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Study Plan

For

Engineered Barrier System Field Tests

SP 8.3.4.2.4.4 Rev.0

(SCP 8.3.4.2.4.4)

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Abstract

This Study Plan (SP) describes field studies entitled "Engineered Barrier System Field Tests" (EBSFT) to be conducted at the potential repository horizon in the Exploratory Studies Facility (ESF) at Yucca Mountain, Nevada. These studies are called for in Section 8.3.4.2.4.4 of the Site Characterization Plan (SCP). The SCP also identifies that before the EBSFT in the ESF, prototype tests should be conducted outside of the ESF. The prototype tests are described as Initial Engineered Barrier System Field Tests (IEBSFT). In order to obtain timely verification and calibration of some model concepts of the coupled thermal-mechanical-hydrological-chemical (TMHC) processes before the main test level in the ESF is available for the EBSFT, a large block test (LBT) will be initiated. The LBT is described in a Scientific Investigation Plan (SIP), SIP-NF-02, Rev. 0. The SP is for planning purposes only. Detailed test design and procedures will be included in Activity Plans.

All tests to study the response of rock mass to the thermal and mechanical loadings of nuclear wastes are constrained by scale, natural properties of the rock mass, and time. The results of the tests will be used to calibrate and validate models that will then be used to predict the near-field environment of a repository. Through the model validation, the EBSFT is designed to assess the issues related to the near-field environment, the performance of waste packages, and the total system performance of a repository, as described in the SCP.

Electrical heaters will be used in the IEBSFT and EBSFT to simulate the radioactive decay heat of waste packages. The emplacement mode for the heaters—in drifts or boreholes—has not been determined; this SP uses drift emplacement for discussion. However, it can be easily revised for borehole emplacement, if necessary. The test concept, test layout, and test design for borehole emplacement are not much different from those for drift emplacement. Scoping model calculations are performed to design the tests.

The IEBSFT will include two tests: an abbreviated test and a long-term test. Each test will have three heater drifts. Each heater drift may be about 36 m in length and 4.5 m in width. Instruments will be installed from observation drifts that are constructed around, above, and under the heater drifts. Based on the scoping model calculations, the abbreviated test will have a full-power heating period of about 18 months followed by a controlled cool-down period of about 6 months, and a natural cool-down period of about 12 months. The peak temperature in the rock mass will be about 214°C. The long-term test will have a 48-month full-power heating period and a

12-month controlled cool-down period followed by a natural cool-down, which may last for longer than 12 months. The EBSFT will also have an abbreviated test and a long-term test. The abbreviated EBSFT test unit will have three drifts; the long-term EBSFT test unit will have five drifts. The heating and cool-down durations of the EBSFT are similar to that of the IEBSFT, except that there is no controlled cool-down period for the abbreviated test.

The parameters to be measured in both IEBSFT and EBSFT include temperature, moisture content, mechanical stress, displacement, permeability, and chemical parameters (e.g., pH, Eh, Cl, Na, Si, O_2, CO_2, etc.) Thermal modeling codes (i.e., V-TOUGH and NUFT) and thermal-hydrological-geochemical codes (i.e., PRECIP and BASIN II) will be used to analyze the test results.

1.0 Purpose and Objectives

The purpose of this Study Plan (SP) is to describe tests known as Engineered Barrier System Field Tests (EBSFT), which are identified by Work Breakdown Structure (WBS) as WBS 1.2.3.12.4. This study is described in Section 8.3.4.2.4.4 of the Site Characterization Plan (SCP). It will provide field measurement of repository horizon near-field hydrological properties (SCP Activity 1.10.4.4.1) and repository horizon rock-water interaction (SCP Activity 1.10.4.4.2). The field results will be used to validate model calculations of fluid flow and transport in the repository horizon near-field environment (SCP Activity 1.10.4.4.3). The EBSFT is to be conducted in the Exploratory Study Facility (ESF) at Yucca Mountain, Nevada. The EBSFT is designed to provide information on the interaction between waste packages (simulated by heated containers), the surrounding rock mass, and its vadose water, so that models that will be used to predict the near-field environment in a repository can be tested and validated. This study encompasses the rock mass in the potential repository horizon that will be perturbed by repository construction and thermal loading from waste packages.

The Yucca Mountain site is being characterized to determine its suitability as a potential deep geological repository for high-level nuclear waste. A successful repository must be capable of retaining the radioactive nuclides in the nuclear wastes to meet the requirements of the U.S. Environmental Protection Agency (EPA) and Nuclear Regulatory Commission (NRC). The SCP, Section 8.3.4, implies that in Yucca Mountain, water is the main medium by which most radioactive nuclides may travel to the accessible environment. It states that the waste package design strategy will take advantage of the unsaturated nature of the Yucca Mountain site. It further states that the near-field environment will be engineered to enhance the unsaturated condition and inhibit liquid water contacting the waste package. Therefore, over 10,000-year period required by federal regulations, the movement of water and the transport of radionuclides must be understood.

Development of a repository and emplacement of nuclear wastes impose disturbances on the repository rock mass. The disturbances include (l) thermal energy and irradiation from the waste packages, and (2) mechanical loading due to the mining of openings, i.e., drifts, alcoves, and boreholes, etc., and the transporting of waste canisters. Depending on thermal loading, the influence of the thermal loading may extend to lithological units, including the saturated zone under the groundwater table in Yucca Mountain (Buscheck and Nitao, 1993b).

In general, the primary purpose of this study is to investigate the coupled thermal-mechanical-hydrological-chemical processes in the near-field environment of a nuclear waste repository. Specifically, the study will investigate the movement of water in the rock mass under the influence of thermal loading, the heat flow mechanism, the relationship between the boiling point isotherm and dry-out, the re-wetting of the dry-out region when the test region is cooled down, and the geochemical processes. The studies described in this SP will be conducted mainly in the densely welded, fractured, nonlithophysal Topopah Spring Tuff, known as TSw2 thermal-mechanical unit.

The primary objective of the EBSFT is to provide *in situ* information on processes affecting the near-field host rock in those areas where the waste package will raise the temperature significantly above the pre-emplacement ambient temperature. The information includes the movement of moisture in the waste package environment, the mechanical behavior of the rock mass in the near-field, and the rock-water interactions in the near-field environment. The EBSFT will also try to reveal any *in situ* synergistic effects that were not identified in laboratory experiments. The EBSFT will be used to verify and validate conceptual and numerical models, such as V-TOUGH and NUFT, that will in turn be used to predict the near-field environment during the life span of a repository. The near-field environment will be used to estimate the corrosion rate and, therefore, the radionuclide release rate from the waste package. The information is required by Section 113, NRC Rule 10CFR60 (US NRC, 1984).

This objective is dictated by requirements contained in Section 135(a) of NRC Rule 10CFR60 which states, in part:

> Packages of HLW [high-level waste] shall be designed so that the *in situ* chemical, physical, and nuclear properties of the waste package and its interactions with the emplacement environment do not compromise the function of the waste packages or the performance of the underground facility or the geologic setting.
>
> The design shall include, but not be limited to considerations of the following factors: Solubility, oxidation/reduction reactions, corrosion, hybriding, gas generation, thermal effects, mechanical strength, mechanical stress, radiolysis,

radiation damage, radioactive nuclide retardation, leaching, fire and explosion hazards, thermal loads, and synergistic interactions.

1.1 Rationale for the Selected Studies

The SCP describes a series of issues and information needs (INs) that address those issues. The issue identified as 1.10 (Waste Package Characteristics—Post-closure) deals with the service environment of the waste package. Section 8.3.4.2 of the SCP states:

> The waste package environment, upon initial emplacement of the package, will depend on the ambient conditions at the repository level and how those conditions are altered by repository construction and operation. The environment following emplacement will depend on the initial emplacement conditions and how those conditions are altered by the waste package. Therefore, there is an interactive process between design and environment characterization. The design is initially based on the ambient conditions and a prediction of how those conditions would alter under the stresses applied by repository construction and waste emplacement. Once a design is available, analysis of that design provides a set of environmental stress factors. Testing is then done to determine the effect of those stresses, i.e., thermal and radiation fields and mechanical stresses, on the package environment. Based on those tests and subsequent analysis, designs may be modified and the test and analysis cycle repeated.

IN 1.10.4 (Post Emplacement Near-Field Environment) is one of several investigations that will provide input to Issue 1.10. IN 1.10.4 and is itself composed of several investigations, including the EBSFT described here. In addition, information from the EBSFT will provide input to verify and validate model calculations that will predict the quantity and quality of moisture in the near-field environment. This information will be input to other INs shown in Table 1.

Table 1. The INs that will receive information from the EBSFT described in this SP.

IN or Investigation	Subject
1.1.1	Site information needed to calculate release to the accessible environment (Section 8.3.5.13.1)
1.4.3	Scenarios and models needed to predict the time to loss of containment and the ensuing degradation of the containment barrier (Section 8.3.5.9.3)
1.4.4	Containment barrier degradation (Section 8.3.5.9.4)
1.5.2	Material properties of the waste form (Section 8.3.5.10.2)
1.5.3	Scenarios and models needed to predict the rate of radioactive nuclide release from the waste package and engineered barrier system (Section 8.3.5.10.3)
1.5.4	Release rates of radioactive nuclides from the engineered barrier system for anticipated and unanticipated events (Section 8.3.5.10.4)
1.10.1	Design information needed (consideration of waste package environment interactions) (Section 8.3.4.2.1)
1.10.3	Waste package emplacement configuration (Section 8.3.4.2.3)
1.11.3	Design concepts for orientation, geometry, layout, and depth of the underground facility to contribute to waste containment and isolation, including flexibility to accommodate site-specific conditions (Section 8.3.2.2.3)
1.11.6	Repository thermal loading and predicted thermal and thermomechanical response of the host rock (Section 8.3.2.2.6)

1.12.2 Seal materials
(Section 8.3.3.2.2)

Waste package performance will also be influenced by processes affecting the post-emplacement environment. Many of the activities described below will provide input to waste package performance assessment models.

The EBSFT will interact with other studies within the Near-Field Environment Technical Area (SCP 8.3.4.2.4). The EBSFT will provide site-specific data on near-field hydrologic, thermal, mechanical, and chemical phenomena during a complete, accelerated thermal cycle in the rock mass. Model calculations indicate that the thermal hydrological processes in a repository space and time scales are similar to that in an ESF testing case, except that the time scale is compressed (Buscheck, et al., 1993). The EBSFT is designed to test some of the coupled processes to be used in the model calculations. The tested models will then be used to predict the near-field environment in the time scale of a repository. The tests in an accelerated thermal cycle may miss some processes that may take a longer time to develop (such as the long-term creep of drifts and some slow geochemical processes); they may also affect the measured result of some time-dependent processes, such as the build-up of gas-phase pressure, which is likely to be dependent on the rate of thermal cycle and permeability of the rock. These time-dependent processes will be studied in performance confirmation tests, which are extensions of the EBSFT, but will be covered by separated study plans. The analysis and interpretation of this information in terms of the coupled thermal-mechanical-hydrological-chemical processes (TMHC) will benefit from the study of hydrological properties (SCP 8.3.4.2.4.2), the study of chemical and mineralogical changes (SCP 8.3.4.2.4.1), and the study of geomechanical attributes (SCP 8.3.4.2.4.3). Conversely, the EBSFT results will provide data for the model testing and validations for those studies. For understanding the near-field environment, the movement of water and steam in pores and fractures in the near-field is of primary interest (thermal-hydrological process). In this case results from the laboratory study of hydrological properties (Study Plan 8.3.4.2.4.2) will be used to interpret the macroscopic phenomena of the thermal-hydrological process observed in this study. The result from this study will be used to validate and check the thermal-hydrological model calculations (i.e., V-TOUGH) that will be used to understand the near-field environment of a potential repository.

