DOE/YMSCO-003

In-Situ Thermal Testing Program Strategy

Prepared by

The United States Department of Energy
Yucca Mountain Site Characterization Project

Publication Date: June 1995

Enclosure

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Abstract

In the past year the Yucca Mountain Site Characterization Project has implemented a new Program Approach to the licensing process. The Program Approach suggests a step-wise approach to licensing in which the early phases will require less site information than previously planned and necessitate a lesser degree of confidence in the longer-term performance of the repository. Under the Program Approach, the thermal test program is divided into two principal phases: (1) short-term in situ tests (in the 1996 to 2000 time period) and laboratory thermal tests to obtain preclosure information, parameters, and data along with bounding information for postclosure performance; and (2) longer-term in situ tests to obtain additional data regarding postclosure performance. This effort necessitates a rethinking of the testing program because the amount of information needed for the initial licensing phase is less than previously planned. This document proposes a revised and consolidated in situ thermal test program (including supporting laboratory tests) that is structured to meet the needs of the Program Approach. A "customer-supplier" model is used to define the Project data needs. These data needs, along with other requirements, were then used to define a set of conceptual experiments that will provide the required data within the constraints of the Program Approach schedule. The conceptual thermal tests presented in this document represent a consolidation and update of previously defined tests that should result in a more efficient use of Project resources. This document focuses on defining the requirements and tests needed to satisfy the goal of a successful license application in 2001, should the site be found suitable. In the next phase of this test definition activity, the longer-term objectives of waste receipt and repository closure will be considered, and a thermal test program will be defined to cover the anticipated needs of those activities.

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1.0 INTRODUCTION

In the past year, the Yucca Mountain Site Characterization Project has implemented a new approach to evaluating the suitability (10 CFR 960: US DOE, 1994) of the Yucca Mountain Site and, if the site is found suitable, for preparing a license application for submittal to the Nuclear Regulatory Commission (NRC). This *Program Approach* suggests a step-wise method to licensing that in the early phases will rely on less site information than previously planned—in contrast to the previous approach, in which licensing would be accomplished in a single step. The Department of Energy (DOE) intends to have sufficient information available by 1998 to make a technical determination of site suitability and, if warranted, to proceed to the initial licensing phase by 2001. Additional characterization and design information will be generated during the 2001 to 2008 time-frame to support amending the license to receive and emplace waste. Because of the later testing period and a lengthened performance confirmation period, the Program Approach reduces the number of tests and analyses required to determine site suitability and to submit a license application. Instead, this approach focuses the characterization activities into three segments:

1. those required for evaluating site suitability (to be completed before 1998),
2. those required for a conceptual (Title I) design of the repository and a more detailed (Title II) design of the waste package along with the bounding of repository system performance (to be completed before 2001), and
3. those required for completing repository design (including thermal load) and confirming postclosure repository performance (to support the 2008 license update).

The first two segments are areas of immediate concern. The third segment defines the activities needed to achieve the emplacement of waste and the final closure of the repository. Perhaps the key issue that must be addressed in all three segments is the uncertainty about the interactions of waste-generated heat with the host rock and the ground water system and how these interactions might affect the waste packages. It is anticipated that in situ heater tests can provide bounding information to achieve limited resolution of design and performance questions prior to the 2001 License Application, with fuller resolution to be achieved prior to the License Application Update to Receive and Possess Waste in 2008.

The Program Approach therefore necessitates a rethinking of the testing program because the amount of information needed for the initial licensing phase is less than previously planned. The near-term objective is to develop information for a construction license. A more detailed understanding of the site and longer-term performance testing will be developed during the initial licensing period and will be needed for subsequent license amendments.

The objectives of this report are first to define the set of information needs and requirements from the end users of in situ thermal test data, and second to propose a conceptual thermal testing program that is aligned with the Program Approach—to be conducted in the Exploratory Studies Facility (ESF), at other field locations, and in the laboratory—that meets the needs of the end users. The focus of this report is on the testing needs for Technical Site

Suitability and the initial License Application. A definition of the testing required for the time period beyond 2001 is also being developed, but it will not be discussed in this version of the integrated thermal test strategy and plan, except for indications of how the early test program transitions into the later, longer-term test program. Subsequent versions of this plan will present the basis and strategy for longer-term thermal testing to support license updates. Although this plan is directed toward a definition of the thermal in situ tests, complemented by a selected group of laboratory thermal process tests, it is recognized that numerous laboratory investigations of intact-rock and fractured-rock thermal, mechanical, and hydrologic properties and processes are ongoing and planned. The results of these laboratory tests are expected to provide essential information for addressing technical site suitability and design issues. The in situ thermal test program is intended to make the maximum use of laboratory data in the test design process and in the interpretation of in situ test results and analyses.

The approach taken in developing this in situ thermal test plan was first to examine the data needs derived from repository and waste package design, preclosure and postclosure performance assessments, and licensing. Next, other constraints such as Project schedules and likely construction methods were considered to arrive at a suite of tests that best meets the data needs and other objectives. Care was taken to assure that the requirements and planning basis were consistent with the DOE "Civilian Radioactive Waste Management Program Plan" (US DOE, 1994), the Draft "Mined Geologic Disposal System Licensing Strategy," and other documents that relate to the Program Approach strategy. In addition, presentation materials used by the DOE in various interactions with the NRC and the Nuclear Waste Technical Review Board were consulted. Much of the background information and schedules presented in this report are derived from these sources.

2.0 THE PROGRAM APPROACH

When establishing a revised thermal test program it is important to understand the basis for the revisions from the basic plan and strategies set forth in the Site Characterization Plan (SCP) (US DOE, 1988). The SCP, issued in 1988, contains an extensive testing, design, and performance assessment program that was designed to produce a comprehensive understanding of Yucca Mountain under both ambient and perturbed conditions. However, the program described in the SCP does not necessarily need to be completed before a license application is submitted. Over the past year, the Yucca Mountain Site Characterization Project has developed a new Program Approach, consistent with the current legislative and regulatory framework of the Project, to achieve the basic goals of the Project within the projected budgetary constraints and on a schedule that would demonstrate significant progress within the next five years. Implicit in this approach is the assumption of additional uncertainty on the part of DOE by accepting that less site information will be available for the initial License Application in return for achieving phased Program Approach goals. Additional testing conducted beyond 2001 will reduce this early uncertainty as our understanding of key processes evolves.

The strategy for achieving these goals involves a step-wise approach to the determination of technical site suitability and the licensing process. This step-wise approach is embodied in the following set of milestones:

- Technical Site Suitability — 1998
- License Application to Construct a Repository — 2001
- Construction Authorization — 2004
- License Application Update to Receive and Possess Waste — 2008
- License to Operate a Repository — 2010

A step-wise approach to site characterization and performance confirmation is required to implement this approach. Because of the schedule for developing the technical basis reports that will support the Technical Site Suitability determination in 1998, the only likely contributor to site suitability from currently planned thermal field tests is the Large Block Test (described later in this report). Early thermal tests in the ESF will provide confirmatory information to support suitability conclusions reached on the basis of laboratory properties and thermal process testing and modeling. For licensing, the Program Approach defines four fundamental tenets that form the basis for the licensing strategy and the testing program required to support the strategy:

1. *Safe repository operations for a significant preclosure period, maintaining the option to retrieve emplaced nuclear waste for up to 100 years after the start of emplacement operations.* This extended period of operations allows for significantly enhanced reliance on performance confirmation testing to demonstrate that repository performance is within acceptable bounds. Thus, some of the testing to reduce uncertainties in postclosure performance issues can be reduced to a level consistent with establishing conservative bounds on the expected behavior of certain subsystems

of the natural and engineered barriers, and some can be delayed until after the initial License Application.

2. *Regulatory confidence in the waste package containment for at least 1,000 years after closure.* Developing high confidence in waste package performance for at least 1,000 years allows greater latitude in the use of bounding estimates to demonstrate reasonable assurance for postclosure system performance. While this approach allows the Project to phase the collection of data regarding postclosure performance issues, it underscores the need for early information on the near-field waste package environment.

3. *Acceptable bounding analyses of radionuclide releases and total system performance for the regulatory period, currently 10,000 years.* To develop acceptable bounding analyses, some testing to address key issues is required. In particular, bounding the range of conceptual models of coupled processes in the near-field is essential, as is some understanding of the far-field effects of thermal loading. To do this will require laboratory testing, detailed analyses, evaluations of natural analogs, and in situ thermal tests.

4. *An adequate testing program to support the design and bounding analyses, particularly with respect to establishing thermal effects on waste isolation.* The testing program must be developed and implemented to support the level of design and expected confidence in system performance required to complete each major phase of the licensing process.

The strategy for the initial License Application involves placing special emphasis on the preclosure period and the ability of the engineered barrier system to contain wastes and inhibit radionuclide mobilization (to offset uncertainties in the natural barrier). Although subsequent testing (after 2001) will be focused on reducing uncertainties in the natural system, early efforts must focus on the preclosure period while also assisting in the development of an understanding of postclosure performance. Therefore, for the initial License Application, implementation of the Licensing Strategy consists of these components:

- *A repository design and operations plan that demonstrates the ability to maintain safe repository operations and the ability to retrieve waste throughout the preclosure period.* The repository design will be primarily at a conceptual level (Title I), except for a few components that are important to radiological safety, waste isolation, and retrievability, which will be designed in more detail (Title II).

- *A flexible repository design that allows for a range of emplacement strategies.* Only the primary repository area will be considered initially, with focus on a design strategy that will accommodate a range of thermal loads. The initial strategy is to (1) demonstrate an understanding of nominal conditions of the site, and (2) demonstrate that the "maximum thermal load," as it will be defined in the license application, will not disturb site conditions to the extent that we can no longer clearly bound the performance of the system. The value of the "maximum thermal load" has not yet been established.

- *A robust waste package design that is compatible with the Multi-Purpose Canister (MPC) concept that maintains substantially complete containment for at least 1,000 years in a realistically conservative near-field environment.* Thermal testing must address a range of potential environments that are associated with the potential range of thermal loads.

- *Realistically conservative performance assessments to provide reasonable assurance that the long-term postclosure performance objectives can be met.* Data from early short-term thermal tests, along with predictive models supported by laboratory and field data, will be required to provide support for the demonstration of compliance with the performance objectives.

The Program Approach allows the thermal test program to be divided into two principal phases: (1) short-term in situ tests (in the 1996 to 2000 time period) and laboratory thermal process tests to obtain preclosure information, parameters, and data along with bounding information for postclosure performance; and (2) longer-term in situ tests to obtain additional data regarding postclosure performance.

The focus of the remainder of this report is on defining the requirements and tests needed to satisfy the goal of a successful license application in 2001 (i.e., the first phase of the thermal test program). Within this first phase, a higher degree of confidence is needed for data necessary to resolve preclosure issues (e.g., worker health and safety). These data include rock-mass properties and information on drift stability and ground support interactions. A need also exists in this first phase to "bound" our understanding of coupled processes to the degree that defensible calculations of postclosure performance can be made. The second phase of the thermal test program, to be developed in a later document, will emphasize the collection of data and information necessary to resolve issues related to coupled processes, particularly those that may not develop during shorter time periods (e.g., geochemical couplings). The requirements, test plans, and test objectives must be consistent with the Licensing Strategy for the Program Approach and the tests themselves must be of reasonable scope to support the major Project milestones.

3.0 THERMAL TEST PROGRAM DEVELOPMENT— PROCESS AND ASSUMPTIONS

To develop the integrated in situ thermal testing program proposed in this report, a team approach to the process was taken. A core team of Project personnel, principally from the participant national laboratories, was established. Numerous other groups were consulted for input on specific requirements, information, and data needs in the areas of repository and waste package design, performance assessment, and licensing. Informal input was also solicited from various groups external to the Project. The major goals of the core team were to (1) clearly define the data and information needs related to thermal testing, within the context of the Program Approach; and (2) achieve some degree of consensus on the conceptual nature of a testing program that can meet the requirements.

3.1 Requirements

The data and information needs that were expected to be provided by the in situ thermal test program are discussed in detail in Section 8.3 of the SCP. Because the basic issues and information needs defined in the SCP have not changed substantially, they form the basis for defining the test requirements. However, the Program Approach now defines a more discrete time-phased approach to developing information for the resolution of the SCP issues and information needs. In addition, the introduction of the MPC has required a shift in waste emplacement strategies. These factors necessitated a thorough review and redefinition of the basic test requirements to ensure that the Program Approach strategy and schedule could be implemented. To accomplish this task, a "customer-supplier" approach to defining requirements was employed. The major "customers" or users of the data and information derived from the thermal test program were asked to provide their requirements, data needs, and expectations of the test program. Major customers included the waste package and repository design teams, preclosure and postclosure performance assessment groups, and site suitability and licensing organizations. As part of defining data and information needs, the level of confidence required to meet the goals of the Program Approach was also discussed. In follow-up discussions, the thermal test program team tried to provide feedback about the types of information that could be generated within the schedule constraints and to derive a clear understanding of the requirements and expectations of the test program. Through this iterative process, a set of requirements was defined that forms the basis for redefining the test program. These requirements, along with the initial SCP basis, are discussed in detail later in this report.

Other sources of requirements or constraints on the definition of the test program were also considered. As discussed in the previous section, the Program Approach and corresponding Licensing Strategy offer an opportunity to narrow the scope of the early phase of the testing program. Also, the desire to provide confirmatory information for Technical Site Suitability at the earliest possible time was considered.

3.2 Test Definition

After the requirements and constraints were defined, a conceptual test program was defined that will, with some degree of confidence, meet the requirements. The near-term test program consists of a set of tests defined at a conceptual level, which are based on the SCP thermal testing program but modified by the changed nature of the test requirements. The test definitions were also greatly influenced by the experience base in thermal testing that was developed over the past decade. Thermal test experience with tuff in G-Tunnel and other locations, testing experience 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 design of the tests. It should be emphasized, however, that the test concepts were derived specifically to meet the program 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.

- In the laboratory testing component, the focus is on tests that address coupled processes. Thermal properties tests are noted where appropriate but not discussed in detail. The laboratory program presented represents examples of tests designed to provide insight into coupled phenomena; these tests will assist in the interpretation of data from the larger-scale in situ experiments. Because of the complexity of the coupled process issue, however, a complete understanding of competing hydrothermal phenomena is not expected from the proposed laboratory program.

- Laboratory tests were also considered in cases where they could provide information that was needed to support the design of an in situ test or assist in the interpretation of in situ test results. The combination of laboratory tests with in situ test data is necessary to satisfy some of the information needs.

- 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, since the larger, more complex tests require several years of design and development; (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; (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. This "walk-before-you-run" strategy could not be fully implemented because meeting program milestones requires that multiple tests be conducted in parallel instead of in sequence. However, the phasing allows test experience to be passed on from one test type to the next.

- 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.

- Account was taken for the fact that the DOE is willing to accept more uncertainty in the amount of data and information from the testing program in trade for meeting phased Program Approach goals. Additional testing done beyond 2001 will improve our understanding of key processes and will be used to support License Application updates.

- In some cases, 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.

- The tests described in this report may continue beyond the designated durations to support data feeds to Technical Site Suitability and initial License Application. It is highly likely that the thermal testing conducted beyond 2001 will include continuations of the early tests in the form of additional heating and/or cool-down monitoring.

In addition to the test program definition, a schedule for conducting each test was developed. The proposed test schedules were integrated with the current ESF construction schedule and are tied to estimated dates when various rock strata and features will be accessible. The schedules are included in Appendix A. As the definition of the test program proceeds, more detailed schedules and logic networks will be developed. The logic networks will include major "feeds" to the testing program from laboratory testing, design activities, and performance analyses. The networks will also indicate how the end products of the testing program (i.e., data and conclusions) are passed on to appropriate end users.

4.0 INFORMATION AND DATA NEEDS

Until the recent implementation of the Program Approach, the SCP was the sole basis for the site characterization testing program. With the Program Approach, as currently viewed, the testing basis must be changed to reflect the new strategy. The needed changes are not as large in basic substance as they are in timing and degree. In addition, other constraints, such as the proposed use of an MPC system, dictate changes in basic testing needs. In this section, a brief review of the SCP basis for thermal testing is presented followed by a more detailed examination of the requirements basis for a thermal test program under the Program Approach. This revised requirements basis was developed using the "customer-supplier" model described earlier. 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 must fit within the basic licensing framework outlined in the SCP (i.e., the issue resolution strategy) and also meet the current needs of the Project.

4.1 Review of the SCP Thermal Test Requirements

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 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.

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

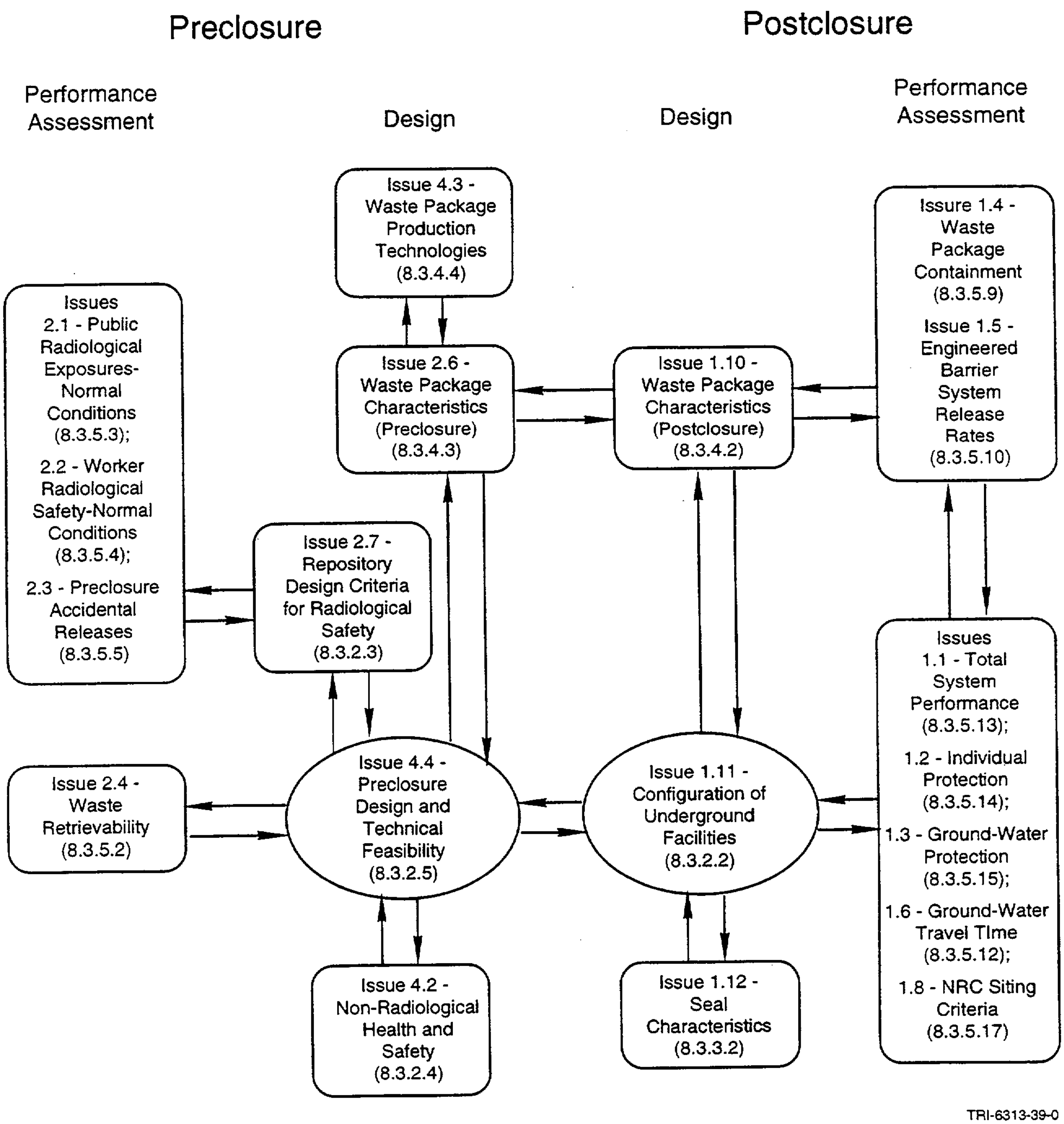


Figure 1. Relationships between design and performance related issues used directly in performance allocation.

