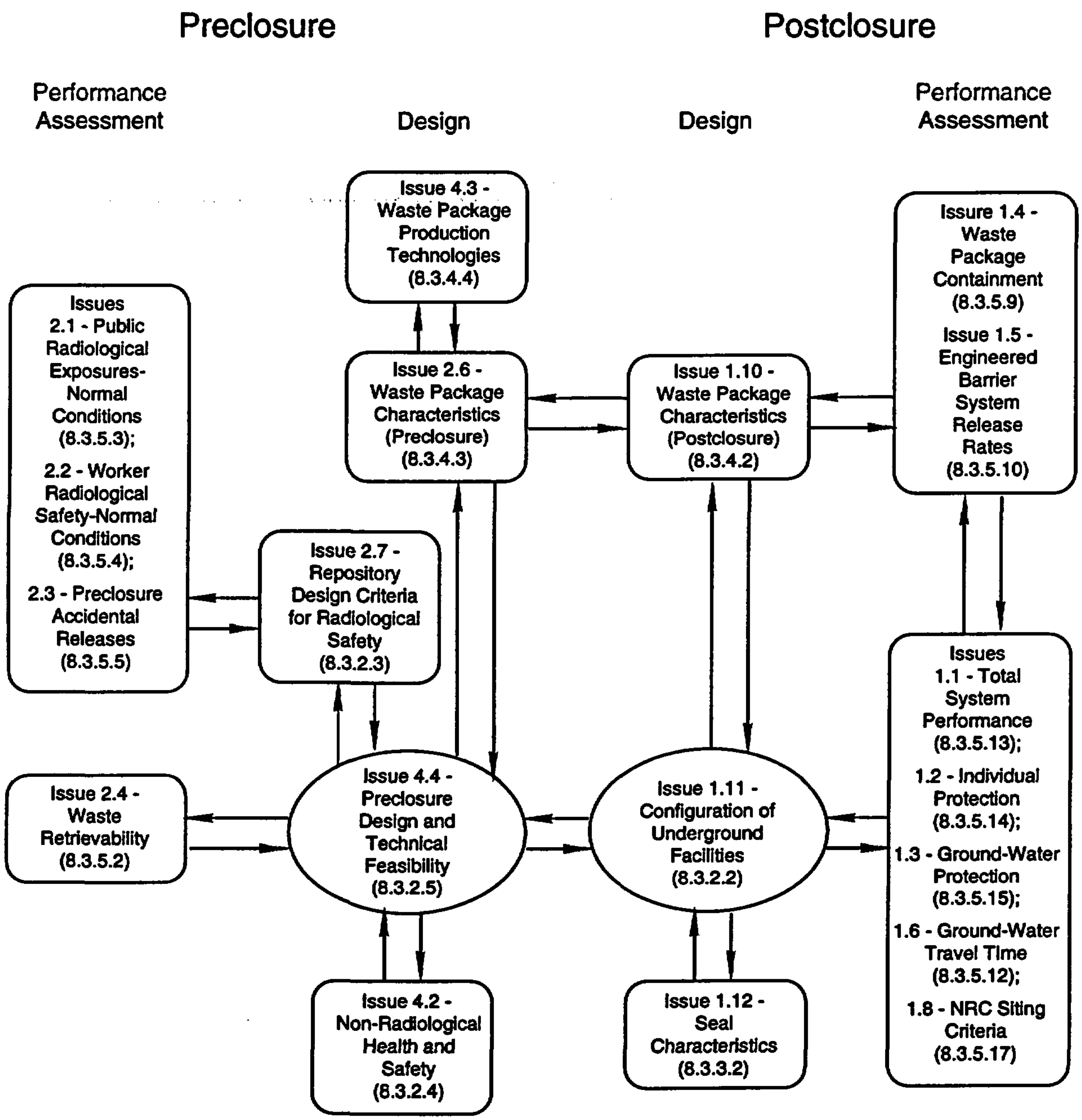


Figure 1. Relationships between design and performance related issues used directly in performance allocation.

performance allocation process. The interaction between design and performance assessment that is needed to determine performance goals and resolve issues is illustrated in Figure 1. A more complete discussion of the issues hierarchy can be found in Section 8.2 of the SCP (DOE, 1988).

In Section 8.3 of the SCP, a number of in situ tests were proposed to investigate various aspects of thermal performance. These tests included measurement of thermal properties, investigations of thermomechanical effects on room stability, and coupled thermal-mechanical-hydrological-chemical (T-M-H-C) processes that may affect the near-field and waste package performance or the far-field natural system performance. The objective of this suite of tests was to provide data for use in determining site suitability, for direct input into repository design, for model development and validation, and for performance assessments of preclosure safety and postclosure performance. In the SCP, the conceptual nature of the testing program was discussed along with the explicit ties to the data needs. Each test was expected to provide primary or confirmatory information for resolving specific performance and design issues within the SCP issues hierarchy. The tests were divided into two main categories: tests focused principally on thermal-mechanical processes to resolve preclosure and postclosure repository design issues (Section 8.3.1.15.1), and tests focused on resolving postclosure waste package design and near-field performance issues (Section 8.3.4.2.4). Table 1 provides a summary of some of the issues and information/data needs addressed by the in situ thermal testing program.

The issues covered by this study plan are those in the Thermal/Mechanical Study Tests. The issues denoted by Waste Package/Near-Field Environment Tests, although addressed by the tests described in this Study Plan, are outside the scope of this study and will be covered under Study Plan 8.3.4.2.2.4.

1.2 Changes from the SCP

The basic issues and information needs identified in the SCP have not changed substantially. However, the tests planned under the In Situ Thermomechanical Properties study have changed for a number of reasons. First, a significant effort was made to consolidate SCP tests. Second, the DOE issued the Program Approach (DOE 5 Year Plan), which changed the strategy of site characterization. Third, changes have been made to the conceptual design of the repository from the conceptual design in the SCP.

1.2.1 Test Consolidation

- The conceptual thermal tests described in this study plan represent a concerted effort to consolidate tests described in the SCP in order to resolve all the data needs identified as efficiently as possible. Three complementary tests have been developed and are described in Chapter 2. The tests represent a strategy based on starting with simpler, smaller-scale tests and progressing to more complex and larger-scale tests. The three proposed tests are:
- Single-Element Heater Tests,
- Plate-Source Thermal Tests, and
- Emplacement Drift Thermal Test.

Table 1. SCP Issues and Data Needs

Testing Program	Issues	Information/Data Needs
Thermal/ Mechanical Tests	1.6 Ground Water Travel Time 1.10 Waste Package-Postclosure 1.11 Underground Configuration-Postclosure 1.12 Shaft and Borehole Seals 2.4 Waste Retrievability 4.2 Nonradiological Health and Safety 4.4 Preclosure Design/Feasibility	• Thermal properties of the rock mass • Thermal expansion • Deformation modulus at elevated temperature • Mechanical properties of fractures at elevated temperature • Thermal performance of backfill materials • Near-field permeability changes at elevated temperature • Thermal effects on ground support
Waste Package/ Near-Field Environment Tests	1.10 Waste Package-Postclosure	• Near-field thermal history • Distribution of liquid water and saturation levels • Changes in near-field mineralogy and fluid chemistry resulting from thermal loading • Changes in near-field hydrologic properties resulting from thermal loading • Rock-mass thermal and mechanical properties • Mechanical and hydrological properties of fractures

These three tests can resolve data and information needs previously addressed by the following eight SCP tests (SCP Sections 8.3.1.15.1.5, 8.3.1.15.1.6, 8.3.1.15.1.7, and 8.3.4.2.2.4):

- Heater Test in TSw1,
- Canister-Scale Heater Test,
- Heated Block Test,

- Thermal Stress Test,
- Heated Room Test,
- Sequential Drift Mining Experiment,
- Plate Loading Test, and
- Engineered Barrier Field Tests.

Thus the conceptual thermal tests presented in this document represent a consolidation of previously defined tests that should result in a more efficient use of Project resources (e.g., through a reduction in redundant data collection activities).

1.2.2 Program Approach

Recently the Yucca Mountain Site Characterization Project implemented the Program Approach, which was a step-wise approach to licensing that would, for the Viability Assessment and the license application to construct a repository, require that the Project rely on less site information than previously planned. Additional testing done beyond 2001 would improve our understanding of key processes and would support license updates. This approach required a rethinking of the testing program. While the Program Approach is no longer the planning basis for the YMP, the test consolidation activities resulting form this programmatic change are still valid and are presented in this Study Plan.

Additional information on how the Program Approach has influenced these tests can be found in the report "A Thermal Testing Program for the Program Approach" (U.S. DOE, 1995).

1.2.3 Changes to the SCP Conceptual Design

In addition to simple parameter measurement, the test objectives included the need to validate thermal and mechanical models to be used for repository design and performance assessment, as well as the need to demonstrate that regulatory requirements could be met. The embodiment of these objectives into the test program required some tests that simulated the repository emplacement geometry and thermal loading strategy. The current repository design and the use of an in-drift waste emplacement system would dictate some changes in the thermal testing program even in the absence of the Program Approach. Table 2 lists the major differences between the SCP conceptual design approach and the current design approach.

Table 2. Major Changes to the SCP Approach

SCP Conceptual Design	Current Design
Small waste package (3 PWR or 6 BWR assemblies)	In-drift waste package (12 to 24 PWR or 24 to 44 BWR assemblies)
In-borehole emplacement	In-drift emplacement
57 kW/acre thermal load with flexibility to go up or down.	Preserve flexibility to define repository thermal load based on overall system performance
Drill and blast construction	Mechanical excavation
Ground support in emplacement rooms appropriate for rock conditions with the ability to perform maintenance	Ground support in emplacement rooms conservative with limited ability to perform maintenance
50-year preclosure period	100-year preclosure period

1.3 Re-evaluation of Data Needs

Given the Program Approach and changes to the SCP conceptual design, the data needs identified in the SCP were revisited. As the supplier of data, the test community worked with the end users or "customers" of the data to reach agreement on the basic information and data that the test program should provide. Major customers for thermal test data include waste package and repository design, preclosure and postclosure performance assessment, and licensing and site suitability activities. These requirements fit within the basic licensing framework outlined in the SCP (i.e., the issues resolution strategy) and also meet with the current needs of the Project.

As noted before, the tests described in this study plan are a result of a concerted effort at test consolidation. As a result, the tests described in this Study Plan will supply information not only for this study, but also will supply information for other studies. A discussion of the additional uses of data from the tests described in this Study Plan will be given in Study Plan 8.3.4.2.2.4 (Engineered Barrier Field Tests).

Table 3 provides a summary of the identified information needs and the principal customers for that information. (It should be noted that repository design has currently defined its data needs in *Repository Design Data Needs* (BC000000-01717-5705-0012 Rev 00) and that the test community will continue to follow procedure QAP 3-12 or equivalent in obtaining design information so that appropriate test designs are achieved.) The data and information needs summarized in Table 3 are essentially the same as those identified in the SCP. The Program Approach tried to identify the level of maturity or completeness in the information that was expected at each step in the process Table 3 indicates the associated completeness level for license application to construct a repository for each information need. *Level of completeness* indicators used in the Program Approach description of activities are:

Table 3. Summary of Information Needs for Licensing Application to Construct a Repository

Data and Information Needs	Customers			
	Waste Package Design	Repository Design	Preclosure Performance Assessment	Postclosure Performance Assessment
Near-field T-M-H-C environment				
• Conductive/convective heat transfer	B	B	B	B
Rock-mass properties over a range of temperature				
• Thermal capacity or specific heat	SF	SF	SF	B
• Thermal conductivity	SF	SF	SF	B
• Thermal expansion		SF	SF	B
• Deformation modulus		SF	SF	B
• Strength		B	B	B
• Normal and shear compliance of fractures		B	SF*	
• Shear strength of fractures		B	SF*	
• Cohesion of fractures		B	SF*	
Drift response/stability under thermal conditions	B	B	B	B
Ground support and design features interactions at elevated temperature				
• Rock mass-ground support interaction		B	B	
• T-H properties of backfill	C			C
• In situ WP material corrosion rates	C			C

*To achieve the stated level of confidence, laboratory or bench-scale tests are required. In situ tests can only provide gross estimates.

Nomenclature: C-Conservative, B-Bounded, SF-Substantially Finished,(blank indicates no need identified)

- **Conservative (C):** Sufficient data and information are available to support a single estimate of a credible extreme or worst-case parameter value, process, condition, scenario, or set of model assumptions.
- **Bounded (B):** Sufficient data and information are available to establish realistic and defensible, either or both, upper and lower extreme for all credible parameter values, processes, conditions, scenarios, or model assumptions relevant to the study.

- **Substantially Finished (SF):** Study has been completed to the point that additional data collection or analyses are considered unlikely to change major results or conclusions.

The assignment of these indicators was based on working group assessments of the level of confidence that each SCP Study Plan could achieve before licensing. These assessments were conducted as part of the development of the Program Approach.

In order to meet customer needs, it is highly desirable to be able to conduct the bulk of the tests in TSw2, with some testing potentially needed in the high-lithophysal region of TSw1. It is also possible to gain some relevant information by testing in the low-lithophysal region of TSw1. Thermal tests can be conducted in drill-and-blast alcoves with no impact on the quality of tests. However, the larger-scale drift stability and drift-scale T-M-H-C phenomenological tests should be conducted in drifts that closely simulate repository emplacement drifts. If mechanical excavation methods will not be available, the tests can still be conducted, but some modifications may be necessary and the data may not be as reliable for predicting future repository performance. This simply requires a testing strategy that is flexible enough to accommodate alternate construction methods.

1.4 Current data and information needs

Current data and information needs were listed in Table 3 above. A more detailed discussion of these needs is presented below.

1.4.1 In Situ Rock-Mass Properties

In situ rock-mass properties to be measured include thermal capacity, thermal conductivity, thermal expansion, deformation modulus, and strength. Each of these properties will also be measured in the laboratory under other studies. The controlled conditions and large number of tests that can be conducted in the laboratory allow for detailed investigation of the material properties, and for the investigation of such issues as variability, the effects of saturation, temperature dependence, time dependence, etc. The in situ experiments are required to validate the extrapolation of the laboratory measurements up to the rock-mass scale.

The thermal capacity, thermal conductivity, and thermal expansion of intact rock samples are being measured in the laboratory under study plans 8.3.1.15.1.1 (Laboratory Thermal Properties) and 8.3.1.15.1.2 (Laboratory Thermal Expansion Tests). The in situ experiments governed by this study are needed to confirm that these properties are valid on the scale of the rock-mass, which is composed of not only intact rock but also of fracture and lithophysae.

The compliance of intact rock samples is being measured in the laboratory under study 8.3.1.15.1.3 (Laboratory Determination of the Mechanical Properties of Intact Rock), and the compliance of individual fractures is being measured in the laboratory under study 8.3.1.15.1.4 (Laboratory Determination of the Mechanical Properties of Fractures). In situ rock-mass deformation measurements at ambient temperature will be made under study 8.3.1.15.1.7 (In Situ Mechanical Properties). However, additional measurements will be made under this study for two reasons. First, this study will provide in situ measurements of deformation modulus not only at ambient temperature but also at elevated temperatures. Second, measurements of deformation modulus will be made under this study because the use of thermal loading is an efficient way to generate high in-situ stresses.