Thermal and mechanical properties are also of interest because of their roles in driving and influencing water movement (geomechanical attributes). The study of geomechanical attributes (Study Plan 8.3.4.2.4.3) investigates thermal-mechanical responses of the rock mass to the thermal loads expected from waste packages. These responses include thermal fracturing and displacement of fractures. This information will be used to understand the thermal-mechanical effect on the movement of water and the associated rock-water interaction. On the other hand, rock-water interaction may affect the mechanical property of the matrix of the rock mass (Lajtai, et al., 1987), and the dissolution and redeposition of minerals on fracture surfaces will affect the mechanical property of the fractured rock mass. The results from the EBSFT will be used for the development of a thermal-mechanical model of a rock mass.

Geochemical processes will also receive attention because of (l) their potential influence on hydrologic behavior, and (2) possible effects on components of the engineered barrier system. Rock-water interaction as a function of temperature and permeability (fracture aperture) will be studied in the laboratory as described in the Study Plan for the Characterization of Chemical and Mineralogical Changes in the Post-Emplacement Environment (Study Plan 8.3.4.2.4.1). The rock-water interaction (such as ion exchange and aqueous speciation) will affect the water chemistry, and the dissolution-redeposition process will affect the permeability of the rock mass. The laboratory results will help interpret the observations in the EBSFT. The results of the EBSFT will be used to develop and validate geochemical models that will be used to characterize geochemical interactions and to reveal any *in situ* synergistic effects that were not identified during laboratory testing, especially the effect of inhomogeneities and mechanical properties on the geochemical processes.

The coupled TMHC processes are expected to exist in a nuclear waste repository as long as the heat generated from waste packages is enough to move the vadose moisture and to cause displacement in the rock mass. The activeness of the process depends on temperature in the rock mass. Codes to be used for the model study of the TMHC processes (i.e., V-TOUGH, NUFT, EQ3/6, PRECIP, and BASIN II) need testing data for verification and validation. These model calculations will be used to help make decisions on certain strategies, e.g., thermal loading. A small-scale field test known as the Large Block Test (LBT) is designed to provide testing on some concepts (e.g., condensate refluxing, heat transfer mechanism, boiling isotherm vs. drying, and re-wetting process) that will be incorporated in the model calculations for understanding the coupled TMHC processes. In this sense, the LBT will be used to help design the EBSFT. The LBT will also test measuring methodologies and instrumentation that will be used in the EBSFT. The LBT is described in a Scientific Investigation Plan, SIP-NF-2, Rev. 0.

As will be discussed in Section 2.2, this proposed study will have a much shorter heating and cooling time than a real nuclear waste repository system, and the region being studied is much smaller than a repository. The time and volume constraints will limit the application of the test results to model verification and validation. The test results may not be directly applicable to characterize the thermal-mechanical-hydrological-geochemical process in a full-scale repository.

The study described in this SP will be combined with the studies mentioned in the paragraphs above to verify and validate conceptual and numerical models, such as V-TOUGH and NUFT, that will be used to predict fluid flow and transport in the near-field of a nuclear waste repository, as required in SCP section 8.3.4.2.4.4.3. As will be described later in this SP, this study will determine spatial and temporal distribution of temperature, moisture content, and permeability. This information, along with mechanical attributes, will be used to validate the models.

2.0 Scope of Work

This study includes three activities. The major activity, LB-02, in situ-testing, includes one or more Engineered Barrier System Field Tests in the ESF as well as the earlier Large Block Test (LBT) on an outcrop of Topopah Springs tuff at Fran Ridge. The LBT planning was documented in a Scientific Investigation Plan.

Another activity, EB-01, Sampling and Sample Analyses, is a service activity to other near-field studies such as 8.3.4.2.4.1 and 8.3.4.2.4.2.

The final activity, EB-03, Pre- and Post-Test Calculations, uses models to predict and analyze in situ tests and in turn uses test results as model validation. Development of the models will be done in other studies.

2.1 Background

The potential Yucca Mountain repository horizon is in a devitrified, partially saturated, lithophysal densely welded tuff (US DOE, 1988). Work to date suggests that the potential repository horizon has a mean matrix porosity of 14% and a mean water saturation of 65% (Montazer and Wilson, 1984). Therefore, the rock mass consists of host rock with pore spaces filled with both air and water.

Waste package emplacement will impose thermal and radiation loads on the rock mass. The thermal load may increase the near-field temperatures and create a region of hot, dry rock (when the temperature is greater than the boiling point of the pore water, the moisture content becomes less than that of the pre-emplacement condition) around the emplacement drifts or boreholes. Evaporation of the vadose water will occur where the temperatures are sufficiently high. Pore gas pressure is expected to increase in the unfractured rock mass. The buildup of pore gas pressure depends on the gas permeability in the rock mass. The gas permeability in the unfractured rock matrix is expected to be on the order of micro darcy (10^{-18} m^2) (Lin and Daily, 1984). The pore gas pressure gradient between the matrix and fractures may be high enough to cause water vapor migration toward the fractures. On the basis of laboratory studies of the dehydration process (Daily, et al., 1987), it is thought that vapor will leave fractures first, and then the moisture in the matrix will flow into the fractures. A dry-out region will be developed around the fractures and it will gradually extend into the matrix. A region of increased saturation is expected to form surrounding the dry-out region as steam condenses within the cooler portions of the rock mass. Part of this condensation will occur along fractures. Some of the condensation may move from the fractures into the matrix because of higher suction potential in the matrix. The remaining water in the fracture may remain immobile because of capillary forces, or it may flow along the fracture under gravity, depending on local fracture aperture and configuration (Ramirez, 1991; Ramirez, et al, 1990). Figure 1 shows a conceptual model for the movement of moisture due to heating based on results of the G-Tunnel test. Since the power output of waste packages decreases with time, the hot region of the rock mass around the emplacement drifts or boreholes eventually decreases in size, and the dry-out region will slowly regain some of the water lost to the surrounding areas.

In conducting preliminary model calculations, Buscheck and Nitao (1993a) indicate that for a given burnup, the most useful macroscopic thermal loading parameter in analyzing long-term thermal performance is the areal mass loading

(AML), expressed in metric tons of uranium per acre. They indicate that even for low AML scenarios, which entirely avoid boiling of the pore water, repository-heat-driven buoyancy flow can dominate fluid flow in both the unsaturated and saturated (below the water table) zones (Buscheck and Nitao, 1993b). The magnitude of repository-heat-driven buoyancy flow in the saturated zone depends strongly on the total mass of emplaced spent nuclear fuel. They also find that for high AMLs, the liquid-phase flux associated with vapor flow and condensate drainage during the heating period, as well as re-wetting of the dry-out zone during the cool-down period, is much greater than the net recharge flux associated with pluvial climatic conditions. Current estimation of the net infiltration flux associated with pluvial climatic conditions based on hypothetical model analysis is about 0.005 mm/yr. (Flint, et al., 1993). Therefore, one of the most important considerations in determining whether the Yucca Mountain site is suitable for the emplacement of heat-producing high-level nuclear wastes is how heat moves fluid that is already present at Yucca Mountain. The heat-driven movement of the vadose fluid is at least as important as the effect of water that has yet to infiltrate at Yucca Mountain (Buscheck and Nitao, 1993b). The study described in this SP is designed to verify and validate Buscheck and Nitao's model calculation results.

Construction of underground facilities (including ramps, drifts, alcoves, and boreholes) and placing of waste packages will disturb the *in situ* stress field in the rock mass. The thermal load from the waste packages will further change the stress field in the rock mass, especially near the emplacement openings. The change in stress field may have an impact on the fracture porosity and connectivity of the rock mass. The change in fracture porosity and connectivity may affect rock-water interaction and the movement of water and steam mentioned in the previous paragraph. The EBSFT will study the effect of the mechanical responses on the movement of moisture and rock-water interaction in the rock mass.The design of the EBSFT will focus on determining the distribution of temperature, moisture, stress and displacement in the near-field environment and the associated rock-water interactions, particularly after the peak temperatures have passed. The EBSFT is distinct from other heater tests in welded tuff, which have focused on the thermomechanical response of a rock mass and on changes in the environment during the heating phase. Heater tests conducted in G-Tunnel at the Nevada Test Site by Sandia National Laboratories (Zimmerman, 1982; Zimmerman, et al., 1984) examined water migration behavior in heated holes in welded tuffs during a heating phase, but the tests did not include monitoring of postheating behavior. The EBSFT will monitor hydrological processes in both the heating and the cool-down phases of the thermal cycle. In the EBSFT, the following will also be monitored: (1) the mechanical response of the rock mass to thermal loading and unloading, and (2) geochemical processes, i.e., dissolution, precipitation, ion exchange, and aqueous speciation, during the entire duration of the test.

The LLNL test conducted in G-Tunnel during 1988-1989 in a 12-in. diameter horizontal borehole (G-Tunnel Prototype Test) confirms that a dry zone develops around the heater borehole, the degree of drying increasing with proximity to the heater's center (Ramirez, 1991). A "halo" of increased saturation develops adjacent to the dry region and migrates away from the heater as rock temperatures increase. Some of the fractures intercepting the heater borehole increase the penetration of hot dry conditions into the rock mass. The G-Tunnel test showed that gravity has a significant influence on the flow of moisture around the heater hole, such that (1) the dry-out region above the heater is narrower than that below the heater, and (2) moisture can be moved radially; the condensate can be shed by gravity away from the dry-out zone.

Prototype testing at G-Tunnel was stopped before the second test was performed. The second test was intended to be the more complete test where geochemistry and geomechanics were included. Subsequently, additional information on the size and type of testing required to look at questions like condensate refluxing, condensate drainage, and thermal convection- vs. conduction-dominated responses has indicated a further need for testing prior to the tests to be performed at ESF. This is particularly important since early decisions, e.g. on thermal loading, must be made prior to the completion of ESF tests and therefore must rely on the result of model studies. In addition, the site characterization should be an iterative process. Some tests will be conducted before the ESF tests so that their result can be incorporated in the design of the ESF tests. For these reasons, a Large Block Test (LBT) has been identified that will provide some of the needed information for testing and verifying the model calculations (e.g., V-TOUGH). This information includes condensate refluxing, condensate drainage, thermal transfer mechanism, etc. The LBT is to be performed at Fran Ridge, Nevada Test Site, Nevada, (east of Yucca Mountain) in an area that is outside of the controlled area, and is not intended as a site characterization study because it is not to be performed at Yucca Mountain; rather it is a study to build confidence in the models that will be used to support the early decisions and the ESF test design/scoping calculations. The LBT will also serve the purpose of testing instrumentation and methodology. The characterization of response of the rock mass in Yucca Mountain to the emplacement of waste will be left to the ESF studies described within this Study Plan. Testing that is not directly related to site characterization is controlled by planning documents called Scientific Investigation Plans (SIPs), which are based on the LLNL QA plans and are at a level in the document hierarchy equivalent to Study Plans. The LBT is discussed in SIP-NF-02, Rev. 0.

