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Study 8.3.1.2.2.4

Characterization of the Yucca Mountain Unsaturated Zone in the Exploratory Studies Facility

U.S. Department of Energy
Office of Civilian Radioactive Waste Management
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Prepared by
U.S. Geological Survey

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INTACT FRACTURE TEST IN THE ESF

YMP-USGS SP 8.3.1.2.2.4.1

This is part of the
Characterization of the Yucca Mountain Unsaturated Zone
in the Exploratory Studies Facility Study Plan
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Assistant Manager for Scientific Programs / Date

James Blaylock for 4/29/96
Director, Quality Assurance Division / Date

Effective Date: 05/30/96 QN

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ABSTRACT

This section of the Characterization of the Yucca Mountain Unsaturated Zone in the Exploratory Studies Facility Study Plan describes the Intact Fracture Test in the Exploratory Studies Facility (Site Characterization Plan activity 8.3.1.2.2.4.1). The objective of this activity is to conduct detailed laboratory analyses of the hydraulic and transport properties of single, variably-saturated fractured rock cores collected from the Exploratory Studies Facility. The results of the Intact Fracture Test will be used to test models for fluid flow in fractured rock (Characterization of Fluid Flow in Unsaturated, Fractured Rock, Study 8.3.1.2.2.8, R1).

The rationale for the Intact Fracture Test is described in Sections 3.1.3 (regulatory rationale and justification) and 3.1.4 (technical rationale for activity selection). The general approach to the activity and a summary of the tests is included in Section 3.1.6. The Intact Fracture Test in the ESF is described in detail in section 3.1.7. Sections 3.1.8 and 3.1.9 discuss data analysis and the application of the results. A list of equipment, a schedule, and the references cited are mentioned in sections 3.1.9, 3.1.10, and 3.1.11, respectively.

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3.1 Intact-fracture test

3.1.1 Objectives of activity

The objectives of this activity are to conduct detailed laboratory analyses of the hydraulic and transport properties of single, variably-saturated natural fractures collected from the Exploratory Studies Facility (ESF).

3.1.2 Purpose of activity

The purpose of this test is to evaluate fluid-flow and chemical-transport properties of single, relatively undisturbed fractures. The test will provide: (1) a better understanding of the physics of fluid flow and chemical transport through variably-saturated fractures under a range of stress conditions; (2) a way to estimate the hydrologic properties of single fractures in various tuffaceous units underlying Yucca Mountain; and (3) direct measurements of unsaturated hydraulic properties of fractured rock for comparisons with results of the unsaturated zone fractured rock modeling efforts (Study Plan 8.3.1.2.2.8). These results will also help address many of the hydrologic issues and technical positions listed in the Site Characterization Plan (DOE, 1988). The SCP describes the geohydrology testing strategy in Section 8.3.1.2 and the issue-resolution strategies for performance assessment in Sections 8.3.2 through 8.3.5.

3.1.3 Regulatory rationale and justification

The results of the Intact Fracture Test will be used to test preliminary numerical models for fluid flow in fractured rock. The choice of initial and boundary conditions for these models is inherently subjective. Testing methods based on actual measurements taken under controlled laboratory conditions are preferred. Testing these models will help detect fundamental problems that may occur as the models are applied to the hydrologic system at Yucca Mountain.

The Intact-Fracture Test will provide data for various hydraulic parameters for individual fractures. These parameters include: (1) permeabilities to water and air, (2) characteristic curves that define the degree of saturation as a function of matric potential, (3) critical saturations (i.e., to initiate fracture flow), (4) relations between stress and effective permeability, (5) breakthrough curves and effective porosities, and (6) flow-channel geometry to evaluate the applicability of different fracture-flow equations.

The results of the Intact-Fracture Test will contribute to resolving the following issues and technical positions in the SCP: pre-waste emplacement travel time (Issue 1), vapor transport (Issue 7), hydrologic flow paths (Issue 9), size effect and extrapolation

(Technical Position 2), host-rock variability (Technical Position 3), testing of the conceptual model (Technical Position 5), gaseous travel time (Technical Position 6), and mathematical models (Technical Position 8). This activity does not address post-waste emplacement conditions.

These issues and technical positions are addressed by studying the following in the Intact-Fracture Test: 1) the conditions for fluid flow in unsaturated, fractured rock; 2) the nature and role of channeling processes; 3) the influence of fracture-matrix interaction on fluid flow; 4) the relative permeability of unsaturated, fractured rock as applied to the estimation of fluid flux; 5) the effects of stress changes on permeability and relative permeability of rough-walled natural fractures; and 6) spatial heterogeneity in fractured-rock permeability.