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.

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 MPC 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.

4.2 Revision of Thermal Testing Requirements

Revision of the thermal test requirements was based on the Program Approach, which suggests that data and information from the testing program can be phased to support a step-wise licensing process. The thermal test requirements presented in this report, although rooted in the SCP information needs, were revised based on input from Project participant organizations responsible for waste package and repository design, preclosure and postclosure performance assessment, and licensing. The process was initiated at a meeting held on July 13, 1994, where representatives from the major customer organizations presented their perspectives on the information needs to resolve issues for Technical Site Suitability and initial licensing. Subsequent to this meeting, representatives of the various customer groups were contacted to discuss the initial list of requirements and to allow the thermal test team to develop a more complete understanding of the actual information and data needs. This section summarizes the results of these customer-focused discussions.

The information and data needs derived from discussions with the customers were grouped into general categories consistent with categories that appear in the SCP. A final category of Licensing Considerations was added based on more recent developments within the Project (e.g., the Program Approach and interactions with the NRC). The general categories are listed below, and the requirements (data and information needs) are described under each category. The rationale for each need is also discussed. Each requirement is tied to the requesting customers. In most instances, more than one customer requested the same piece of data or information.

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

Table 2. Major Changes to the SCP Approach

SCP Conceptual Design	**Current Design**
Small waste package (3 PWR or 6 BWR assemblies)	MPC-based waste package (12 to 24 PWR or 24 to 40 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	Tunnel boring machine excavation
Ground support in emplacement rooms appropriate for rock conditions with the ability to perform maintenance	Ground support in emplacement rooms very conservative with no ability to perform maintenance
50-year preclosure period	100-year preclosure period

4.2.1 Near-Field Environment

1. *Corrosion processes and rates.* Corrosion processes and rates are the key to estimating waste package lifetimes. Information on the near-field environment that is critical to determining corrosion processes include:

(a) *Water contact and chemistry.* The amount and chemistry of water entering the Engineered Barrier System (EBS) are the essential pieces of information. (Note that a distinction is made between the waste package alone and the EBS.) Water entering the EBS has the potential to contact the waste packages; therefore, if possible, it should be quantified. Also, the chemistry of the water, as potentially altered by repository thermal processes, has a direct bearing on corrosion rates and processes.

(b) *Water movement and behavior.* This is a basic process issue that ties to the issue of water contact and chemistry. The nature and extent of processes, including the formation and movement of potential condensate caps or the development of circulatory refluxing systems, are of concern and need to be bounded.

The principal customers for this information are Waste Package Design and Postclosure Performance Assessment.

2. *Hydrologic properties.* Both undisturbed and thermally disturbed properties are needed. Properties such as permeability (matrix, fracture, and rock mass) and capillary pressure will certainly depend to some degree on temperature. Changes in permeability in the near-field resulting from excavation of drifts and thermal loading can best be addressed by in-situ tests. Other parameters will be derived from laboratory testing. The principal customer is Postclosure Performance Assessment.

3. *Mineralogical and geochemical properties.* Both undisturbed and disturbed properties are needed. Effects such as changes in mineral coatings on fractures due to changes in recirculating water chemistry may be important for longer-term evaluations of the near-field environment. Changes in water chemistry (e.g., pH, dissolved solids, etc.) may have a significant impact on waste package performance (as well as potential deleterious interactions with ground support). The potential changes in fracture coatings (fillings) can have a major impact and can change the transport properties of the rock mass as a function of time. This in turn can affect the coupled phenomena that may occur in the near-field environment. The principal customers are Waste Package Design and Postclosure Performance Assessment.

4. *Conceptual model/hypotheses testing (model validation).* Field-scale data on rock-mass behavior are needed to examine the following issues, which are critical to developing and validating appropriate process level models for performance assessment:

(a) Conductive versus convective heat transfer.
(b) Propagation of a "drying front" and the effects of heterogeneity on the process.

(c) Residual water saturation in the "dry zone" (vapor pressure lowering).
(d) Reflux of liquid phase by fracture flow and the effects of heterogeneity on the process (including the potential for forming heat pipes), and condensate drainage by "fast paths" to regions below the repository.
(e) Significance of enhanced vapor diffusion.
(f) Potential for buoyant gas convection.

Previous testing in G-Tunnel (see Section 6.1) has demonstrated that issues (a) through (d) can be addressed to some degree by in situ thermal tests focused on developing information for site suitability and initial licensing. Measurements related to (a) through (d) are specifically needed to demonstrate some understanding of T-M-H coupling. Issues (e) and (f) are more strongly related to the higher end of the thermal loading spectrum but are also concerns, to a lesser degree, for lower repository thermal loadings. The principal customer for this information is Postclosure Performance Assessment.

4.2.2 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.

4.2.3 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 that would cause water movement into operational areas. 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 and Postclosure Performance Assessment.

4.2.4 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 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 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.

3. *Thermal and Hydrologic Properties of Backfill.* Although the concept of backfilling the emplacement rooms is not currently being pursued by the repository design team, it represents an alternative design feature that should be investigated. The current draft Licensing Strategy also requires that part of the strategy for meeting the "reasonable assurance" criterion is to consider placing some reliance for performance on backfill. Because the in-drift emplacement mode puts any emplaced backfill in contact with the waste package, the thermal properties, hydrological characteristics, and chemical implications of backfill are of concern. Many of these issues can be addressed by laboratory testing. However, opportunities to gain in situ information should not be neglected. The principal customers for this information are Waste Package Design and Postclosure Performance Assessment.

4. *In Situ Corrosion Rates and Processes.* Validation of corrosion models based on laboratory data would provide added confidence to waste package material selection

and performance assessments. Coupons of proposed materials could be placed in a room-scale thermal test with little additional cost or effort. The principal customers for this information are Waste Package Design and Postclosure Performance Assessment.

4.2.5 Licensing Considerations

The primary issues regarding ESF thermal testing from a licensing perspective are:

1. NUREG 1466 - Staff Technical Position on Geologic Repository Operations Area Facility Design (Nataraja and Brandshaug, 1992). The NRC expects DOE to present a systematic understanding of coupled T-M-H-C response of the Geologic Repository Operations Area. The DOE must consider coupling of T-M-H-C processes in a manner unlikely to underestimate unfavorable aspects of repository performance or overestimate favorable aspects. In situ thermal tests are expected to support this effort principally by assisting in the effort to determine which couplings are important and which can be neglected. The early phase of thermal testing is expected to provide some bounds on the nature of important coupled processes. However, thermal testing is of necessity an "accelerated" process, and a clear understanding of how to apply results from accelerated tests in a conservative manner to site model validation and estimates of performance must be developed.

2. Bounding analyses with reasonable conservatism as designated in the Program Approach should be acceptable to the NRC.

3. "Strict" model validation may not be needed for arguments based on "reasonable assurance." However, field data are essential for confirmation and calibration of models (including empirical design tools).

4. The initial License Application will emphasize preclosure compliance and provide predictions of long-term performance to support a "reasonable assurance" finding.

5. The draft Licensing Strategy suggests that the waste package design should be robust enough to "maintain substantially complete containment for at least 1000 years in a realistically conservative near-field environment relative to corrosion potential." The initial strategy then is to develop a waste package that will perform in a "worst case near-field environment." If testing, performance assessments, and systems studies demonstrate that this objective cannot be met, then the Project must be able to "bound" the near-field environment conditions in a region of less aggressive corrosion conditions. Given that the repository thermal loading has yet to be established, the thermal test program must seek to establish some bounds on near-field environments over a range of possible thermal loads.

4.3 Summary of Requirements

The above discussions provide the requirements, the rationale for those requirements, and the connection between the data requested and the licensing strategy being pursued under the Program Approach. In this section the requirements for data and information to support the Licensing Strategy are summarized in a form that will be used through the remainder of this report to connect the requirements to specific tests and the testing strategy.

Table 3 provides a summary of the identified information needs and the principal customers for that information. Licensing is not shown as a customer in Table 3 because its requirements focus on the broad strategy for licensing and are essentially satisfied by meeting the needs of the immediate customers: design and performance assessment. However, the in situ thermal test program must also support the licensing strategy and address the licensing concerns discussed above. A short discussion on how the proposed testing program does this is presented in later sections of this report along with the descriptions of the proposed tests.

The data and information needs summarized in Table 3 are essentially the same as those identified in the SCP (Table 1). The Program Approach also tries to identify the level of maturity or completeness in the information that was expected at each step in the process. *Level of completeness* indicators used in the Program Approach description of activities are:

- **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 extrema 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.

Table 3 indicates the associated completeness level for initial licensing for each information need. The assignment of these indicators was based on Program Approach 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 addition, the relative state of completeness of design and performance assessment activities at the time of licensing was considered. These appraisals are summarized below.

Table 3. Summary of Information Needs

Data and Information Needs	Customers			
	Waste Package Design	Repository Design	Preclosure Performance Assessment	Postclosure Performance Assessment
Near-field T-M-H-C environment				
• Changes in rock saturation	B			B
• Drift humidity	B			B
• Water chemistry (liquid reflux)	B			B
• Mineralogic changes	B			B
• Propagation of "drying front" (heterogeneity)				B
• Residual water saturation in "dry zone"	B			B
• Drainage/reflux of liquid by fracture flow (heterogeneity, heat pipes, fast paths)	B			B
• Rock mass and fracture permeability changes (induced by construction and thermal load)				B
• 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	
• Effect of materials on near-field water chemistry	C			C
• Effect of near-field environment on ground support components		C	C	
• 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

4.3.1 Waste Package Design

The waste package design must be developed to a Title II level for the initial License Application to support the substantially complete containment strategy. The Licensing Strategy suggests heavy reliance on a robust waste package with high confidence in waste package containment for at least 1,000 years after closure.

4.3.2 Repository Design

The repository design need only be at a Title I (preliminary) level for most components at the time of initial licensing. The Title II design will be completed before the construction authorization is given.

4.3.3 Preclosure Performance Assessment

Preclosure performance assessment issues must be developed near resolution at the time of License Application. For licensing, both personnel safety and risks of accidents resulting in releases of radioactive materials must be addressed. The principal concerns over the operational life of the repository are stabilities of the openings under changing thermal conditions. The thermal conditions are also a concern for the selection and maintenance of ground support. These concerns will be addressed principally through modeling exercises that require both thermal and mechanical data as inputs and other field data to assist in validating the models used.

4.3.4 Postclosure Performance Assessment

Postclosure performance assessment issues require sufficient data to develop bounding estimates of subsystem and system-level performance at the time of license application. Final postclosure performance assessment issue resolution may not be required until closure.

It seems reasonable to conclude that large changes in the conceptual nature of the testing program outlined in the SCP are not necessary to provided the needed information. What is needed is a careful evaluation of the focus and level of confidence required and the other constraints (discussed below) for selecting a limited set of SCP tests that can be used directly or modified to provide the needed information.

5.0 OTHER CONSTRAINTS ON IN SITU TESTING

The Program Approach, projected budgets, and construction schedules also impose a set of constraints on the in situ thermal testing program that must be considered. These are discussed below.

5.1 Time Constraints

Rock-mass properties data will be needed to support the determination of technical site suitability scheduled for 1998. If the site is found suitable, additional design and performance assessment data will be required for the initial phase of licensing in 2001. The construction schedule of the ESF dictates that the earliest reasonable start for fielding thermal tests is probably late in FY 1996 (testing could begin earlier with an accelerated program). This means that some basic testing must be started and the results finalized within an 18 to 24-month window. This time constraint is part of the rationale for suggesting that some simple tests be conducted first, along with the inclusion of a set of smaller-scale laboratory tests that focus on thermally driven flow processes, which would provide essential data to meet the early information needs dictated by the tight schedule. Longer-term efforts needed principally for the initial licensing phase could also be started in FY 1996 with a potential time window of approximately three to four years. These in situ tests are expected to provide approximately two years of data gathering before the initial License Application is finalized. They will likely continue beyond License Application to support resolution of performance issues for the 2008 License Amendment. The current schedule plus the Program Approach strategy of achieving only partial completion of studies sufficient to bound most parameters leads to the following set of guidelines for early thermal testing:

- Rock-mass thermal properties and coupled T-H-C tests of simple geometries (e.g., a single-heater test) should be conducted as early as possible and be designed to produce data in less than one year. This would allow time for the tests to provide confirmatory data before Technical Site Suitability deadlines. It would also allow multiple tests to be conducted to better bound the problem and to gain some understanding of spatial variability for arguments of data representativeness. After initial licensing, additional testing could continue if needed.

- Other testing to address issues of near-field T-M-H-C environment, ground support interactions, and drift stability, which must by their nature involve larger-scale testing, should be limited to a few well-defined tests with a data gathering period of at least two years before licensing. This allows approximately six months for construction, six months for test setup, and one year for data evaluation and documentation (four years or less total time). This schedule will require that (1) test geometries (and the corresponding amount of construction) be as simple as possible, (2) heating rates probably be higher than nominal repository conditions, and (3) the volume of rock affected probably be less than expected in the near-field of a repository emplacement drift. These shortcomings do not appear serious given that the Program Approach calls for larger-scale and longer-term tests to be completed prior to the 2008 License Update for waste emplacement. Because of the construction overhead for in situ thermal tests, it is expected that many of the follow-on tests will be extensions of the early tests (e.g., the early tests would not be terminated after two years of observation). In addition, any new tests that would be defined to address longer-term data needs should use areas adjacent to the early tests, allowing reuse of access drifts and other facilities.

5.2 Location Constraints

Because of the need to start as early as possible, the range of locations for the tests will be more limited. Numerous discussions have been held recently regarding possible locations for testing alcoves, but no resolution of this issue is presently in hand. However, it seems certain that by late FY 1996 test alcoves could be driven into the upper part of the TSw2 repository horizon either at the end of the north ramp or as part of a north ramp extension. For thermal testing 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. Therefore one alternative for initiating thermal testing earlier would be to start by conducting a simple test in TSw1. Such a test would be considered only if construction delays arise that would significantly delay access to TSw2. This route may become particularly attractive if TSw2 is not available by late FY 1996 or early FY1997. This possibility requires that the testing strategy be fairly flexible in terms of location and size of facilities needed to conduct the tests.

5.3 Construction Methods

Because of the construction schedule and proximity to the repository block, most testing is currently envisioned to take place in alcoves off the north ramp or in a north ramp extension. Construction of these alcoves can certainly be conducted by drill-and-blast. Other methods may be available at the time that construction must start, but availability cannot be guaranteed. Thermal properties tests can be conducted in drill-and-blast alcoves with no impact on the quality of the test. 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. Again, this simply requires a testing strategy that is flexible enough to accommodate alternative construction methods.

6.0 LESSONS LEARNED FROM PREVIOUS IN SITU THERMAL TESTS

When translating a set of information needs into a set of tests that can accommodate those needs, previous experience in designing and conducting tests should be considered. Although it is undesirable to be overly constrained by past efforts, previous tests can provide information on test techniques that have proven effective, and they can provide a context of realism in terms of the potential for failures, logistical problems, and the difficulties of interpreting field data. In this section several in situ test programs are reviewed briefly to highlight lessons learned from each test effort that may have application to the design of the thermal tests at Yucca Mountain. This is by no means an exhaustive survey, but it is sufficient to provide a flavor of the available experience base for in situ thermal tests.

6.1 G-Tunnel Underground Facility

A number of prototype tests in support of the Yucca Mountain Project were conducted in welded and non-welded tuff in the G-Tunnel Underground Facility (GTUF). A few relevant tests are noted here.

6.1.1 Small-Diameter Heater Experiments

[Reference: SAND84-2621]

The major focus of these tests was to evaluate thermal models of the rock mass, emphasizing thermal properties. A secondary focus was hydrothermal measurements. Three tests were conducted in which a single heater was used in a small diameter (127 mm) borehole. Steady-state power was applied over a 1.2 m length in holes ranging from 2.4 to 3.2 m deep. Heater power levels ranged from 400 to 1200 W. The heater was oriented vertically for two tests and horizontally for the third. The tests with a vertical orientation were conducted in fractured, welded tuff and a non-welded tuff. The horizontal test was conducted in welded tuff. Each test was run for approximately 30 days. Heater-hole wall temperatures slightly exceeded 200°C with rock temperatures at a radius of 250 mm reaching 150°C. Thermocouples, neutron probes, and one multi-point extensometer were used to measure the thermal, hydrological, and mechanical response.

Conclusions/Lessons Learned

- Basic instrumentation worked well.
- Liquid water migrated toward the heater hole.
- Vapor movement away from the above boiling region was observed. Flow directions were governed by fracture density.
- No difficulties were encountered to suggest that scaling to larger heated volumes would be a problem. A central heater with additional guard heaters may be required.

6.1.2 Heated Block Experiment

[Reference: SAND84-2620]

In this experiment a 2×2 m block was defined in the floor of an alcove by line drilling along the four edges. Flatjacks were grouted into the slots created by the line drilling. Two rows of heaters were installed outside the block and parallel to two opposing edges. The block was extensively instrumented on the top surface with horizontal displacement gauges. Measurements were also made in several vertical boreholes. Attempts were made to measure the response of a single fracture running through the block as thermal and mechanical loads were applied. Permeability, aperture changes, and normal and shear displacements along the fracture were measured. Global measurements of block stress and deformation, both horizontal and vertical, were also made.

Conclusions/Lessons Learned

- Several problems were encountered with the flatjack loading system, including a failed flatjack.
- Block-scale displacement measurements were adequate for determining deformation modulus.
- Detailed measurements made on a single fracture were difficult to correlate and interpret.
- Heaters and temperature measurements work well. The top of the block should be better insulated to prevent the development of a vertical temperature gradient in the block due to heat losses.

6.1.3 Thermal-Hydrological Field Test

[Reference UCRL-ID-106159]

This G-Tunnel test consisted of a single heater emplaced in a horizontal borehole. The purpose of the test was to study thermal-hydrological processes (dehydration and rehydration) in a complete heating and cool-down cycle and to prototype test methodology and instrumentation. The output of the heater was 1.1 kW/m, which was greater than the 0.4 to 0.7 kW/m typical of borehole emplacement package designs common at the time of the test. The test was designed to dry out a volume of rock approximately 0.7 m in radius within the scheduled heating duration of 196 days. The heating phase included a constant power heating for 128 days and a ramp down of 98 days. Another 172 days after ramp down were required to cool from a temperature of approximately 52°C to 22°C. Parameters measured and instrumentation used included the following: temperature (thermocouples), gas pressure and barometric pressure (pressure transducers), air permeability (single borehole injection, measuring flow rate, pressure, and temperature), suction potential (thermocouple psychrometer), relative humidity (resonant cavity and humicap), water saturation (neutron logging and high frequency electromagnetic tomography), water condensing from vapor that invaded the heater hole (electrical resistance water level sensor), time and fracture location and aperture (borehole camera).