In situ measurement of rock-mass strength is similar to in situ measurement of rock-mass deformation modulus. Laboratory measurements of intact rock strength are being conducted under study 8.3.1.15.1.3 (Laboratory Determination of the Mechanical Properties of Intact Rock) and laboratory measurements of shear strength and cohesion are being conducted under study 8.3.1.15.1.4 (Laboratory Determination of the Mechanical Properties of Fractures). In situ measurements are required to confirm these predictions. Rock-mass strength under ambient temperature will be measured under study 8.3.1.15.1.7 (In Situ Mechanical Properties). However, rock-mass strength will also be measured in this study because this property must be known under elevated temperature conditions and because thermal loading is an effective way to generate the high stresses required to cause failure.

1.4.2 Drift Stability under Thermal Loading

The effect of elevated temperatures makes the potential repository unique among underground civil construction projects. Design methods used for other underground openings, based on empirical data bases, are not directly applicable to repository openings at elevated temperatures. This study will be used to extrapolate current design methods used to design stable underground openings for use in designing underground openings that will experience high thermal loading by (1) providing direct simulation of repository conditions and (2) providing data that can be used to calibrate thermal-mechanical rock-mass numerical methods.

Directly simulating repository conditions provides useful data for designing repository openings that will be subjected to thermal loads. There are limitations, however, to direct simulation. First, repository conditions cannot be completely simulated. The simulation must be conducted in a much shorter time period than what will occur in a repository. The maximum temperatures and stresses expected in a repository may be simulated, but because of the much shorter time of the simulation compared to what will occur in a repository, temperature and stress gradients will be significantly different. Second, direct simulations of a repository will be limited to, at most, very few configurations. Repository designers will need to predict drift stability for different drift sizes, shapes, and configurations; different thermal loadings; and different rock-mass qualities.

Numerical methods are therefore required to extrapolate test results from a very limited number of thermal tests to the different configurations and conditions that will occur in a repository. In order to have confidence in results from numerical methods, the codes to be used must be calibrated against the in situ tests.

1.4.3 Ground Support—Rock-Mass Interaction at Elevated Temperatures

Elevated temperatures can cause degradation of ground support performance because of degradation of the ground support materials and induced stress resulting from the differences in the thermal expansion of the ground supports and the rock-mass. Because the elevated temperatures of a repository are not typical for civil underground construction, the effects of elevated temperature on ground support are not known. By including different types of ground support in the in situ thermomechanical properties study test drifts, the effects of elevated temperatures on ground support will be investigated.

1.4.4 Near Field Thermal-Mechanical-Hydrologic Environments

In a repository, the thermal, mechanical, hydrologic, and chemical responses of the rock mass will all be coupled. The in situ thermomechanical properties study will examine one aspect of thermal-mechanical-hydrologic coupling.

As a result of construction and thermal loading, fracture apertures will change. Changes in fracture aperture will result in changes in the permeability of the rock mass. Both increases and decreases in fracture apertures, resulting in both increases and decreases in permeability of the rock mass, are expected in the near field surrounding repository openings. Changes in permeability of the rock mass will result in changes to the flow of fluids in the rock mass. These changes in flow must be understood to assess the performance of the repository in isolating waste. The in situ thermomechanical properties experiments will investigate the changes in fracture apertures resulting from construction and thermal loading.

1.4.5 Data to be Collected under Other Studies

The tests described in this study, in addition to supplying the information summarized above, will also supply data for other studies. The additional data will be described in Study Plan 8.3.4.2.2.4 (Engineered Barrier Field Tests). Using the same tests to collect data needs addressed by different studies was the result of a concerted effort to consolidate thermal tests. (U.S. DOE, 1995) These additional data needs include information on the near-field environment (changes in rock saturation, drift humidity, water chemistry, mineralogical changes, propagation of a drying front, residual water saturation in the "dry zone," and drainage/reflux of liquid by fracture flow) and interactions of design features at elevated temperatures (effect of materials on near-field water chemistry, thermal-hydrologic properties of backfill, and in situ waste package material corrosion rates).

1.5 Revision of SCP tests

Current test design concepts, which are discussed in Chapter 2, are based upon the SCP thermal testing program but modified by the concerted effort of test consolidation, the impact of the Program Approach, and changes from the original SCP conceptual design of the repository. In addition, thermal test experience developed over the past decade from other projects such as the Waste Isolation Pilot Plant, and the extensive laboratory testing and coupled model analyses conducted during the past few years, all contributed to the conceptual designs of the tests (a discussion of lessons learned can be found in U.S. DOE, 1995). It should be emphasized, however, that the test concepts were derived specifically to meet the program and customer requirements, information needs, and objectives. In addition, the following assumptions or strategies were employed as part of the test definition process:

- Only tests with a thermal component were defined. Standard rock mechanics tests needed to develop data, principally for repository design, were not included. They are the subject of other study areas and will be addressed separately.
- The in situ tests are defined at a conceptual level based on generic analyses and a basic understanding of the physical processes involved. To date no detailed analyses of the specific test configurations presented here have been conducted. These will be done as the test program is refined and detailed designs of the individual tests are completed.
- A concerted effort was made to define a complete and integrated set of tests that is phased so that simpler tests are conducted first and (1) actual field testing could begin as early as possible; (2) the experience gained in fielding the early, simpler tests can be used in the final design and fielding of larger, more complex (and expensive) tests; and (3) testing is accomplished at increasingly larger rock-mass scales to develop some understanding of the effect of scale on the phenomena of interest and the threshold at which specific phenomena manifest themselves.
- To reduce construction time and cost, an attempt was made to reduce, as much as possible, the amount of drifting, alcove construction, and complex test and facility geometries.
- Alternative test locations, geometries, and numbers are proposed in an effort to allow the proposed test program maximum flexibility. Also, where possible, an attempt was made to take advantage of opportunities afforded by the ESF design, layout, or construction sequence.
- Preferences were specified for construction methods, but it is realized that machine excavated openings may not be feasible. Thus alternatives to machine excavation were considered.

2.0 SCOPE OF WORK

In this section a suite of in situ thermal tests are described that (1) will provide the desired data and information needs summarized in Chapter 1, (2) are simple and flexible enough to fit within the construction and operational constraints of the ESF during the early construction period, (3) are integrated with the recommended laboratory testing to enhance the level of information generated, (4) can be traced to Study Plans identified in the SCP, thus negating the need for large-scale baseline changes in the testing program, and (5) will provide data and information necessary for the evaluation of conceptual models and hypotheses. It must be emphasized, however, that the tests proposed here are not simply a selection of tests defined in the SCP. The set of tests discussed below were derived from a careful examination of the requirements, from past experience and lessons learned in thermal field tests, and from the need to integrate the information derived from these tests with laboratory test data to form a complete set of information for licensing.

2.1 Description of In Situ Thermal Tests

The proposed ESF tests described in this Study Plan are presented in general order of scale and complexity. The first test, the *single-element heater test*, is intended to represent the first step in the "testing" strategy. The volume of rock energized above boiling by this test will be on the order of 1 m radially from the heater. Rock-mass properties and coupled process investigations are the focus of the single-element heater test. Because the physical scale of the single-element heater test may not result in the activation of a network of fractures, the *plate-source thermal test* is proposed. The plate-source thermal test is intended to raise a significantly larger volume of rock above boiling, with a large portion of the rock-mass response intended to be one-dimensional. The scale and geometry of the plate-source test should therefore increase the potential for the development of persistent coupled interactions. Information gained from these initial tests will help in the interpretation of data obtained in the largest test, the *emplacement drift thermal test*. The purpose of the emplacement drift thermal test is to extend the scale and dimensionality of the investigations beyond the plate-source test to assess coupled phenomena on a scale consistent with the near-field, and to do so using a geometry consistent with current repository concepts.

For each test described below, the information needs that the test will satisfy are noted. Then a brief description of the test is given. Also discussed are other test considerations such as preferred locations, number of tests needed, rock type, alcove type, and desired construction method.

2.1.1 Single-Element Heater Tests

2.1.1.1 Objectives

The objectives of these tests are to:

- Provide measurements of rock-mass thermal properties at several locations representative of the repository rock conditions
- Measure the thermal expansion of the rock mass

- Examine the validity of conductive thermal models
- Measure changes in rock-mass and fracture permeability
- Measure rock-mass modulus under thermal conditions using the Goodman Jack method
- Develop an in situ test experience base using the simplest test
- Evaluate rock-mass strength and ground support interactions.

These tests will also supply information to Study 8.3.4.2.2.4.. The additional obejectives that will be met by these tests for Study 8.3.4.2.2.4 are to:

- Measure changes in rock saturation before, during, and after tests (including changes from ventilation)
- Investigate the propagation of a drying front and subsequent re-wetting
- Measure residual saturation levels in the dry zone (above boiling)
- Observe occurrences of liquid reflux in fractures
- Determine changes in the chemistry of reflux water.

2.1.1.2 Rationale

The need for a simple, small-scale field test is clear. First, the field test teams need to start the thermal test program with a fairly well developed type of test. As skills improve and operational experience is gained, the larger tests, to be fielded later, will be designed better and fielded more efficiently. Second, the conduct of the test should be fairly well established. Experience in G-Tunnel suggests that this type of test can be designed to easily meet the objectives. Third, the geometry of this test and the exclusion of larger-scale phenomena such as heat pipes make the interpretation of data easier. Finally, the geometry is suitable for measuring thermal property data. This test will allow the scaling of laboratory thermal property data to the rock-mass scale with reasonable assurance. While this test is primarily focused on T-M coupled effects, it will help set the stage for the design and conduct of the larger-scale tests for T-M-H-C coupled investigations. This test is the starting point for the implementation of the testing strategy to move from small-scale to larger-scale testing.

2.1.1.3 Data and Information Needs Addressed

The single-element heater test is intended to address the information needs listed below in Table 4. These information needs are a subset of those discussed earlier. Also noted is whether this test is intended to be a *primary* means of addressing the information needs or whether the information is derived as a byproduct or *secondary* objective of the test.

2.1.1.4 Description

The single-element heater test is a straightforward modification of the canister-scale heater test discussed in Section 8.3.1.15.1.6 of the SCP. The SCP test was designed to simulate a single canister in a borehole with the objective of measuring rock-mass response in the near-field. Although borehole emplacement is not considered likely at this point, the geometry of the test is still extremely useful for directly measuring rock-mass thermal properties such as thermal conductivity and heat capacity. There are two suggested geometries for this test: horizontal emplacement into a drift wall and vertical in-roof heater emplacement. The horizontal in-wall emplacement is considered the preferred geometry for the basic test. The in-roof geometry has both advantages and disadvantages over the horizontal test and is discussed below as an option to the basic test. A mix of in-wall and in-roof tests is suggested.

Table 4. Data and Information Needs Addressed by the Single-Element Heater Test

Information Needs	Single-Element Heater Tests
Near-field T-M-H-C environment	
• Rock-mass and fracture permeability changes	Primary
• Conductive/convective heat transfer	Primary
Rock-mass properties over a range of temperature	
• Thermal capacity or specific heat	Primary
• Thermal conductivity	Primary
• Thermal expansion	Primary
• Deformation modulus	Secondary
• Strength	Primary (optional roof test only)
Ground support and design features interactions at elevated temperature	
• Rock mass-ground support interaction	Secondary (optional roof test only)
• Effect of near-field environment on ground support components	Secondary (optional roof test only)

The basic test consists of emplacing a long heater rod horizontally (or at a slight incline) in the wall of an alcove (Figures 2 and 3). The desired configuration is to place the heater in a wall parallel to another drift or near a corner so that instrumentation access can be gained from locations both parallel and perpendicular to the heater (Figures 2 and 3). The configuration also allows permeability measurements to be conducted from boreholes before the second leg of the L-shaped room is developed. The changes in permeability resulting from stress changes during construction can be monitored. Permeability changes in the rock mass and selected fractures will also be measured during the test. Instrumentation holes will be used to measure rock mass modulus using the borehole based Goodman Jack method. Other geophysical methods, such as ultra-sonics, could also be applied to measure changes in the physical properties of the rock mass as it is heated.

The horizontal geometry of this test is ideal for measuring water movement around the heater because gravity will cause liquid condensate to move back toward the heater. In a horizontal heater test conducted in G-Tunnel, investigators were able to collect water in the heater hole itself

(Zimmerman et al., 1987). If the heater hole and instrumentation holes are angled upward at a slight incline, the natural drainage will allow the collection of reflux water at multiple points using a packer system to isolate segments of the borehole. It will also allow for inspection of the fracture system in some boreholes to examine the nature of fracture flow, if encountered. In addition, the horizontal test is well suited to measuring thermal expansion because the displacement gages can be installed along radial lines to measure radial expansion of the rock mass.

The heater power can be adjusted so that within six to twelve months rock-mass temperatures within a 1 m radial distance will reach approximately 200°C. The temperature range selected for this test is based on a number of considerations. First, it is desirable to measure the thermal properties over as wide a range of temperatures as might be expected in the repository over a range of thermal loads. Second, testing to examine the movement of a boiling front and other related phenomena should encompass enough volume of rock to confidently capture the effects of the local fracture structure and other inhomogeneities. Finally, it is possible to heat a significant volume of rock to approximately 200°C to examine the effect of silica phase transformations on thermal properties and thermal expansion. Laboratory experiments indicate that thermal expansion resulting from phase transformations could be significant and could have serious implications for near-field stability in hotter repository scenarios. Field information concerning the potential significance of these phase transformations is essential for the thermal loading decision process.

Thermocouples and displacement gages will be installed in boreholes parallel and perpendicular to the heater axis at various radial distances from the heater (note that not all instrumentation is shown in Figures 2 and 3, only typical placement). Neutron probe measurements in boreholes can also be used to monitor the development of a radial drying zone around the heater as the rock exceeds the boiling point. In addition, observation holes can be used to monitor vapor or liquid water movement through the fracture system. These boreholes will include a packer system to isolate individual fractures or fracture zones so that the general location of drainage can be determined and hydraulic communication among the fractures in the borehole can be prevented. Sampling for water chemistry before, during, and after the test would also be conducted on liquid condensate collected in boreholes and on water extracted from the rock matrix. It is also expected that mineralogical changes will be evaluated, to the extent practical, using core samples obtained before, during, and after the test. After the heating phase is completed, observations could be made on a periodic basis during cool-down. These holes will also be used to measure rock-mass modulus using the borehole-based Goodman Jack method.

Because of the axisymmetric configuration, simple one- or two-dimensional parameter estimation techniques can be applied to the temperature measurements made as a function of time and radial distance. These techniques allow the calculation of thermal conductivity and heat capacity along with the ability to quantify uncertainty associated with the measurements. The simple geometry also lends itself to model validation exercises. Because both the temperature field and the drying zone will be measured, both conduction models (such as COYOTE II) and coupled thermal-hydrologic models (such as TOUGH2) could be used to compare with the data.