2.2 In Situ Test Descriptions

A logical testing sequence for verification and validation of thermal-hydrological and geochemical models, to be used in studying the near-field environment in a potential repository at Yucca Mountain, is as follows (in the order of increasing scale): laboratory tests on cores and small blocks, large block tests, prototype *in situ test*, and *in situ* test in the Exploratory Studies Facility (ESF). The laboratory tests are usually on cores and blocks of sizes from a few to several tens of centimeters. The samples are either intact or containing one single fracture. The large block test deals with a block of several meters in size and contains multiple fractures. The prototype *in situ* test will have the same scale as the *in situ* ESF test; it will provide an opportunity for developing and testing methodology and instruments to be used in the *in situ* ESF test. The prototype test may not be performed in the ESF, therefore cannot be used directly for license application. The laboratory test of the hydrological properties in the near-field environment is described in Study Plan 8.3.4.2.4.2. The laboratory test of geochemical processes is described in Study Plan 8.3.4.2.4.1. The large block test is described in Scientific Investigation Plan SIP-NF-02, Rev 0. This study plan describes tests that will provide field measurement of repository horizon near-field hydrological properties (SCP Activity 1.10.4.4.1) and repository horizon rock-water interaction (SCP Activity 1.10.4.4.2). The field results will be used to validate model calculations of fluid flow and transport in the repository horizon near-field environment (SCP Activity 1.10.4.4.3). This study plan covers both the prototype test, which is identified as Initial Engineered Barrier System Field Tests (IEBSFT), and the Engineered Barrier System Field Tests (EBSFT) in the ESF. Section 8.3.4.2.4.4 of the SCP calls for prototype tests to develop and validate the test procedures and protocols of EBSFT. The SCP identifies that the prototype tests were to be conducted in G-Tunnel in Rainier Mesa, Nevada Test Site. G-Tunnel was closed before the prototype tests could be completed (Ramirez, 1991). The IEBSFT may be conducted in Rainier Mesa or Busted Butte, where the hydrogeologic setting is similar to that at Yucca Mountain, or at locations outside of the repository horizon in the ESF. Therefore, the results from the IEBSFT are not intended to be used directly for license application. The description of the activities, parameters to be measured, methodology and instruments, and test schedule given later in this SP are applicable to both IEBSFT and EBSFT.

The IEBSFT and EBSFT may be conducted in at least three parallel heater drifts. Each of the heater drifts will be about 36 m in length and 4.5 m in width. The peak temperature in the rock mass will be about 214°C. Instrument (diagnostic) drifts above and below the heater drifts are required, as shown in Figure 2.

2.2.1 Initial Engineered Barrier System Field Tests

Drift emplacement, as shown in Figure 2, is to be tested in IEBSFT. The SCP baseline design is for borehole emplacement. However, the current trend is to change the baseline design to drift emplacement. If the baseline is not changed before the construction of the test, then borehole emplacement will be chosen as the final emplacement mode. The information will be included in Activity Plans. The test methods, test configuration, and construction described in this SP can also be applied to vertical borehole emplacement. Two tests will be conducted in the IEBSFT: an abbreviated test and a long-term test. One test unit, as shown in Figure 1, will be constructed for each of the two tests. The two units may be constructed side-by-side or separated, depending on the area available for the tests. Both the abbreviated and long-term tests may start at the same time. The abbreviated IEBSFT will be used to study the responses of rock mass in a complete heating and cool-down cycle. The long-term IEBSFT will have sufficient heating duration to dry out a large enough volume of the rock mass at appropriate rates so the data obtained is more representative of the potential repository. Scoping model calculations indicate that an 18 month heating period for the abbreviated test and a 48 month heating period for the long-term test are required. The controlled cool-down duration for the abbreviated and long-term IEBSFT will be 6 months and 12 months, respectively. These test durations may change based on the actual response of the rock mass. The changes will be documented in Scientific Notebooks. The criteria of determining the volume of a dry-out zone will be given in Section 2.6. The dry-out rate during the heating period should be slow enough that the condensate water will be in contact with rock for at least several months, allowing rock-water interaction (dissolution, precipitation, ion exchange, and aqueous speciation) to be monitored. The IEBSFT will also evaluate test methodologies and instrumentation in an environment similar to that at EBSFT. The results of the IEBSFT are to be used to (1) design the EBSFT and (2) validate part of the long-term EBSFT.

2.2.2 Engineered Barrier System Field Tests

The EBSFT will be conducted in the main test area in the ESF. The layout of the EBSFT is similar to that of the IEBSFT. Drift emplacement will also be used. One three-drift unit will be used for the abbreviated EBSFT; one five-drift unit will be used for the long-term EBSFT. As described later, the abbreviated EBSFT will have an 18 month heating period and a 6 month controlled cool-down period. The long-term EBSFT will have a 48 month heating phase and a 12-month controlled cool-down period. These test durations may change based on the actual response of the rock mass. The changes will be documented in Scientific Notebooks. The controlled cool-down period in both tests will be followed by a natural cool-down period, which may last for 12 months or even longer, depending on the response of the rock mass. Similar to the abbreviated IEBSFT, the abbreviated EBSFT is designed to investigate the thermal-mechanical-hydrological-chemical responses of the rock mass at the potential repository horizon in a complete heating and cool-down cycle. The results of the abbreviated EBSFT will be compared with that of the IEBSFT to validate the results of the long-term IEBSFT. The long-term EBSFT will continue beyond the license application (assumed to be in the year 2001) as a performance confirmation test, and will have a complete heating and cool-down cycle.

There is a possibility that IEBSFT may not be conducted. Without the IEBSFT (1) the test methodologies and instruments to be used in EBSFT cannot be tested, (2) the design of EBSFT will be performed without the benefit of a prototype test, and (3) none of the model concepts can be verified and calibrated in an underground environment before the EBSFT. The LBT is intended to partially meet the IEBSFT objectives, such as calibration and verification of some of the model concepts of the coupled TMHC processes. The LBT can provide an opportunity for characterizing the block before and after the tests, which is very important for model calibration and verification. However, the LBT can only provide limited development of methodologies and instruments because of its limited physical size and near-surface condition. Therefore, without the IEBSFT, at least three tests will have to be conducted in the EBSFT. Also, without IEBSFT more test methodologies and types of instruments will have to be used in the EBSFT. One of the three tests will be the long-term test, in which the full-power heating will last for at least 4 years, followed by a controlled cool-down period of at least 1 year and a natural cool-down period. The other two tests will be abbreviated tests with different cool-down durations, in which the heating period will be about 18 months. The two different cool-down scenarios being considered are (1) full-power heating followed by a controlled cool-down and a natural cool-down, and (2) a full-power heating followed by a natural cool-down. These cool-down scenarios will allow investigation of the effect of cool-down duration on the re-wetting process of the dry-out region.

2.3 Constraints and Limitations

Similar to all field tests for nuclear waste management, the EBSFT is constrained by the natural properties of the rock mass, the time available for the testing, and the volume of rock mass to be tested. Scoping calculations are used to design the EBSFT (i.e., test duration) as discussed in this SP. However, the test duration may have to be changed during the test due to the fact that the actual response of the rock mass may be different than what has been predicted by scoping calculations. The change will be documented in Scientific Notebooks. These constraints are described in detail in the following sections.

2.3.1 Natural Properties of the Rock Mass

The EBSFT will test the responses of the rock mass to the thermal and mechanical loads caused by heater assemblages simulating nuclear waste. These responses include changes in temperature, dry-out of a portion of the rock mass, flow of steam, vapor, and liquid water, interaction between the rock and water (including liquid water, vapor, and steam), generation of new cracks, relative movements of the fracture surfaces, etc. The extent and rate of these responses are strongly influenced by the thermal loading conditions, which can be engineered to some extent, and the physical properties of the rock mass, i.e., thermal conductivity, fracture and matrix permeability, initial moisture content, etc., which cannot be significantly changed by engineering. It is not practical to try to change these properties. We plan to monitor the responses of the rock mass to the heating. For certain techniques of measurement, the measured values of the parameters and the time required for the measurement are dictated by natural properties of the rock mass.

2.3.2 Time Constraint

Heating of the rock mass due to the heat generated by the radioactive decay of the nuclear waste is very slow. Hundreds of years are required for the temperature in the rock mass in the vicinity of the waste packages to reach its peak value. In the EBSFT, a highly compressed heating schedule must be adopted. It is not practical to simulate the slow heating of the rock by nuclear waste packages. To circumvent the problem, the EBSFT is designed to generate data of the coupled TMHC processes in the near field. The data will be used to calibrate and validate calibrate and validate model calculations, which will be used to predict the near-field environment of the entire life-span of a repository.

To accurately simulate all aspects of the near-field environment of the waste package in a repository, the heat source in tests of the performance of a repository should be designed to have the same physical dimensions, power loading (power per unit length of waste package), and power decay curves (temporal variation in power output for the waste packages) as the real nuclear waste package. An actual simulation would also include radiation comparable to that of the nuclear wastes to be disposed of. However, not all of these requirements can be met in the EBSFT. A true repository-scaled test would provide data that are most likely to represent the important environmental conditions in the repository, i.e., radiation effects, peak rock temperatures, waste package temperatures, rock thermal gradients, and moisture gradients in the rock mass. The physical dimensions and the power loading chosen for the tests can easily be designed to match those for the emplacement drifts in the repository. For example, Buscheck, et al. (1993) have shown that at least three parallel heater drifts are needed in a test so that the peak temperature in the rock mass can be maintained at about 214°C which does not exceed below the range of temperatures (180-275°C) at which the alpha/beta cristobalite transformations may occur, and while generating a usable dry-out volume in the rock mass (Hill and Roy, 1958; Meike and Glassley, 1990). The volume change associated with the transformations may change fracture porosity in the rock mass; it may change permeability and affect rock-water interaction. They also indicated that for *in situ* heater tests to be applicable to understand repository conditions, a minimum test duration of 6 to 7 years, including 4 years of full power heating, is required. These test durations are very short relative to the heating and cooling of waste packages in a repository. This requirement is an intrinsic limitation of the tests that affects the range of environmental conditions in the near-field rock mass.

Because of safety/handling and licensing issues relative to emplacement of radioactive sources, there are no plans at this time to include radioactive wastes as a heat source in the EBSFT. Under the current plans, the radiation effects on the *in situ* rock properties will not be studied. Durham, et al. (1986) report that radiation has no significant effect on the mechanical properties of granites. Radiation effects will be studied in laboratory experiments as described in the study plan of "Mechanical Attributes of Waste Package Environment" (SP 8.3.4.2.4.3). If these plans change, a revision to this SP will be prepared.