Conclusions/Lessons Learned

- A drier region was created around the heater.
- A condensate halo was developed around the drier region, which was smaller than expected and not symmetrical with respect to the heater cross section.
- Heat conduction was the dominant heat transfer mechanism.
- Fractures served as the predominant mass transfer paths for gases and liquids, including condensate shedding beside the heater.
- Re-wetting occurred during cool-down in the heater hole and in the drier regions adjacent to fractures. The re-wetting lagged behind the thermal field.
- The "boiling zone" acted as an umbrella shielding the rock below the heater from the downward drainage of condensate generated above the heater.
- Vapor moved into the heater hole, but the amount of water condensed was much less than predicted.
- Measurements in radial directions from the heater axis as well as vertically above and below the heater are needed to completely resolve the hydrological processes.
- Measurements in both matrix and fractures are needed to understand better their roles in the process.
- Studies with various cool-down periods are needed to understand better the process of re-wetting.
- The effect of grout in neutron logging holes needs to be determined.
- Thermocouple psychrometers did not provide consistent results.
- The field calibration process for the high frequency electromagnetic tomography system was found to be inadequate.

6.2 Waste Isolation Pilot Plant

[References SAND89-2671 and SAND90-2749]

Large-scale thermal in situ tests have been conducted at the Waste Isolation Pilot Plant (WIPP). In particular, two large-scale tests were conducted in long drifts to evaluate the thermal-mechanical response of the host rock to thermal loads that could result from the disposal of Defense High level Waste (DHLW) at the WIPP. These tests are the Room A (three drift) 18 W/m^3 Mockup for DHLW, and the Room B (one drift) Overtest for DHLW.

Both tests were fielded beginning in 1984 with data acquisition from remote gages continuing through 1988 (Room B) and 1990 (Room A). These two thermal experiments were the main focus of the experimental activities at the WIPP during the time periods they were active and required the unified efforts of many SNL, subcontractor, and Westinghouse field, instrumentation, and analysis personnel, primarily during the planning and fielding of the experiment. Also, numerous personnel were required for maintenance of the instrumentation and data acquisition systems during the experiment. The experiments included the fielding of many thermal and mechanical gages. A summary of the gage totals and other pertinent information is given in Table 4 below.

Table 4. Summary of WIPP Large-Scale Thermal Test Information

	Room A (three rooms)	**Room B (one room)**
Heated Length of Room	259 ft.	244 ft.
Total gages installed	2,214	871
Total number of instrument boreholes	1,011	328
Total "footage" of instrument boreholes	15,095	7,198
Total number of heaters	68	29
Total Heater Power	57.4 kW	58.6 kW
"Remote" gage failure rate	14% (thermal response gages only)	36%

Conclusions/Lessons Learned

- About a two-year lead time was used for pre-test design/analyses.
- Close cooperation/coordination was required between mining/drilling/gage installation crews.
- A key component to success in these tests was that the test organization was given both the responsibility and the authority to field the tests (i.e., the sponsor was supportive of completing the tests).
- Installation of instrumentation required up to three drilling crews in operation at one time, as well as two crews of gage installers.
- A crew of six working full time for approximately 10 months was required to run instrumentation cabling and to set up the data acquisition system for each test.
- The WIPP heaters did not include "baffles" or filling materials to reduce internal convection. Subsequent heater designs should consider these improvements.
- Most of the gage failures occurred in the halite in the near field, probably a result of corrosion.

- Nearly all the stress meters failed.
- Both tests were designed with a gage redundancy of approximately a factor of four.
- Instrument hole drilling and gage installation should be practiced in situ prior to actual fielding of such tests.
- Mining was conducted 24-hrs/day.
- Drilling was conducted on two shifts/day.

6.3 Underground Research Laboratory (Canada)

[References: TR-652, COG-94-478, URL-EXP-022-R32 (AECL Research)]

The Canadian Nuclear Waste Program, managed by Atomic Energy of Canada Limited (AECL), recently completed a series of small-scale heater tests in their Underground Research Laboratory (URL) near Pinawa, Manitoba. The tests were conducted at the 420 m level of the URL in a massive (unfractured) granite pluton. This is a region of very high horizontal stress (55 to 60 MPa maximum horizontal stress) and high stress difference (10 to 14 MPa minimum horizontal stress), which has caused large-scale damage and breakouts in the excavations. The tests were conducted to examine the stability of boreholes for potential in-floor borehole emplacement of nuclear waste. In the Canadian concept, waste is to be aged so that no waste packages will exceed boiling, even in the very near field.

A set of three tests was conducted with approximately the same geometry. In these tests a square array of four heaters was emplaced in the floor, with heaters at each corner of the square. A 600-mm borehole was drilled in the center of the square so that the heaters were 1 m from the edge of the hole. Because of the high in situ stresses, breakouts were observed in the borehole prior to heating. The heaters were run at constant power for several weeks until the wall of the borehole reached 85°C. The first test was conducted by drilling the central hole first, then turning on the heaters. The second test reversed the process by heating the floor, then drilling the hole. The final test used two neighboring holes with the heaters concentrated to heat the web of material between the two holes. Instrumentation consisted of pore pressure measurement, vertical multi-point extensometers, convergence pins (to look at floor heave), and thermocouple arrays.

Conclusions/Lessons Learned

- The order of conducting the test made a significant difference (e.g., drilling the hole first or heating first).
- The configuration lent itself to estimations of rock-mass thermal properties by comparisons with analyses.
- Compressive strength of the rock mass was estimated by calculating the total stress in the web between the two holes in the last test at the time of failure.

- The heater rods had to be inserted into sealed copper sleeves before emplacement to prevent excessive corrosion from ground water.

- Pore water was released into the fractures near the borehole and heater holes and collected in the bottom of the holes. (There were no pre-existing fractures. The fracturing in the near-field of the boreholes was a result of damage from in-situ and thermal stresses).

- Most instrumentation worked well. There were some failures as a result of ground loops from the heaters causing excessive corrosion of instrumentation connections.

6.4 Basalt Waste Isolation Project

[Reference: Proc. 22nd U.S. Rock Mech. Symp.]

The Basalt Waste Isolation Project (BWIP) conducted two in situ canister-scale heater experiments, Full Scale Heater Test # 1 (FS#1) and Full Scale Heater Test # 2 (FS#2), as well as a heated block experiment. The canister-scale tests were conducted to study the rock-mass response to thermal loading and to evaluate the onset of thermally induced emplacement borehole instability. Four types of instruments were used in the canister-scale experiments: thermocouples (Type K and Type E), borehole deformation gages (BDG), vibrating wire stress meters (VWS), and extensometers. FS#1 was comprised of a central canister heater (457-mm diameter) surrounded by eight guard heaters in a circular pattern 0.9 m away. (FS#2) was comprised of a single 457-mm diameter canister heater. Both tests were planned to run for a period of two years at variable canister heater powers of up to 5 kW. Heater temperatures at the midpoint of the canister heaters reached 359°C after 9 months. A total of 562 instruments were installed in the two tests (273 in FS#1, and 289 in FS#2).

Conclusions/Lessons Learned

- Measured temperatures at the canister heater mid planes were 20-25% less than calculated, probably because of water within the rock mass.

- Problems were encountered in 32% of the extensometer anchors (expandable copper anchors).

- Many of the BDG and VWS stress gages produced questionable data. The overall failure rates for the BDG were 15% for FS#1 and 25% for FS#2 after nine months of operation.

- 72% of the VWS stress gages required replacement in FS#1 and 22% in FS#2.

- Failure of the stress meters was probably caused by corrosion of the gage body. The need for hermetically sealed gages resistant to corrosion was noted.

6.5 Stripa Underground Test Facility

[References: LBL-7061, 7063, 7072, 7073, 7082, 8423, 9392, 10559, 13531]

In situ heater experiments were performed at a depth of 340 m in drifts excavated in saturated granitic rock adjacent to an abandoned iron ore mine in Stripa, Sweden. Three heater experiments were carried out from 1977 to 1980. A time-scale experiment was switched on June 1, 1978, and two full-scale experiments, on July 3, 1978 and August 24, 1978. The heating experiments ran for 12 months followed by a 6-month cooling period.

The two full-scale experiments were conducted in 0.4-m boreholes drilled to a depth of 5.5 m beneath the floor of one drift. They were designed to assess the near-field thermal-mechanical response of the rock near the heater canisters in the short term, and under simulated conditions of rock temperature in the long term. The first of the full-scale heaters was operated at a power output of 5 kW, corresponding to that expected from a canister of reprocessed high-level waste only 3.5 years after removal from a reactor. This heater was surrounded by eight peripheral heaters on a radius of 0.9 m that operated at 1.1 kW and were turned on at a later stage to increase the rock temperature. The second full-scale heater was operated at 3.6 kW, corresponding to the thermal output of reprocessed high-level waste five years after removal from the reactor.

The time-scale experiment was conducted in a separate drift and was comprised of eight 0.8-m long heaters placed in vertical boreholes on 7×3 m centers drilled to a depth of about 11 m below the floor. Initially the power output of each heater was 1.1 kW to simulate the reduction in heat output resulting from radioactive decay over a period of 20 years. This experiment was designed to study the interaction between adjacent heaters and to measure the in situ response of a larger volume of rock than could be accomplished in the full-scale experiments.

Conclusions/Lessons Learned

- The heaters performed satisfactorily.
- In situ values of thermal conductivity and thermal diffusivity extracted from an analysis of field data are only slightly higher than the corresponding laboratory values, indicating no significant "size effect" in the thermal properties of the granitic rock mass.
- Temperature measurements indicate heat flow in the rock mass is predominantly by convection and that theoretical calculations using laboratory values of thermal coefficients can be used to predict rock temperatures reasonably well.
- Thermally induced displacements, calculated using linear thermoelasticity theory, were found to be significantly larger than actually measured in the full-scale heater experiments, indicating that either rock expansions may be absorbed into pre-existing fractures or rock properties are temperature-dependent.

- Decrepitation from spalling, in the time-scale and both full-scale experiments, was investigated by direct observation of the walls of the boreholes. The only serious decrepitation occurred on the wall of the 5 kW heater hole after the peripheral heaters were turned on and temperatures in the vicinity of the borehole wall exceeded 300°C.

- Throughout the experimental period, 35 rod extensometers operated at Stripa; they yielded an essentially continuous record of the displacements of 140 points within the rock mass.

- During the course of the experiments, 36 vibrating wire stress meters were installed in 15 boreholes (two per hole), and 30 USBM deformation gages were installed in 30 boreholes (one per hole). The gages were installed in both vertical and horizontal boreholes and were subjected to temperatures ranging from 10°C to 120°C. Of the 36 vibrating wire stress meters, six failed; the rest operated satisfactorily. Of the 30 USBM deformation gages, 22 failed and much data in the early stages of the experiments was not recorded.

- A total of 385 Chromel-Alumel thermocouples (including replacements) were used in these heater experiments with a 12.5% failure rate. Two types of catastrophic failures occurred: one caused by corrosion of the protective sheath material and the other caused by mechanical breakage of thermocouple leads during removal and installation of other instruments in the same borehole.

7.0 LABORATORY THERMAL TESTS

Laboratory experiments are an integral part of the proposed thermal testing program. The intent of the laboratory component of this thermal testing strategy is to evaluate, under laboratory conditions, processes that may occur during the in situ experiments. As such, the laboratory experiments will provide information that will assist in the design and evaluation of the in situ thermal tests. The laboratory tests are primarily designed to understand the mechanisms that drive processes so that our interpretations of in situ data can be made with greater confidence. Laboratory experiments are essential for meeting the early information needs dictated by the tight schedule of the Program Approach. Laboratory experiments can be categorized into two types:

- measurements of necessary thermal and thermal-hydrologic property data, and
- observation and analysis of key processes and mechanisms, such as fast paths and heat pipe effects.

There are many studies in the SCP on the evaluation of rock matrix and fracture properties for tuff samples from Yucca Mountain. Some that have a thermal component are listed below:

- Thermal properties of intact rock, including heat capacity, thermal conductivity, and thermal expansion (SCP 8.3.1.15.1.1 and 8.3.1.15.1.2).
- Rock-water interactions at elevated temperature (SCP 8.3.4.2.4.1).
- Single and two-phase fluid system properties (SCP 8.3.4.2.3.2).
- Moisture retention curves of intact rocks at ambient and elevated temperature near the boiling point of water (SCP 8.3.4.2.4.4).
- Thermal expansion of the matrix (SCP 8.3.1.15.1.2), thermally induced displacement across one fracture (SCP 8.3.1.15.1.4), and thermal fracturing (SCP 8.3.4.2.4.3).

Key issues in the response of Yucca Mountain to the thermal load of a repository involve the potential development of fast preferential paths of water flow, migration of transient water pulses through heated regions near the repository horizon, and the presence or absence of heat pipe conditions in the near field. The space and time scales of the planned in situ underground heater tests are such that only limited results are expected to be available in time to meet the tight deadlines envisioned for the early phases of the Program Approach (Technical Site Suitability determination by 1998, License Application by 2001). Smaller-scale thermal testing in the laboratory has the advantages of being faster and less expensive than in situ testing. Accordingly, the thermal testing program includes a laboratory component of thermal testing that will be closely integrated with the field tests. The combination of laboratory and field tests will allow the Project to develop and demonstrate an early understanding of the major physical and chemical processes induced by thermal load and to partially resolve waste package and repository design and performance issues. By focusing the laboratory program on thermally-driven flow processes, much can be learned to provide timely answers to important site-suitability and licensing questions. The results of laboratory testing are also expected to be useful for the design and analysis of the in situ tests. In particular, the issues that will be addressed in the laboratory thermal testing program are the following:

(1) Redistribution of moisture due to thermal load

(2) Development of fast flow paths

(3) Waste canister environment with regard to water saturation, water chemistry and temperature

(4) Development of heat pipes

(5) Thermally driven buoyant gas flow

(6) Enhancement of vapor diffusion

(7) Thermal alteration of rock-matrix hydrologic properties

(8) Geochemical and mineralogic alteration.

These issues were identified by Waste Package Design and Postclosure Performance Assessment as being important and requiring "bounding" information (Table 3).

Laboratory tests that specifically deal with thermal-mechanical-hydrological-chemical coupled processes have been proposed, and some are being conducted in connection with the Large Block Tests (SCP 8.3.4.2.4.4). They are laboratory tests performed on small blocks in order to probe:

- thermal-hydrological processes, such as fracture flow versus matrix imbibition and condensation of vapor along a fracture;
- rock-water interaction resulting from increased temperature and movement of moisture.

Four types of laboratory tests are described here as examples of the tests that may be performed under existing studies to support the field testing efforts and provide data early enough to support Technical Site Suitability technical basis reports. In general, the customer requirements for the suite of conceptual laboratory tests presented are the same as for the suite of in situ tests discussed later. Fast paths and heat pipe conditions at Yucca Mountain are expected to show a great deal of intrinsic variability as a result of formation heterogeneities on many scales. For thermally-driven flows in heterogeneous fractured media, there may be no such thing as "typical" behavior, only a broad range of behavior types. Therefore, experiments on one or a few fractures and cores should not be expected to provide an easily generalized outlook. This caveat is also pertinent to field work, but it is especially important within the context of smaller-scale laboratory experiments.

Accordingly, experiments should be carried out on a range of samples and for different parameters.

7.1 Laboratory Test Group I: Direct and Indirect Observation of the Pattern and Rates of Water Flow Along Fractures in a Thermal Field

7.1.1 Objectives

Preferential flow of water along fractures is a serious concern for the suitability of the Yucca Mountain site because such flow could give rise to fast transport of water-soluble contaminants. This experimental study seeks to determine the ability of fractures to carry water under conditions of partial saturation and elevated temperatures (SCP 8.3.4.2.4.2).

7.1.2 Data and Information Needs Addressed

The information needs are a subset of those discussed earlier and summarized in Table 3:

- Potential for fast preferential paths,
- Water chemistry changes, and
- Thermal-hydrologic environment of waste packages as related to the formation of heat pipes.

7.1.3 Description

Previous small block tests on matrix and fracture flow were designed for fractures composed of two smooth saw-cut rock surfaces separated by gold shims of known thickness. Because heterogeneity in the fracture apertures critically controls the development of fast paths, the tests here will be performed only with natural fractures or transparent replicas of natural fractures. This will ensure that experiments probe the natural surface roughness, aperture heterogeneity, and distribution of asperities. Results on a number of different fractures on different scales are desirable. The test designs are intentionally kept simple so that all tests can be carried out for a range of conditions (average temperature, temperature gradient, heating rate, inclination of the fracture relative to the vertical). Deionized water, as well as water containing some dissolved solids (e.g., J-13 water, etc.), would be used in the tests. In the latter case, concentration buildup near the heaters would be monitored.

For direct observation of flow patterns, use of transparent replicas of fractures is proposed. These replicas would be partially saturated with water plus dye and completely sealed along all edges. The fracture replicas would be inclined at some angle with respect to the vertical, heated from below, and the thermally driven flow patterns observed (Figure 2a). As a

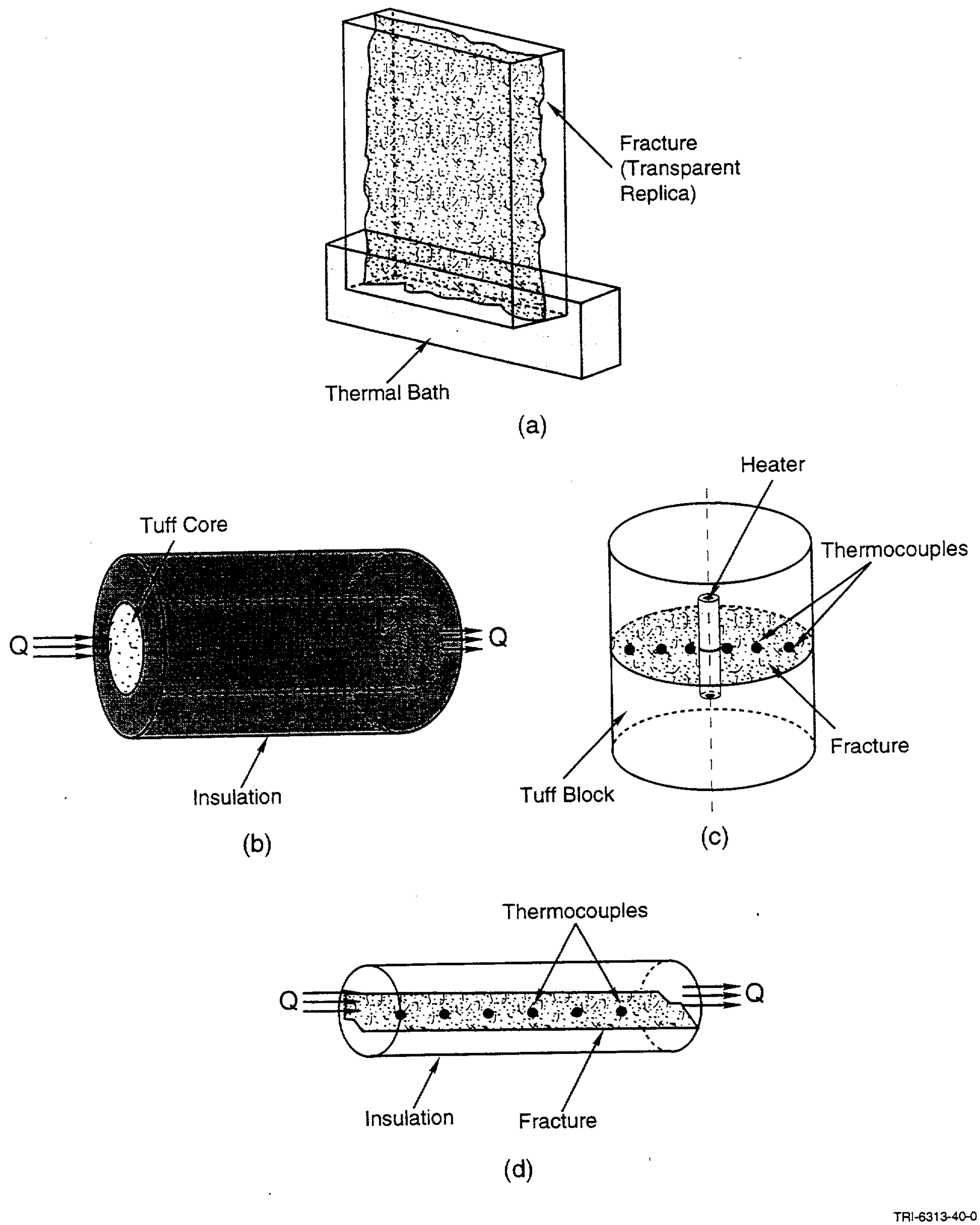


Figure 2. Possible laboratory thermal process tests: (a) laboratory thermally driven fracture flow test, (b) and (c) laboratory evaluation of heat pipe tests, (d) laboratory vapor diffusion test.

variation, water could be introduced into a pre-heated dry fracture to evaluate the ability of liquid flow to proceed through dry regions with temperature above the nominal boiling point. The experimental setup can be made less artificial by using a transparent replica only for half the assembly, mounting it against the actual rock of the opposite fracture face. These flow visualization experiments can be carried out relatively quickly and at a low cost. Nonetheless, they are expected to provide important qualitative and semi-quantitative information on the likelihood and geometrical properties of fast liquid pathways. At somewhat greater effort and cost, visualization using x-rays, gamma-rays, or microwaves can be performed on actual rock fracture specimens, avoiding the distortion in wetability due to the transparent replicas.