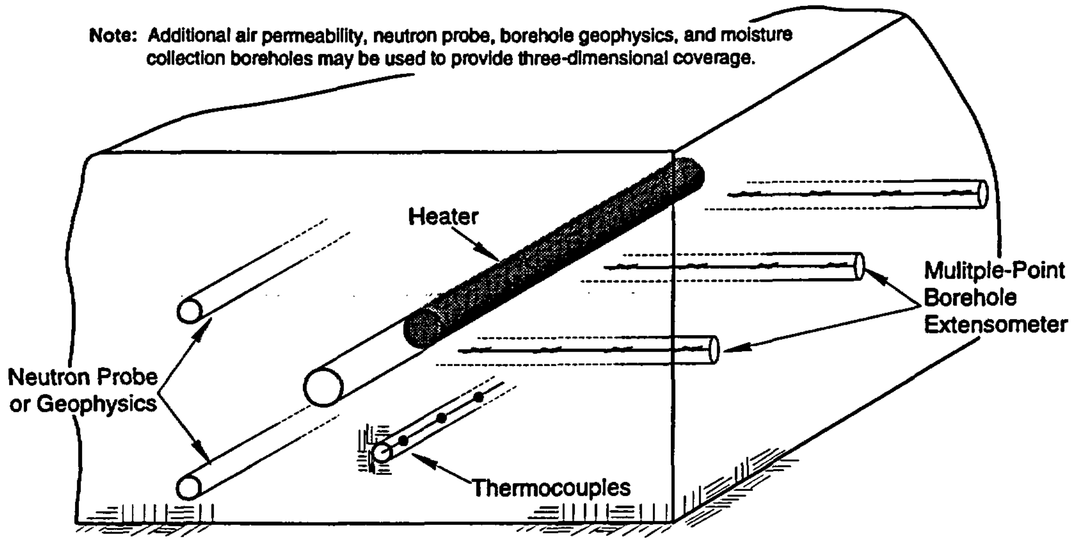


Figure 2. Conceptual layout for the single-element heater test—horizontal configuration, isometric view.

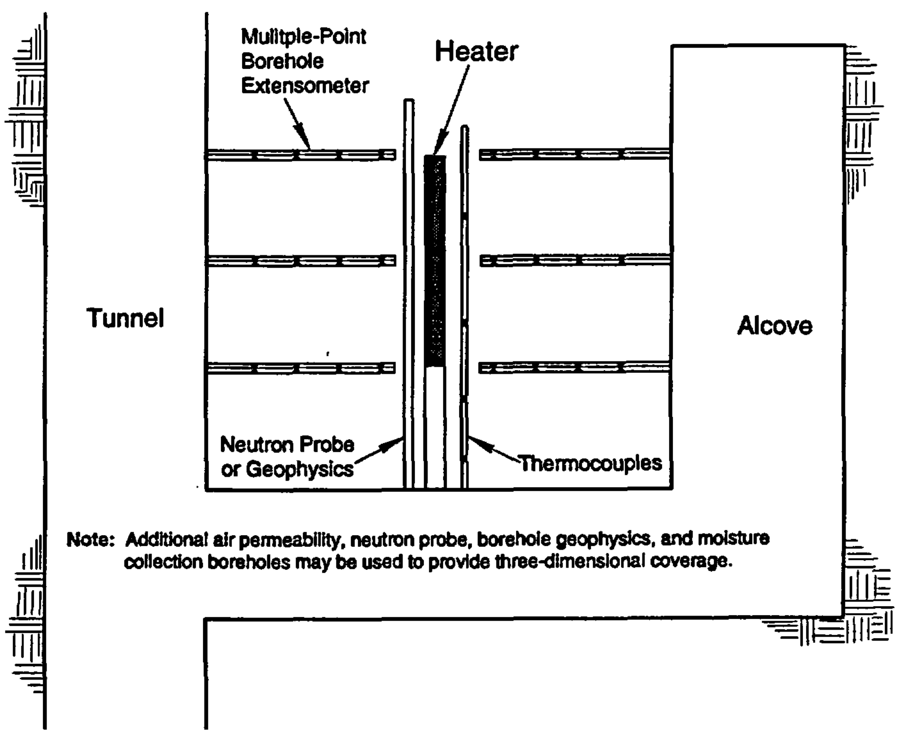


Figure 3 Conceptual layout for the single-element heater test—horizontal configuration, plan view.

2.1.1.5 Optional Test Configuration

One interesting variation of this test should be considered. Instead of conducting the test by emplacing the heater in the wall of a drift, at least one test could be conducted by emplacing the heater in the roof (Figure 4). The alcove would have to be constructed with a longer-span flat roof with special supports. This test configuration has three major advantages: (1) water condensing and moving through the fracture system will naturally drain into the drift and can be collected to determine the number of fractures carrying water, the approximate amounts, and the chemistry changes; (2) the roof will have ground support installed and thus provide some indication of potential interaction effects between the ground support and the heated rock mass; and (3) the thermal stresses could be elevated to maximum expected repository levels to verify that rock-mass strength is properly bounded. The last can be implemented with smaller risk of roof failure than overdriving a room-scale test. Room-scale tests are so complex and expensive that there is great reluctance to heat to the point of potential failure. The disadvantages of this configuration are that it is more difficult to install and there would be significant added costs to install a protective structure.

2.1.1.6 Test Locations and Other Considerations

The test should be conducted in at least two different locations in the TSw2 repository horizon (possibly one horizontal in-wall and one in-roof test). The locations should be representative of the range of rock quality (fracture density) and mineralogy expected in the proposed repository. Decisions regarding the actual locations of the tests will not be made until the access drift is constructed. Then the range of rock characteristics exposed will be evaluated and test locations selected. Because only a relatively small alcove is required, the tests could be conducted just off the north ramp or off an extension drift from the north ramp or main drift.

The SCP suggested that thermal testing of this kind should also be conducted in the high lithophysal region of TSw1. The reason for this suggestion is that in constructing the repository, it is highly likely that high lithophysal regions will be encountered in TSw2 along some of the proposed emplacement drifts. Thermal-response information for high lithophysal rock mass is critical to be able to determine whether to emplace in these regions or whether these regions must be abandoned or isolated (similar to a fault zone). The Program Approach suggests that testing to meet this information need can be deferred to the later phase of thermal testing as repository design progresses towards completion.

Multiple tests are recommended even for the early phase of testing because some measures of spatial variability and representativeness need to be developed for these important thermal parameters. In the selection of sites it is important to consider different rock quality, orientation with respect to the major joint sets, and local rock mineralogy. It should be stressed that the final location of the test is dependent on examination of rock conditions so that the objective of representativeness can be met.

No constraints need to be placed on the construction method for these alcoves, assuming that if drill-and-blast construction is used it will be under carefully controlled conditions to limit near-field damage.

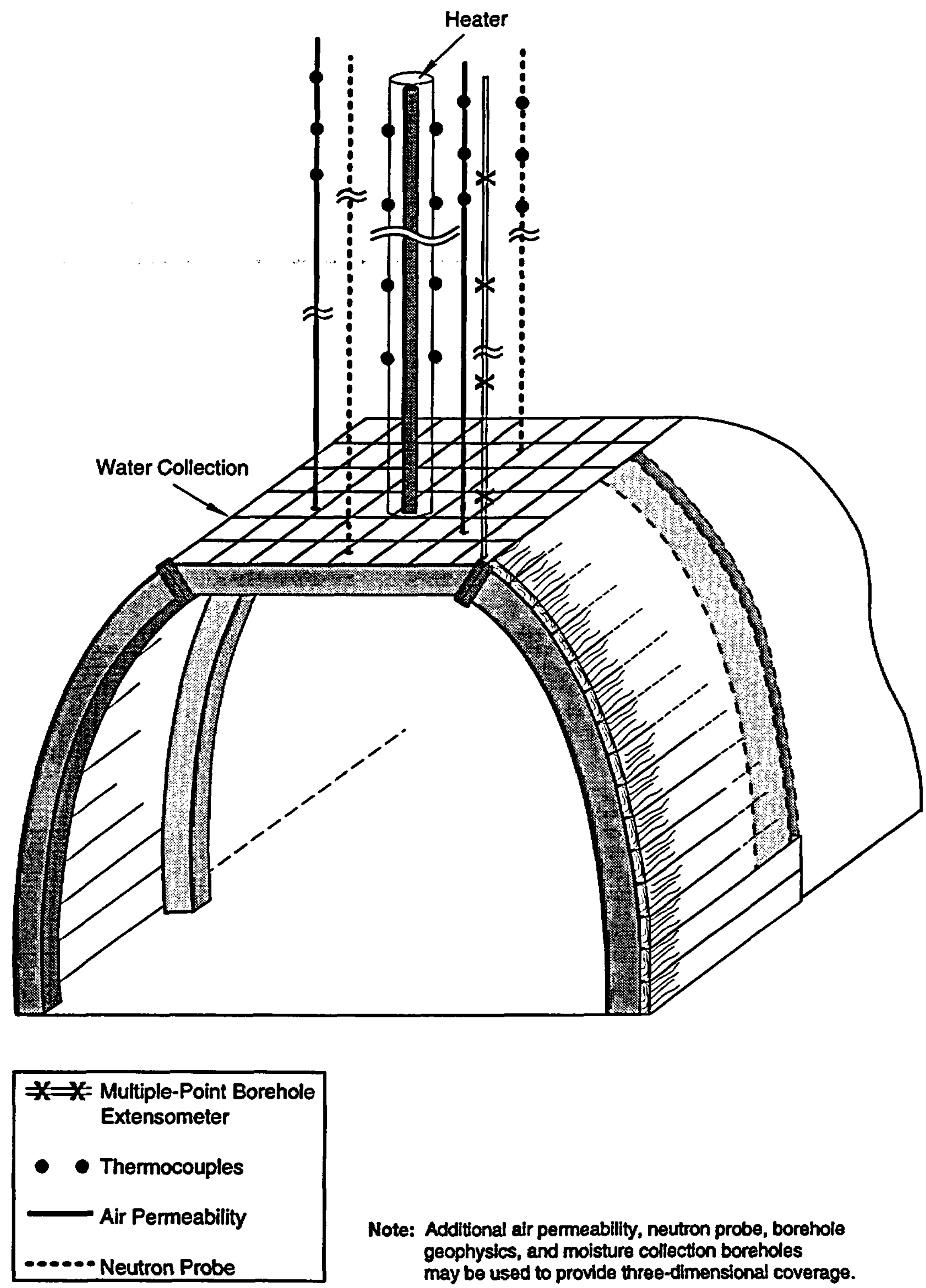


Figure 4. Conceptual layout for the single-element heater test—vertical configuration, isometric view.

2.1.1.7 Interface with Laboratory Testing

To completely meet the information needs, in situ tests must be integrated with the laboratory testing efforts. For the single-element heater tests, there are a number of laboratory efforts that must be coordinated with the in situ testing to provide information for test design and pretest analyses, and for post-test analysis of the in situ test data. These activities are summarized below.

- *Thermal properties of intact rock* (SCP 8.3.1.15.1.1 and 8.3.1.15.1.2). Thermal properties (including thermal expansion) of the intact rock near each test site should be determined. This information is used in the modeling efforts that will be conducted as part of the data interpretation and model validation phases of the test. One objective of the in situ tests is to examine the validity of heat conduction models used for design and performance assessment. Also, if laboratory properties can be correlated with rock-mass properties, then questions of spatial variability and representativeness would be more easily addressed because considerably more laboratory data will be collected as part of the ESF and surface-based test programs. Samples for laboratory testing will be collected from instrumentation core holes in each test area. Part of the site selection criteria also includes choosing sites that have a range of silica phase mineralogy so that effects of phase transformations can be assessed. Mineralogical samples should be collected and analyzed for each potential site.
- *Water chemistry and mineralogy* (SCP 8.3.4.2.4.1 and 8.3.1.3.2.2). Changes in water chemistry, particularly in reflux water, should be evaluated. Water and core samples will be collected, to the extent practical, before, during, and after the heating cycle. In situ saturation of the rock should be evaluated before final site selection. Samples should be recovered from the "dry zone" and other locations during the test to evaluate changes in saturation, chemistry, and mineralogy (matrix and fracture).
- *Mechanical Properties of Fractures* (SCP 8.3.1.15.1.4). Normal and shear compliance, shear strength, and cohesion are important parameters for modeling the rock mass. Changes in fracture aperture resulting from thermally induced stresses or mineralogical changes are important to the understanding of T-M-H coupling. To interpret measurements of changes in fracture permeability and rock-mass modulus, laboratory tests on fractures (including fracture fillings) are essential. Fracture samples (particularly vertical fracture sets) should be recovered from each test site. Measurements of fracture roughness and normal stiffness should be made. With these data and the in situ modulus measurements, estimates of fracture behavior on the rock-mass scale can be made.
- *Laboratory thermal process testing*. The laboratory tests probe the response of the fractured rock mass to a thermal load. The issues that are addressed in the laboratory test program are the redistribution of moisture resulting from thermal load, the propagation of a "drying front," the development of fast flow paths, the thermal-hydrological environment of waste packages relevant to the formation of heat pipes, and the waste package environment with regard to water saturation, water chemistry, and temperature. These are the same issues being studied in the in situ tests, only on a smaller scale. Therefore, the results of these laboratory tests are directly applicable to the design of the in situ test as well as to the interpretation of the data resulting from the tests.

2.1.2 Plate-Source Thermal Test

2.1.2.1 Objectives

The objectives of these tests are to:

- Measure the thermal expansion of the rock mass
- Measure rock-mass modulus at elevated temperatures
- Examine the validity of conductive thermal models on an intermediate scale and provide data to validate coupled thermal-hydrologic models.

These tests will also supply information to Study 8.3.4.2.2.4.. The additional obejectives that will be met by these tests for Study 8.3.4.2.2.4 are to::

- Measure changes in rock saturation before, during, and after testing (including changes from ventilation)
- Investigate the propagation of a drying front and subsequent re-wetting at intermediate rock-mass scale
- Measure residual saturation levels in the dry zone (above boiling)
- Observe the formation of a condensate cap
- Observe occurrences of condensate drainage and liquid reflux in fractures
- Observe the possible formation of heat pipes
- Measure changes in rock-mass and fracture permeability
- Determine changes in the chemistry of reflux water.

2.1.2.2 Rationale

This test allows for the investigation of key coupled T-M-H-C processes on an intermediate scale that is large enough to develop some, if not all, of the phenomena of interest in evaluating the near-field environment of the waste package. The test is geometrically simple and can be simulated by two-dimensional modeling using a plate source. The test also allows thermal-mechanical properties such as thermal expansion and rock-mass modulus to be measured in a straightforward way, thus eliminating the need to field special tests for rock-mass mechanical properties. Fracture properties, such as normal and shear compliance, cannot be measured directly for this test. However, the combination of laboratory data on fracture properties, scaling methods based on laboratory data, and the rock-mass modulus measurements from this test will form a sufficient data set to estimate fracture properties on a rock-mass scale.