The proposed Exploratory Studies Facilities (ESF) Intact Fracture Test will evaluate fluid-flow and chemical-transport properties of single, relatively undisturbed fractures. The objectives of the test are to provide the following: (1) a better understanding of the physics of fluid flow through variably saturated fractures under a range of stress conditions; (2) a means of testing numerical and analytical fracture-flow models; and (3) a way to estimate the hydrologic properties of various tuffaceous units underlying Yucca Mountain. These objectives will be accomplished by conducting stress-permeability tests in the laboratory which will provide hydraulic transport parameter measurements under a range of mechanical conditions. These permeability tests would include single- and two-phase permeability studies using conservative tracers for transport investigations. Also, flow-channelization tests will be conducted, which will provide information on the geometry of the fluid-phase distributions and fracture apertures. These results will help address many of the hydrology-related site characterization issues.

3.1.4 Technical rationale for activity selection

Fractures are potential flow paths in the unsaturated zone at Yucca Mountain. However, characterizing fracture flow is complicated by numerous problems, three of these are: (1) the possibility of non-Darcian flow; (2) the interaction of the three-dimensional stress field and three-dimensional flow field in the rock; and (3) extrapolating individual discrete fracture methods to large-scale, equivalent porous media representations.

The first problem complicating the characterization of fracture flow occurs as a result of nonlinear flow in rock fractures, which can result from turbulent flow (Sharp and Maini, 1972) and gas-slip phenomena (Klinkenberg, 1941). Turbulent flow is probably not significant in deep sections of the unsaturated zone at Yucca Mountain. However, flow of the nonwetting phase (air) through unsaturated fractures may be nonlinear at small flow rates (Montazer, 1982).

The second problem arises from the interaction of stress and rock-mass properties. Changes in stress can change the fracture aperture and affect the permeability and effective porosity of the fracture. A change in the effective porosity of the fracture can correspond to a change in fracture saturation. Permeability is a function of saturation, and therefore, any changes in saturation conditions could result in a second order permeability change (Montazer and Wilson, 1984).

The third problem, extrapolation of discrete fracture methods to equivalent porous media representations, results from the scale-dependence of applying Darcian flow theory; and, the limited access to the fracture network. Developing an equivalent porous media representation would depend on defining a Representative Elementary Volume (REV). If an REV was defined, at the scale of the REV, the medium being represented could be replaced, conceptually, with an equivalent porous medium. Due to the highly heterogeneous medium expected at Yucca Mountain, an REV is questionable. These approaches are described in the Study Plans 8.3.1.2.2.8 and 8.3.1.2.2.9.

These problems are addressed partially by investigating flow phenomena in individual, relatively undisturbed fractures under controlled, steady-state and transient conditions. The result of tests on single fractures then can be used as building blocks for designing, testing, and interpreting larger-scale tests, including the following Site Characterization Plan activities: the Percolation (8.3.1.2.2.4.2), Radial Boreholes (8.3.1.2.2.4.4), and Excavation Effects (8.3.1.2.2.4.5) Tests.

The ESF intact fracture test will conduct detailed laboratory analyses of the hydraulic and transport properties of single, variably saturated natural fractures collected from the ESF. Minimally disturbed core samples with a single fracture will be collected from different rock types, locations, and orientations in the ESF that are representative of natural, rough-walled fractures in the unsaturated zone. Information collected by the Radial Boreholes Test and the Major Faults Test (SP 8.3.1.2.2.4) will provide guidance selecting fractures based on the measured permeabilities and calculated pneumatic apertures. Laboratory analyses performed under controlled laboratory conditions will provide hydraulic, transport, and geometric parameters in fractured rock and an opportunity to directly observe fluid-flow processes over a range of hydraulic and mechanical conditions.

The most common flow model, the Poiseuille flow equation, assumes smooth parallel plates as a fracture analogy. Experimental evidence by Maini (1971), however, shows that flow in natural fractures occurs over paths that are anastomosing and irregular.