7.2 Laboratory Test Group II: Assessment of Heat Pipe Conditions in Heated Rock Fractures.

7.2.1 Objectives

Heat pipe conditions (water-vapor counterflow) can have a tremendous impact on thermal-hydrologic conditions in the near-field. If existent, heat pipes will limit rock dry-out and peak temperatures. Through repeated vaporization-condensation cycles they may also cause large increases in the salinity of the aqueous phase near the waste packages. Heat pipe conditions are easily recognized in experimental data by small temperature gradients resulting in "flat" temperature profiles. This set of experiments is designed to determine the likelihood of heat pipe conditions in fractures.

7.2.2 Data and Information Needs Addressed

The information needs are a subset of those discussed earlier and summarized in Table 3:

- Potential for heat pipe conditions in fractures,
- Changes in moisture and temperature conditions near heaters, and
- Changes in formation water chemistry (salinity) near heaters.

7.2.3 Description

Experiments designed to evaluate the potential for heat pipe conditions are proposed in several different configurations, including heater experiments in fractured cores (Figure 2b) and cylinders (Figure 2c). To determine the presence of heat pipes, temperatures would be monitored in several places near the plane of the fracture. Regions of low temperature gradient would correspond to water-vapor counterflow occurrence. Changes in salinity can be recognized by measuring electrical receptivity or by post-test visual examination of solidsdeposition on the fracture walls. Heat-pipe behavior may also be visually observed and monitored in transparent fracture replicas (Figure 2a).

7.3 Laboratory Test Group III: Measurement of Gas-Phase Buoyant Flow in a Temperature Gradient

7.3.1 Objective

The Yucca Mountain site is expected to be highly permeable to gas flow through networks of interconnected fractures. Thermally buoyant flow of gas could establish a fast path toward the land surface for gas-borne radionuclides, such as C-14 in the form of CO_2 or CH_4. Apart from raising concerns about site suitability, buoyant gas flow may also offer opportunities for repository performance monitoring and confirmation. Single-phase gas flow tests in fractures will be conducted to assess the potential of gas-borne contaminant migration and to determine the likely impact of buoyant gas flow on gas phase composition and conditions at the waste packages.

7.3.2 Data and Information Needs Addressed

The information needs include:

- Geochemical near-field environment of the waste packages, and
- Potential for gas-borne migration of contaminants.

The information needs were identified by Postclosure Performance Assessment (conceptual model/hypotheses testing). Because some of these needs will probably not be sufficiently addressed by early in situ tests, it is important to include them in laboratory testing to help develop bounding arguments for initial License Application. Later, longer-term in situ tests will better address these issues.

7.3.3 Description

Gas tracer tests would be performed in vertical and inclined fractures; "real" tuff fractures as well as replicas may be used. The buoyant flow is established by introducing a tracer to a heated fracture and monitoring its upward transport. As an alternative to thermally-induced buoyancy, one may introduce a gas lighter than air, such as helium.

7.4 Laboratory Test Group IV: Study of Enhancement of Vapor Diffusion

7.4.1 Objective

Enhanced vapor diffusion is a well known phenomenon in soils, where it arises from liquid-phase transport mediated by condensation-vaporization processes at liquid islands. If present in fractured welded tuff, such enhanced diffusion could have a significant impact on thermal-hydrologic conditions resulting from a thermal load. In soil physics studies, the enhancement is usually observed as an enhanced effective thermal conductivity. At Yucca Mountain, enhanced vapor diffusion can impact repository temperatures, dry-out and re-wetting behavior, gas phase composition, redox conditions at waste packages, and thermally buoyant gas flow.

7.4.2 Data and Information Needs Addressed

The information needs are a subset of those discussed earlier and summarized in Table 3:

- Dry-out behavior during heating,
- Propagation of a "drying front,"
- Effective thermal conductivity, and
- Evolution of gas pressures and flows near repository drifts.

7.4.3 Description

Tests would be carried out on fractured and unfractured tuff samples of different sizes (Figure 2d) using a range of liquid saturations, temperatures, and temperature gradients. Effective thermal conductivities of the samples on different scales and under various thermal-hydrological conditions would be measured. The vapor diffusion enhancement is expected to be observed as enhanced thermal conductivity, from which effective vapor diffusivity can be deduced. The effect is expected to be strongest at "intermediate" water saturations, since at large water saturation diffusive processes in the gas phase are generally diminished because of low gas saturation; at low water saturations the enhancement diminishes as fewer and smaller liquid islands are present.

8.0 PROPOSED IN SITU THERMAL TESTS

In this section a suite of in situ thermal tests are proposed that (1) will provide the desired data and information needs summarized in Table 3, (2) can be fielded within the allowable time windows to provide the information for Technical Site Suitability and the early phase of licensing, (3) are simple and flexible enough to fit within the construction and operational constraints of the ESF during the early construction period, (4) are integrated with the proposed laboratory testing to enhance the level of information generated, (5) can be traced to Study Plans identified in the SCP, thus negating the need for large-scale baseline changes in the testing program, and (6) will provide data and information necessary for the evaluation of conceptual models and hypotheses (see the discussion in Section 4.2.1). 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. The general testing strategy of fielding the simpler, smaller-scale tests first, and then moving to the more complex larger scale tests, also had a significant impact on test definition. Finally, because the uncertainties are greater in our current understanding of coupled T-M-H-C processes and phenomena than those associated with thermal and mechanical material properties, more focus was given to investigating coupled processes.

The proposed ESF tests described in this report 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 "walk-before-you-run" 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. Prior to the presentation of detailed descriptions of the ESF thermal tests, a discussion of the Large Block Test is presented. The Large Block Test is already under way and will feed information to the design of ESF in situ tests as well as provide a test bed for the evaluation of instrumentation.

For each test described below, the information needs (Table 3) 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. An integrated test schedule that is phased with the construction process and follows the testing strategy guidelines presented earlier (i.e., simpler tests first) is given in Appendix A.

8.1 Large Block Test

8.1.1 Objectives

The Large Block Test will meet three objectives:

- Develop and evaluate techniques and instrumentation for monitoring or observing changes in thermal and hydrological (and to a limited extent chemical and mechanical) properties in a heated rock mass
- Observe thermal-hydrological processes and evaluate current models
- Provide preliminary data for model development and design of other in situ thermal tests.

8.1.2 Rationale

The Large Block Test will provide a test bed for instrumentation and diagnostic techniques. Although the boundary conditions are different than those that will be experienced by the ESF tests, the Large Block Test should allow for a preliminary evaluation of the predictive models that will be used for detailed ESF test designs and interpretive analyses. The Large Block Test may also provide preliminary information regarding coupled thermal processes that can be used to support Technical Site Suitability.

8.1.3 Data and Information Needs Addressed

The Large Block Test is intended to address the information needs listed below in Table 5, which are a subset of those discussed earlier. Also noted is whether this test addresses the data needs as a *primary* function of the test or whether the information is derived as a byproduct or *secondary* objective of the test.

8.1.4 Description

The Large Block Test is already under way and is described in detail in Scientific Investigation Plan SIP-NF-02, Rev 0. Laboratory-scale testing associated with this test was noted in the previous section. In this section, only a brief description will be provided. A large block measuring 3×3×4 m was excavated as a free-standing column in a pit created in the TSw2 outcrop at Fran Ridge. The block will be fitted with heater assemblies and

Table 5. Data and Information Needs Addressed by the Large Block Test

Information Needs	Large Block Test
Near-field T-M-H-C environment	
• Changes in rock saturation	Primary
• Water chemistry (liquid reflux)	Secondary
• Propagation of "drying front" (heterogeneity)	Primary
• Residual water saturation in "dry zone"	Primary
• Drainage/reflux of liquid by fracture flow (heterogeneity, heat pipes, fast paths)	Primary
• Rock-mass and fracture permeability changes	Secondary
• Conductive/convective heat transfer	Primary
Rock-mass properties over a range of temperature	
• Thermal capacity or specific heat	Secondary
• Thermal conductivity	Secondary
• Thermal expansion	Secondary

instruments to monitor temporal and spatial distributions of temperature, moisture content, relevant chemical parameters, stress, and displacement. Thermal and moisture barriers and guard heaters will be installed around the outside of the block so that the movement of moisture in the block is as close to one-dimensional as possible. In order to work within the schedule, the block will not be pressurized (loaded externally) as was originally planned. The block will be restrained by straps and anchored to the ground to maintain its integrity. The test will be conducted in stages, starting with sub-boiling heating and cool-down that can be reached quickly.

8.2 Single-Element Heater Tests

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

8.2.2 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. 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. The need for early success in the ESF in situ thermal testing program is also supported by this test. The information and experience gained from the Large Block Test will contribute to a better design and instrumentation package for this test.

8.2.3 Data and Information Needs Addressed

The single-element heater test is intended to address the information needs listed below in Table 6. 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 6. Data and Information Needs Addressed by the Single-Element Heater Test

Information Needs	Single-Element Heater Tests
Near-field T-M-H-C environment	
• Changes in rock saturation	Primary
• Water chemistry (liquid reflux)	Secondary
• Mineralogic changes	Secondary
• Propagation of "drying front" (heterogeneity)	Primary
• Residual water saturation in "dry zone"	Primary
• Drainage/reflux of liquid by fracture flow (heterogeneity, heat pipe, fast paths)	Secondary
• 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, only for optional roof test)
Ground support and design features interactions at elevated temperature	
• Rock mass-ground support interaction	Secondary (optional roof test only)
• Effect of materials on near-field water chemistry	Secondary (optional roof test only)
• Effect of near-field environment on ground support components	Secondary (optional roof test only)

8.2.4 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.

The basic test consists of emplacing a long heater rod horizontally (or at a slight up dip) in the wall of an alcove (Figures 3 and 4). 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 3 and 4). 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. 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 desirable to heat a significant volume of rock to approximately 200°C to examine the effect of silica phase transformations on thermal properties and thermal

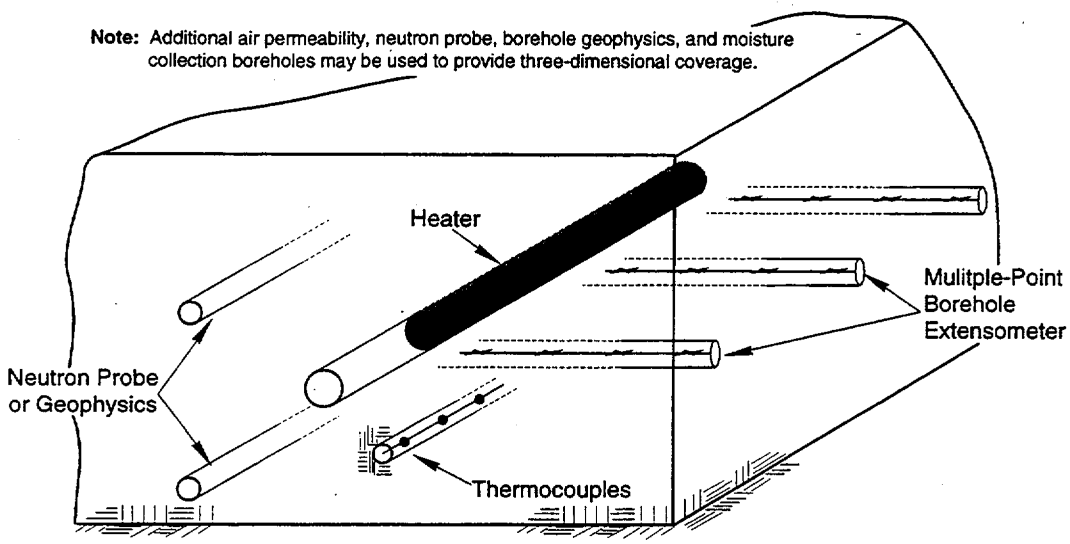


Figure 3. Conceptual layout for the single-element heater test—horizontal configuration, isometric view.

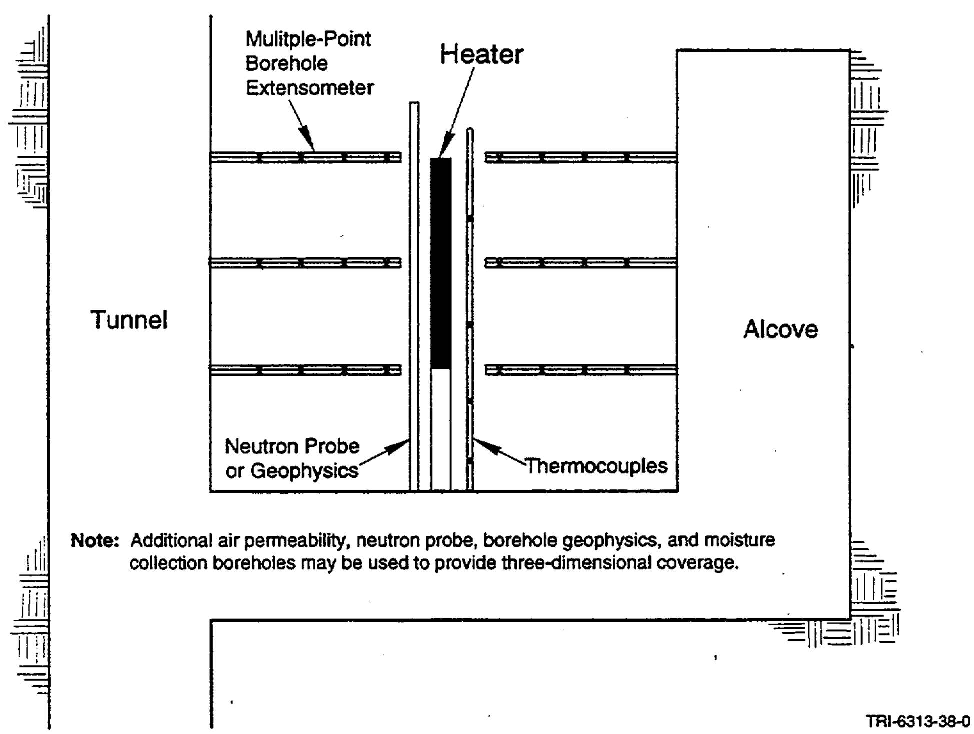


Figure 4. Conceptual layout for the single-element heater test—horizontal configuration, plan view.

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 3 and 4, only typical placement). Neutron probe measurements in boreholes will 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 mineralogic 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. 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.

8.2.5 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 5). 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

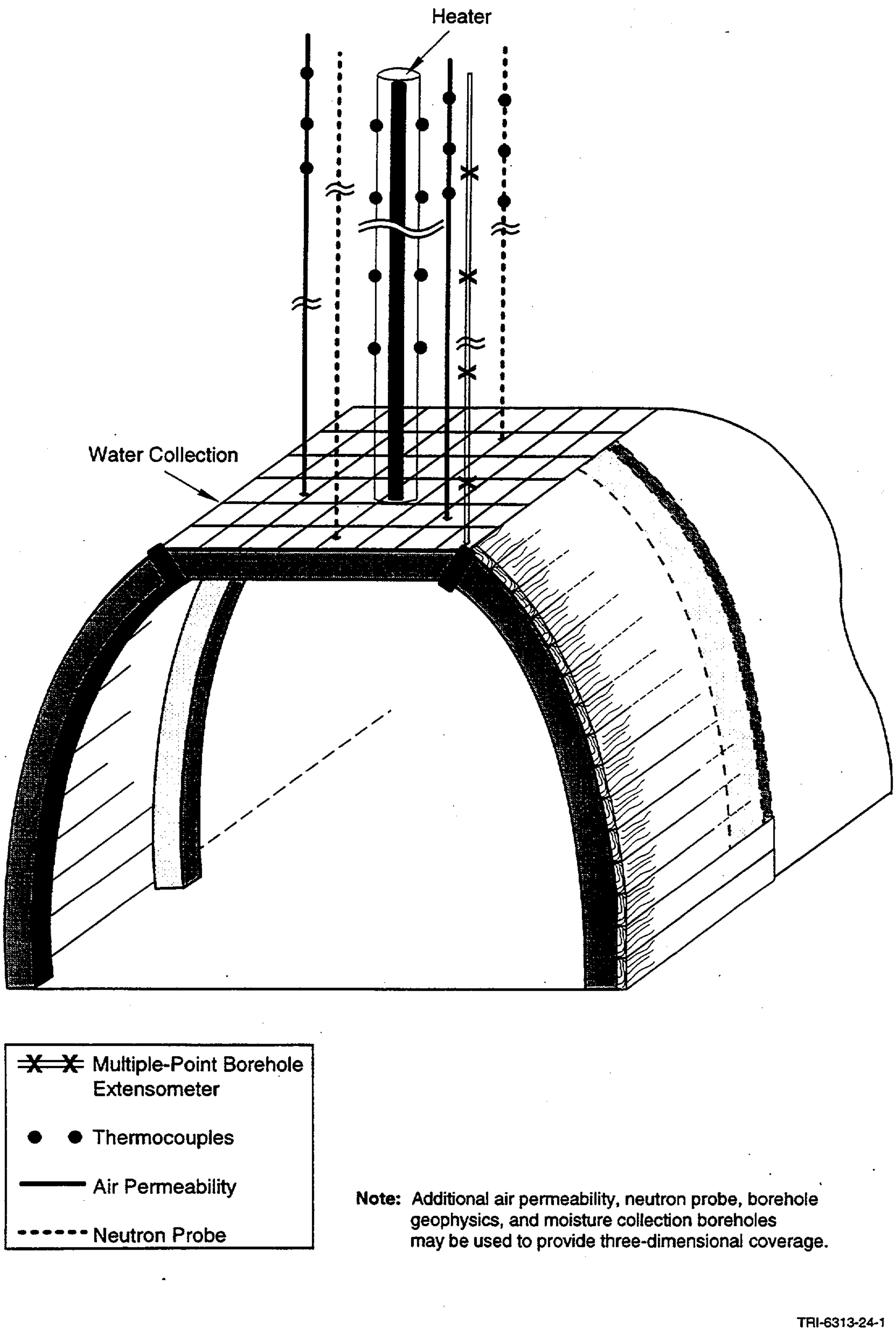


Figure 5. Conceptual layout for the single-element heater test—vertical configuration, isometric view.

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.