The use of multiple heaters in a horizontal plane represents the next step in the testing strategy's scaling process. The increase in scale will allow better investigation of coupled processes and provide a good test-bed for model validation. This test is also easily expandable to larger scales if larger-scale testing is later determined necessary.

2.1.2.3 Data and Information Needs Addressed

The plate-source thermal test is intended to address the information needs listed below in Table 5. These information needs are a subset of those discussed earlier. Also noted is whether this test is intended to be a *primary* means of addressing the information needs or whether the information is derived as a byproduct or *secondary* objective of the test.

Table 5. Data and Information Needs Addressed by the Plate-Source Thermal Test.

Information Needs	Plate Source Thermal Test
Near-field T-M-H-C environment	
• Conductive/convective heat transfer	Primary
Rock-mass properties over a range of temperature	
• Thermal capacity or specific heat	Secondary
• Thermal conductivity	Secondary
• Thermal expansion	Primary
• Deformation Modulus	Primary

2.1.2.4 Description

The plate-source thermal test is a derivative of several test concepts, including the canister-scale heater test and the heated block test discussed in SCP Section 8.3.1.15.1.6, the plate loading test discussed in Section 8.3.1.15.7, and the engineered barrier system tests discussed in Section 8.3.4.2.2.4. The test represents an intermediate-scale test of modest complexity.

The test configuration consists of a row of long heater rods emplaced horizontally (or at a slight incline) in the wall of an alcove. The desired configuration is to place the heaters in a wall parallel to another drift or near a corner so that instrumentation access can be gained both parallel and perpendicular to the heater. A second small alcove is also constructed parallel to the axis of the heaters (Figures 5 and 6). This small alcove is to allow for the installation of a plate-loading apparatus used to measure the rock-mass modulus under both nominal and elevated temperature conditions. Note that the small alcove does not have to be sized to support the drilling of instrumentation holes (such as for the multi-point extensometers used in the plate loading test). Holes for instrumentation perpendicular to the heater axes can be drilled from the main drift prior to excavation of the small alcove. The configuration in Figure 5 also allows permeability measurements to be conducted from boreholes before the main test alcove and the small side alcove are constructed. The changes in permeability resulting from stress changes during construction can be monitored. Permeability changes in the rock mass and selected fractures will also be measured during the test.

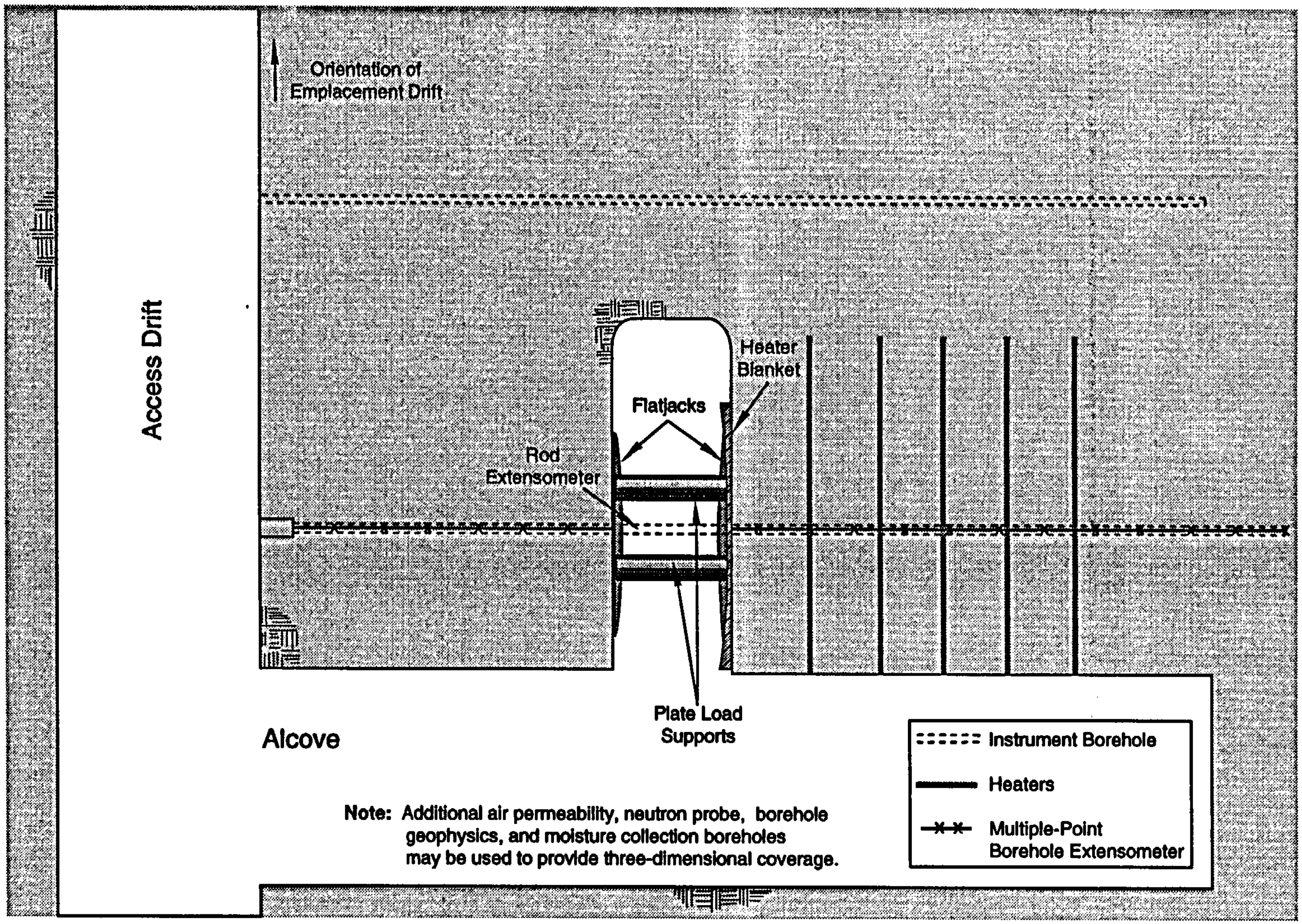
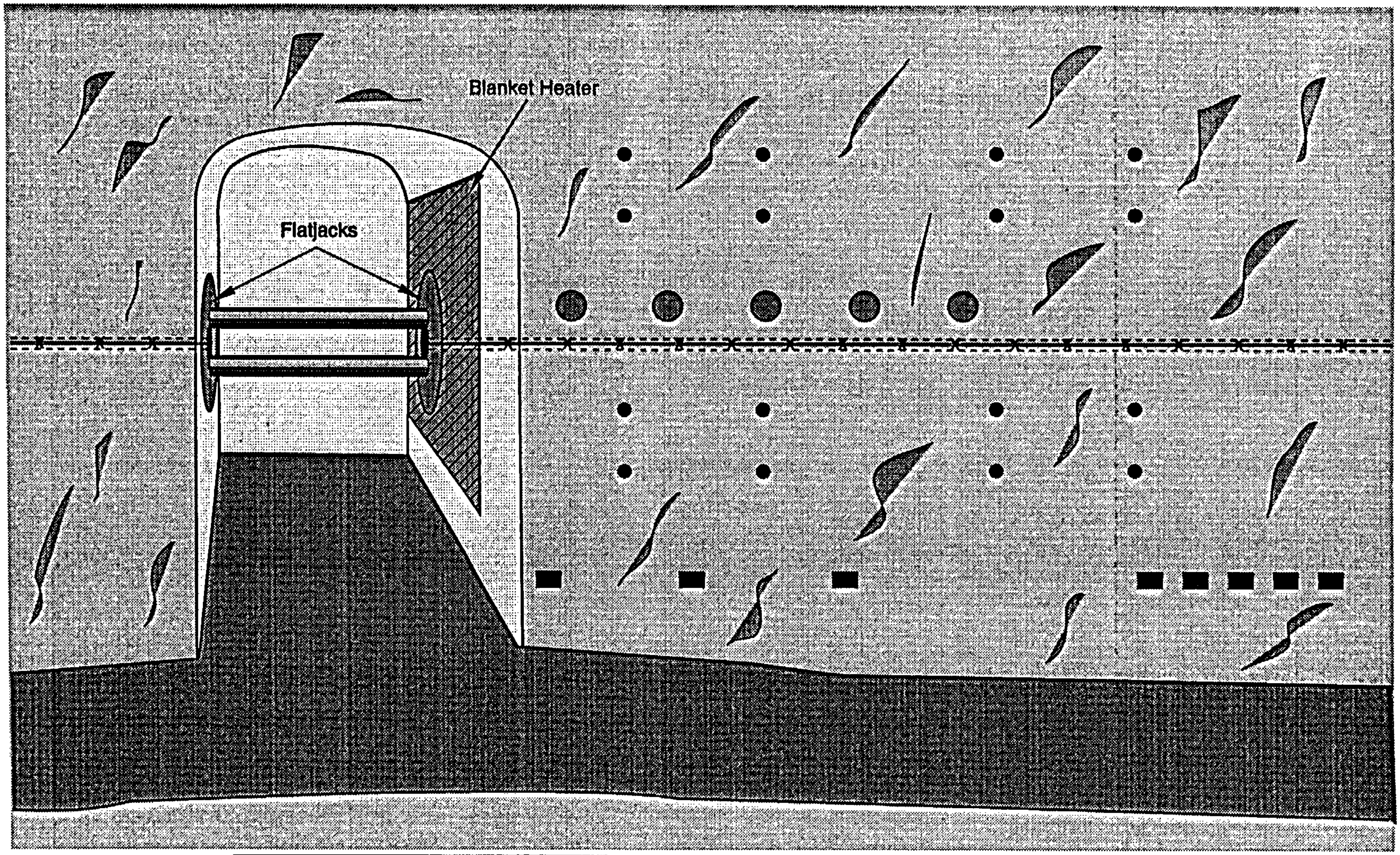


Figure 5. Conceptual layout for the plate-source thermal test—plan view.



Note: Additional air permeability, neutron probe, borehole geophysics, and moisture collection boreholes may be used to provide three-dimensional coverage.

Figure 6. Conceptual layout for the plate-source thermal test—isometric view.

The heaters are arranged so that they simulate a "plate" source. A sufficient volume of rock can be heated to stimulate the formation of a condensate "cap" above the heater plane and allow condensate water to drain around the edges or through fast paths to regions below the heater plane. A series of holes (Figure 6) will be drilled at the alcove floor elevation that run under the heater plane to allow for the monitoring and collection of condensate drainage and for the possible identification of fast flow paths. These boreholes can include a packer system to isolate individual fractures or fracture zones so that the general location of drainage can be determined and hydraulic communication can be prevented among the fractures in the borehole. The scale of the test may be sufficient to allow the formation of a heat pipe. Both pressure and temperature sensors will be installed in an array around the heated plane to monitor the progress of the boiling front and to detect the formation of a heat pipe if it occurs. Neutron probes, geophysical tomography, or other moisture-change sensors can be used in the borehole array to monitor the movement of water and saturation levels above and below the heater plane. This horizontal plate-source test is ideal for measuring water movement around the heater plane because gravity will cause liquid condensate to move back toward and around the heaters. In a horizontal heater test conducted in G-Tunnel, investigators were able to collect water in the heater hole itself (Zimmerman et al., 1987). If the heater holes and instrumentation holes are angled at a slight incline, the natural drainage will allow the collection of reflux water at multiple points. The geometry also allows three-dimensional coverage—all sides, above, and below the heater horizon. This configuration addresses a major concern that arose as a result of the G-Tunnel experience, i.e., instrumentation coverage needs to be fairly complete to capture the thermal-hydrological phenomena of interest.

It will also allow for inspection of the fracture system in some boreholes to examine the nature of fracture flow, if encountered. Sampling for water chemistry before, during, and after the test could be done on liquid condensate collected in boreholes and on water extracted from the rock matrix. It is also expected that mineralogical changes will be monitored, to the extent practical, using core samples obtained before, during, and after the test. After the heating phase is completed, observations could be made on a periodic basis during cool-down. The plate-source thermal test is also designed to measure the thermal expansion and modulus of the rock mass. Multipoint borehole extensometers will be installed normal to the small alcove. As the rock mass heats up, differential displacement can be measured to estimate thermal expansion. The modulus is determined from a plate-loading test conducted in the small alcove. Using a double-acting set-up, the modulus on the heated side of the small alcove can be measured at the same time as the modulus on the unheated side. On the heated side, a blanket heater is placed on the alcove wall to act as a guard heater to minimize thermal gradients near the alcove and allow for the measurement of the modulus in a rock mass of nearly uniform temperature.

The power for the plate-source heater array can be adjusted so that within six to twelve months rock-mass temperatures within a 1 m radial distance from the heaters will exceed 150^{o}C. The exact size, spacing, and power rating of the heaters needed to develop a reasonably uniform plate source in a short time period will be determined from detailed analyses. The temperature range selected for this test is based on a number of considerations. First, it is desirable to measure thermal properties and to gain some understanding of coupled phenomena that might be expected in the repository for a range of thermal loads. Thus, thermal properties and other data should be collected over the maximum expected temperature range to assist in the decision-making process. Second, testing to examine movement of a boiling front and other related phenomena should encompass enough volume of rock to ensure that the effects of the local fracture structure and other inhomogeneities are captured.

Because of the plate-like nature of the heat source used in this test configuration, two-dimensional modeling techniques can be applied. Thus, the simple geometry lends itself to model validation exercises. Because both the temperature field and the drying zone will be measured, both conductive models (such as COYOTE II) and coupled thermal-hydrologic models (such as TOUGH2) could be used to compare with the data.

Whereas the single-element heater configuration lends itself to simple one- or two-dimensional parameter estimation techniques for calculating thermal conductivity and heat capacity, the horizontal plate source geometry will likely result in a more complex thermal distribution, making estimation of thermal properties more difficult. However, the horizontal plate-source geometry provides a more rigorous test for the validation of coupled thermal-hydrological models. The plate-source test also has distinct advantages for the measurement of thermal expansion and other mechanical properties. This test represents an essential step in the progression towards designing and conducting a more complex (and truly three-dimensional) room-scale test.

The plate-source geometry is also readily expandable to larger scales. By adding additional heaters to the row, a larger plate can be formed. This might be a desirable means for using the same test to look at intermediate-scale effects in the near term, then expanding the test to a larger scale if early testing demonstrates the need. The expansion to larger scales and longer times would take place in the 2000 to 2008 time frame or sooner, as circumstances dictate.

2.1.2.5 Test Locations and Other Considerations

The plate-source thermal test should be conducted in at least two different locations in the TSw2 repository horizon. The locations should be representative of the range of rock quality (fracture density) and mineralogy. Decisions regarding the actual locations of the tests will not be made until the access drift is constructed. Then the range of rock characteristics exposed will be evaluated and the test locations selected. Because only a relatively small facility is required (perhaps as much as 50 m total length), the tests could be conducted just off the north ramp or off an extension drift from the north ramp or main drift. It is highly likely that both a single-element heater and a plate-source heater test could be conducted in the same alcove, if properly spaced. If circumstances dictate (as described for the previous test), an early plate-source heater test could be performed in the nonlithophysal section of TSw1. This may afford some schedule advantage, but it would require a considerable effort to design and field. It is highly recommended that at least one single-element heater test be conducted before attempting the plate-source thermal test, which represents a significant increase in complexity and scale. Therefore, it would seem unlikely that a plate-source thermal test in TSw1 would be of significant benefit to the tests(s) that must be conducted in TSw2.