Although field testing cannot cover the entire volume of a repository, it cannot simulate the actual heating, cool-down, and irradiation conditions of a repository either; but it can be designed so that the coupled thermal-mechanical-hydrological-chemical processes are adequately activated and monitored. As stated in Section 1.0, the EBSFT is to provide data for testing and validating models. For that purpose, the dry-out volume of the rock mass should be large enough to include as large a heterogeneous distribution of fracture and matrix properties in every radial direction from the heater as possible so that the test result will be as representative of a repository as possible. Buscheck, et al. (1993) showed that in a test with 21 5.5-kW heaters placed in three parallel drifts, the dry-out zone after 4 years of full-power heating is at least 4.5 m (which includes more than ten fractures) from the boundary of the heater drifts. The model of Buscheck, et al., represents a concept of an extended dry repository. The volume of the dry-out zone in the extended dry concept is likely to be the upper bound for an EBSFT. This model is used in this SP so that the EBSFT can be designed to accommodate all possible testing scenarios. The criteria of determining the volume of the dry-out zone in the EBSFT will be shown in Section 2.6. The information is used as a planning guide only. Additional scoping calculations will be performed to support the final design of the tests. Final test designs will be included in subsequent Activity Plan(s). As mentioned above, the EBSFT is highly compressed in the time scale as compared with the thermal loading rate of a repository. The EBSFT will have a higher thermal loading rate than that in a repository. In order to generate conditions for rock-water interaction to occur, the thermal loading rate should be such that the rate at which moisture is driven through the rock mass does not exceed the rate at which some geochemical processes, i.e., dissolution,precipitation, ion exchange, and aqueous speciation, take place. The rates of these geochemical processes are discussed in the study of "Chemical and Mineralogical Changes in the Post-Emplacement Environment" (Study Plan 8.3.4.2.4.1 and Study Plan 8.3.1.20).

A number of scaling trade-offs can be considered. One alternative is to design a test in which the heat source dimensions and initial power loads are the same as those expected to be in a repository while using the compressed power decay curve. Another option is to use a higher initial power loading for testing in order to heat the rock faster and approach maximum rock temperatures quicker. Still another option, for the case of borehole emplacement, is to vary the physical dimensions of items such as emplacement borehole diameter and adjust initial power loading appropriately. Buscheck and Nitao (1993a) and Buscheck, et al. (1993) have examined these trade-offs using numerical simulations. An equivalent continuum model, using the V-TOUGH code, is used in their scoping calculations. Scoping calculations by Buscheck, et al. (1993) proposed test configurations of heaters emplaced in parallel drifts. Figure 3 shows the dry-out process of a model consists of three parallel heater drifts.

All of these trade-offs have a potentially significant impact on the testing conditions imposed. The scoping calculations have been used to select those which impose near-field conditions that will provide the most appropriate data sets needed for model validation. Some of the scoping calculations are used to develop this SP. The IEBSFT and/or LBT are designed on the basis of the scoping/sensitivity studies. The results of the LBT will be used to verify and improve the scoping model calculations for the IEBSFT and EBSFT. One of the purposes of the initial tests is to confirm that the physical processes accounted for in the models are both accurate and sufficiently inclusive. Therefore, the IEBSFT and/or LBT may not be identical to the EBSFT in terms of scale and other test parameters. The model calculations will then be used in the test design of the EBSFT. The discussion that follows presents some of the scaling trade-offs that have been considered and their potential impacts on the near-field environment. The discussion applies equally to the LBT, IEBSFT, and EBSFT.

The full power loading (kilowatts of power per meter of heater), full power heating duration, and cool-down duration will be designed so that, based on scoping calculations, the test will examine several parameters, which include the velocity of the dry-out front, the size and duration of the condensate refluxing and shedding, the peak rock temperature, the rate of temperature change, and the volume of the dry-out zone. The power loading may be the same as the power per waste package planned for some thermal loading scenarios in a repository. However, power decay curves for the tests will be greatly compressed relative to the heat decay of waste packages. The heating cycle will last on the order of 12 to 18 months for the abbreviated test and at least 4 years for the long-term test, whereas the heating cycle for a waste package in the repository will last on the order of several hundred years. A possible negative consequence of driving the heaters with a power loading equal to that of the waste packages but with a greatly compressed time scale is that the volume of rock dried out around the test drifts or boreholes will be much smaller than that around the repository-emplacement drifts or boreholes. Thus, the effects of fractures and other discontinuities on the test results may be substantially different during testing. Also, maximum rock temperatures are likely to be much lower in the tests than in the repository environment, thereby affecting temperature-dependent processes such as mineral precipitation/dissolution or alteration (particularly of secondary minerals and zeolites). Because these geochemical processes are functions of both time and temperature, it is impossible to properly scale the field experiments. Laboratory tests and analytical modeling will be required to augment the field tests to address the geochemical and petrologic effects. Experiments of rock-water interaction as a function of temperature and fracture aperture will be conducted in the laboratory. The laboratory results will be analyzed by model calculations such as PRECIPand I-D REACT. The LBT will be used to investigate the rock-water interaction in a larger scale with more fractures. The model calculations will be tested and verified using the result from the LBT. The scale effect of power loading will be investigated as part of this augmentation.

2.3.3 Limitations

As mentioned in Section 2.3.2 and 2.6, the EBSFT is designed so that the region of study is big enough to cover as much heterogeneity as possible. However, the volume of the rock mass being studied is still much smaller than that of a real repository. In addition, the heating and cool-down durations of the EBSFT are much shorter than that in a real repository. The time and volume constraints will limit the application of the test results to validation and interpretation of modeling. The test results may not be directly used to represent the performance and functioning of a real-scale repository. However, through model validation and verification, the test results can be used to confirm the performance of a repository.

2.3.4 Interference

There are other studies planned to be conducted in the ESF. These include the *in situ* thermomechanical property test (SP 8.3.1.15.1.6). If those studies are going to be conducted at about the same time as the EBSFT, there should be a stand-off distance between this study and other studies that will have the potential of disturbing the thermal, hydrological, mechanical, and chemical states of the rock mass. The stand-off distance will be determined by scoping calculations and will be included in Activity Plans. The basic requirement is that other studies should not change the ambient states of the rock mass within a region where temperature, moisture content, and mechanical states will be altered by this test.

Measures will be taken to minimize potential interference among measurements in this study. For example, for boreholes that require grouting, such as temperature and neutron logging holes, a two-stage grouting technique will be used to prevent the grout from traveling too far in fractures from the grouted holes. No grout will be used in or near holes where chemical measurement and sampling will be conducted. No grout will be used in or near holes where moisture sensors will be used. In those holes other means of sealing will be used.

2.4 Parameters to be Measured

The following parameters will be measured for each test before, during, and after the thermal cycle is completed in order to characterize the behavior of the rock mass in the near-field of a waste package. The parameters and instruments listed below are tentative selections based on results of scoping calculations and information available to date, and on the G-Tunnel Prototype Test. This selection of parameters and instruments may be modified as results of more detailed scoping calculations and information become available and test planning progresses. More detailed information, as well as a listing, will be included in Activity Plan(s) which are subordinated to this SP. Activity Plans are controlled documents approved by the LLNL-YMP Technical Project Officer and Quality Assurance Manager.

Instruments will be arranged so that these parameters, especially temperature, moisture content, and chemical parameters, can be measured along the vertical axis both below and above the heaters. Instruments should also be located so that a three-dimensional distribution of the parameters can be determined. Data from most of the instruments will be recorded by the Data Acquisition System (DAS). Most of the instruments will be installed in boreholes and the instrument holes will be sealed so that their effect on the measurement will be minimized.

Temperature. Rock mass temperatures are needed to reconstruct the thermomechanical and thermohydrological responses of the rock and to evaluate the performance of the test equipment during the heating and cool-down phases. Temperature will be measured as a function of time and location with respect to the heaters (Lin, et al., 1991). The commercially available J-type thermocouple and RTD are adequate for the temperature measurement. These temperature measuring devices are rated for much greater temperatures(650°C for RTD and 750°C for the thermocouple), therefore the expected temperature range will not cause degradation of them. These thermocouples/RTD will be enclosed in sheaths made of corrosion resistant metals, such as stainless steel and Inconel. It is not expected that they will degrade with time within the time frame of the proposed tests. Tests will be conducted in the LBT to investigate whether thermocouples/RTD can be put in thin-wall tubings. If so, they can be replaced during the test if necessary.

The expected range of temperatures is from ambient to about 250°C. The achievable accuracy of the temperature measurement is about 1 to 2°C.

Moisture Content. Changes in the moisture content and pore pressure are used to reconstruct the flow regime of liquid water in the rock mass. The spatial variations in moisture content will be used to infer the flow paths of the liquid water and to define regions that are losing or gaining water as a function of time.

Several methods will be used to determine the moisture content in the rock mass. These include: (1) determination of relative humidity at point locations using moisture sensors such as a resonant cavity (Latorre, 1989), an electro-optical liquid sensor to determine moisture content, and a Humicap; (2) determination of moisture content along a line using neutron logging; and (3) determination of moisture content distribution in an area using relative electrical resistivity tomography and high-frequency electromagnetic (relative dielectric constant) tomography.

The moisture sensor measures air humidity and/or moisture content at a point; therefore, they will be installed in sections in boreholes that will be packed off by packers. The boreholes will be located at strategic locations to be determined later and will be included in the Activity Plan. Thermal neutron and gamma density techniques measure moisture content and density along boreholes (Ramirez, et al., 1990). Both relative electrical resistivity tomography (Ramirez, et al., 1992) and relative dielectric constant tomography (Daily and Ramirez, 1989) take a snapshot of the distribution of moisture in an area in the rock mass.

The expected range of moisture content in the rock mass is from a few percent of pore volume saturation (in the dry-out zone) to close to 100% pore volume saturation (in the saturation halo). The expected range of relative humidity in the rock mass is from zero to about 100%. The achievable accuracy of the moisture content measurement is about 5% in terms of relative humidity, or about 3% in terms of pore volume saturation level.

Chemical Analysis. Chemical characterization of rock samples and petrologic studies will be performed on the samples obtained before and after the heating cycle is completed. Cores of rock will be collected before and after the test for the study of mineralogical changes. Water samples will be collected from the condensate zone during this test in the field. The laboratory studies on the samples are described in the SCP under the Characterize Chemical and Mineralogical Changes in the Post-Emplacement Environment Study (SCP 8.3.4.2.4.1), and Hydrologic Properties of Waste Package Environment Study (SCP 8.3.4.2.4.2). Both of the laboratory studies of the chemical characteristics and hydrological properties of the rock samples and water samples are covered by separate Study Plans. The purpose of these studies will be to detect possible dissolution or alteration of minerals in the matrix and fractures of rock mass as well as precipitation of dissolved materials as water evaporates/boils and recondenses in the near-field. Other geochemical processes under consideration include ion exchange, aqueous speciation, and change of of silica polymorphs. The information from those laboratory studies will be used in the data analysis of this study.