8.2.6 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. 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. If circumstances dictate, an early horizontal heater test could be performed in the nonlithophysal section of TSw1. This may afford some modest gain in the schedule but would require a considerable effort to design and field by early FY 1996. The nominal schedule proposed for this test is given in Appendix A.

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.

Figure 6 gives approximate locations where the single-element heater tests could be conducted. Multiple tests are recommended even for the early phase of licensing 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.

8.2.7 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

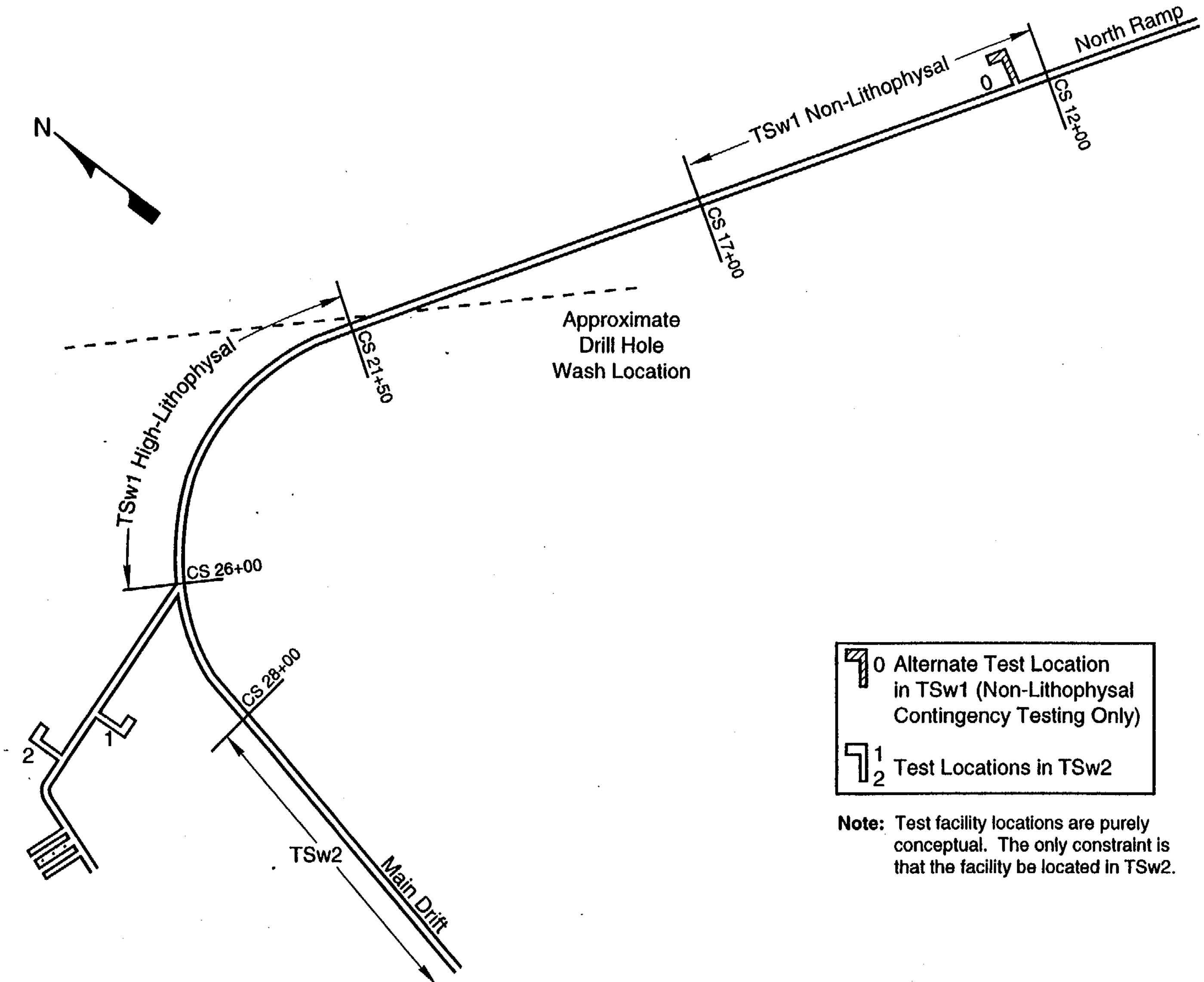


Figure 6. Estimated locations for single-element heater tests.

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, 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 mineralogic 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* (identified in this document). 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 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.

8.3 Plate-Source Thermal Test

8.3.1 Objectives

The objectives of these tests are to:

- Measure changes in rock saturation before, during, and after test (including changes from ventilation)
- Measure the thermal expansion of the rock mass
- Measure rock-mass modulus at elevated temperatures
- 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
- Examine the validity of conductive thermal models on an intermediate scale and provide data to validate coupled thermal-hydrologic models
- Measure changes in rock-mass and fracture permeability
- Determine changes in the chemistry of reflux water.

8.3.2 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, it is thought that 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.

8.3.3 Data and Information Needs Addressed

The plate-source thermal test is intended to address the information needs listed below in Table 7. 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.

8.3.4 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.

Table 7. Data and Information Needs Addressed by the Plate-Source Thermal Test.

Information Needs	Plate Source Thermal Test
Near-field T-M-H-C environment	
• Changes in rock saturation	Primary
• Water chemistry (liquid reflux)	Primary
• Mineralogic changes	Primary
• Propagation of "drying front" (heterogeneity)	Primary
• Residual water saturation in "dry zone"	Primary
• Drainage/reflux of liquid by fracture flow (heterogeneity, heat pipe, fast paths)	Primary
• 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	Secondary
• Thermal conductivity	Secondary
• Thermal expansion	Primary
• Deformation Modulus	Primary

The test 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 to the heater and perpendicular to the heater. A second small alcove is also constructed parallel to the axis of the heaters (Figures 7 and 8). 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 7 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.

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 8) 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 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 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. 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 would be done on liquid condensate collected in boreholes and on water extracted from the rock matrix. It is also expected that mineralogic 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

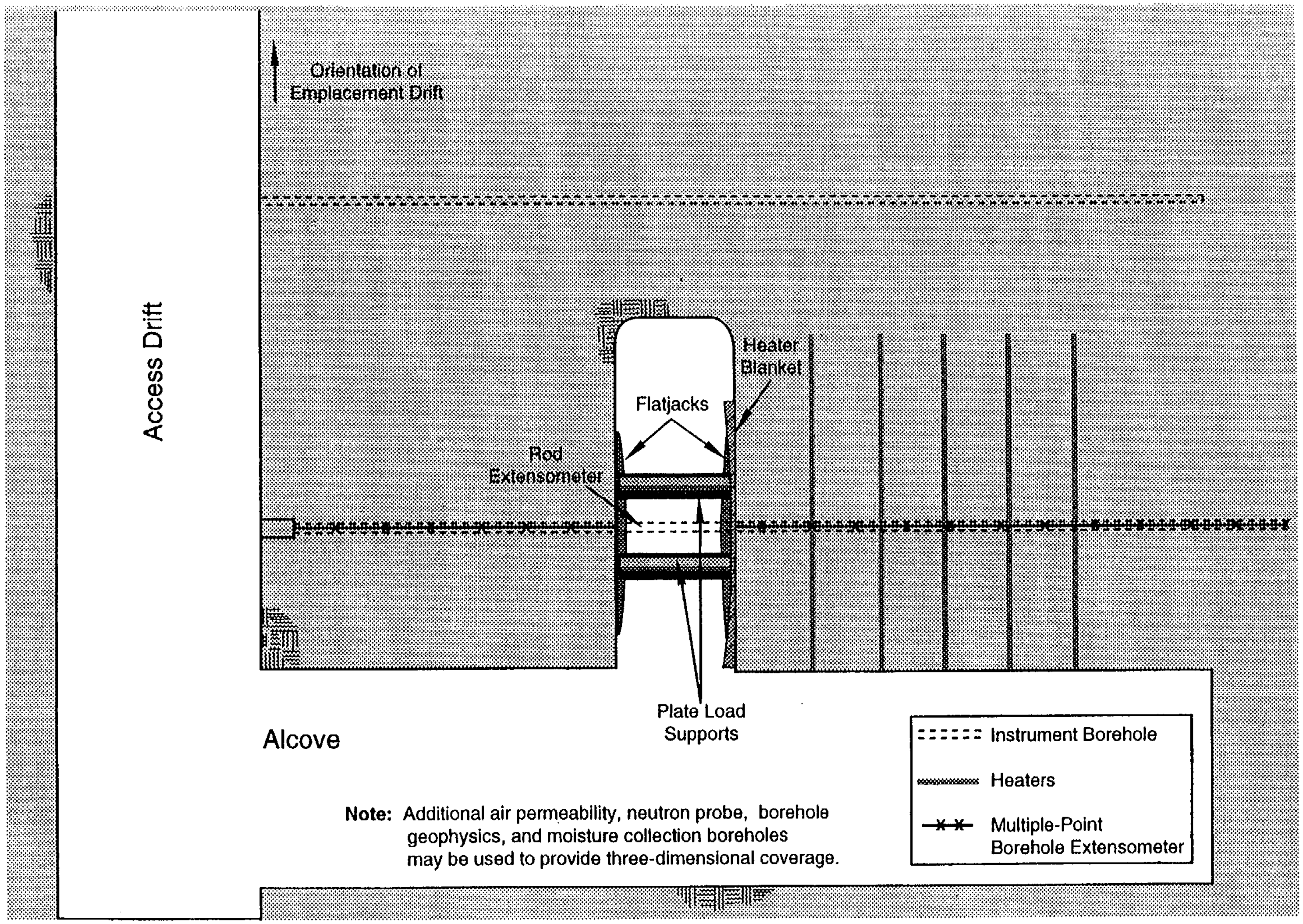
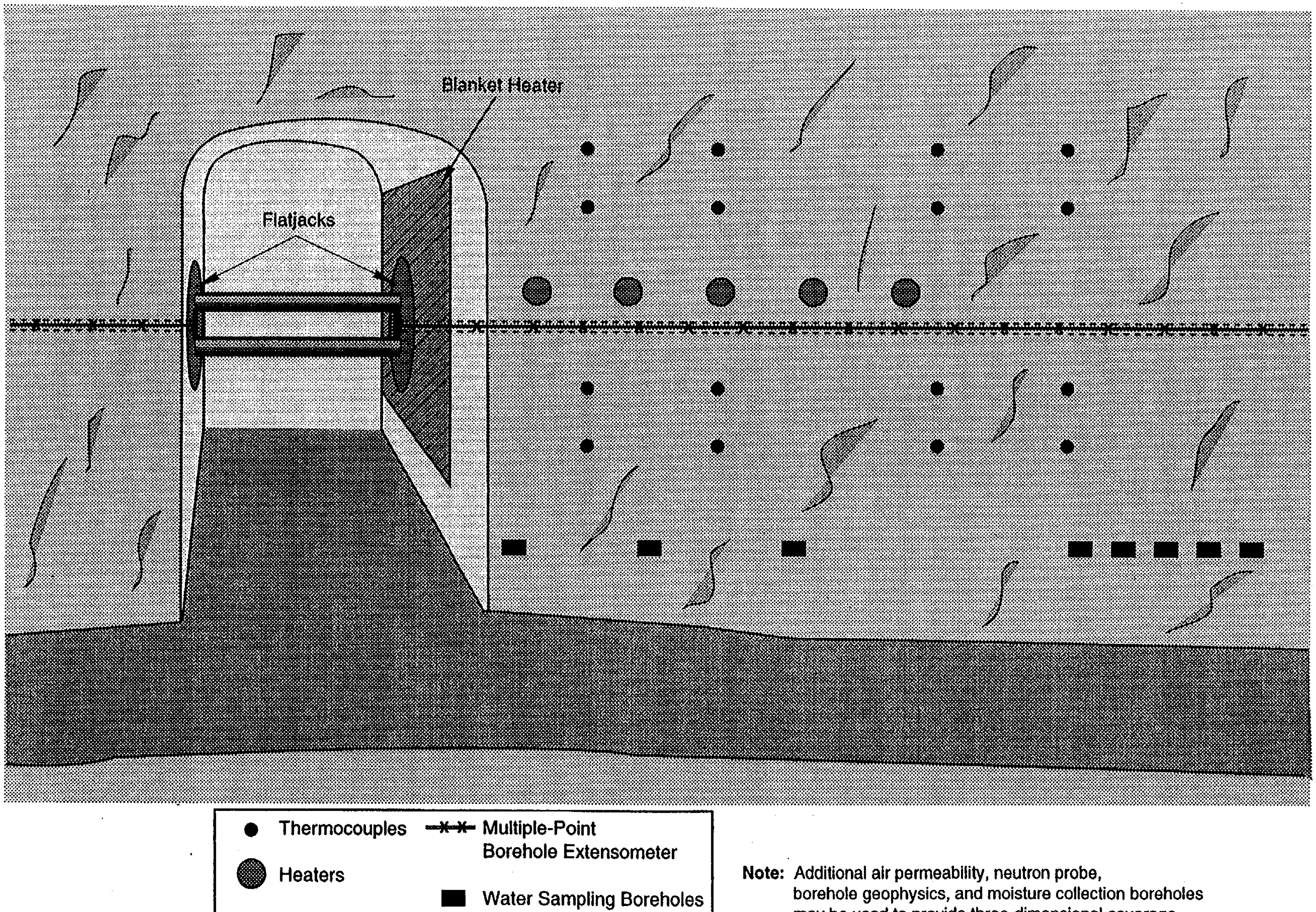


Figure 7. Conceptual layout for the plate-source thermal test—plan view.



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

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Figure 8. Conceptual layout for the plate-source thermal test—isometric view.

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°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.

8.3.5 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 by early FY 1996. It is highly recommended (as shown in the phased schedule in Appendix A) 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.

Figure 9 gives approximate locations where the plate-source thermal tests could be conducted. 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 initial licensing 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.

8.3.6 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 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.

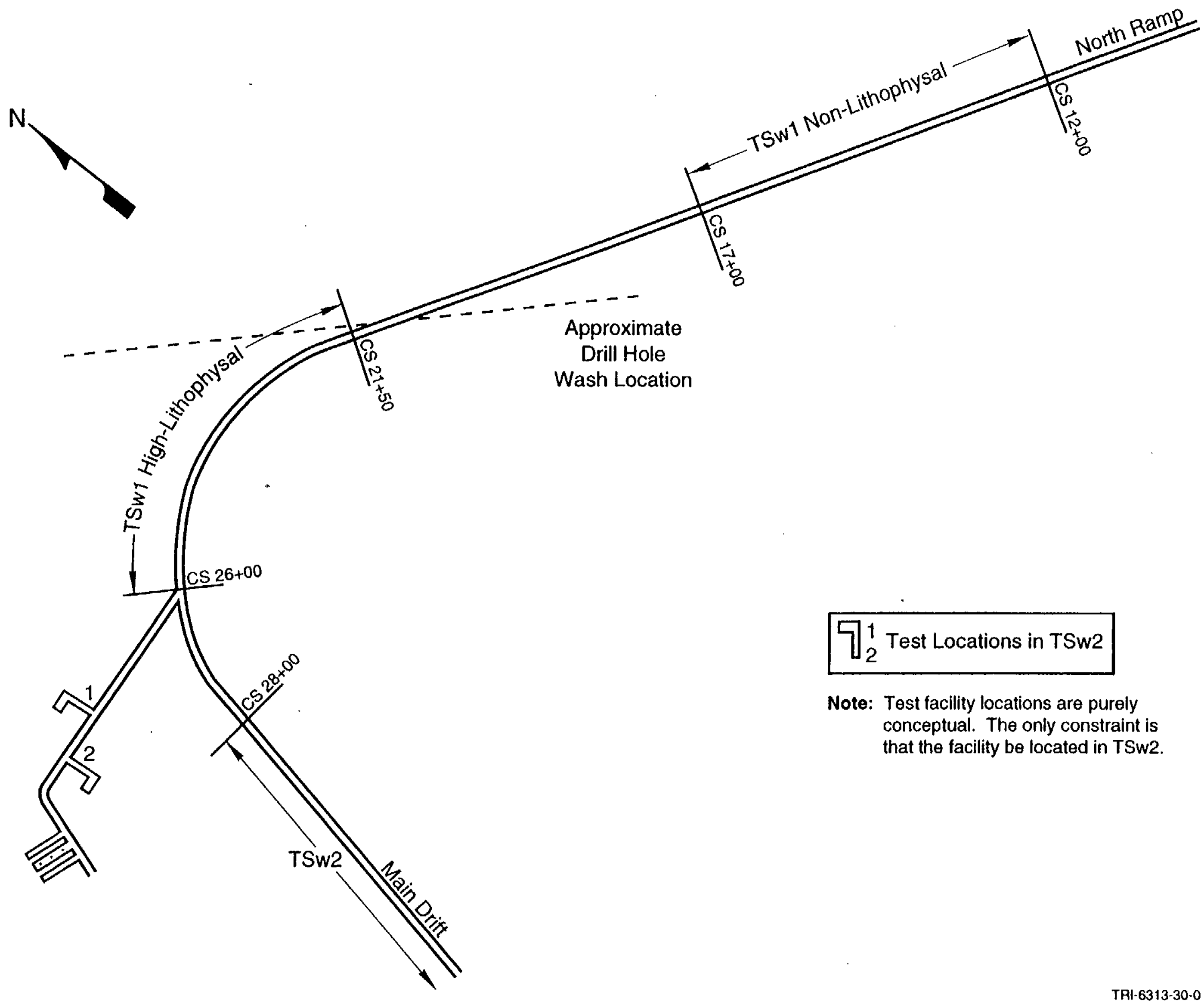

Figure 9. Estimated locations for plate-source thermal tests.

- *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 mineralogic 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* (identified in this document). 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.

8.4 Emplacement Drift Thermal Test

8.4.1 Objectives

The objectives of this test 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 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
- 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
- Measure corrosion rates on typical waste package materials under in situ conditions
- Provide detailed measurements of the response of the rock mass to the construction and heating of an emplacement-drift-scale opening
- Provide bounding measurements on the thermal-hydrologic behavior of backfill materials.

8.4.2 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.

8.4.3 Data and Information Needs Addressed

The emplacement drift thermal test is intended to address the information needs listed in Table 8. 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.

8.4.4 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 10 through 12. 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

Table 8. Data and Information Needs Addressed by the Emplacement Drift Thermal Test

Information Needs	Emplacement Drift Thermal Test
Near-field T-M-H-C environment	
• Changes in rock saturation	Primary
• Drift humidity	Primary
• Water chemistry (liquid reflux)	Primary
• Mineralogic changes	Primary
• Propagation of "drying front" (heterogeneity)	Primary
• Residual water saturation in "dry zone"	Primary
• Drainage/reflux of liquid by fracture flow (heterogeneity, heat pipe, fast paths)	Primary
• Rock-mass and fracture permeability changes	Primary
• 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 and design features interactions at elevated temperature	
• Rock mass-ground support interaction	Primary
• Effect of materials on near-field water chemistry	Primary
• Effect of near-field environment on ground support components	Primary
• T-H properties of backfill	Primary
• In situ WP material corrosion rates	Primary

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. An example of a configuration for extensive access is shown in Figure 13. 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.