It is desirable that the test be oriented so that the heater axes are parallel to the anticipated heading of the repository emplacement drifts. Multiple tests are recommended even for license application to construct a repository because some measures of spatial variability and representativeness need to be developed. In the selection of sites it is important to consider different rock quality, orientation with respect to the major joint sets, and local rock mineralogy. It should be emphasized that the final location of the tests is dependent on examination of rock conditions so that the objective of representativeness can be met.

No constraints need to be placed on the construction method for these alcoves, assuming that if drill-and-blast construction is used it will be under carefully controlled conditions to limit near-field damage. More care is required in constructing the small (plate loading) alcove because near-field damage (within 1 m of the surface) will have an impact on the measured values of modulus. Line drilling this small alcove may be possible.

2.1.2.6 Interface with Laboratory Testing

To completely meet the information needs, in situ tests must be integrated with the laboratory testing efforts. For the plate-source thermal test, there are a number of laboratory efforts that must be coordinated with the in situ testing to provide information for test design and pretest analyses and for post-test analysis of the in situ test data. These activities are summarized below.

- *Thermal properties of intact rock* (SCP 8.3.1.15.1.1 and 8.3.1.15.1.2). Thermal properties (including thermal expansion) of the intact rock near each test site should be determined. This information is used in the modeling efforts that will be conducted as part of the data interpretation and model validation phases of the test. One objective of the in situ test is to examine the validity of heat conduction models used for design and performance assessment. Also, if laboratory properties can be correlated with rock-mass properties, then questions of spatial variability and representativeness would be more easily addressed because considerably more laboratory data will be collected as part of the ESF and surface-based test programs. Samples for laboratory testing will be collected from instrumentation core holes in each test area. Part of the site selection criteria also includes choosing sites that have a range of silica phase mineralogy so that effects of phase transformations can be assessed. Mineralogical samples should be collected and analyzed for each potential site.
- *Water chemistry and mineralogy* (SCP 8.3.4.2.4.1 and 8.3.1.3.2.2). Changes in water chemistry, particularly in reflux water, should be evaluated. Water and core samples will be collected, to the extent practical, before, during, and after the heating cycle. In situ saturation of the rock should be evaluated before final site selection. Samples should be recovered from the "dry zone" and other locations during the test to evaluate changes in saturation, chemistry, and mineralogy (matrix and fracture).
- *Mechanical Properties of Fractures* (SCP 8.3.1.15.1.4). Normal and shear compliance, shear strength, and cohesion are important parameters for modeling the rock mass. Changes in fracture aperture resulting from thermally induced stresses or mineralogical changes are important to the understanding of T-M-H coupling. To interpret measurements of changes in fracture permeability and rock-mass modulus, laboratory tests on fractures (including fracture fillings) are essential. Fracture samples (particularly vertical fracture sets) should be recovered from each test site. Measurements of fracture roughness

and normal stiffness should be made. With these data and the in situ modulus measurements, estimates of fracture behavior on the rock-mass scale can be made.

- *Laboratory thermal process testing*. The laboratory tests probe the response of the fractured rock mass to a thermal load. The issues addressed in the laboratory test program are the redistribution of moisture resulting from thermal load, the propagation of a "drying front," the development of fast flow paths, the thermal-hydrological environment of waste packages relevant to the formation of heat pipes, and the waste package environment with regard to water saturation, water chemistry, and temperature. These are the same issues being studied in the in situ test, only on a smaller scale. Therefore, the results of these laboratory tests are directly applicable to the design of the in situ tests as well as to the interpretation of the data resulting from the tests.

2.1.3 Emplacement Drift Thermal Test

2.1.3.1 Objectives

The objectives of this test are to:

- Evaluate the effect of ground support interactions with the heated rock mass, including the effect of materials used for ground support on the near-field water chemistry
- Provide data on a larger scale, commensurate with the size of blocks defined by the rock-mass jointing
- Provide detailed measurements of the response of the rock mass to the construction and heating of an emplacement-drift-scale opening

These tests will also supply information to Study 8.3.4.2.2.4. The additional objectives that will be met by these tests, for Study 8.3.4.2.2.4, are to:

- Examine the near-field thermal-hydrologic environment that may impact the waste package (i.e., liquid saturation in rock and backfill, room humidity, propagation of "dry" conditions, liquid drainage in fractures, chemical evolution of liquid reflux, and changes in permeability)
- Provide a conceptual model and hypothesis test-bed where thermal and coupled thermo-mechanical-hydrologic-chemical (T-M-H-C) models can be used to examine issues of heat transfer, fluid flow, and gas flow that will help put realistic bounds on the expected nature of the near-field environment
- Measure corrosion rates on typical waste package materials under in situ conditions
- Provide bounding measurements on the thermal-hydrologic behavior of backfill materials.

2.1.3.2 Rationale

The emplacement drift thermal test is geometrically more complex and of a larger scale than the previously described tests. It is intended to address several information needs that can only be answered by tests that approach emplacement-drift scale and to provide supporting data for other information needs at a larger scale. This test allows investigation of the near-field waste package environment and associated coupled T-M-H-C processes on an emplacement-drift scale.

Conducting a test at a room-scale is essential to the investigation of coupled phenomena that may directly affect the near-field environment of the waste package. The test should reflect the geometry and heating mode that are expected in the repository. This is the only way to realistically estimate the near-field environment. A simulated emplacement drift test also allows the investigation of engineering features such as ground support and invert materials, backfill, and waste package materials in a repository environment. Finally, heating an emplacement-drift sized opening provides a demonstration that proposed engineering measures to assure long-term stability and performance will work.

The emplacement drift thermal test is designed to examine the effects of a specific emplacement mode on processes and rock-mass response for a geometry consistent with current repository designs. Beyond being a demonstration for a specific emplacement mode, the room-scale test represents an important step in the investigation of coupled phenomena at increasing scales. It is recognized that, should the assumed emplacement mode change, the need for additional room-scale tests consistent with these changes would need to be evaluated.

2.1.3.3 Data and Information Needs Addressed

The emplacement drift thermal test is intended to address the information needs listed in Table 6. The information needs addressed are a subset of those discussed earlier. Also noted is whether this test is intended to be a *primary* means of addressing the information needs or whether the information is derived as a byproduct or *secondary* objective of the test.

Table 6. Data and Information Needs Addressed by the Emplacement Drift Thermal Test

Information Needs	Emplacement Drift Thermal Test
Near-field T-M-H-C environment	
• Conductive/convective heat transfer	Primary
Rock mass properties	
• Thermal capacity or specific heat	Secondary
• Thermal conductivity	Secondary
• Thermal expansion	Secondary
• Strength	Primary
Drift response/stability under thermal conditions	Primary
Ground support at elevated temperature	
• Rock mass-ground support interaction	Primary
• Effect of near-field environment on ground support components	Primary

2.1.3.4 Description

The emplacement drift thermal test is based on an integration of test objectives and strategies that were discussed under both waste package environment and thermal-mechanical testing in the SCP. The design of this test can, in general, be traced back to the Heated Room and the Thermal Stress tests described in SCP Section 8.3.1.15.1.6, the Sequential Drift Mining Test described in Section 8.3.1.15.1.5, and the Engineered Barrier Field Test described in Section 8.3.4.2.2.4. The experiment is designed to address specific phenomenological issues associated with the waste package environment and preclosure issues of ground support and stability, while at the same time simulating a repository- or near-repository-scale opening under thermal loads. The test arrangement represents a compromise between the need to observe and measure certain phenomena on a large scale, the need to accelerate the heating process so that sufficient data can be gathered in a two to three year time frame, and the desire to simulate, as closely as possible, an actual repository emplacement room.

The suggested configuration of this test is shown in Figures 7 and 8. Instrumentation access drifts will be developed parallel to the test drift. The access drifts will be developed first so that instrumentation can be installed to monitor changes in rock displacements, permeability, and stresses as the main test room is excavated. These drifts can be excavated in a number of ways. The first way is to excavate two separate drifts parallel to the test drift. One of the drifts would be excavated with a slight decline so that in the central test region the elevation of the drift is about one drift diameter (4 m) below the test drift. This configuration would allow water that may drain below the test room to be collected in a series of moisture probe holes. Such collection is needed to provide estimates of the volume of liquid reflux that may form, to determine if fast flow paths exist, and to allow for geochemical analysis of reflux water. If it is determined that access is needed below the test drift, or that better three-dimensional access is needed, a single decline could be excavated forming a U-shaped drift. This type of access drift would start from the main drift and run parallel to the test drift at approximately a 5% decline. The drift would then turn around behind the end of the test drift and run parallel to the test drift on the other side. By using a continuous decline, this geometry results in the lowest part of the instrumentation drift being approximately two to three drift diameters (8 to 10 m) below the test drift. If geophysical tomographic methods are used extensively for tracking the flow of water and vapor, more extensive access may be required. Before extensive drifting for diagnostic access is proposed, numerous studies need to be performed to consider the costs and benefits of alternative geometries. The commonly held view is that sufficient access, even for geophysical tomographic methods, can be gained by limited drifting and extensive use of boreholes, but this remains to be demonstrated.

After the access drifts are excavated and the initial instrumentation is in place, the main test room will be excavated. This room should have the approximate dimensions of an emplacement room. With the main test drift completed, a series of mockup in-drift waste emplacement heaters (approximately 3 to 5) will be installed to simulate heating of the near-field by waste containers. Additional heater rods could be installed in the rock mass horizontally from the drift to provide additional heating of the system. The advantages of including heaters in the walls of the drift are:

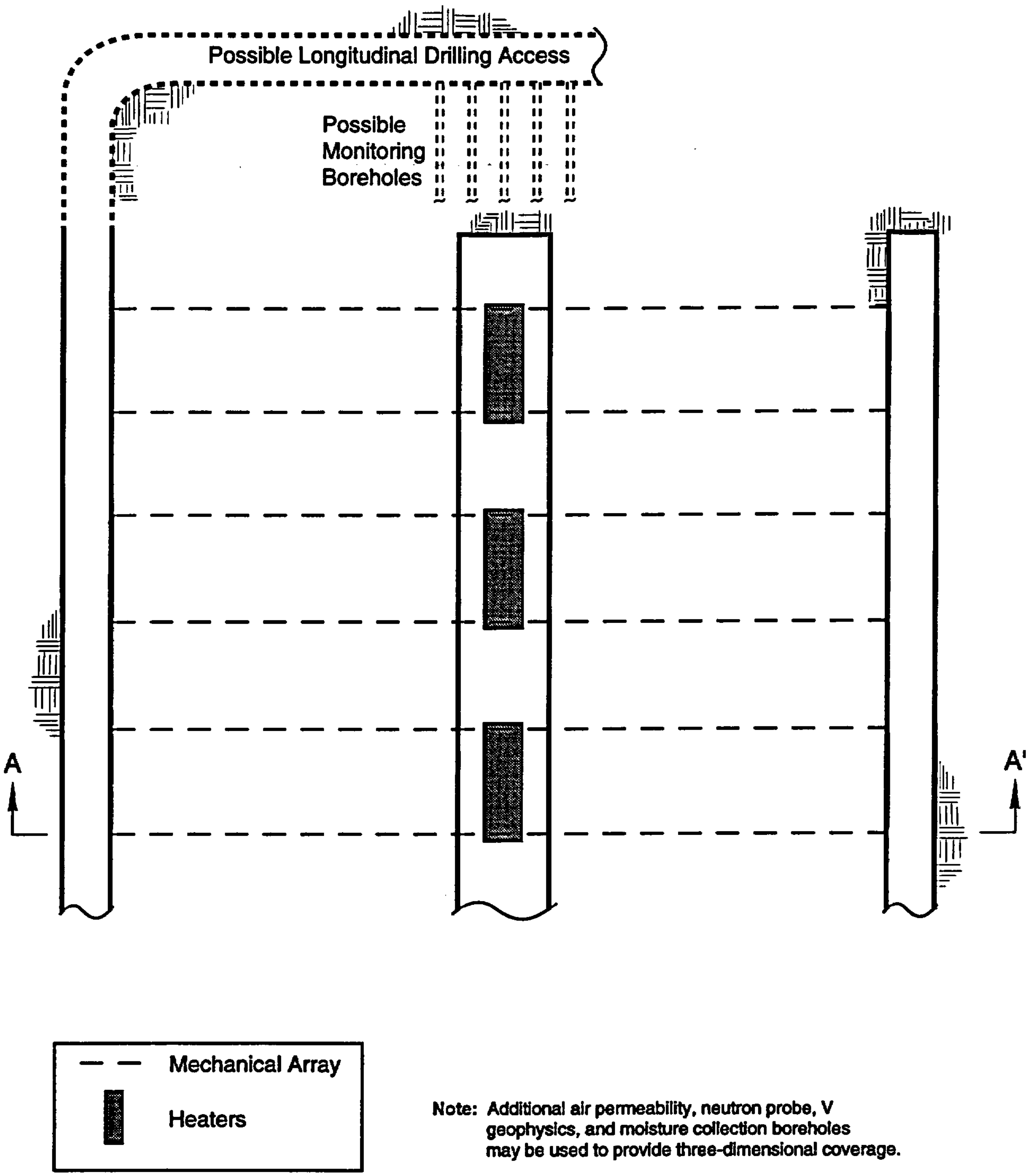


Figure 7. Conceptual layout for the emplacement drift thermal test—plan view.