In addition, optical fibers (if adequately developed by the time of the study) and the microchemical sensors to be used in the LBT will be installed in the rock mass, both in the fractures and matrix, and infrared spectroscopy and Raman spectrometry will be used to (l) determine pH values and the concentrations of certain chemical species (e.g., Si, Na, Cl, Ca, etc.), and (2) monitor geochemical processes (i.e., dissolution, precipitation, ion exchange, and aqueous speciation). Probes will be installed at the proper locations in the rock mass for sampling liquid and vapor during the test. The concentration of chemical elements is expected to be on the order of parts per million. The achievable accuracy of the concentration of dissolved chemical elements will be better than ±10%. The accuracy needed to determine rock-water interaction processes is about 10 to 20%.

Mechanical Properties. Measurements of rock displacements and changes in stress will help determine (l) how fracture apertures change in response to the mechanical behavior of the rock mass, and (2) other geomechanical responses to thermal perturbations, such as thermal fracturing, shear displacement, etc. Measurements of acoustic emissions/microseismic activities will help identify any microfracturing that develops, which will be important in determining the mechanism of permeability changes, if they occur. Some rock samples will be collected for determining mechanical properties in the laboratory. The measurement of the mechanical properties is described in the study of geomechanical attributes (SP 8.3.4.2.4.3).

In situ stress-meters, extensometers, and other geomechanical instruments will be used to determine distributions of stress changes and relative displacement of the rock mass on both sides of fractures. Acoustic emission and/or relevant instrumentation will be used to monitor the generation of new cracks. The expected range of stress change in the rock mass is from a few tenths of a megapascal (MPa) to a few tens of MPa, depending on distance from the heaters and the existence of fractures. The achievable accuracy of the stress change measurement is about 0.1 MPa. The expected range of displacement is from zero to a few millimeters. The achievable accuracy of the displacement measurement in the field is about 0.01 mm.

Air Permeability. Cross-hole air permeability and single borehole injection air permeability will be measured before and after the tests to evaluate the effect of heating on the permeability of the rock mass (Lee and Ueng, 1991). As mentioned previously, the emplacement mode in the EBSFT has not been determined. This SP uses drift emplacement as a reference for discussion. The final emplacement mode will be included in Activity Plan(s). Air permeability measurement is the only test in the EBSFT that depends on the emplacement mode. Therefore, both drift emplacement and borehole emplacement are discussed here. For the scenario of borehole emplacement, the air permeability measurement can be done in the emplacement hole or with other appropriate boreholes. For drift emplacement, new holes will be drilled in the emplacement drift for measuring post-test air permeability. During the air permeability measurement, the air flow will be mainly along fractures. The moisture content in the matrix will not be affected. The air pressure and flow rate will be kept at minimum so that their effect on the moisture content in fractures will be minimized. Related discussion of this subject will be included in Activity Plans. Based on results from the G-Tunnel test the expected range of the *in situ* permeability is from 10^{-18} to 10^{-12} m^2. The achievable accuracy of the permeability measurement is about 50% of the measured values.

Gas Pressure and Atmospheric Pressure. Pressure transducers and barometric transducers will be used to measure the total gas pressure in the rock mass and the atmospheric pressure in the alcove and/or drift. Gas pressure in the rock mass and atmospheric pressure in the alcove or drift are needed to reconstruct the flow regime of the air and water vapor in the rock mass (Lin, 1991a). The expected range of these pressure measurements is from 1 atm to a few tens of atmospheres. The achievable accuracy of these measurements is about 0.1 atm. We will also determine the partial pressure of H_20, O_2, and CO_2 in the near-field as close to the heater as possible. These will be used to assess the oxidation/corrosion potential of waste packages in the near-field environment. The partial pressure of H_2O can be determined by measuring the relative humidity, the total pressure, and temperature sensing devices that can be used at temperatures up to about 130°C.

Heater Wattage. Heater wattage will be monitored to document the thermal loading history of the tests. We expect to energize the heaters with a power up to several kilowatts per heater. The achievable accuracy of the power measurement is about 1%.

Time. Time is needed as a reference for all measurements and will be recorded along with all data. The test may last for several years. Time is kept by the clock in the computer of the DAS. The sampling rate of the DAS will be about one per hour, although time measurements will be maintained to within ±10 min.

Infiltration of Water. As stated in Section 2.1, the infiltration of water into a repository is not as important as the *in situ* vadose water for high AML scenarios, and is of equal importance for low AMLs. However, it is worthwhile to utilize the EBSFT setup to investigate the infiltration process. The infiltration test will be conducted at the end of the abbreviated test. The heaters will be energized again, and infiltration of water during the heating and cool-down phases will be conducted to investigate the effect of thermal load on the flow of water in fractures and the matrix in the dry-out zone. The expected range of moisture content in this measurement is the same as in the moisture content measurement described above. The achievable accuracy is also the same.

Fracture Locations and Orientations. Fractures will be located and mapped on all exposed surfaces in the drifts (both heater emplacement and instrumentation drifts) prior to final selection of instrumentation and emplacement borehole location. The results of the mapping will be used to make the final determination of the location of the test, the location of emplacement and instrument boreholes, and the emplacement locations for surface mounted instrumentation. The location of fractures on exposed surfaces can be determined to within a few millimeters. In addition, fractures will be mapped in instrumentation and heater emplacement boreholes by core analyses, and/or by borehole scope and/or borehole TV surveys. The accuracy of determining the location of fractures in a borehole is about 1 cm. The results of all fracture mapping will be used to determine the specific location for the test and for instrumentation sensors, etc. The results will also be used for comparison with similar fracture mapping that will be performed after completion of the tests. This comparison is needed to understand the effects of heating on the stability of the emplacement drift walls and establish the changes in fracture connectivity caused by the heating and cooling cycle. It will also aid in interpretation of the flow regime of vapor and liquid water in the rock mass and the results of air permeability measurements. The achievable accuracy of the fracture location in rock mass, inferred from surface and borehole fracture mapping, is about 5 cm.

Relative Humidity in the Heater Drifts/Boreholes. Dependent on the bulk permeability, during the heating phase pore pressure gradient may build up such that steam may flow toward the heater drifts or boreholes. The relative humidity in the emplacement drift/hole, which will be closed after the emplacement, will be measured using a resonant cavity. Temperature in the emplacement drift/hole will also be measured. The amount of moisture in the emplacement hole/drift can be calculated from the temperature and relative humidity data.

Analysis of Debris or Dust from Heater Drifts. Debris or dust will be sampled from the heater drifts or boreholes. Catch pans will be mounted at strategic locations in the drifts and boreholes (i.e., under a fracture) to collect the debris. Debris will be analyzed for evidence of microfracturing of the matrix or dehydration of fracture-filling materials. This will allow assessment of the impact on hydrological properties of any microfracturing of rock or dehydration of fracture-filling materials.

Properties of Post-Testing-Phase Rock Samples. Post-testing rock cores will be obtained in strategic locations for evaluating the effect of heating on geochemical processes and mechanical and hydrological properties. The rock samples will be tested in the laboratory. Geochemical properties testing will be covered in the Study Plan entitled, "Characterize Chemical and Mineralogical Changes in the Post-Emplacement Environment" (SP 8.3.4.2.4.1). Determination of mechanical properties will be covered by the Study Plan entitled "Geomechanical Attributes of Near-Field Environment" (SP 8.3.4.2.4.3). Determination of hydrological properties will be covered by a Study Plan of "Hydrological Properties of Near-Field Environment" (SP 8.3.4.2.4.2).

Geochemical/Petrographic Properties of Post-Testing-Phase Grout Samples. Post testing phase grout samples will be obtained by overcoring the grouted boreholes. These samples will be used for geochemical/petrographic analyses to evaluate the impact of grout on geochemical processes.

Corrosion of Waste Container Materials. Corrosion of the candidate materials for waste containers will be tested. Either the heater canisters will be made of the candidate materials or coupons of the candidate materials will be placed near the heater. These materials will be examined after the test for evidence and mechanism of degradation and oxidation.

Self-Potential Measurement. Electrical current in the ground may flow through the metallic waste canisters and affect their corrosion-resisting capability. The current can be natural and/or man-made. The natural electrical current is generated by self-potential that may be caused by hydrothermal and mineralogical in rock. These conditions include thermal gradient, fluid flow, and clay minerals. An effort will be made to determine the self-potential in the near field.

2.5 Activities

Work performed in support of the IEBSFT and EBSFT has been divided into the following activities for quality assurance grading. These activities will be further discussed in one or more Activity Plans.

Activity Number	Description
EB-01	Sampling and Sample Analyses

Collect and analyze material samples (rock, gas, and water). This activity includes sampling activities before, during, and after heating of the rock. The material samples will be analyzed in the laboratory. Hydrologic properties of the rock samples will be determined. Chemical analyses will be performed on the gas and water samples to determine pH, Cl^-, Na^+, Si^{+4}, etc. The laboratory determinations of hydrological properties of rock samples will be controlled by a study plan entitled "Hydrological Properties of the Near-Field Environment" (SP 8.3.4.2.4.2). The laboratory analysis of gas and water samples will be covered by a study plan entitled "Characterization of Chemical and Mineralogical Changes in the Post-Emplacement Environment (SP 8.3.4.2.4.1). Sufficient rock samples will be collected to represent all heterogeneous rock properties within the test region. Detailed sampling procedures will be included in Activity Plan. The actual sampling techniques and procedures will be determined by the Principal Investigator (PI) based on field situations.

EB-02 — *In Situ* Testing

This main test activity includes:

1) Planning: develop detailed work planning documents for the EBSFT when applicable (e.g., activity plans, technical implementing procedures, and criteria letters). The documents include specific scientific control documents for portions of the work performed under activities described below. The activity also includes revising procedures developed for the LBT.

2) Component and Technique Developments: This sub-activity includes checkout and debugging of techniques and hardware. It also includes the performance of comparative evaluations of candidate test components methods, the procurement of equipment for these evaluations, purchasing or manufacturing of test components, and calibration and installation of test components.

3) *In Situ* Testing:

Conduct test, record and archive data. These data include all measurements and test controls performed before, during, and after heating of the rock mass.

EB-03 Pre- and Post-Test Calculations

V-TOUGH is used to perform equivalent continuum model calculations in suport of (1) design of the test, and (2) development of planning documents, such as this SP and Activity Plans(s). This activity includes the verification and validation (V&V) process necessary to qualify the numerical metods to be used if such V&V has not been accomplished in the LBT. The V&V process requires that the temperature and moisture distributions in the test region be compared with those predicted by the model calculations. The model will be adjusted according to the test result. The model will then be used in the post-test model calculation for reducing and analyzing test data and reporting test results. Thermal-hydrological codes (such as V-TOUGH, and NUFT), chemical codes (i.e., EQ3/6, PRECIP, I-D REACT, and BASIN II), and thermal-mechanical codes (i.e., FLAC), will be used to analyze the coupled TMHC process.