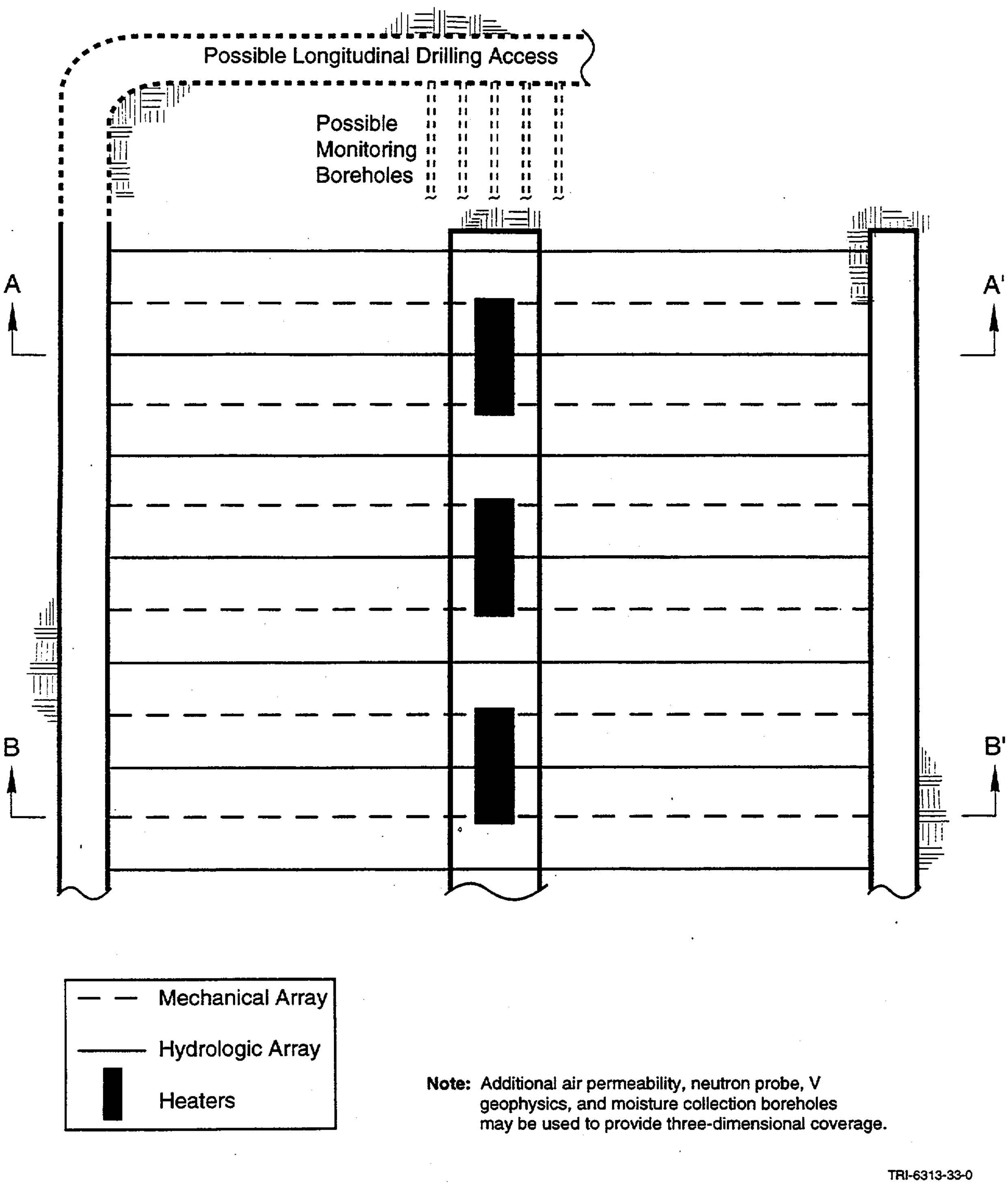

Figure 10. Conceptual layout for the emplacement drift thermal test—plan view.

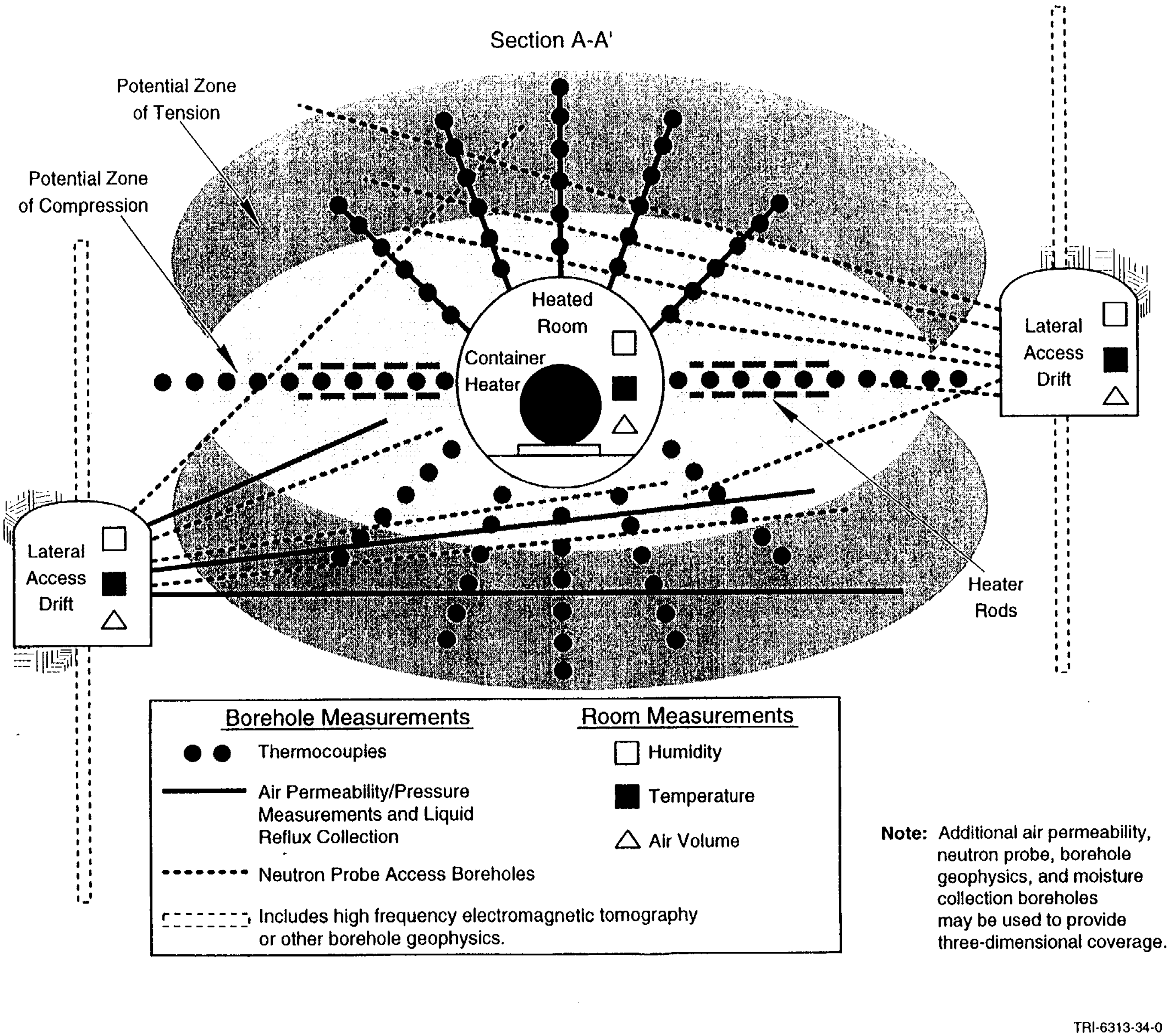

Figure 11. Conceptual layout for the emplacement drift thermal test—section AA'—thermal-hydrology instrumentation/measurements.

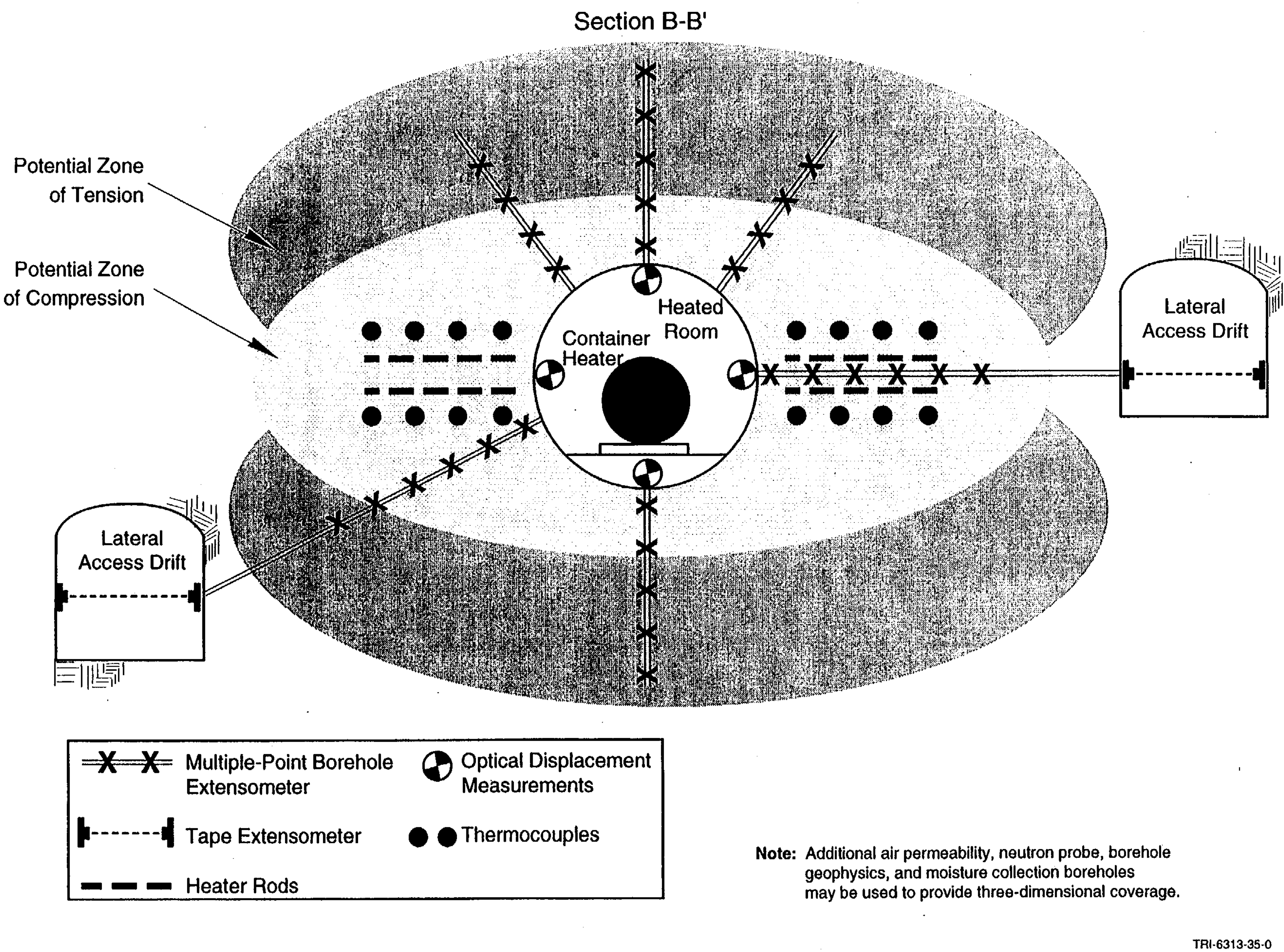

Figure 12. Conceptual layout for the emplacement drift thermal test—section BB'—thermal-mechanical instrumentation/measurements.

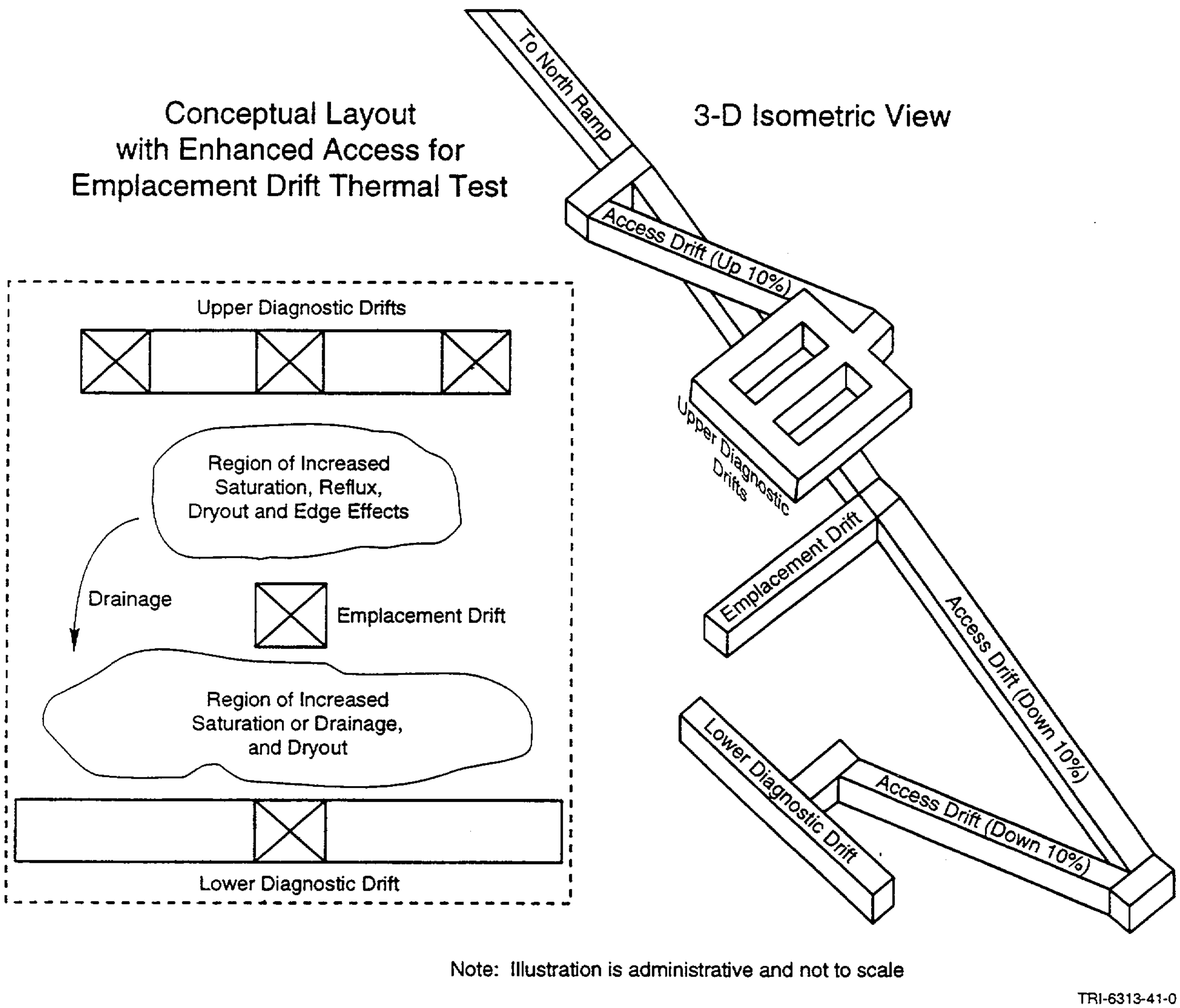

Figure 13. Conceptual layout for the emplacement drift thermal test—extensive access option.

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 MPC 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: (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 test 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. Development of the drying zone will be monitored by measurements of saturation using neutron probes in boreholes, geophysical tomographic methods, or other techniques. Air samples from the heated drift will be extracted for measurement of humidity and gas composition. Sufficient instrumentation can be inserted from the test drift and the adjacent access drifts to provide complete three-dimensional coverage of areas of interest above and below the test drift. Borehole tomographic methods or other geophysical techniques will likely be used to detect and track the movement of moisture. Of special interest is the detection of large-scale phenomena such as heat pipes. Observation boreholes will be used to collect and monitor liquid water movement in the fracture system at various locations. 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. The lateral instrumentation drifts will provide access via boreholes both above and below the heated room for collection of liquid reflux and drainage. In the U-shaped access drift configuration, access would also be available to drill holes above and below the test drift that are parallel to the axis of the drift.

Sub-horizontal placement of liquid collection boreholes will maximize the likelihood of detecting liquid flow in the vertical fracture network and facilitate liquid collection by self-drainage. Air permeability measurements will be made in boreholes within and around the thermally perturbed zone. This test will also provide an opportunity to use the mechanical stress field generated by the thermal perturbation to measure fracture permeability as a function of mechanical stress in zones under both compression and tension. Boreholes used for air permeability measurements and liquid collection should be mapped by borehole televiewer techniques to assist in the placement of packers and in the interpretation of results. Finally, coupons of perspective waste package materials could be emplaced in the room along with instrumentation to monitor local conditions and to evaluate corrosion mechanisms and rates under in situ conditions.

Chemical analyses of samples of liquid reflux will provide information on water-rock geochemical interactions. It is also expected that mineralogic changes will be monitored, to the extent practical, using core samples obtained before, during, and after the test.

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.

8.4.5 Test Locations and Other Considerations

The test should be conducted in the TSw2 repository horizon. Figure 14 shows a potential location for the test. 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 under break 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. An approximate schedule for fielding this test is given in Appendix A.

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

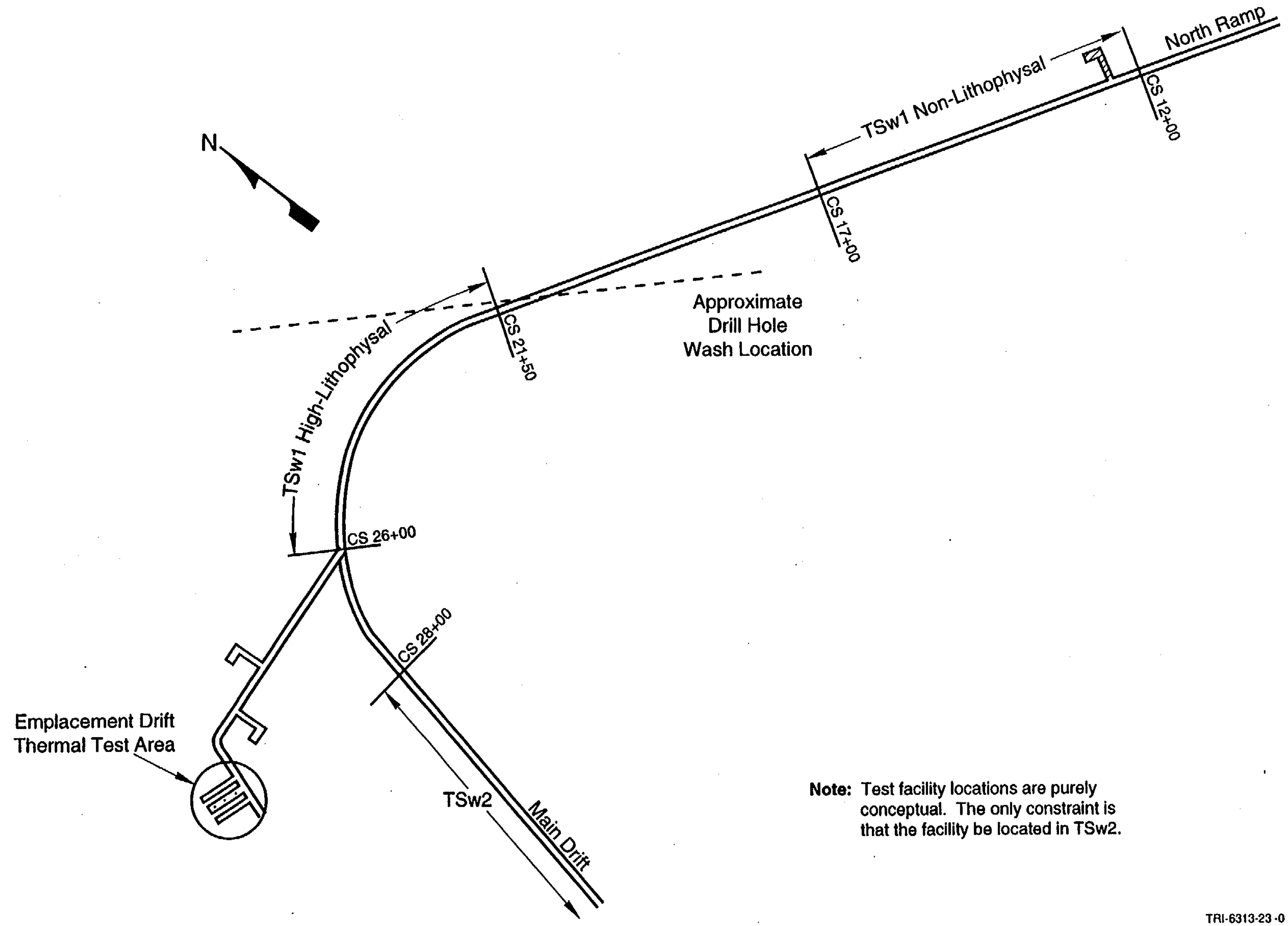

Figure 14. Estimated location for the emplacement drift thermal test.

