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**Technical Basis and Programmatic Requirements
For
Engineered Barrier System Field Tests**

Wunan Lin

November 1992

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Technical Basis and Programmatic Requirements

For

Engineered Barrier System Field Tests

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1.0 Purpose

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 1.2.2.2.4. This study is described in Section 8.3.4.2.4.4.1 of the Site Characterization Plan (SCP). 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.

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). In a deep nuclear waste repository, water is the main medium by which radioactive nuclides travel to the accessible environment. Therefore, the movement of water over the approximate 10,000-year lifetime required for radioactive nuclide decay must be understood.

Development of a repository and emplacement of nuclear wastes impose stress loadings on the repository rock mass. The stress loadings include (1) thermal energy and irradiation from the waste packages, and (2) mechanical stress due to the mining of openings, such as drifts, alcoves, and boreholes, etc., and the transporting of waste canisters. The influence of the thermal stress may extend to all lithological units, including the saturated zone under the ground water table, in Yucca Mountain. In general, the purpose of this study is to investigate the movement of water in the rock mass under the influence of the thermal loading of the waste packages. Specifically, the study will investigate heat flow mechanism, relationship between boiling and dry-out, and the re-wetting of the dry-out region when the repository is cool-down.

Heater assemblies will be installed in drift or borehole openings and energized to heat the surrounding rock mass. Spatial

distribution of the moisture content in the rock mass and its temporal variation will be measured during heat-up and subsequent cool-down of the rock mass. In some tests, infiltration of water into the heated rock mass will be studied. Throughout the heating and cool-down cycle, instruments installed in the rock will monitor such parameters as temperature, moisture content, concentration of some chemical species, and stress and strain. Rock permeability measurements, rock and fluid (water and gas) sampling, and fracture pattern measurements will also be performed before and after the test.

2.0 Rationale for the Selected Studies

2.1 Information Needs

The SCP is divided into 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, such as 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. is itself composed of several investigations, including the EBSFT described here. In addition, information from the EBSFT will provide input to other INs shown in Table 1.

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

The EBSFT will provide site-specific data on near-field hydrologic, thermal, and chemical phenomena during a complete, accelerated thermal cycle in the rock mass. Movement of water and steam in pores and fractures in the near-field is of primary interest, while thermal and mechanical properties are also of interest because of their roles in driving or influencing water movement. Geochemical processes will also receive attention because of (1) their potential influence on hydrologic behavior, and (2) possible effects on components of the engineered barrier system. The objectives of the EBSFT with regard to geochemical characteristics are to validate, to the extent practical, the results of laboratory studies that characterize geochemical interactions, and to reveal any in situ synergistic effects that were not identified during laboratory testing. These laboratory studies are described in the Study Plan (SP) for the Characterization of Chemical and Mineralogical Changes in the Post Emplacement Environment Study (SCP 8.3.4.2.4.1), WBS 1.2.2.2.1.

Table 1.

<u>IN or Investigation</u>	<u>Subject</u>
1.4.2	Material properties of the containment barrier (Section 8.3.5.9.2)
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

Configuration of the underground
facility (Section 8.3.2.2)

1.12.2

Seal materials (Section 8.3.3.2.2)

2.2 Applicable Regulations

The primary objective of the EBSFT is to provide in situ information on the environmental 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. 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, hybridizing, gas generation, thermal effects, mechanical strength, mechanical stress, radiolysis, radiation damage, radioactive nuclide retardation, leaching, fire and explosion hazards, thermal loads, and synergistic interactions.

2.3 Constraints

The EBSFT is constrained by the natural properties of the rock mass and the time limit imposed by the License Application schedule of the Yucca Mountain Site Characterization Project (YMP). 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 loadings caused by heater assemblages simulating nuclear

wastes. These responses include changes in temperature, boiling of in situ water, 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, such as thermal conductivity, fracture and matrix permeability, initial moisture content, in situ stress, etc, which can not 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. The measured values of the parameters are constrained by the rock mass. Without prototype testing, the selection of instruments and the location of instrumentation may not be appropriate, and unexpected situations may occur.