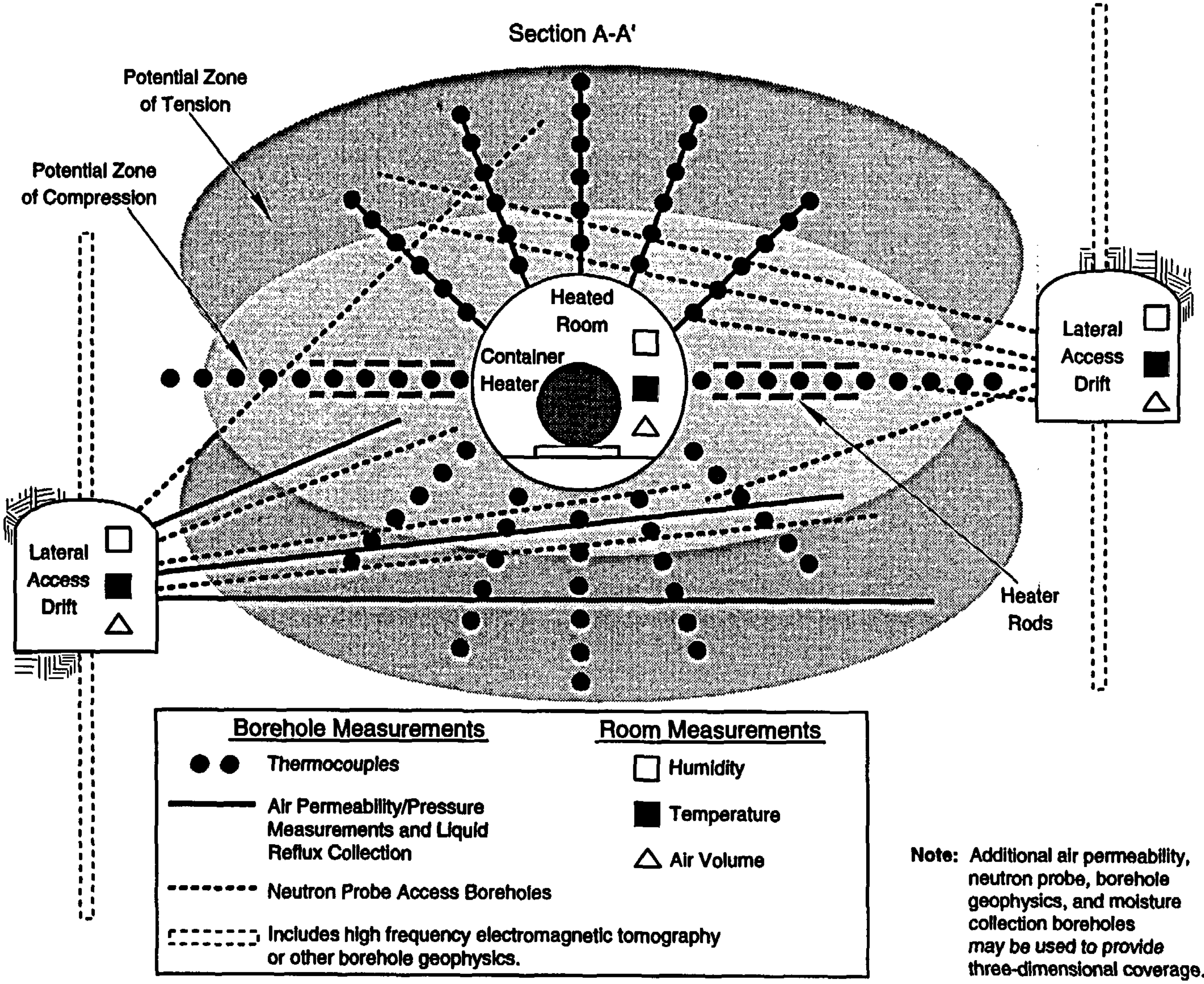


Figure 8. Conceptual layout for the emplacement drift thermal test—section AA'—thermal-hydrology instrumentation/measurements.

(1) a larger volume of rock can be heated in a given time, (2) the geometry would create a broader condensate cap of high saturation above the test room to evaluate the ability of the boiling zone to support the cap, and (3) lateral heating would approximate the impingement of heat from parallel drifts (as in a repository layout) without the need for multiple heater drifts.

The exact heating profile and other test details will depend on several considerations. First, elements of the conceptual repository design, as it develops, need to be considered. Proposed initial thermal loading, drift size and spacing, and variability in waste package thermal output are all elements that should be factored into the final test configuration. Additionally, ranges of proposed ground support should be considered. The test room could be divided into test segments where different ground support is installed. The materials interactions and impacts on geochemistry could then be evaluated. Use of backfill materials along the invert would also be a possibility. Second, alternative heating cycles for this test must recognize that the repository thermal loading has not yet been established, and therefore a range of loadings must be considered. Finally, the waste package environment and the coupled process phenomena associated with it may be considerably different for a low thermal load than for a high thermal load. Additional work will be required to fully define the test conditions.

Instrumentation will consist of thermocouples, thermal flux gages, pressure sensors, and displacement gages. Stress changes and ground support reactions will be monitored as the drift is heated. The interaction of the changing stress and temperature field with various types of ground support will also be examined. Instrumented rock bolts or rock bolt load cells and other instrumentation will be used to monitor the ground support performance, provided they can be hardened to survive the elevated temperatures.

2.1.3.5 Test Locations and Other Considerations

The test should be conducted in the TSw2 repository horizon. The orientation of the drift should coincide with the anticipated orientation of the repository emplacement rooms. The test room should be constructed by mechanical excavation in a manner similar to that expected for the repository. Dimensions should also be near repository scale. If suitable mechanical excavation methods are not likely to be available, the test can be designed to be conducted in a drill-and-blasted drift with an approximately round cross section. Drill-and-blast construction would have to be executed carefully to avoid excessive damage to near-field rock. It may also be possible to underbreak the initial excavation and bring in a mobile excavation machine to finish the excavation to shape, greatly reducing the damage zone near the walls and better simulating a bored opening.

The detailed design of this test will depend on a number of decisions related to basic repository design concepts and investigative emphases. Repository design issues that need to be addressed during the next phase of test design include:

- Basis for waste emplacement density (areal mass loading or areal power density)
- Planned repository construction sequence related to preserving a range of thermal loading options
- Waste stream characteristics
- Waste package dimensions and capacities

- Layout of engineered items in the emplacement drifts (e.g., invert material, ground support systems, waste package support systems).

The above design information will allow the test to be designed so that realism related to the engineered system is captured where practical. This realism will have to be balanced with the test's ability to provide useful information related to the basic test objectives. Therefore, repository design features can only be added to test designs if they do not overly complicate the gathering of data or the modeling of test results.

2.1.3.6 Additional Test Options

Non-uniform heat distribution within the repository could be investigated by using in-drift waste emplacement-scale canister heaters with different powers within the heated drift. This configuration would test the degree to which heat is redistributed within the drift. From a hydrologic perspective, a non-uniform heat distribution could test the possibility of migration of liquid water toward lower temperature zones above the heated drift and onto the heater canisters.

2.1.3.7 Interface with Laboratory Testing

To completely meet the information needs, in situ tests must be integrated with the laboratory testing efforts. For the emplacement drift thermal test, a number of laboratory efforts must be coordinated with the in situ testing to provide information for test design and pretest analyses and for post-test analysis of the in situ test data. These activities are summarized below.

- *Thermal properties of intact rock* (SCP 8.3.1.15.1.1 and 8.3.1.15.1.2). Thermal properties (including thermal expansion) of the intact rock near each test site should be determined. This information is used in the modeling efforts that will be conducted as part of the data interpretation and model validation phases of the test. One objective of the in situ test is to examine the validity of thermal models used for design and performance assessment. Samples for laboratory testing will be collected from instrumentation core holes in each test area.

- *Intact rock mechanical properties* (SCP 8.3.1.15.1.3). One objective of the emplacement drift thermal test is to develop data for validation of rock-mass models needed for design and performance assessment. These models use laboratory properties of intact rock and fractures to estimate rock-mass behavior. Core samples should be taken from instrument holes or nearby locations for laboratory tests to determine the intact rock modulus and failure envelope at both nominal and elevated temperatures.

- *Mineralogy and geochemistry* (SCP 8.3.4.2.4.1). Changes in rock mineralogy and water chemistry are important variables to bound. Rock samples should be tested before and after heating along with analysis of the water chemistry. Fractures in cores from instrumentation holes should be examined for coating along with samples recovered after the heating cycle is completed.

- *Mechanical Properties of Fractures* (SCP 8.3.1.15.1.4). Normal and shear compliance, shear strength, and cohesion are important parameters for modeling the rock mass. Changes in fracture aperture resulting from thermally induced stresses or mineralogical changes are important to the understanding of T-M-H coupling. To interpret measurements of changes in fracture permeability and rock-mass modulus, laboratory tests on fractures (including fracture fillings) are essential. Fracture samples (particularly vertical fracture sets) should be recovered from each test site. Measurements of fracture roughness and normal stiffness should be made. With these data and the in situ modulus measurements, estimates of fracture behavior on the rock-mass scale can be made.

- *Laboratory thermal process testing*. The laboratory tests probe the response of the fractured rock mass to a thermal load. The issues addressed in the laboratory test program are the redistribution of moisture resulting from thermal load, the propagation of a "drying front," the development of fast flow paths, the thermal-hydrological environment of waste packages relevant to the formation of heat pipes, and the waste package environment with regard to water saturation, water chemistry, and temperature. These are the same issues being studied in the in situ test, only on a smaller scale. Therefore, the results of these laboratory tests are directly applicable to the design of the in situ test as well as to the interpretation of the data resulting from the tests.

2.2 Representativeness of Results

There are three factors to consider when discussing the representativeness of results: spatial variation of rock mass properties, experiment configuration, and temporal considerations.

It is known that rock mass properties will vary spatially throughout the repository, and this variability will be categorized by other experiments including; rock mass strength experiments geologic mapping, the laboratory test programs, and excavation investigations.

The fracture density and orientations and the lithophysal content of the Emplacement Drift Thermal Test are expected to represent the site-specific conditions found within the potential Yucca Mountain repository block. As is the case with most other large-scale experiments planned for the ESF, only one or two of these experiments will be performed. Spatial variation in rock mass properties from other experiments will be used to assess the representativeness of the results. "Characterization of TSw2 will be conducted in the main drift, other excavations in TSw2 and the thermal test area. The results of such characterization will assist in evaluating the spatial representativeness of the test."

The experiment configuration of the planned tests are representative of repository plans that are current at the time of this writing. Minor variations in opening size are not likely to greatly influence the representativeness of experiment results. Changes in the repository operating concept (e.g. hot versus cold repository) will affect the representative of the results, and may require modifications to this study plan.

Temporal considerations also affect the representativeness of results. The Emplacement Drift Thermal experiment is planned as a relatively long-term experiment. Because the experiment will be initiated well before any waste is stored at the site, potential long-term effects would show up in the experiment before they could occur in the repository drifts. Changes in support requirements and repository operating procedures could be initiated at that time.

"The ESF thermal test is one component in a suite of activities ranging from tests in the laboratory, in the ESF, analog studies, modeling analyses and performance confirmation monitoring/testing. Comprehensive synergistic analyses of the outcome of these activities are expected to address the issue of temporal representativeness."

2.3 Necessity of Simulating Repository Conditions

Only one of the experiments, the Emplacement Drift Thermal Test, is designed to simulate actual repository conditions. Sufficient flexibility in the design has been incorporated to accommodate changes in thermal load by changing the deployment and power of heaters.

2.4 Alternative Test Methods

2.4.1 Introduction

In this section alternative tests to the proposed tests presented earlier in this chapter are discussed. These alternative tests are currently judged to be less suitable than the proposed tests for meeting Project requirements, but they are described here to discuss some of the additional concepts that could be fielded.

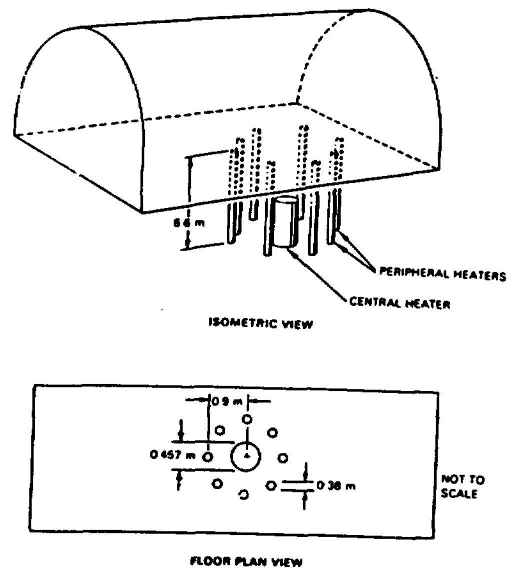
2.4.2 Alternatives to the Single-Element Heater Test

Three alternates to the single-element heater tests are shown in Figure 9. The first (Figure 9a) is similar to an experiment performed at Stripa (Hood et al., 1979) and is depicted as later repeated at Hanford (Gregory and Kim, 1981). Hood et al. (1979) describes the experiment at Stripa involving a 5-kW heater surrounded by 1-kW peripheral heaters. The central heater was energized first, followed by the peripheral heaters some 200 days later. Hood noted that the central borehole suffered severe decrepitation during the experiment, but only after the peripheral heaters were energized (Figure 10). The central/peripheral concept is relatively easy to field, and the peripheral heaters can be sized and spaced as desired to represent the required thermal load.

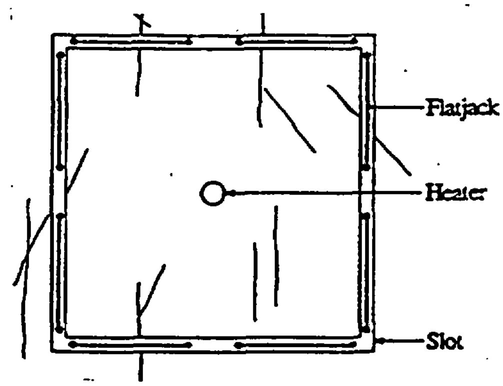
The second concept (Figure 9b) has not been reported in the literature, but would represent a method of simulating field stresses around a single-borehole heater test. This is essentially a block test configuration within the perimeters of which a canister-scale heater is placed. The stresses in the flatjacks would be carefully controlled to represent the desired stresses. This experiment affords a great degree of control over the boundary conditions, but has the disadvantage that flatjack pressure must be maintained for long periods of time in a potentially hostile thermal environment.

Figure 9c shows 30°C isotherms calculated around a time-scaled array of heaters. The time-scaled heater test (Cook and Witherspoon, 1978) was developed to study the effects of thermal interaction between waste canisters. Such interactions would gradually develop in the repository depending on the thermal load and waste package spacing. In order to study them in a much shorter time period, all the linear dimensions of the test, including heater spacing, were reduced according to scaling relationships. There is some controversy over whether these time-scaling relationships make the experiment unreasonably small with respect to the rock structure in jointed rock, and such an arrangement is probably not appropriate for Yucca Mountain welded tuff.

a) Full-Scale Heater Test #1 at BWP (after Stripa Design Gregory & Kim, 1981)



b) Single-heater Flatjack Concept



c) Time-Scaled Heater Experiment (Cook and Witherspoon, 1978)

A plan view of the time-scaled experiment at Stripa showing the 30°C increment isotherms at times of 7, 30, 90, 365 and 730 days calculated using the theory of linear heat conduction. The scaling of this experiment is about 1/3 linear scale and 1/10 time scale, so that the final isotherm corresponds to about 20 years in full scale.

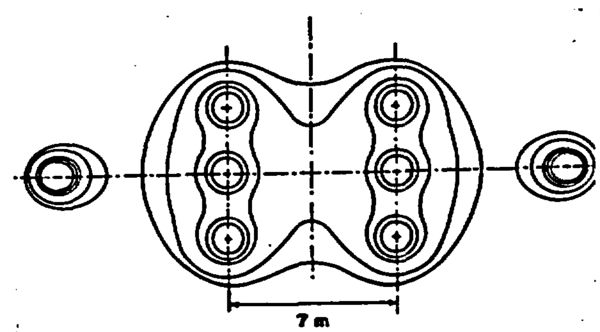


Figure 9. Three options for borehole heater experiments.