- 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.

8.4.6 Additional Test Options

Because of the time constraints on acquiring results from thermal testing, it might be desirable to perform a forced rewetting test over part of the heated room. This could be accomplished by injecting water into boreholes above the heated room after the initial heating phase is completed. Such a test would provide data on the rewetting process more quickly and could also simulate the effect of higher flux conditions (e.g., a climate change) during the retreat of the boiling front.

Non-uniform heat distribution within the repository could be investigated by using MPC-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.

8.4.7 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 mineralogic 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* (proposed in this document). 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.

9.0 SUMMARY AND CONCLUSIONS

This concluding section covers four elements. First, a summary of the process and results of this planning exercise are presented, including confirmation that the test program will meet the identified information needs and is consistent with the Licensing Strategy. Second, a brief summary of test scheduling is presented to show how the phasing of tests will integrate with the construction and Program Approach milestone dates. Third, an overview is presented to show how this first step in developing an integrated thermal test program and strategy will fold into follow-on activities that are needed for licensing updates and performance confirmation. Finally, some thoughts on how to proceed from planning to implementation of a test program are presented.

9.1 Summary

The objective of the original suite of thermal tests proposed in the SCP was to provide a comprehensive 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. Recently the Yucca Mountain Site Characterization Project has implemented the Program Approach, which is a step-wise approach to licensing that will, for Technical Site Suitability and initial License Application, require that the Project rely on less site information than previously planned. Additional testing done beyond 2001 will improve our understanding of key processes and will support license updates. This approach requires a rethinking of the testing program. The objective of this report is to propose a thermal testing program that meets the needs of the Program Approach in developing confirmatory data from laboratory and in situ thermal tests to support the 1998 Technical Site Suitability determination and to provide more detailed test results for the subsequent initial phase of licensing in 2001. The initial phase of licensing requires a focus on the preclosure period and the impacts that thermal-mechanical-hydrologic-chemical processes may have on the early waste package environment, on operational safety, and on retrievability—with lesser emphasis on the longer-term performance issues. Although the tests described here are intended primarily to satisfy information needs for the License Application and are of necessity "accelerated" to some degree, they also form the basis for proceeding to the next steps in the process: enhanced testing to build confidence and resolve issues for the License Update to Receive and Possess Waste, and the extended performance confirmation period prior to closure. A more detailed understanding of the site and longer-term performance testing will be developed during the licensing process and will be needed for subsequent license amendments.

The approach taken in this report was to first examine the data needs derived from repository and waste package design, preclosure and postclosure performance assessment, and licensing. Then other constraints were considered, such as Project schedules and likely test locations and construction methods, to arrive at a suite of three complementary test configurations (single-element heater test, plate-source thermal test, and emplacement drift thermal test) that will meet the near-term data needs and Project objectives. The testing program described in this report consists of in situ tests plus a laboratory component. The laboratory component is a selected set of tests that focus on thermally driven coupled processes. The tests are also integrated into an overall testing strategy that is based on starting with simpler, smaller-scale tests and progressing to more complex and larger-scale tests. The three proposed in situ thermal tests are:

- Single-Element Heater Tests,
- Plate-Source Thermal Tests, and
- Emplacement Drift Thermal Test.

These three tests should 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).

The Large Block Test is already under way and is a precursor to the ESF in situ tests. The Large Block Test will provide valuable information on thermal processes and instrumentation that can be used in the design the ESF test program.

The tests described in this report were designed to:

1. Provide the data and information needs required by the Program Approach for Technical Site Suitability and the early repository construction licensing phase at a level of confidence consistent with the Program Approach and the Licensing Strategy.
2. Be fielded within the allowable time windows with a phased schedule of testing that would provide some confirmatory information for Technical Site Suitability and more comprehensive information for the License Application.

3. Be simple and flexible enough to fit within the construction and operational constraints of the ESF during the early construction period.
4. Be traceable to SCP activities and studies, thus assuring that issue resolution processes for meeting the regulatory requirements will remain intact and negating the need for large-scale baseline changes in the testing program.

The correspondence of identified information needs and customers to the tests that will provide the information is summarized in Table 9. Customers are identified as Waste Package Design (WP), Repository Design (RD), Preclosure Performance Assessment (PC), and Postclosure Performance Assessment (PA). Also in the table, the level of confidence in the information provided by a given test is assessed as being sufficient for conservative bounds (C), reasonable bounding estimates (B), or at a level that additional testing is unlikely to improve significantly (SF).

It should be noted that the designators used in Table 9 are applied only to the information generated by the tests outlined here and the way that information fits into the Program Approach strategy for licensing. For example, rock-mass modulus at elevated temperature is estimated to be determinable at a B level from the plate-source thermal test. This does not mean that other tests to determine rock-mass modulus need not be conducted. There are requirements for estimating spatial variability of modulus and the modulus in other units. These requirements will be satisfied by other in situ test programs. In addition, some parameters may be determined quite accurately (at an SF level) by smaller-scale tests but are listed as being at level B because of the uncertainty in scaling to repository dimensions. In a similar way, the in situ test may only provide bounding data, which must be combined with laboratory data and analyses to achieve a greater level of confidence. The laboratory tests identified in the fourth column under "tests" represent all laboratory tests. These include the coupled thermal process tests discussed specifically in this report as well as other supporting laboratory tests identified as having a direct interface with the in situ thermal test program.

9.2 Schedules

Appendix A 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 the initial License Application. The schedule is integrated with the construction schedule (Figure 15) and reflects the desire to have some data from the early tests available to support Technical Site Suitability, although it is doubtful that data from in situ tests can be generated in time to support the technical basis documents for preclosure and postclosure rock characteristics. 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. The phasing of the tests with the major milestones in the Program Approach are shown in Table 10.

Table 9. Summary of Information Needs Satisfied by In Situ Tests

Data and Information Needs	**Tests**				
	Single-Element Heater	Plate Source Thermal	Emplace Drift Thermal	Large Block and Laboratory	**Customers**
Near-field T-M-H-C environment					
• Changes in rock saturation		B	B	B	WP, PA
• Drift humidity			B		WP, PA
• Water chemistry (liquid reflux)	B	B	B	C	WP, PA
• Mineralogic changes		B	B	B	WP, PA
• Propagation of "drying front" (heterogeneity)	B	B	B	C	WP, PA
• Residual water saturation in "dry zone"	SF	SF	B	B	WP, PA
• Drainage/reflux of liquid by fracture flow (heterogeneity, fast paths, heat pipes)	B	B	B	B	WP, PA
• Rock-mass and fracture permeability changes (induced by construction and thermal load)	B	B	B		WP, PA
• Conductive/convective heat transfer	B	B	B	B	WP, RD, PC, PA
Rock-mass properties over a range of temperature					
• Thermal capacity or specific heat	SF	B	B	SF	WP, RD, PC, PA
• Thermal conductivity	SF	B	B	SF	WP, RD, PC, PA
• Thermal expansion	B	SF	B	SF	RD, PC, PA
• Deformation modulus	B	B			RD, PC, PA
• Strength	B		B		RD, PC, PA
• Normal and shear compliance of fractures**		B		SF	RD, PC
• Shear strength of fractures**		B		SF	RD, PC
• Cohesion of fractures**		B		SF	RD, PC
Drift response/stability under thermal conditions			B		WP, RD, PC, PA
Ground support and design features interactions at elevated temperature					
• Rock mass-ground support interaction	C*		B		RD, PC
• Effect of materials on near-field water chemistry	C*		C		WP, PA
• Effect of near-field environment on ground support components	C*		B		RD, PC
• T-H properties of backfill			C		WP, PA
• In situ WP material corrosion rates			C		WP, PA

* This result is only for the single-element heater test conducted in the roof.

** Fracture properties will be address primarily by laboratory experiments. The laboratory data in conjunction with the results of the multiple-element horizontal heater tests will allow these properties to be bounded for the rock mass.

C-Conservative, B-Bounded, SF-Substantially Finished, WP-Waste Package Design, PC-Preclosure Performance Assessment, RD-Repository Design, PA-Postclosure Performance Assessment

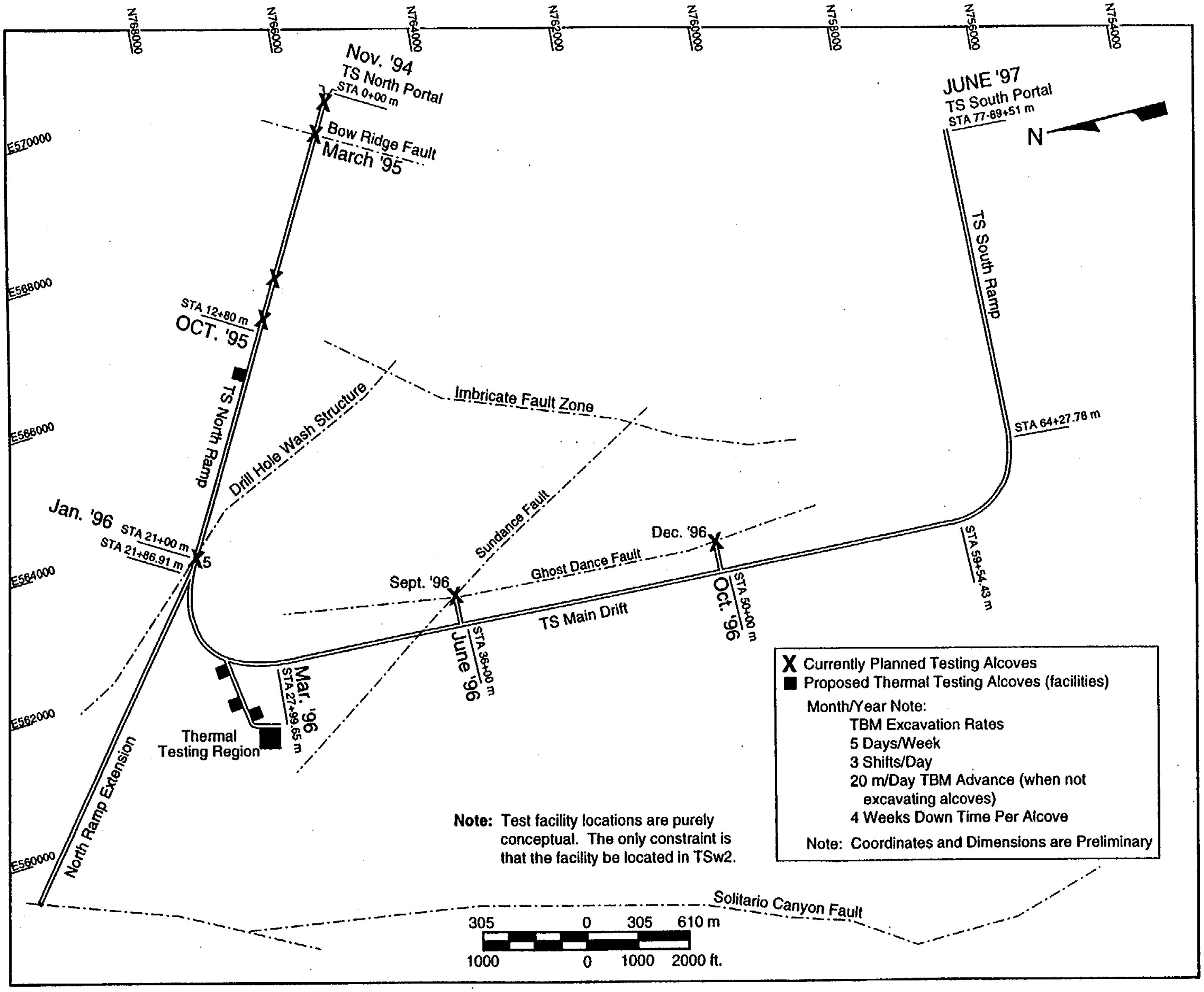

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Figure 15. ESF layout/construction schedule.

TSw1 as early as possible (possibly early in FY 1996). The reasons for this suggestion, outlined below, are not principally to satisfy explicit information needs, but directed more toward programmatic viability. The single-element heater test is considered ideal for this effort because it is the simplest test possible and would provide a "shake down" of the thermal testing process prior to subsequent testing in TSw2. The other benefits of early testing in the TSw1 are listed here:

- The TSw1 is the first repository-like rock unit encountered where test results would have some application
- The test would develop an early understanding of rock thermal response
- The test would develop confidence in equipment, instrumentation, and test techniques
- The test would build teamwork among all participants.

The negative aspect of this proposal is that it would require an accelerated effort beginning almost immediately. It is not clear whether the resources can be mustered and whether other planned activities may need to be sacrificed. Another negative aspect is that a test effort in the TSw1 would detract from the urgency of getting a facility set up in the TSw2 for the more important thermal tests.

9.4.2 Team Approach to Thermal Testing

The scope of work proposed in this report for the next five years is enormous. No single organization has the staff resources and range of expertise needed to complete the proposed effort. Therefore the thermal testing program must be implemented as a Project team effort. For each test, a team should be assembled that will shepherd the test from start to finish. Because the schedule demands that multiple tests be conducted in parallel, several teams will have to operate at any given time. The teams should include appropriate Principal Investigators from across the Project and consultants external to the Project, including experts from local universities and international nuclear waste programs. Staff from the Test Coordination Office should also be assigned to each team. With this approach, a more seamless test organization can be built that will be capable of developing, fielding, analyzing, and documenting the test program.

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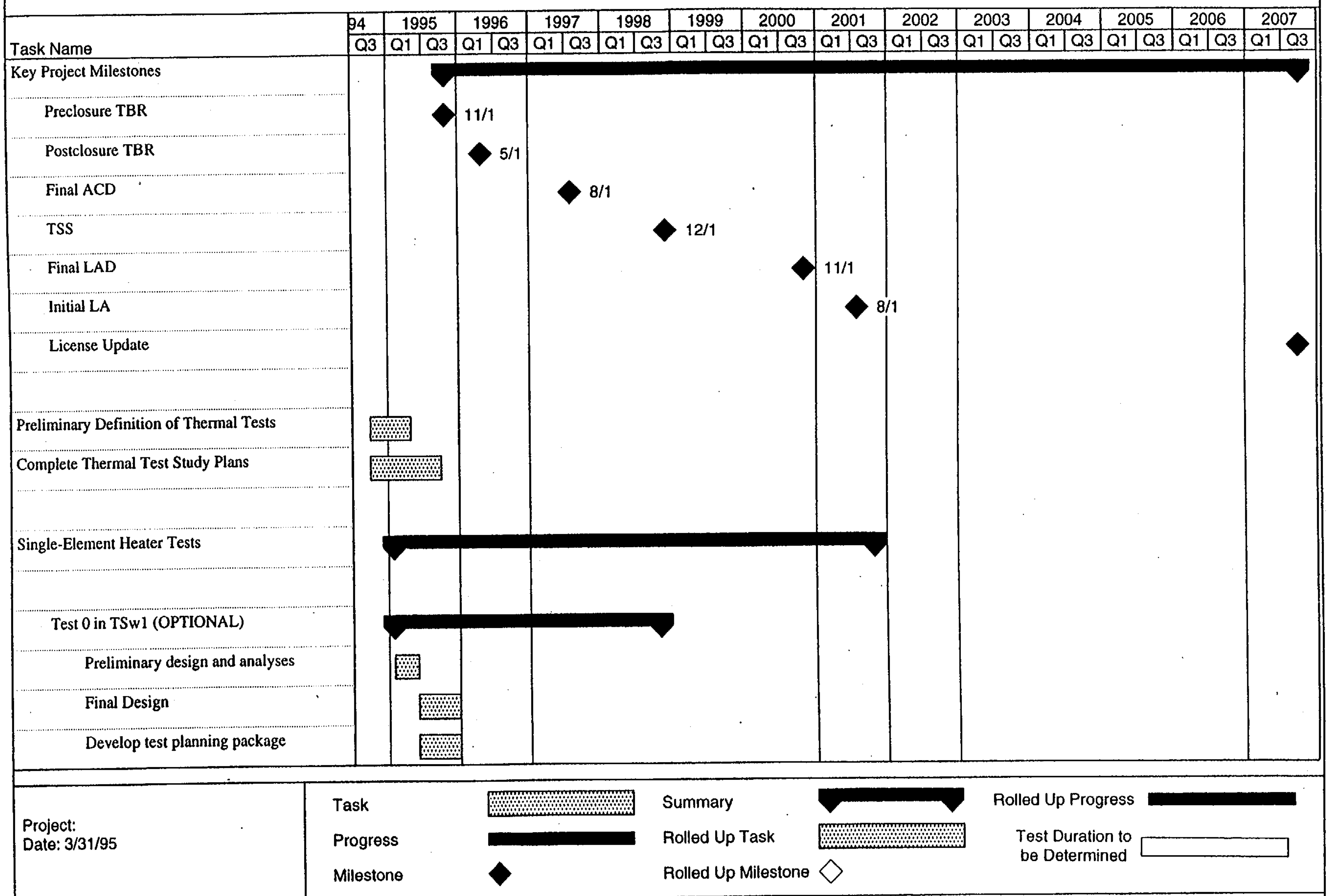
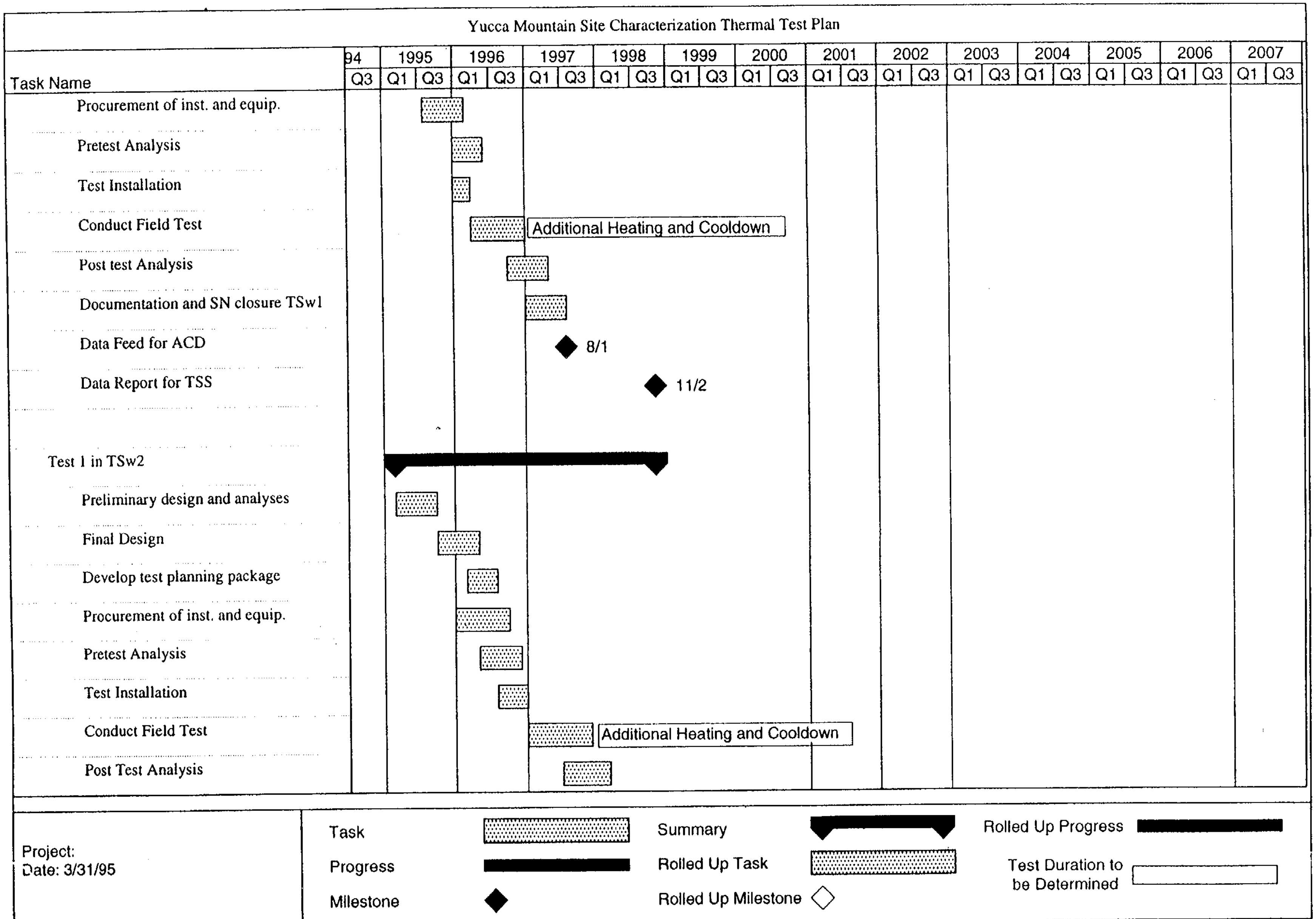
APPENDIX A