2.3.2 Time Constraint

Heating of the rock mass due to the heat generated by the radioactive decay of the nuclear wastes 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. In addition, the license application schedule of YMP requires that the EBSFT duration be further reduced.

In order to provide sufficient information for the license application, we have designed testing procedures that include an abbreviated and a long-term initial EBSFT (IEBSFT) and an abbreviated and a long-term EBSFT. In the IEBSFT, which was planned to be conducted outside of the potential repository horizon in Yucca Mountain so that it can be started earlier (Therefore, the result from the IEBSFT may not be qualified for license application.), the abbreviated test will be used to study the responses of the rock mass in a complete heating and cool-down cycle, while the long-term test will be of sufficient duration to dry out a volume of the rock mass that is big enough for the data obtained to be more representative of the potential repository. The results of the IEBSFT will be used to (1) design the abbreviated EBSFT, and (2) validate part of

the results of the long-term EBSFT, which will be just in part of the heating phase before the license application schedule. The long term EBSFT will continue beyond the license application as performance confirmation test, and will have complete heating and cool-down phases. Without the IEBSFT we have to conduct at least 3 tests at the ESF. One of the tests will be the long-term test; the rest will be the abbreviated tests with different cool-down durations. The various cool-down durations will allow us to investigate the re-wetting process in the dry-out region.

To accurately simulate all aspects of the near-field environment of the waste package, the EBSFTs should be designed to have the same physical dimensions, power loading (power per unit length of waste package), and power decay curves (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. A true repository-scaled test would provide data that are most likely to represent the important environmental conditions in the repository, such as radiation effects, peak rock temperatures, waste package temperatures, rock thermal gradients, and rock moisture gradients. 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 below the cristobalite-quartz transformation temperature while a usable dry-out volume in the rock mass is generated. They also indicated that for in situ heater tests to be applicable to actual repository conditions, a minimum test duration of 6-7 years, including 4 years of full power heating, is required. However, the power decay curves for the EBSFT will have to be highly compressed in time relative to the decay curve of the waste package. 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 EBSFT. Under the current plans, the radiation

effect on the in situ rock properties cannot be studied. If these plans change, a revision to this SP will be prepared.

While field testing cannot simulate the actual heating, cool-down, and irradiation conditions of a repository, it can be designed so that the most important coupling processes are adequately activated and monitored. For that purpose, the dry-out volume of the rock mass should be large enough to include as many heterogeneous distribution of fracture and matrix properties in every radial direction from the heater as possible. Buscheck et al (1993) showed that in a test with 21 5.5 kW heaters placed in 3 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. And 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 geochemical processes take place.

A number of scaling trade-offs can be considered. One alternative is to design a test with the same dimensions and initial power loads as those of the 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 (1993) and Buscheck et al (1993) have examined these trade-offs using numerical simulations. Buscheck et al (1993) have proposed test configurations of heaters emplaced in multiple parallel drifts.

All of these trade-offs have a potentially significant impact on the testing conditions imposed. Scoping calculations will be used to investigate tradeoffs and to select those which impose near-field conditions that will provide the most appropriate data sets needed for model validation. The IEBSFT will be designed on the basis of the scoping/sensitivity studies; however, 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 may not be identical to the EBSFT in terms of scale and other test parameters. 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 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 meet some criteria, which include the velocity of 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 loading planned for the waste packages in the repository. However, power decay curves for the tests will be greatly compressed. 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, and laboratory and analytical modeling will be required to augment the field tests to address the geochemical and petrologic effects. The scale effect of power loading will be investigated in this test.

3.0 Description of the Study

3.1 Background

The potential Yucca Mountain repository horizon is in a devitrified, partially saturated, nonlithophysal densely welded tuff. 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 will increase the near-field temperatures and create a region of hot, dry rock around the emplacement drifts or boreholes. Rapid evaporation or possible boiling of the vadose water will occur where the temperatures are sufficiently high. A buildup of pore gas pressure is expected to develop in unfractured rock mass. Steam and vapor are expected to flow within the fractures and unfractured rock in response to the gas pressure gradients that develop. On the basis of laboratory studies of the dehydration process (Daily et al., 1987), vapor and/or steam will leave fractures first, and then the moisture in the matrix will flow into the fractures. A dry-out region will be developed around fractures, and it will gradually extend into the matrix. A region of increased saturation is expected to form adjacent to and outside of 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. Since the power output of the 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.