2.6 Description of Activities

This section provides a general description of the IEBSFT and EBSFT and other activities. Specific details will be provided in Activity Plan(s) that will be prepared and approved prior to performing the designated quality-affecting activities and that meet the requirements of the various LLNL-YMP Quality Assurance (QA) procedures that govern control of scientific investigations. Two types of tests will be conducted in the EBSFT: abbreviated tests and a long-term test. Both tests have the same general procedures (i.e., drift arrangement and layout), calibration and installation of instruments, parameters to be monitored, etc. The abbreviated tests will be used to study the movement of moisture in both the heating and cool-down phases before the license application, whereas the long-term test will achieve a proper dry-out volume of the rock mass and ensure that the dry-out rate is not greater than the rate of geochemical processes (i.e., dissolution, precipitation, ion exchange, and aqueous speciation). The main difference between the two tests is the duration of the heating and cooldown phases. Specific details of both types of tests will be discussed in Activity Plans.

The volume of the dry-out zone in a test should be big enough to cover enough inhomogeneities (e.g., fractures) so that it is more representative to the repository condition. Wilder (1993) indicates that the dry-out zone should include at least 100 fractures so that it will have at least ten fractures to serve as pathways for fluid flow. The test location will be determined when the ESF is constructed. It will be chosen to be typical of the potential repository horizon.

2.6.1 In Situ Test Arrangement and Layout

The Engineered Barrier System (EBS) design and emplacement configuration are not fully determined at this time. The details of any EBSFTs will depend on the EBS design because the interactions between the environment and the EBS must be considered. Therefore, this Study Plan emphasizes the principles of the testing and important general considerations. Further configuration details, including the test location, will be provided in subsequent Activity Plan(s) after the design has matured. Figure 1 shows one possible general configuration of the emplacement drift, instrumentation drifts, and instrumentation boreholes for the abbreviated test of the drift emplacement scenario. The drift emplacement scenario is used as an example for discussion only; other configurations would be similar in test design, i.e., drifts and instrumentation, but may vary in terms of details of access and numbers of drifts. A detailed test design will be included in the Activity Plan.

As mentioned, the discussed layout is merely an example of the type of test configuration being considered. The specific layout of test(s) will be discussed in implementing documents (Activity Plans) that will be developed based on more complete information than is currently available. Where a layout needs to be discussed, the reference design of drift emplacement will be referenced but changes to this design may be made in subsequent Activity Plan(s). For convenience, emplacement drifts are referred to here without noting that vertical borehole emplacement is an option. In general, resistance heaters will be installed in drifts or boreholes in the devitrified densely- welded nonlithophysal Topopah Spring tuff (TSw2) along the North Ramp or in the Main Test Level of the ESF. The test region will be chosen to be as representative of the potential repository as possible. And the test is designed so that enough inhomogeneities will be included in the test region, therefore, the test results will be representative of the response of the potential repository.

Instrumentation boreholes will be drilled vertically (from both above and below) and horizontally into the emplacement drifts to provide three-dimensional access for measurements. Rock cores will be collected from some of the boreholes for hydrological and geochemical analyses (Activity EB-01). The instrumentation boreholes will be drilled dry so that the change in the initial moisture content in the rock mass due to the drilling will be minimized. Due to the low permeability of the mass of Topopah Spring Tuff (Lin and Daily, 1984), dry-drilling may not affect the ambient moisture content of the rock mass except in the region adjacent to the borehole wall. Dry-drilling is used in the surface-based testing for determining the ambient moisture content of Yucca Mountain (SP 8.3.1.2.4.4).

2.6.2 In Situ Test Sequence

Location of test-specific heater (emplacement) drifts and instrumentation boreholes or test layouts will be determined on the basis of mapping and fracture descriptions and orientations noted in the test area. Prior to installation of the heaters and instruments, heater (emplacement) drifts and instrumentation boreholes will be inspected to map the locations and orientations of fractures. In addition, air permeability will be measured in some of the instrumentation boreholes. Rock and vadose water samples will be collected for laboratory analysis. Following installation and checkout of instruments, all boreholes and emplacement drifts will be sealed, either by grout or packers, so that their effect on fluid flow during the test is minimized. In the geochemical holes, where chemical processes will be monitored, no grout will be used to seal the holes. Science Engineering Associates Membrane Insitu Sampling Technology (SEAMIST) system will be used to seal those holes and to mount monitoring sensors. The effect of the grout on the geochemical processes will be evaluated based on the results of lab tests, the LBT, and IEBSFT. These results will be used to guide the design of the EBSFT. Then, preheat measurements will be made to establish the baseline conditions for all parameters to be monitored.

The rock mass will be heated using electrical heaters in the heater drifts. Details of how the power will be applied will be included in Activity Plan(s), but there will likely be a constant power level followed by a controlled cool-down with a gradual power reduction, and a natural cool-down when the heater power is turned off.

During the heating phase, temperature and moisture content will be monitored to track moisture movement into and away from the heater drifts and into the cooler rock mass. During the cool-down phase, moisture movement back into the dried-out regions will be monitored. In addition, geomechanical and geochemical monitoring will be done during the heating and cool-down phases. During the heating and cool-down phases, water and gas samples will be collected for analysis in the laboratory.

Following the test, the instruments not grouted in place in boreholes will be removed for inspection, evaluation, and recalibration, although a limited number of instruments will be recovered from grouted boreholes by overcoring. Selected boreholes will be reinspected for changes in fracture pattern and permeability. Heater canisters and coupons of candidate waste package material will be examined for evidence of moisture condensation, corrosion, or other deleterious effects.

At the conclusion of the test, rock and vadose water samples will be taken and analyzed for changes. Additional rock samples may be available from the overcoring operation that is used to remove instruments sealed or grouted in place prior to the test.

2.6.3 Sampling and Sample Analyses

This activity obtains samples for use in other near-field studies. Samples will be obtained using Project Level Procedures (consolidated sampling) or procedures developed for this study.

2.6.4 Pre- and Post-Test Calculations

In some cases, in situ test results will be used to validate coupled process models which will then be used to predict repository performance. In addition, the models will be used to design the tests such that the coupled processes are expected to be manifested. Pre-test calculations will be produced prior to testing, for later comparison with test results.

2.7 Interfaces

Construction of the test area, including mining of the drifts and drilling of boreholes will be performed by Reynolds Electrical and Engineering Company (REECO), or any contractor identified by YMP, through the Test Coordination Office (TCO). Raytheon Services Nevada (RSN) will provide engineering support of the field activities. The test will be performed within the Exploratory Study Facility (ESF), therefore all supporting facilities (i.e., communication, power, health and safety support, etc.) will be provided by ESF. A stand-off distance will be determined and included in the Activity Plan so that the thermal disturbance on the rock caused by this test will not affect other testing activities in the ESF, and vice versa.

3.0 Application of Results

The results from this study support EBS design, repository design, site suitability determination, and performance assessment (PA). The data from the EBSFT will be used by EBS near-field subsystem PA modeling to support EBS design and repository design, and to provide source terms for the total system PA. On the basis of the analysis of the data from this study, models will be constructed that describe the coupled thermal, hydrological, chemical, and mechanical behavior of the geologic environment. The spatial and temporal distributions of temperature and moisture content obtained from this study will be used to verify and validate the thermal hydrological models that are being developed in the task of determining the hydrological properties in the near-field environment, which is controlled by Study Plan 8.3.4.2.4.2, "Hydrological Properties of the Waste Package Environment." The thermal hydrological modeling will be described in that Study Plan. The rock-water interaction results from this study will be used to verify and validate thermal-chemical models developed under the Study Plan entitled, "Characterization of Chemical and Mineralogical Changes in the Post-Emplacement Environment," (SP 8.3.4.2.4.1). The results of mechanical responses of the rock mass to heating will be used to validate thermal mechanical models to be developed under Study Plan 8.3.4.2.4.3 "Mechanical Attributes of Waste Package Environment."

The data will be compiled, reduced, and provided throughout the course of the test to the investigators responsible for developing the near-field hydrological and geochemical models. These results will be incorporated with integrated testing to develop a flow and transport mechanistic model, which is covered under SP 8.3.4.2.4.2. The model results will be used as EBS design input. The model itself will be incorporated into the PA suite of models. PA results, in turn, support site suitability determination.

Information to be developed during the course of this test includes:

- Data from the various instrument readout systems and characterization of the test regions (i.e., V-TOUGH, NUFT, EQ3/6, PRECIP, BASIN II, I-D REACT, and FLAC).
- Testing, verification, and validation of models that describe hydrological/geochemical/geomechanical and thermal evolution of the rock mass system near a heater emplacement drift/borehole.
- Testing and validating of models for geomechanical response (model development to be performed under SCP 8.3.4.2.4.3).
- Analysis of rock samples for rock hydrological properties (to be performed under SCP 8.3.4.2.4.2).
- Rock/water samples for geochemical analysis (to be performed under SCP 8.3.4.2.4.1).
- Rock/water/grout samples for geochemical analyses of impact of man-made materials (analyses to be performed under SCP 8.3.4.2.4.5).
- Testing and validating of models for metallurgical performance of various candidate waste package materials (to be performed in SCP 8.3.4.5.9).
- Evaluation of equipment and instrument performance.

The hydrologic environment expected to develop around a heater during thermal loading is as follows: With time, the heat will dry the originally partially-saturated rock near the emplacement drifts. The water vapor formed will be driven by vapor pressure gradients through the matrix until it intersects a fracture; it will then move down-gradient along the fracture, as noted in laboratory work performed by Daily, et al. (1987) and in the field by Daily and Ramirez (1989). The water vapor will condense where the temperatures are sufficiently low. Part of this water might move into the matrix because of capillary suction; the remainder might stay in the fracture held by capillary forces or flow along the fracture down-gradient. The percentage of water that moves into the matrix will depend on the degree of saturation of the matrix, the matrix hydraulic conductivity, and the contact time between the water in the fracture and matrix. Because of the influence of gravity, it is expected that the region below the heater will dry out more quickly and the dry-out zone will extend farther away from the heater than in the regions above and to the sides of the heaters. When the dried region is allowed to cool, it is expected to re-wet slowly because of the pore pressure and saturation gradients that develop in the rock around the heater. A faster re-wetting rate in regions above and to the sides of the heater than below the heater is expected to be observed. The re-wetting near fractures is expected to be faster than in unfractured regions (Ramirez, et al., 1990).

Physical examination of the boreholes, permeability measurements in the boreholes, and results of the geomechanical measurements will provide values of the rock fracture and porosity parameters for the heat and mass transport models. Analyses of rock samples and geochemical measurements will provide information on chemical, mineralogical, porosity, and moisture content at various distances from the emplacement drifts that have a history of thermal, hydrological, geochemical, and mechanical disturbances. They can also shed light on the fracture healing that has been observed in the laboratory (Daily, et al., 1987; Lin, 1991b).

The above information, in conjunction with laboratory studies of (1) dissolution/precipitation kinetics, rock/water interaction, and fluid composition, and (2) mechanical fracture properties, will provide input to the characterization of factors affecting the hydrologic properties of tuff under anticipated repository conditions.