Thermal Test Program Schedules
(by fiscal year)

Yucca Mountain Site Characterization Thermal Test Plan

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Q3
Procurement of inst. and equip.
Pretest Analysis
Test Installation
Conduct Field Test
Additional Heating and Cooldown
Post test Analysis
Documentation and SN closure TSw1
Data Feed for ACD
8/1
Data Report for TSS
11/2
Test 1 in TSw2
Preliminary design and analyses
Final Design
Develop test planning package
Procurement of inst. and equip.
Pretest Analysis
Test Installation
Conduct Field Test
Additional Heating and Cooldown
Post Test Analysis
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Date: 3/31/95
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Rolled Up Task
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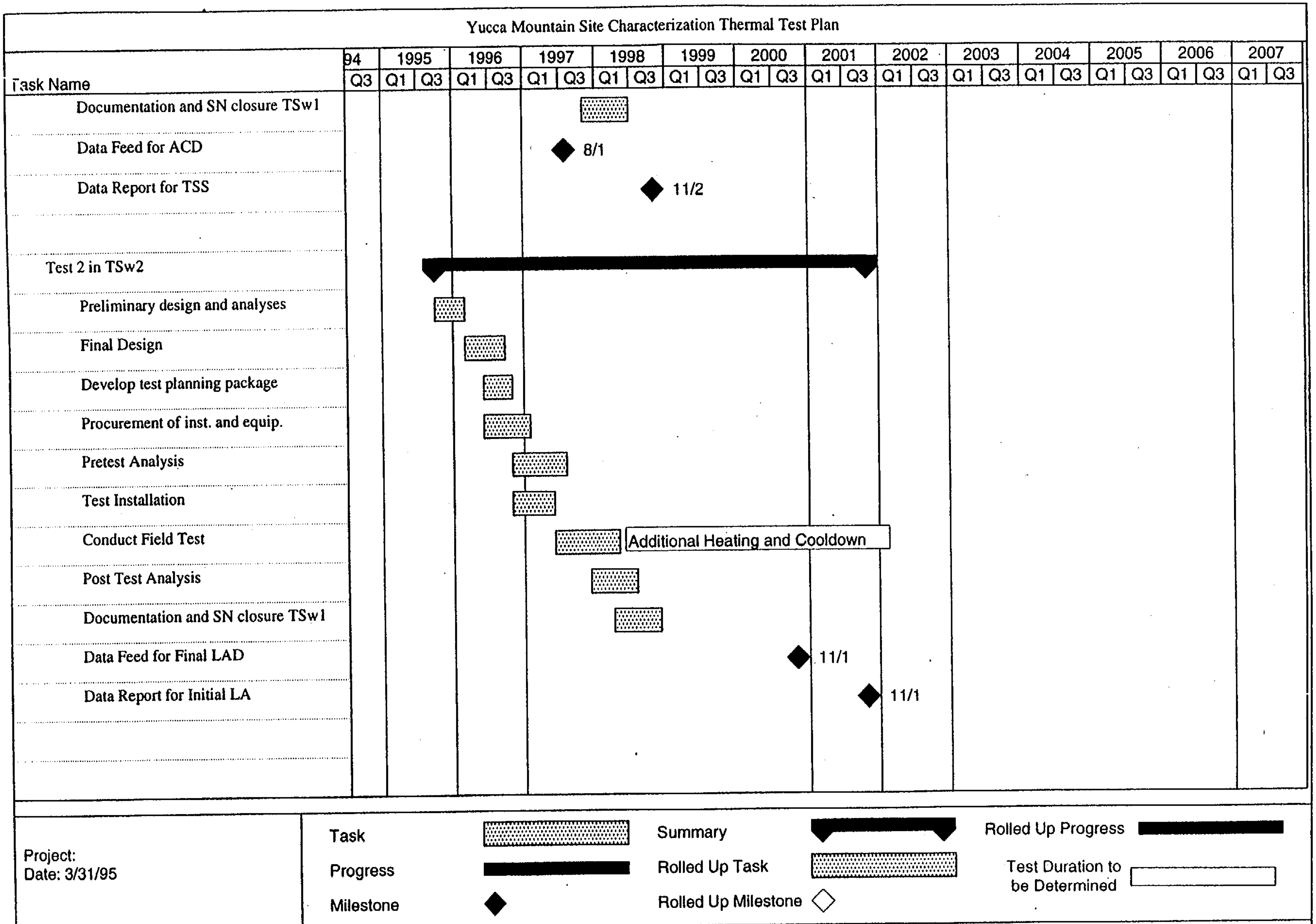
Rolled Up Progress
Test Duration to be Determined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Q1
Q3
Documentation and SN closure TSw1
Data Feed for ACD
8/1
Data Report for TSS
11/2
Test 2 in TSw2
Preliminary design and analyses
Final Design
Develop test planning package
Procurement of inst. and equip.
Pretest Analysis
Test Installation
Conduct Field Test
Additional Heating and Cooldown
Post Test Analysis
Documentation and SN closure TSw1
Data Feed for Final LAD
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Data Report for Initial LA
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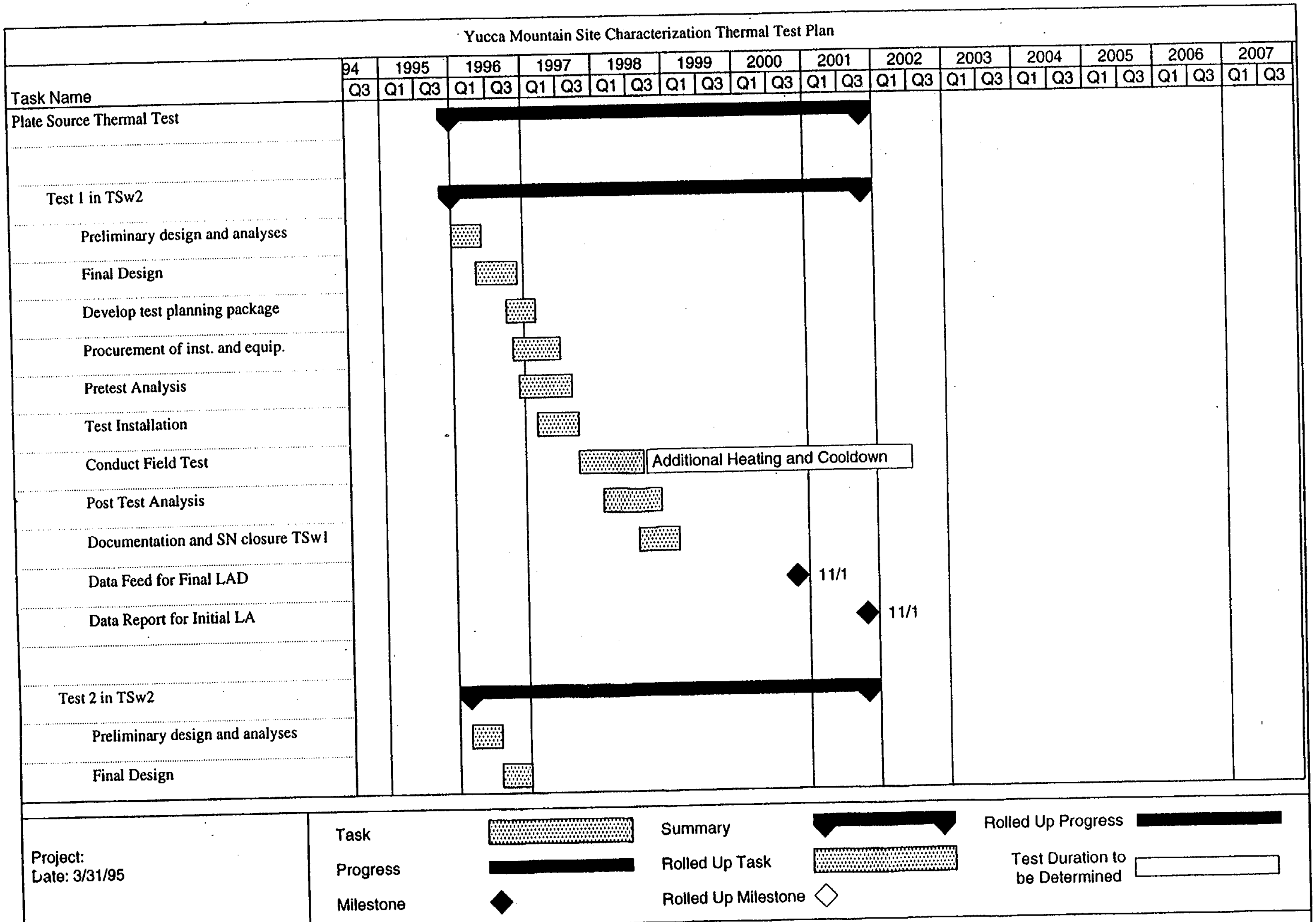
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Plate Source Thermal Test
Test 1 in TSw2
Preliminary design and analyses
Final Design
Develop test planning package
Procurement of inst. and equip.
Pretest Analysis
Test Installation
Conduct Field Test
Additional Heating and Cooldown
Post Test Analysis
Documentation and SN closure TSw1
Data Feed for Final LAD
11/1
Data Report for Initial LA
11/1
Test 2 in TSw2
Preliminary design and analyses
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Date: 3/31/95
Task
Progress
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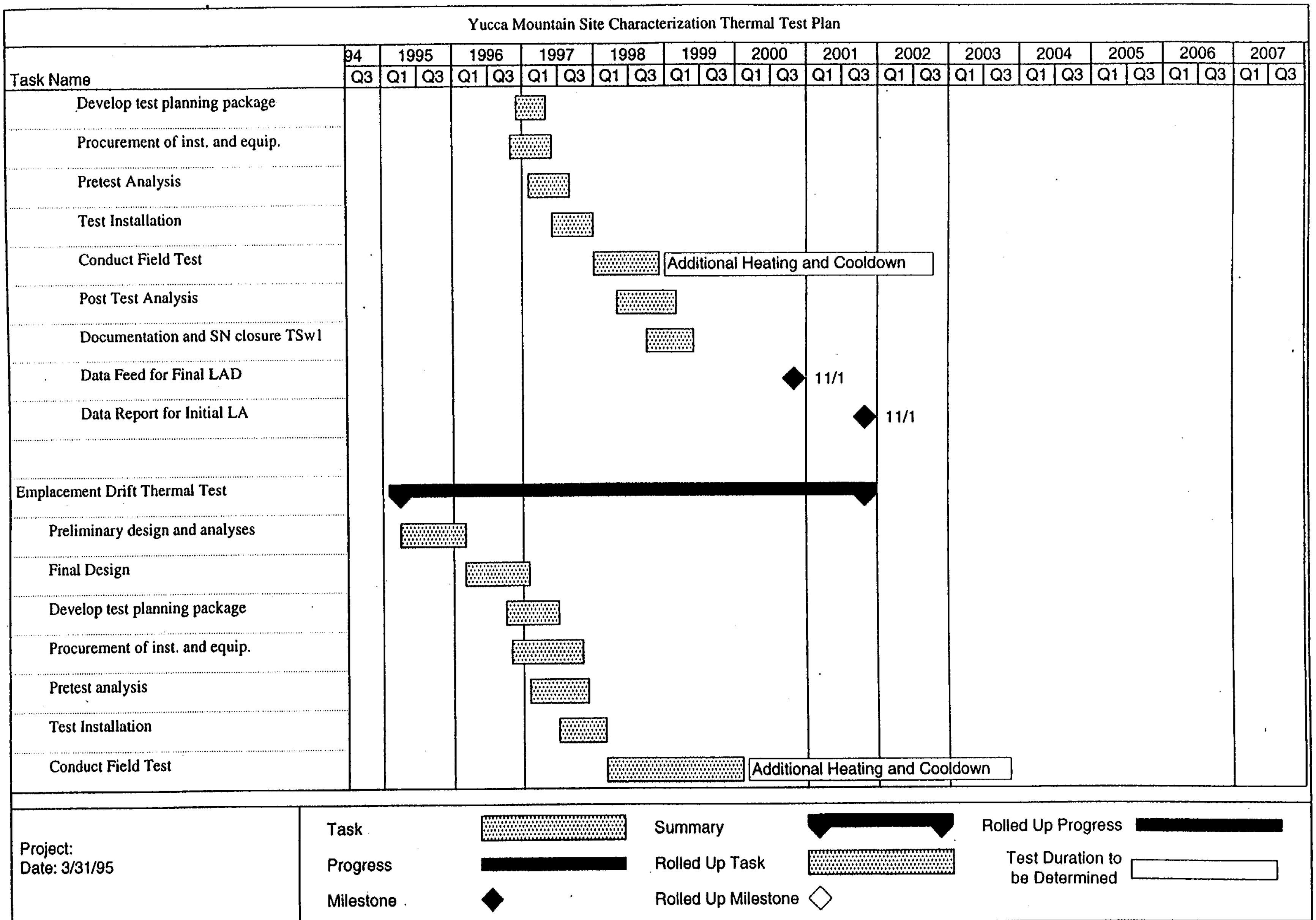
Test Duration to be Determined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Data Report for Initial LA
11/1
Emplacement Drift Thermal Test
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Final Design
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Test Installation
Conduct Field Test
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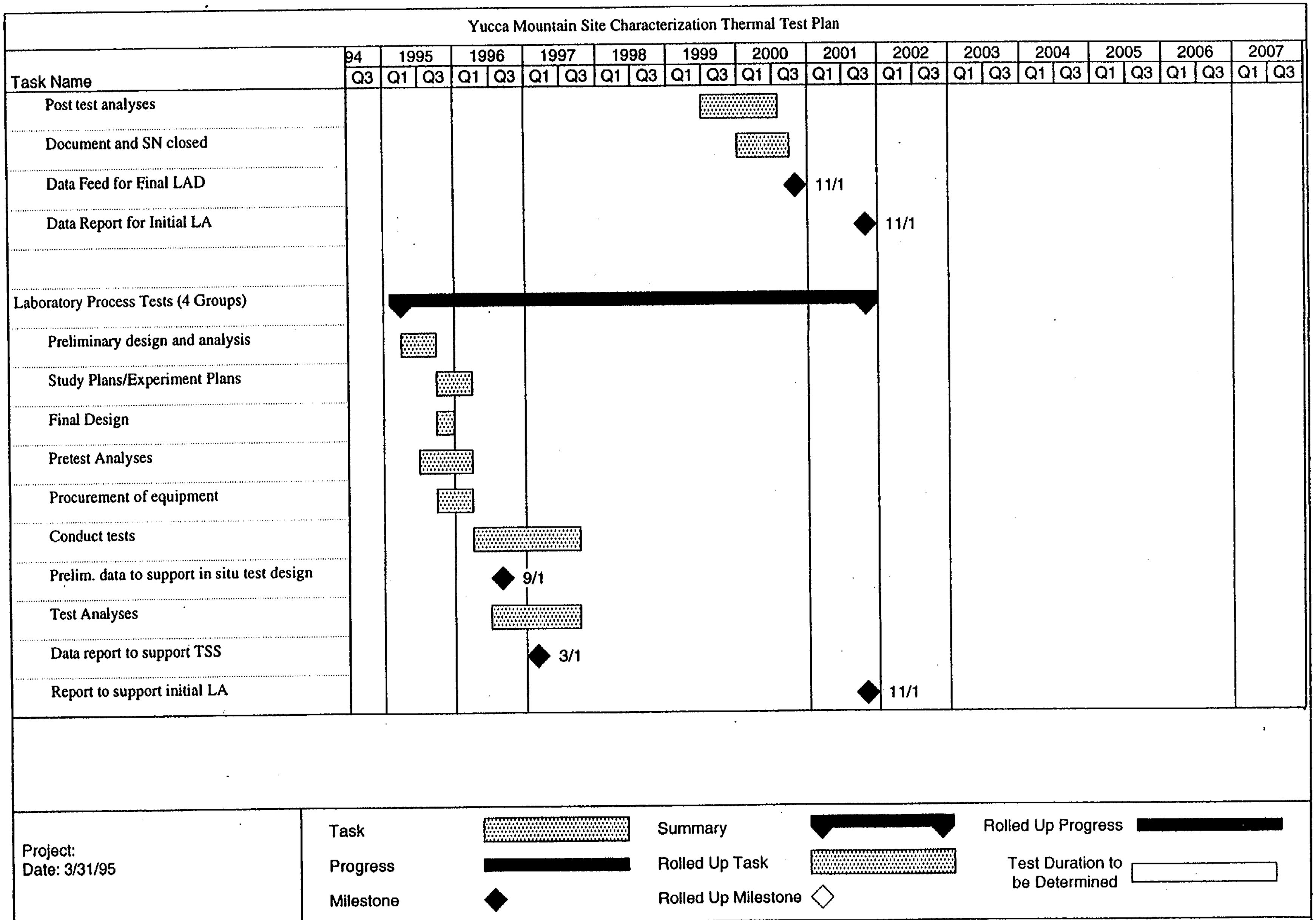
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Q3
Post test analyses
Document and SN closed
Data Feed for Final LAD
11/1
Data Report for Initial LA
11/1
Laboratory Process Tests (4 Groups)
Preliminary design and analysis
Study Plans/Experiment Plans
Final Design
Pretest Analyses
Procurement of equipment
Conduct tests
Prelim. data to support in situ test design
9/1
Test Analyses
Data report to support TSS
3/1
Report to support initial LA
11/1
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Rolled Up Milestone
Rolled Up Progress
Test Duration to be Determined