Buscheck and Nitao (1993) find 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 that entirely avoid boiling of the pore water, repository-heat-driven buoyancy flow is found to dominate fluid flow in both unsaturated and saturated zone. 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 that liquid-phase flux associated with vapor flow and condensate drainage during the boiling period as well as re-wetting of the dry-out zone during the post-boiling period is much greater than the net recharge flux associated with pluvial climatic conditions. Therefore, the most important consideration 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 impact of water that has yet to infiltrate at Yucca Mountain is of secondary importance for high AMLs, and is, at best, of equal importance for low AMLs.

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 last paragraph.

The design of the EBSFT will focus on determining the distribution of moisture in the near-field environment, 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 addresses both the loading (or heating) and the unloading (or cool-down) phases of the thermal cycle. In the EBSFT, we will also monitor (1) the mechanical response of the rock mass to thermal loading and unloading, and (2) geochemical processes during the entire duration of the test.

The QA level III tests 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. A buildup of pore gas pressure develops in rock regions where vigorous evaporation is occurring. The air permeability of the fracture system exhibits a strong heterogeneity.

The G-Tunnel test reports 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 not the same as below, and (2) water can be shed radially away from the dry-out zone.

3.1.1 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 listed below are tentative selections based on results of scoping calculations available to date and on the G-Tunnel Prototype Test. This selection of parameters may be modified as results of more detailed scoping calculations become available and test planning progresses. More detailed information as well as a listing will be available in implementing procedures.

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).

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 by thermocouples as a function of location with respect to the heaters and time (Lin et al., 1991). The commercially available J-type thermocouple is adequate for the temperature measurement. The expected range of temperatures is from ambient to about 350°C. The tolerance of the temperature measurement is about 1 to 2°C.

Moisture Content. The air humidity in the rock mass will be used to calculate the pore pressure gradients that drive the movement of liquid water within the rock mass. Changes in the moisture content will also be measured by (1) neutron well logging, and (2) the tomography of relative electrical resistivity and the dielectric constant. 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.

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

Both resonant cavity and electro-optical liquid sensor measure air humidity and/or moisture content at a point; therefore, they will be embedded at strategic locations in the rock mass. Thermal neutron and gamma density loggings 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 about 30% to about 100%. The achievable tolerance 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 water and rock samples and petrologic studies will be performed on rock/water samples obtained before and after the heating cycle is completed. Cores will be collected from some of the instrumentation holes. These studies will be performed 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). Chemical characterization studies are described under a separate SP. 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.

In addition, optical fibers will be installed in the rock mass, both in the fractures and matrix, and infrared spectroscopy and Raman spectrometry will be used to (1) determine pH values and the concentrations of certain chemical species, and (2) monitor geochemical processes. 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 accuracy of the concentration of chemical elements needed to determine geochemical processes is about 10 to 20%.

Mechanical Properties. Measurements of rock displacements and changes in stress will help determine (1) how fracture apertures change in response to the mechanical behavior of the rock mass, (2) other geomechanical responses to thermal perturbations. 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.

In situ stress-meters, extensometers, and other geomechanical instruments will be used to determine stress distributions 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 megapascals, depending on distance from the heaters and the existence of fractures. The tolerance of the stress change measurement is about 0.1 MPa. The expected range of displacement is from 0 to a few millimeters. The tolerance of the displacement measurement is about 0.01 mm.

Air Permeability. Cross-hole air permeability and single borehole injection air permeability will be measured before and after the testings to evaluate the effect of heating on the permeability of the rock mass (Lee and Ueng, 1991). 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. The expected range of the in-situ permeability is from 10^{-14} to 10^{-12} m². The tolerance of the permeability measurement is about 50% of the measured values.

Gas Pressure and Atmospheric Pressure. Gas pressure in rock mass and atmospheric pressure in 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 1 atm to a few tens of atmospheres. The tolerance of these measurements is about 0.1 atm. We will also determine the partial pressure of H₂O and O₂ in the near field, as close to the heater as possible. The partial pressure of H₂O can be determined by measuring the relative humidity, the total pressure, and temperature. The partial pressure of O₂ can be determined by O₂ sensing device 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 up to several kilowatts per meter power. The tolerance of wattage measurement is about 0.01 kW.