Maini's (1971) experiments also demonstrate that flow tends to deflect around narrow portions of the fracture openings. Consequently, flow paths in a fracture conduct flow in a manner analogous to several attached conduits of different sizes. Only when aperture variation along a flow path is small can the flow be well approximated by parallel plate flow with an opening equal to the mean flow path aperture (Iwai, 1976; Neuzil and Tracy, 1981). Based on these observations, idealized fracture models can be constructed in which the flow paths are represented by an opening that varies continuously normal to the flow, but with a constant aperture in the flow direction.

Numerous models have been developed to investigate fluid flow in fractures. One approach is a stratified percolation model to analyze saturated and unsaturated fluid flow through single fractures (Pyrak-Nolte et al., 1990). The type of flow geometry observed in laboratory experiments was reproduced based on the fractal characteristics of contact area, flow path tortuosity, and aperture variations. Firoozabadi and Hauge (1990) proposed a phenomenological model to describe capillary pressure measurements of fractures between matrix blocks. The model depicted fracture surfaces as covered with cones, each contacting the tip of an opposing cone. Data collected from centrifuge tests were compared with simulations using the cone phenomena. A conceptual and numerical model describing multiphase flow was proposed by Pruess and Tsang (1990). A rough-walled rock fracture was viewed as a two-dimensional heterogeneous porous medium. It was found that the sensitivity of the relative permeabilities depended on the type and range of spatial correlation between apertures.

Permeability tests will be conducted in the laboratory under varying stress conditions that simulate the natural stress environment. The intact fracture samples will be subjected to a range of stresses similar to the lithostatic pressures that are present in the ESF. The effects of these incremental variations in stress are exhibited primarily as changes in the size of the fracture aperture (Gale, 1982). The geometry of fracture surfaces is the most important variable in determining the ability of a fracture to transmit water (Snow, 1966, 1970; Neuzil and Tracy, 1981; Witherspoon, 1981). Therefore, characterization of fracture flow must include an assessment of fracture geometry and its variation within the in situ stress environment.

Numerous studies have been conducted concerning multiphase flow in fractures. Some of these studies indicate that two-phase flow in fractures is similar to flow in porous media (Pruess and Tsang, 1990; Keuper and McWhorter, 1991; Reistma and Keuper, 1994). Phase structure or occupancy of the void space in fractures can strongly affect fluid permeability. Interference between fluid phases can influence the sum of wetting and nonwetting phases such that the sum of the relative permeabilities does not equal one (Pruess and Tsang, 1990; Persoff et al., 1991; Persoff and Pruess, 1993). This is contrary to previous work that has indicated that the sum of the relative permeabilities equal one (Romm, 1966; Pruess et al. 1983, 1984; Bodvarsson et al. 1987). This test will obtain relative permeabilities primarily based on the energy status of the fracture plane and the rock matrix, inflow and outflow data (using mass flowmeters, pressure transducers, and gravimetric measurements), and resistivity values. Phase structure will probably influence these measurements.

Conservative tracers (bromide, iodide, and/or meta-(trifluoromethyl) benzoic acid (m-TFMBA) will be introduced during the hydraulic tests. Breakthrough curves (tracer concentration vs. time), for example may be used to evaluate the effect of diffusion on environmental-tracer movement through the unsaturated zone. These results will also be used to compare actual measurements of hydraulic properties to the results of computer model simulations.

In addition, flow-channelization tests will be conducted. These tests will provide another means of characterizing fracture flow. Flow channelization along the fracture plane is one of the major uncertainties and one of the most important variables when analyzing unsaturated flow and chemical transport through natural fractures. Because the ability of a fracture to transmit water depends primarily on the size of the opening (fracture aperture), attempts have been made at defining the relations between fracture geometry and hydraulics. A knowledge of aperture roughness properties and flow hydraulics provided by flow-channelization experiments can indicate whether or not flow paths in fractures can be represented by simple hydraulic flow models (Montazer and Harrold, 1985).

To summarize, the Intact-Fracture Test will provide hydraulic parameters for individual fractures. These include: (1) permeabilities to water and air, (2) characteristic curves that define the degree of saturation as a function of matric potential, (3) critical saturations (i.e., to initiate fracture flow), (4) relations between applied stress and effective permeability, (5) breakthrough curves and effective porosities, and (6) flow-channelization simulations that evaluate the applicability of different fracture-flow equations.

3.1.5 Constraints on Study

3.1.5.1 Potential impacts of activities on the site

Samples will be collected from the drifts, walls, alcoves, and ramps of the ESF. Core samples will be collected from numerous locations in the following five informal hydrogeologic units in the ESF: 1) the Tiva Canyon welded (the North and/or South ramp), 2) the Paintbrush nonwelded (the North and/or South ramp), 3) the Topopah Spring welded (main test level), 4) the vitric Calico Hills nonwelded, and

5) the zeolitized Calico Hills nonwelded. Sample locations will be chosen by the PI using detailed mapping information.