Evaluation of equipment and instrument performance for future use in the ESF will consist of two considerations: (1) reliability/operability/ maintainability under the test environmental conditions, and (2) agreement among those instruments measuring moisture content and migration, e.g., electrical resistivity tomography, high-frequency electromagnetic tomography, neutron probes, and moisture-measuring devices.

The time and volume constraints mentioned in Section 2.3 will limit the application of the test results to the validation and interpretation of model studies. The test results may not be directly used to represent the performance and functioning of a full-scale repository. However, through model verification and validation, the test results will have potential application as the performance confirmation of a repository.

4.0 Schedule and Milestones

The discussion of the schedule and milestones of this study uses the time when the test region is available as a reference. The time when the test region is available will be designated as the beginning of the test. A test region is considered available when the heater drifts (or boreholes) and all instrumentation drifts and boreholes are mined and drilled. Procurement and calibration of instruments should be completed before the test region is available. Figure 4 shows the schedule of the events of the study. As mentioned in Section 2.3.2, abbreviated tests will be conducted with various cool-down durations. In this SP only one cool-down duration of the abbreviated test is discussed as an example. Other cool-down durations being considered include eliminating the controlled cool-down (i.e., turn the heater off at the end of the heating phase) and extending the natural cool-down duration to 18 months, keeping the same controlled cool-down duration as shown below but extending the natural cool-down duration to indefinite, etc. The schedule of the study is described below. This testing schedule is for planning purposes only; it will be finalized in Activity Plan(s).

Fracture Mapping and Pre-Test Air Permeability Measurements. Mapping of the fractures in the boreholes and drifts and the measurement of pretest air permeability will be completed within 2 months after beginning the test. Completing the fracture mapping and the air permeability measurements will be a milestone.

Installation of Instruments. The installation of instruments in the boreholes and drifts will be completed 6 months after the fracture mappings, i.e., 8 months after beginning the test. Completion of installing the instruments will be a milestone.

Background Data Acquisition. Acquisition of the background conditions before heating will last for about 1 month.

Heating Begins. The heaters will be energized after the acquisition of the background data is completed, i.e., 9 months after beginning the test. Starting the heating will be a milestone.

Heating Duration. The heating duration is expected to be 18 months for the abbreviated tests, and 48 months for the long-term tests. These times may be changed in Activity Plans.

Controlled Cool-Down Begins. The controlled cool-down will be started at the end of the heating phase. For the abbreviated tests, the controlled cool-down will be started 27 months after the beginning of the test. For the long-term tests, it will be started 57 months after the beginning of the test. A decision for starting the controlled cool-down phase will be made, based on information that enough data have been obtained for thermal-hydrological processes (SP 8.3.4.2.4.2), chemical processes (SP 8.3.4.2.4.1), and mechanical processes (SP 8.3.4.2.4.3).

Controlled Cool-Down Duration. The controlled cool-down duration is 6 months for the abbreviated tests, and 12 months for the long-term tests.

Natural Cool-Down Begins. The natural cool-down phase for the abbreviated tests will be started 33 months after beginning the test. For the long-term tests, the natural cool-down phase will start 69 months after beginning the test. A decision will be made to start the natural cool-down phase based on input from SP 8.3.4.2.4.2.

Natural Cool-Down Duration. When the temperature in the rock mass decreases to within 5°C above the ambient temperature, the test region is considered cooled. The time required for that to occur depends on the peak temperature and the volume of the heated rock mass. It may take 12 months for both the abbreviated test and the long-term test.

Post-Test Air Permeability Measurements. Post-test air permeability measurements for the borehole emplacement scenario will be started after the heaters are removed from the heater holes. For the abbreviated test, the post-test air permeability measurement in the emplacement borehole will be started about 45 months after the beginning of the test. It will be about 81 months after the beginning of the long-term test before the post-test air permeability measurement in the emplacement borehole can be started. For the drift emplacement scenario, boreholes will have to be drilled in the heater drift for cross-borehole air permeability measurements. It may take 4 months to dry-drill boreholes for air permeability measurements. Therefore, for the abbreviated tests with drift emplacement, the post-test air permeability measurement may start about 49 months after beginning the test. For the long-term test it will be 85 months. The post-test air permeability measurements themselves will last for about 1 month. Completing the post-test air permeability measurement will be a milestone.

Post-Test Overcoring. The post-test overcoring for obtaining rock and grout samples for geochemical analyses will start after the post-test air permeability measurements. In other words, the overcoring will start about 46 months after the beginning of the test for the abbreviated test with borehole emplacement, 82 months for the long-term tests with borehole emplacement, 50 months for the abbreviated tests with drift emplacement, and 86 months for the long-term tests with drift emplacement. The post-test overcoring takes about 3 months. A decision will be made to determine the location of the over-coring, based on input from SP 8.3.4.2.4.1 and SP 8.3.4.2.4.3.

Analysis of Post-Test Cores. Evaluation and analyses of the post-test cores will take about 3 months. They will be completed in about 52 months after the beginning of the test for the abbreviated test with borehole emplacement, 88 months for the long-term test with borehole emplacement, 56 months for the abbreviated test with drift emplacement, and 92 months for the long-term test with drift emplacement.

Post-Test Data Analysis. Reduction and analysis of the data will be started soon after the completion of the baseline measurements and continued throughout the data collection period. Comparative analysis of the various parameters measured is also performed during this period. The post-test data analysis will take about 4 months after the test is completed.

Report of the Test. The final report of the tests will be completed about 6 months after the reduction of data. Submitting a report of the test will be a milestone.

4.1 Relationship with Other Activities

The EBSFT receives input from scoping thermal-hydrological model calculations (SCP 8.3.4.2.4.2), study of chemical and mineralogical changes in the post-emplacement environment (SCP 8.3.4.2.4.1), and near-field geomechanical attributes (SCP 8.3.4.2.4.3) as guides to the test design. The Principle Investigators of these studies are co-investigators on this study; they will receive results throughout the study and as indicated in Section 4.0. The results of EBSFT will be used by these studies to validate their model calculations. The validated models will be used to predict the hydrological and geochemical properties in the near-field environment. The near-field environment information will be used to assess the issues described in Section 1.1. Input from the studies listed above will be used to make decisions as shown in Figure 4.

5.0 Acknowledgments

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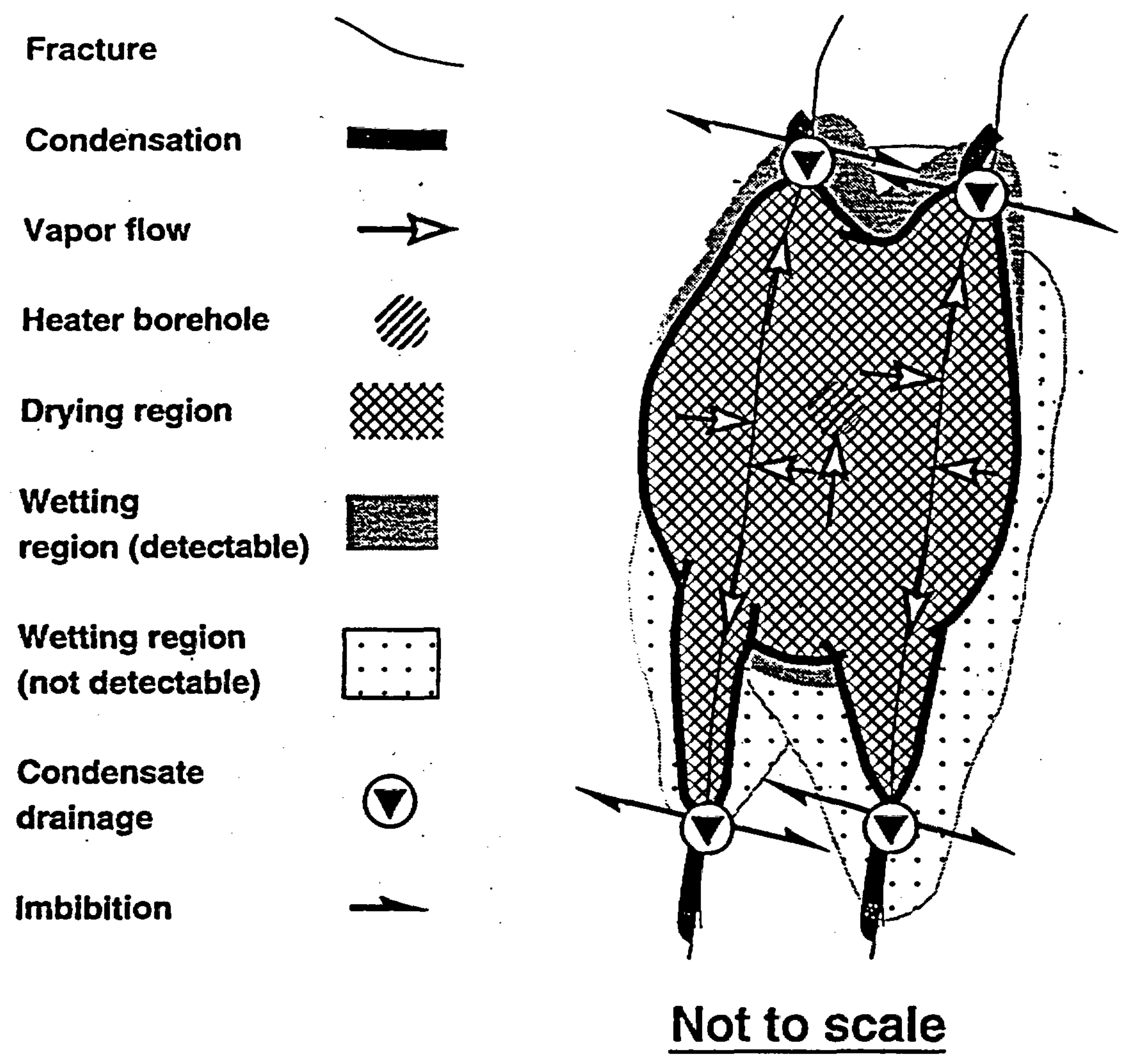


Figure 1. Conceptual model proposed for the flow above and below the heater for the case of a fracture striking parallel to the heater axis. A transect along a matrix block intersected by a fracture is shown. (Ramirez, 1991)