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 tolerance of time measurement is about one hour.

Infiltration of Water. Infiltration of water during the heating and cool-down phases will be carried out to investigate the effect of thermal load on the flow of water in fractures and matrix. The expected range of moisture content in this measurement is the same as in the moisture content measurement described above. The tolerance is also the same.

Fracture Locations and Orientations. Fractures will be mapped by borehole scope and/or borehole TV surveys, which will be performed in all of the boreholes before installation of instruments and along the emplacement drifts before and after the tests are completed. This information is needed to (1) understand the effects of heating on the stability of the emplacement drift walls, and (2) 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 tolerance of the fracture location determination is about 5 cm.

Volume of Steam Invading the Heater Drifts/Boreholes. The volume of steam that flows into the heater drifts or boreholes during the heating and cool-down phases will be measured to estimate how much vapor flows toward the heater borehole, as part of model validation. The amount of water condensed from the steam invading the heater drifts or boreholes is expected to be tens of liters. The tolerance of the water volume measurement is about 0.1 liter.

Debris or Dust from Heater Drifts. Debris or dust will be sampled from the heater drifts or boreholes after heater removal. This sampling will allow assessment of the impact on hydrological properties of any microfracturing of rock or dehydration of fracture-filling materials.

Post-Testing-Phase Core Sampling. Post-testing rock core will be obtained in strategic locations for geochemical/petrographic analyses to evaluate the effect of heating on geochemical processes.

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 pieces 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 conditions in rock. These conditions include thermal gradient, fluid flow, and clay minerals. We will try to determine the self-potential in the near field.

3.2 Activities

Work performed in support of the EBSFT has been divided into the following activities for quality assurance grading.

<u>Activity Number</u>	<u>Description</u>
EB-01.2	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.

EB-02.2

This is the main test activity, which includes planning, evaluating test components, procurement, calibration and installation of test components, data acquisition, and test controls. It also includes developing 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 prototype tests.

This activity also include the following sub-activities: (1) Evaluate test components. This activity includes checkout and debugging of techniques and hardware. It also includes the performance of comparative evaluations of candidate test components and methods and the procurement of equipment for these evaluations. These evaluations may be performed in the laboratory or during the course of field experiments. (2) Conduct, test, record, and archive data. These data include all measurements and test controls performed before, during, and after heating of the rock mass. (3) Procure or manufacture test components. This activity includes the development of specifications and requirements for the equipment, including reassessment of specifications previously derived for prototype test equipment. (4) Calibrate and install test components.

EB-05.2

Perform scoping calculations in support of (1) design of the test, and (2) development of planning documents, such as study plans. This activity includes the verification and validation process necessary to qualify the numerical methods to be used. Reducing and analyzing test data and reporting test results are also parts of this activity.

3.3 Description of Activities

This section provides a general description of the EBSFT. Specific details will be provided in implementing procedures that will be prepared and approved prior to performing 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 test will be conducted in the EBSFT: abbreviated tests and long-term test. Both tests have the same general procedures, such as 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, 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. The main difference between the two tests is the duration of the heating and cool-down phases, which will be discussed in activity plans.

3.3.1 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. Figure 1 shows a general configuration of the emplacement drift, instrumentation drifts, and instrumentation boreholes of each test of the drift emplacement scenario. This general layout assumes a drift emplacement scenario. Drift emplacement has two major advantages over borehole emplacement: (1) Temperatures on the waste package and the drift wall for a same dry-out volume in the rock mass are lower than that of borehole emplacement. This is a very important factor to be considered in order to achieve the extended dry-out condition. (Buscheck and Nitao, 1992). Multiple drifts (at least three drifts) are used so that the volume of the dry-out zone will be large enough to serve the purpose of the test while the peak rock temperature is not too high

(Buscheck et al, 1993). (2) Ponding of water near waste packages can be eliminated in the drift emplacement; but may not be avoided in the borehole emplacement. Specific layout of test(s) will be discussed in implementing documents. Where a layout needs to be discussed, the reference design of emplacement in drifts will be referred to, but changes to this design may be made in subsequent implementing documents. 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 Exploratory Study Facility (ESF).