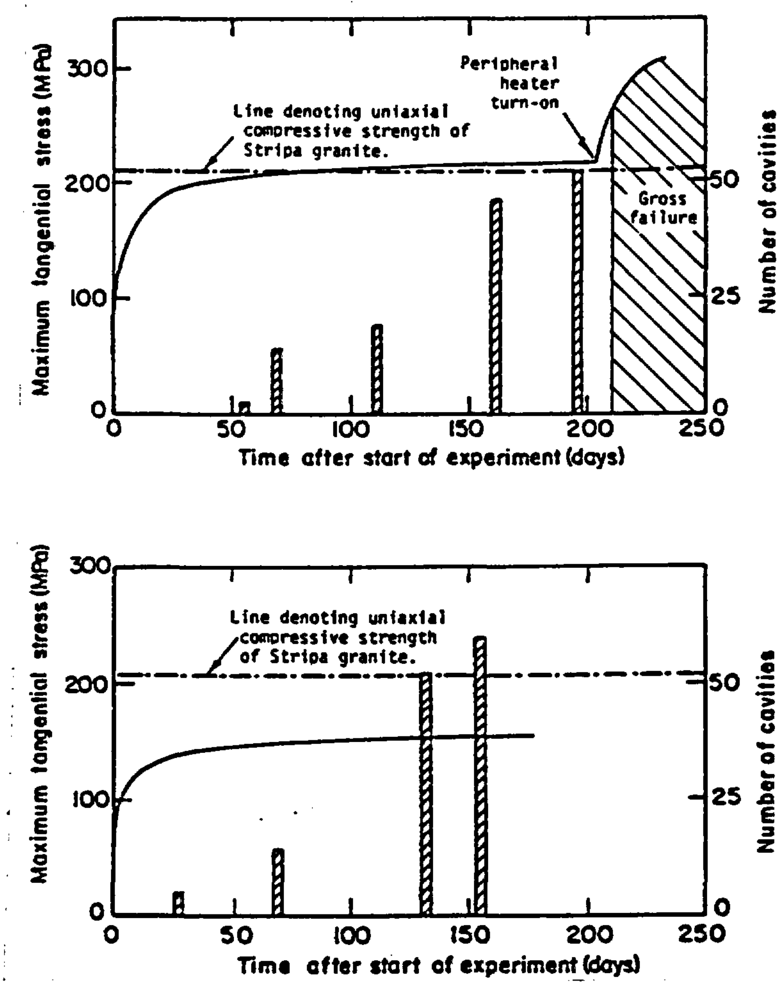


Figure 10. Results from STRIPA (Hood et al., 1979); bars represent number of cavities in borehole walls.

2.4.3 The Heated Block Experiment

The single-element heater experiment enables determination of basic thermal parameters. However, it provides only indirect information on the variation of deformation modulus and lateral strain ratio as a function of temperature and on the variation of the thermal expansion coefficient as a function of stress. These relationships can be provided by a heated block (HB) experiment at an intermediate scale.

Figure 11 is a schematic layout of the HB experiment at one time planned. The experiment was to be conducted in an alcove excavated in an area where the rock mass quality and stress environment are representative of the potential repository. In this experiment, a 2-m block would be carefully located, oriented, and excavated in the floor of the alcove. Instrumentation and heaters would be installed, and the block would be subjected to various heating and loading cycles intended to provide information on rock mass performance within the expected range of repository conditions. Ambient temperature load cycles were to be of relatively short duration (less than one day) while thermal cycles would take several days or weeks. Heater locations were to be selected to achieve rapid heating and uniform heat distribution in the block.

Temperatures, displacements, and stresses were to have been monitored at a number of locations inside and outside the block using thermocouples, thermal flux gages, long-gage surface extensometers (SX) with tiltmeters, MPBXs, and borehole stress cells or similar instruments.

2.5 Potential Test Impacts

The thermal tests will heat portions of the rock-mass in drifts located at the repository level, but will have limited impact on the site. Test-to-test interference will be avoided by fielding tests outside the thermal zones of heated rock surrounding each of the thermal tests. Separate drifting will have to be excavated to field the thermal tests, but otherwise interference with ESF construction is not anticipated.

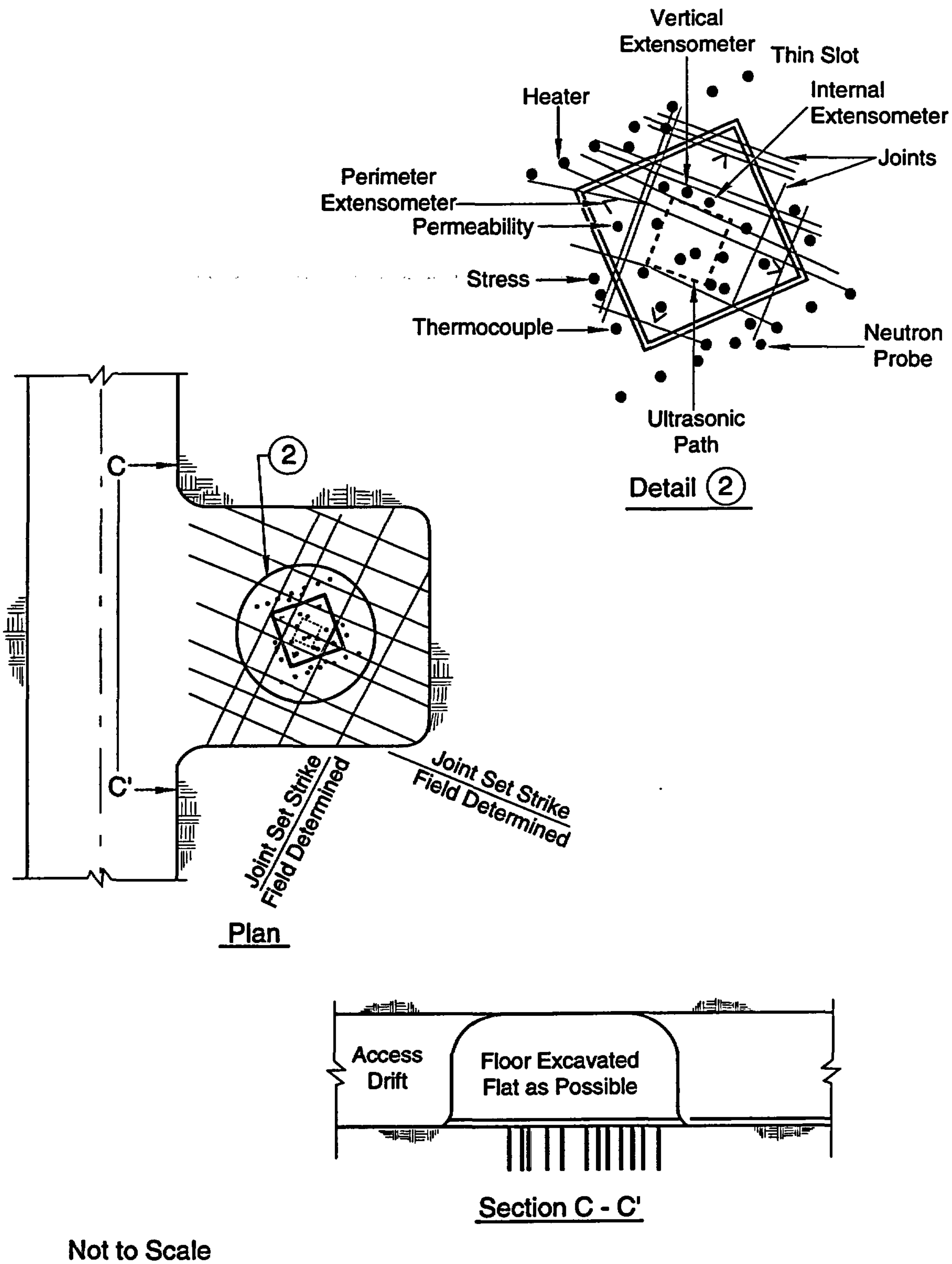


Figure 11. Schematic of heated block experiment (from DOE, 1988).

3.0 APPLICATION OF RESULTS

3.1 Introduction

In this chapter, a detailed discussion of how data to be obtained under this study will be used. This discussion is in terms of end users or "customers" of the data. Major customers for thermal test data include waste package and repository design, preclosure and postclosure performance assessment, and licensing and site suitability activities. As the supplier, the test community tried to work with the customers to reach agreement on the basic information and data that the test program should provide. These requirements are consistent with the basic licensing framework outlined in the SCP (i.e., the issue resolution strategy) and also meet the needs identified in 10 CFR 60 and the current needs of the Project. The results will ultimately be used in supporting a license application.

As noted before, the tests described in this study plan are a result of a concerted effort at test consolidation. As a result, the tests described in this Study Plan will supply information not only for this study, but also will supply information for other studies. A discussion of the additional uses of data from the tests described in this Study Plan will be given in Study Plan 8.3.4.2.2.4 (Engineered Barrier Field Tests), but will also be listed briefly in this chapter.

3.2 Near-Field Environment

There is experimental evidence (e.g., Hood et al., 1979) that heat is transmitted largely by conduction, even at the rock-mass scale. There is also evidence from small-scale tests in G-Tunnel that fractures can have a profound effect on heat transfer through possible convection (Zimmerman et al., 1987; Ramirez et al., 1991). Data on the rock-mass scale are needed to investigate the relative amount of heat transferred by conduction versus convection. This information is needed by waste package design, repository design, preclosure performance assessment, and postclosure performance assessment.

Additional near-field environment issues that will be addressed by tests described in this study plan, but are outside the scope of this study, include:

- the amount and chemistry of water entering the engineered barrier system,
- hydrologic properties,
- mineralogical and geochemical properties, and
- conceptual model testing, including propagation of a drying front, residual water saturation in a dry zone, reflux of liquid phase water, significance of enhanced vapor diffusion and potential for buoyant gas convection.

3.3 Rock-Mass Properties Over a Range of Temperature

1. *Thermal properties.* As part of the modeling of the repository system, temperature histories must be calculated, which requires thermal properties of the rock mass—specific heat and thermal conductivity. The thermal properties of the rock mass are also important as part of the input to calculations of the expected temperature history of the waste

packages. Waste package temperature is important for understanding waste form degradation and waste package corrosion. Current design and performance assessment models are based on a layered representation of the host geology. Therefore thermal properties of all the units are desired. Laboratory data on intact samples from units outside the host unit (TSw2) are acceptable. In situ thermal properties from the host unit will be important confirmation for rock-mass thermal properties derived from laboratory data, which are used in the models. It is also essential to understand the spatial variability of these properties. The spatial variability issue is best handled by the laboratory test program, which is designed to systematically measure intact rock thermal properties over the site. However, some indication of the representativeness of data on rock-mass properties from field-scale tests is needed. This may require a limited number of duplicate in situ tests at different locations. Principal customers for this information are Waste Package and Repository Design, and Pre- and Postclosure Performance Assessment.

2. *Thermal expansion.* The thermal expansion of the rock mass is the mechanism for coupled thermal-mechanical (stress changes) and mechanical-hydrological (fracture aperture changes) behavior. Thermal expansion is an essential input to all coupled modeling efforts. Principal customers for this information are Repository Design and Pre- and Postclosure Performance Assessment.

3. *Mechanical properties.* Rock-mass properties (deformation modulus and Poisson's ratio) are essential for calculating the stresses induced by thermal expansion. Generally these properties will be determined empirically or analytically from relationships between intact rock properties, measures of the degree and nature of rock-mass fracturing, and fracture properties. However, these properties need to be determined at elevated temperatures representative of repository conditions, which are beyond the normal range of applicability of most commonly used empirical methods. Therefore, these models must be validated by some field measurements of rock-mass properties at elevated temperature. Principal customers for this information are Repository Design, and Pre- and Postclosure Performance Assessment.

4. *Fracture properties.* The rock mass in the repository horizon is highly jointed, with the intact rock blocks having relatively high strength. Thus, the fractures or jointing will control the bulk of the deformation and structural weaknesses. Therefore, fracture properties (normal and shear compliance, shear strength, and cohesion) are essential to estimates of rock-mass deformation and strength. Early information from laboratory testing is essential, but scaling to rock-mass scale may be a problem. Thus, some in situ data are required. These properties must be determined at elevated temperatures representative of repository conditions. Customers for this information are Repository Design and Preclosure Performance Assessment.

5. *Rock-mass strength.* As with other rock-mass properties, rock-mass strength is usually estimated by empirical relationships or other modeling techniques. Because regions where failure may occur are likely to be heated, failure criteria must be applicable to temperatures representative of repository conditions. Therefore, some validation (calibration) of proposed methods is needed. Principal customers for this information are Repository Design, and Pre- and Postclosure Performance Assessment.

6. *Temperature effects on rock thermal and mechanical parameters.* Most of the above mentioned parameters may be functions of temperature and temperature history (e.g., thermal expansion coefficient may be different for heating than for cooling). These effects are being investigated in detail in laboratory determinations of intact-rock thermal, mechanical, and fracture properties. However, some rock-mass-scale measurements of temperature effects need to be made to determine if the effects are significant and if the models used incorporate the effects in a reasonable way. The principal customer for this information is Postclosure Performance Assessment.

3.4 Drift Response and Stability Under Thermal Conditions

1. *Thermal response of drifts.* Many design analyses deal with the response of drifts or shafts as they are constructed and then subjected to thermally induced loads. Data from repository drift-scale tests are needed to validate models of thermal-mechanical response and provide bounding estimates of the extent of possible short-term alteration of the hydrologic system. Principal customers for this information are Repository Design and Preclosure Performance Assessment.

2. *Long-term drift stability under thermal conditions.* The concern here is to be able to estimate the probability of rock falls that would impact the waste packages. Sizes and amounts of rock fall are of interest to waste package and repository designers from the standpoint of retrievability as well as for establishing the potential for a rock-fall-induced package breach. Also of interest is rubble contacting the waste package (like backfill), which has the potential to affect thermal management within the package and assist water contact and corrosion processes. Information on the size and probable frequency of roof falls is needed. This can be estimated with analytical techniques, provided that in situ rock-mass strength can be bounded and data on drift response under thermal conditions can be obtained. Principal Customers for this information are Waste Package Design, Repository Design and Postclosure Performance Assessment.

3.5 Ground Support and Design Feature Interactions at Elevated Temperature

1. *Ground Support T-C Interactions.* The interaction of ground support materials with the near-field environment is an issue of interest to Repository Design and Waste Package Design. The longevity of the ground support has an impact on design considerations for impacts from rock falls, and the chemical interaction of the ground support materials has an impact on waste package corrosion issues. Other design features, such as the use of concrete or crushed tuff inverts in emplacement rooms, should be tested to determine their potential for affecting the near-field chemistry. The principal customers for this information are Waste Package Design, Repository Design and Postclosure Performance Assessment.

2. *Ground Support T-M Interactions.* All openings in the repository will have some ground support installed. Ground support will consist of steel bolts, cementitious materials, and other structural components. Information on the behavior of these materials at elevated temperature, as well as the interaction of the ground support with the host rock at elevated

temperature, is needed. The principal customers for this information are Repository Design and Preclosure Performance Assessment.

Additional near-field environment issues that will be addressed by tests described in this Study Plan, but are outside the scope of this study, include thermal and hydrologic properties of backfill and in situ corrosion rates and processes.