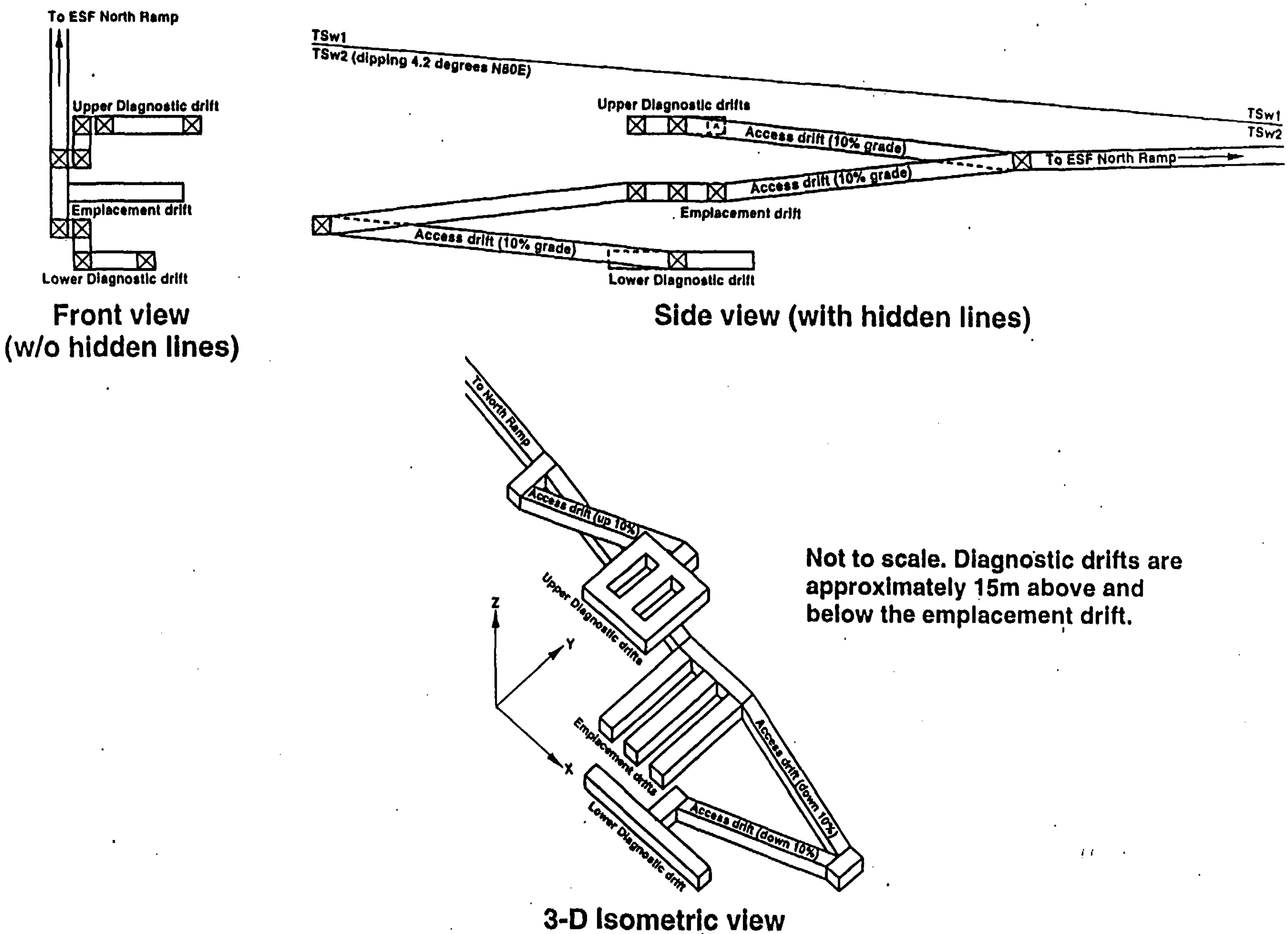


Figure 2. A conceptual layout for *In Situ* thermal testing.

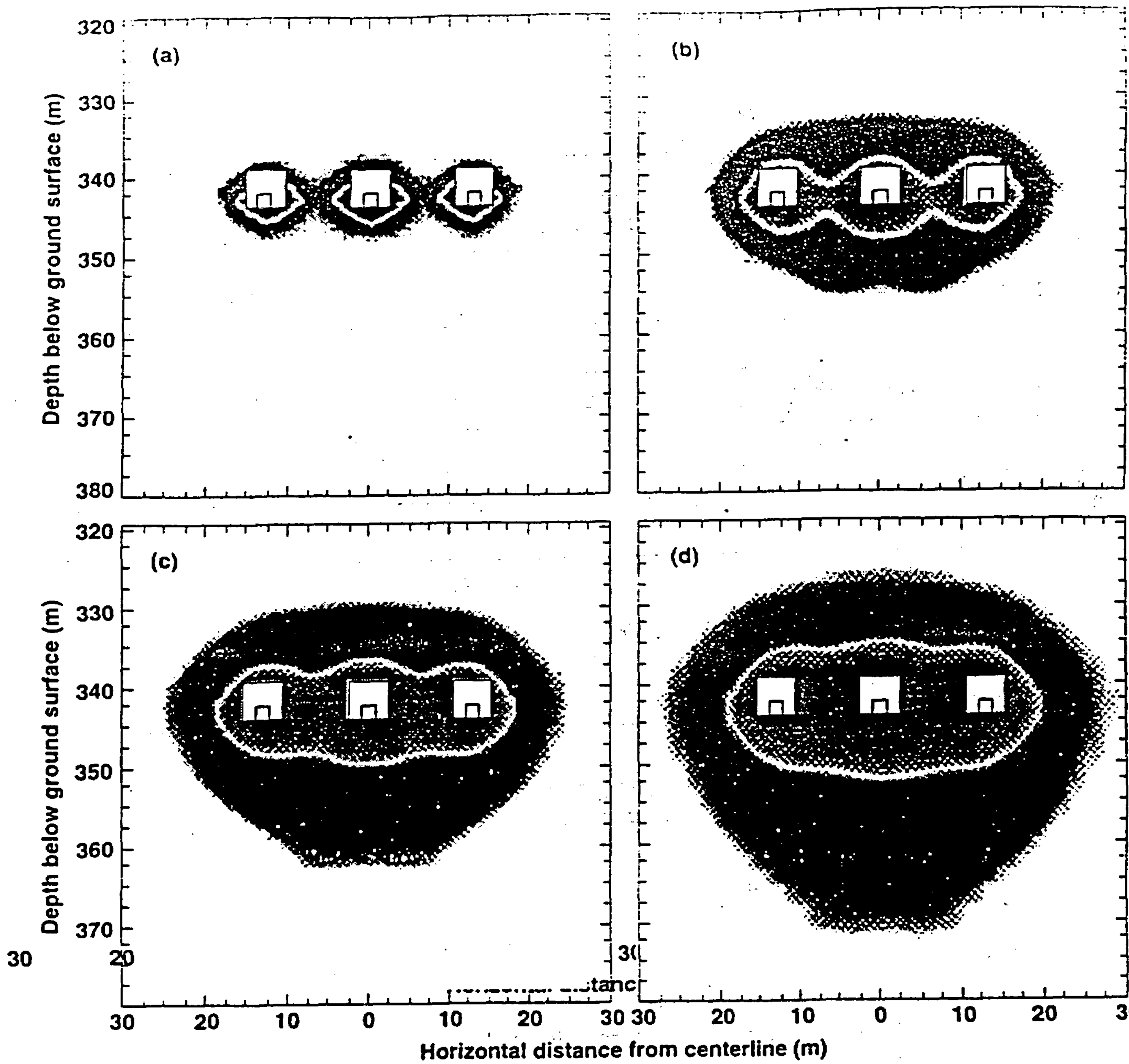
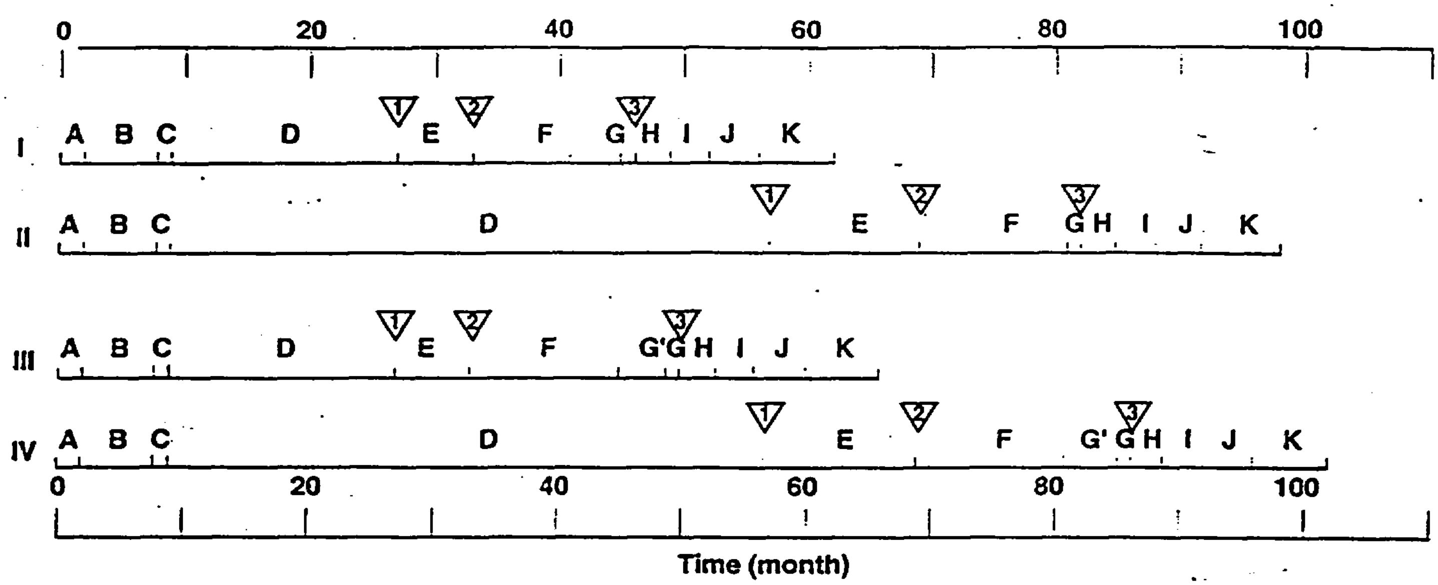


Figure 3. Dimensionless liquid saturation distribution orthogonal to an array of three infinitely-long, parallel heater drifts, each generating 1.0 kW/m of drift, at t = (a) 1, (b) 2, (c) 3, and (d) t = 4 years. Medium shaded areas next to the heater drifts correspond to regions that are drier than ambient liquid saturation (dry-out zones). Dark shaded areas correspond to regions that are wetter than ambient liquid saturation (condensation zones). No shading indicates no change in liquid saturation. (Buscheck, et al, 1993)



A. Fracture Mapping and Pre-test Air Permeability Measurement
B. Installation of Instruments
C. Background Data Acquisition
D. Heating
E. Controlled Cool-down
F. Natural Cool-down
G'. Drilling for Post-test Air Permeability Measurement
G. Post-test Air Permeability Measurement
H. Over-coring
I. Post-test Core Analysis
J. Post-test Data Analysis
K. Reporting

Decision Points

(1) : To decide on starting the cool-down phase
(2) : To decide on starting the natural cool-down phase
(3) : To decide where to conduct the over-coring

Figure 4. Events and schedules of EBSFT for scenarios: I. Abbreviated test in borehole emplacement; II. Long-term test in borehole emplacement; III. Abbreviated test in drift emplacement, with one cool-down schedule; and IV. Long-term test in drift emplacement.

M&O/LLNL-SP-8.3.4.2.4.4, R0

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