Instrumentation boreholes will be drilled vertically (from both above and below) and horizontally into the emplacement drifts to provide three-dimensional access for measurements in boreholes and cross-boreholes. Rock cores will be collected from some of the boreholes for hydrological and geochemical analyses (Activity EB-01.2). The instrumentation boreholes will be drilled dry so that the initial moisture content in the rock mass will not be changed due to the drilling.

The effect of the waste package layout configuration on the thermohydrological and thermomechanical responses of rock mass will be investigated. Thermal interference between the heated drifts will also be studied. The effect of the scale of power loading will be investigated.

3.3.2 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 heater and instruments, heater (emplacement) drifts and instrumentation boreholes will be inspected to map location and orientation 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 will be sealed, either by grout or packers, so that they do not become hydrologic sinks

during the test. Then preheat measurements will be made to establish 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 found in implementing procedures, but there will likely be a constant power level followed by a controlled cool-down, 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 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 shut in boreholes will be removed for inspection, evaluation, and recalibration. Selected boreholes will be reinspected for changes in fracture pattern and permeability. Heater canisters and test pieces 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.

4.0 Application of Results

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

- Data from the various instrument readout systems.
- Analysis of rock samples for rock properties (to be performed under WBS 1.2.2.2.2).
- Evaluation of equipment and instrument performance.
- Physical examination of boreholes.
- Rock/water samples for geochemical analysis (analysis to be performed under WBS 1.2.2.2.1).
- Development of a conceptual model that describes hydrological and thermal evolution of the rock mass system near a heater emplacement drift/borehole.
- Development of conceptual models for geomechanical response (model development to be performed under WBS 1.2.2.2.3).
- Rock/water/grout samples for geochemical analyses of impact of man-made materials (to be performed under WBS 1.2.2.2.5).
- Development of conceptual models for metallurgical performance of various candidate waste package materials.

On the basis of the analysis of the data, a conceptual model will be constructed that describes the thermal, hydrologic, chemical, and mechanical evaluation of the geologic environment. These data will be compiled, reduced, and provided throughout the course of the test to the investigators responsible for developing the heat and mass transport model (Near-Field Flow and Transport Model).

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, we expect 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 rewet slowly because of the pore pressure and saturation gradients that develop in the rock around the heater. We expect to observe a faster rewetting rate in regions above and to the sides of the heater than below the heater. The re-wetting near fractures is expected to be faster than in un-fractured region (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. Analysis 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.

5.0 Schedule and Milestone

The discussion of the schedule and milestone of this study uses the time when the test region is available as a reference. 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 when the test region is available. We will designate the time when the test region is available as the beginning of the test. Figure 2 shows the schedule of the events of the study. AS mentioned in Section 2.3.2, we will conduct abbreviated tests 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 extend the natural cool-down duration to 18 months, keeping the same controlled cool-down duration as shown below but extend the natural cool-down duration to indefinite, etc. The schedule of the study is described as follows.

Fracture Mapping and Pre-Test Air Permeability Measurements. Mapping of the fractures in the boreholes and drifts and the measurement of pre-test air permeability will be completed within 2 months after the beginning of the test.

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 the beginning of the test.

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 the beginning of the test.

Heating Duration. The heating duration will be 18 months for the abbreviated tests, and 48 months for the long-term tests.

Controlled Cool-Down Begins. The controlled cool-down will be started right 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.

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 the beginning of the test. For the long-term tests, the natural cool-down phase will start 69 months after the beginning of the test.

Natural Cool-Down Duration. The time required for the temperature in the rock mass to decrease to near the ambient temperature 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 the beginning of 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.

Post-Test Over-Coring. 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.

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.

6.0 Acknowledgements

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(a) Top View

Figure 1: General layout of emplacement drifts, instrumentation drifts, and instrumentation boreholes. (a) Top view, (b) Front view, and (c) Side view.

(b) Front View

(c) Side View

Figure 2. Events and schedules of EBSFT for the 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.

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