3.6 Validation of Thermomechanical Models

One of the data uses identified in the above discussion is to validate models of thermal-mechanical response.

Validation of thermomechanical models of in situ rock mass behavior must be recognized as being quite different from the classical validation approach used for models of *engineered* materials and structures. This is a common situation in many practical engineering problems and will always be the case in practical rock mechanics problems because of the variable nature of geologic materials. Even under the best circumstances, repository design and performance analyses will be conducted in a very *data-limited* environment as described by Starfield and Cundall (1988), where there is never enough information about the rock mass for it to be modeled unambiguously. Thus, using thermomechanical models to make absolute local predictions, which are then compared to test results (a more classical form of validation), is unlikely to produce meaningful results and could lead to disqualification of useful analytical tools. Instead, validation should be considered a process of developing sufficient confidence in the models so they can be used to explore and evaluate potential tradeoffs and alternatives to achieve the necessary performance. Validation should also be an iterative process. The results of a validation exercise can be used to improve or *calibrate* the model, which would then be subject to further validation exercises (to the extent that the end use by design and performance assessment requires).

Figure 12 depicts the detailed process for conducting a validation exercise with experiments. The implementation of a specific validation exercise must be focused on physical phenomena or processes that can be shown to be of key importance in the application of the model to design or performance assessment. Experiment configurations and test conditions are then developed to test those aspects of the model. The iterative process of modeling the conceptual experiment and then refining the experiment design is critical to ensuring that (1) the experiment will test the critical features of the model, and (2) that the experiment can be modeled with as little uncertainty as possible. This means that boundary conditions, geometry, and other factors need to be designed to accommodate modeling restrictions and simplifying assumptions.

Once the experiment is designed, pre-test predictive analyses should be performed. Such analyses are essential because they provide a baseline analyses for comparisons with the experimental data and other analyses that are performed after the experiment is completed. Once the experiment is completed, an extensive evaluation of both the experiment and the model parameters must be performed. Additional analyses must be performed to evaluate the effects of differences between planned and actual test conditions. Back-analyses are also executed to determine if variations of material properties or other model parameters could produce better agreement with test results than those originally predicted.

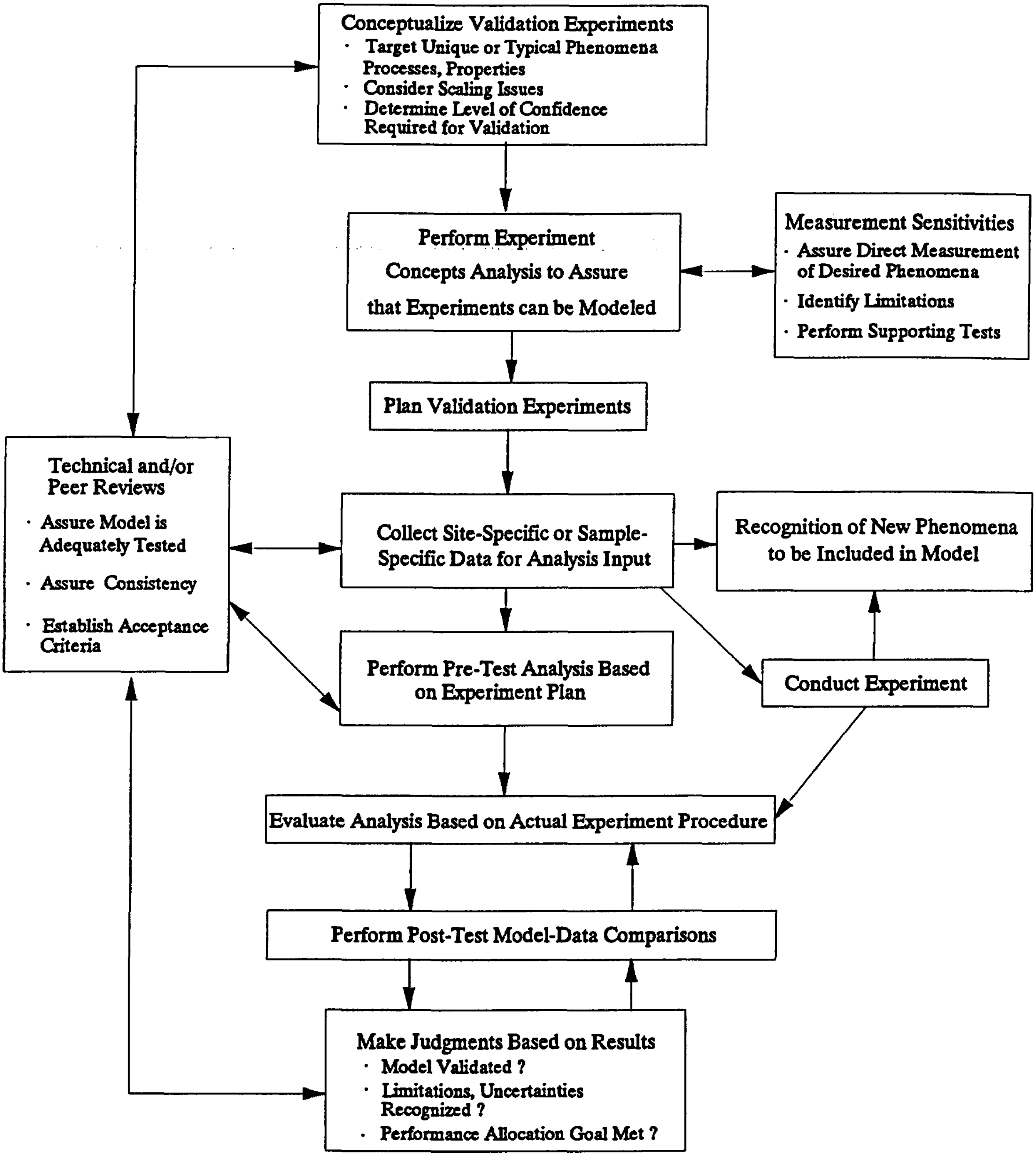


Figure 12. Detailed Validation Exercise

A model cannot be declared valid or invalid based on the results of one such exercise. Validation is an iterative process of collecting information and building a case to support the judgment that a model is valid for some intended application. The process includes using the results of various validation exercises to improve the model, if necessary, and to better understand and define the limitations and uncertainties associated with the model. The process has no definite termination point, but as more and more information is collected from various validation exercises, more confident judgments can be made as to the validity and limitations of the model. At submission of the repository license application, design and performance assessment must be based on validated models. At that time, sufficient evidence must be available to base a credible claim that the models are sufficiently validated to allow further construction and monitoring of the repository. Full validation of some aspects of the thermomechanical models might be delayed until later milestones in the repository life cycle.

An important component of the type of validation exercise is the oversight that might be provided through independent technical and peer reviews. In order to be able to make and defend judgments regarding the validity of the model in the context of its application in design or performance assessment, broad-based acceptance of the methods and results is needed. Criteria for acceptable comparisons must be generally agreed upon and must consider the intended use of the models.

Model-data comparisons are a key element of the validation exercise (Figure 13). The model output used in the model-data comparison can be point comparison, system comparison or a combination of both. Examples of point data used for comparisons include temperature, displacement, stress or convergence. Examples of system-based comparisons would be to compare modeled, or predicted, stability with field performance using parameters such as frequency and magnitude of rock fallouts, frequency of drift ground support maintenance/rehabilitation, or damage to a container due to borehole-rock movement. Traditionally, point comparisons have been used in validation exercises even though it has long been recognized that large scatter in single-point comparison results from measurement errors and large local variability in rock structure and rock properties. To validate their thermal model, Hocking et al. (1990), successfully used plots of measured versus predicted data to determine the correlation coefficient between these two data sets. In this approach, the impact of local divergence of modeled and measured results was weighted into the total goodness of fit.

Because of the history of using numerical modeling for structural design, it is often assumed that point-by-point comparisons of field and modeled data will be an adequate test of the model. This assumption is often valid when dealing with models of structural steel or other *engineered* materials. However, in rock structures, the variability of rock properties and rock mass conditions is often so great that it makes point-by-point comparisons meaningless. Other comparison techniques must be developed. One potential technique is to extrapolate measured data at several points to create a full-field data set. For example, displacement measurements at several points along a drift might be extrapolated, using geostatistical methods, to predict the expected displacement everywhere around the drift. This extrapolated displacement field would then be compared to the calculated displacement field. Thus, judgments regarding validation can be based on comparisons of expected/measured displacement versus predicted (calculated) displacement over a large volume of rock and not just a few points.

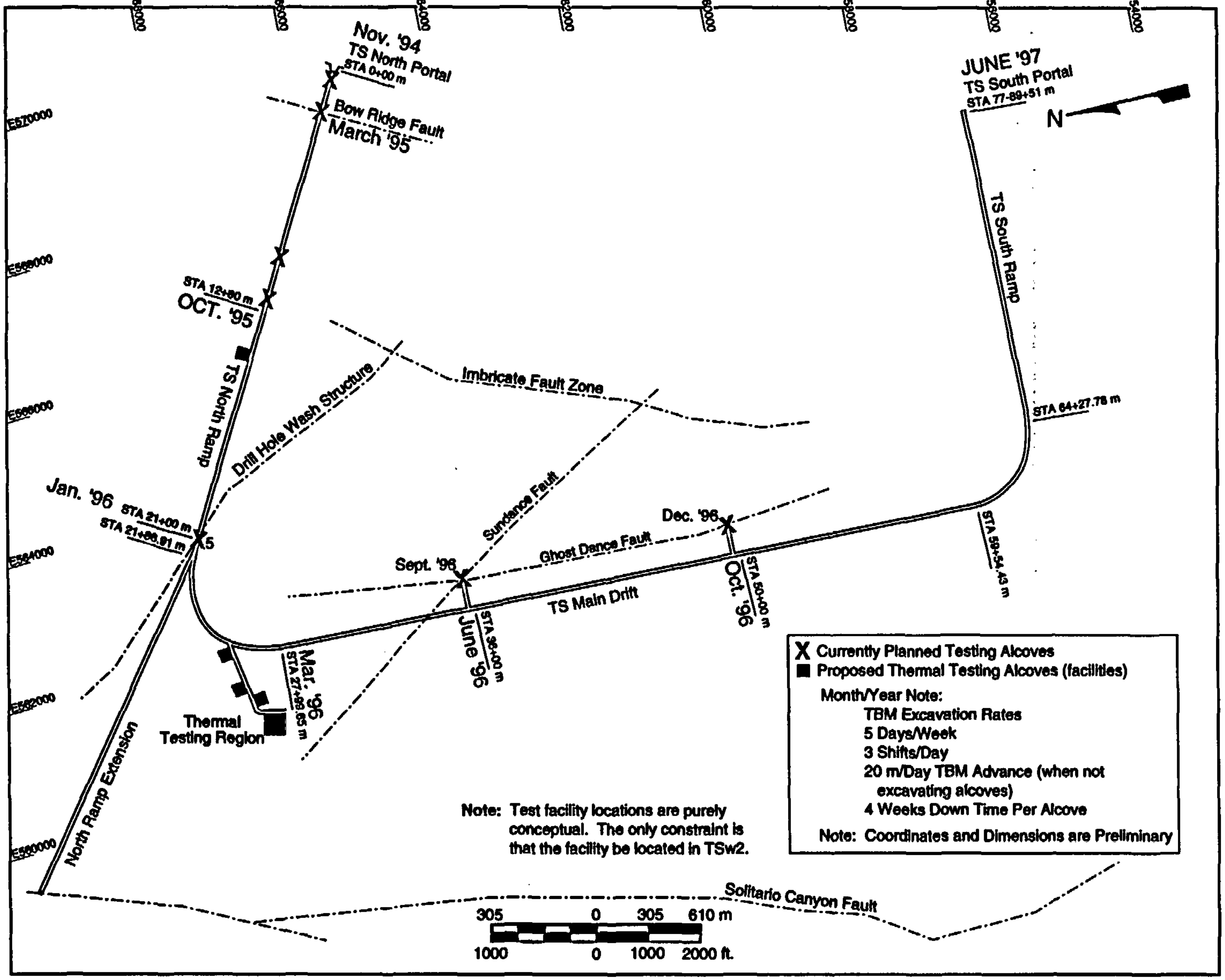


Figure 13. ESF layout/construction schedule.

Examples of post-test model-data comparisons are provided by Hocking et al. (1990), Heuze et al. (1992), Costin and Chen (1988), and Costin (1990). There are no examples of pre-test model analysis results being used exclusively for a validation exercise with good results. Examples of failures of pre-test analysis are available, but in most cases, the pre-test analysis was completed before adequate site characterization had been completed. This is why the validation strategy must employ both pre- and post-test evaluations.

Assuming that suitable methods of comparing test data with model predictions will be developed, the question remains: Which criteria should be applied when making the assessment of model adequacy? Specific criteria must depend on the particular type of model and its intended application. However, there are at least two general criteria that should be considered when developing conclusions regarding the validity, limitations, and uncertainties of a model.

- *Adequacy of model physics.* This criterion generally applies only to theoretical models and addresses the questions: Is the physics good enough to predict essential behavior and can important phenomena that may not be incorporated directly in the model, such as scale effects, be accounted for by back-analysis or other calibration so that the model can be used to extrapolate to other cases? The testing strategy for validation of thermomechanical models was designed to address this question by requiring that tests be performed at several scales. The results from tests at different scales can be used along with some additional analysis to determine if the model is capable of appropriate scaling and to determine the limitations of the scaling capability.

- *Prediction of behavior.* This criterion applies to both empirical and theoretical models used for design or performance assessment and addresses the question: Does the model represent the physical world well enough to develop performance goals and to provide means for verifying that a design has met those goals? This criterion indirectly addresses the larger question of what is good enough. For thermomechanical models, the end application will be in the area of design. The strategy used in the SCP is to establish performance goals for systems of components to ensure that the potential repository will meet all regulatory requirements. This performance allocation process requires the use of models to assist in establishing goals, for example, for near-field thermal conditions, that will ensure the design will meet requirements for retrievability and long-term stability of the rock mass. By applying models and design parameters to those goals, a quantitative measure can be developed of the model requirements. These measures can then be used to assess the model's performance in a validation exercise.

4.0 SCHEDULE

Table 7 provides a proposed schedule of in situ testing that will allow the initial phases of all the tests to be completed and documented in time to support a License Application to construct a repository. The schedule should be integrated with the construction schedule (Figure 13) and reflects the desire to have some data from the early tests available to support a viability assessment.. The schedule is structured along the lines of the basic testing strategy to conduct the simpler, smaller-scale tests first and use experience gained in these efforts to the best advantage when planning the larger, more expensive tests. The larger tests also take more time and effort to design and plan properly.

Table 7. Summary of Thermal Test Schedule

Test	Data Available for Viability Assessment and LA to construct a repository	Documentation Complete for Viability Assessment and LA to construct a repository
Single-Element Heater	6/98	1/99
Plate-Source Thermal	1/99	6/99
Emp. Drift Thermal	2/00	12/00

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