An alcove may be needed if the core samples are collected where a drill rig and dust collector may block through traffic. The PI will work with the ESF Test Coordination Office to identify and specify design requirements related to potential interferences with traffic in the ramps and/or drifts. If alcoves are required, dry construction is required.

Suitable sample locations will be chosen by the PI. No interference envelope is defined, but the envelope will be small since only rock cores are to be collected.

Flexibility in sampling locations is required to locate suitable fractures. Drilling and overcoring will be done using dry methods. Only sample collection will be conducted in the ESF; therefore, no hydrological, chemical, or thermal disturbance is expected from this activity.

The core samples do not have to be collected during construction. However, these cores shall be collected as soon as possible so the lengthy laboratory tests to be conducted can be started. The rock cores should be collected before any lining material is installed in the ESF or the sample locations marked before any lining material is installed so the samples can be collected later.

3.1.5.2 Interrelationships of tests involving significant interference with other tests

This test should not interfere with other tests conducted in the ESF. When possible, these cores will be collected in coordination with the following tests: a) Overcore Stress Test (SCP Activity 8.3.1.15.2.1.2), b) Excavation Effects Test (SCP Activity 8.3.1.2.2.4.5), c) Fracture Mineralogy Activity (SCP Activity 8.3.1.3.2.1.3), and d) Radial Boreholes Test (SCP Activity 8.3.1.2.2.4.4) and Major Faults Test (SCP Activity 8.3.1.3.2.4.10). The core samples will be collected so that data collected from the four previously mentioned tests can be used to interpret, collaborate, or bound the laboratory tests conducted on the collected core samples.

The Overcore Stress Test will provide in situ stresses. The Excavation Effects Test will provide information regarding air permeability changes due to excavation. The Fracture Mineralogy Activity will provide data concerning fracture coatings and matrix mineralogy. Lastly, the Radial Boreholes Test and the Major Faults Test will provide information on fracture permeability and pneumatic apertures. However, these tests are not required to collect core for this test. The core samples can be collected without collaborating with these tests. The data collected by these tests will enhance the conduct of the Intact-Fracture Test. The core can be collected wherever competent, single fractures occur.

3.1.6 General approach and summary of tests and analyses

Intact-fracture core samples will be collected from the ramps, main drifts, and test rooms of the ESF. Suitable sampling sites will be chosen using the fracture mapping data collected (Underground Geologic Mapping, Study 8.3.1.4.2.2) and by visual inspections. Relatively undisturbed rock cores containing a single, through-going fracture will be collected. These cores will have fractures of two different orientations. The first type, radial fractures, will have a fracture approximately perpendicular to the axis of the core. The second type, axial fractures, will have a fracture approximately parallel to the axis of the core.

A number of core samples will be collected for the stress-permeability studies. Six to twelve core samples of each fracture orientation (axial and radial) will be collected from each hydrologic unit sampled. The fractures will be subjected to a series of laboratory tests including air and water permeability tests, tracer tests, and flow-channelization tests.

3.1.7 Detailed Description

3.1.7.1 Test configuration

The intact fracture laboratory test will include the following major tasks: 1) input to computer modeling (codes developed under Study Plan 8.3.1.2.2.8), 2) stress-permeability tests, 3) tracer tests, 4) flow-channelization tests, and 5) data analysis. These tasks will be performed specifically to better understand fluid flow in fractured rock for two fracture orientations, radial (perpendicular to the core axis) and axial (parallel to the core axis).

Figure 3.1-1 illustrates the overall approach to the intact fracture laboratory test. The development of unsaturated zone fractured rock computer models are discussed in Study Plan 8.3.1.2.2.8 (Characterization of Fluid Flow in Unsaturated, Fractured Rock). Axial and radial fractures will be tested. A blank sample is used to test the vessel and fluid flow field. Samples previously collected from the G-Tunnel Underground Facility at the Nevada Test Site, NV will subsequently be tested (i.e., stress-permeability, tracer, and flow channelization tests). The direct measurements of unsaturated hydraulic properties of fractured rock will be compared with results of the unsaturated zone fractured rock preliminary modeling efforts (Study Plan 8.3.1.2.2.8). The

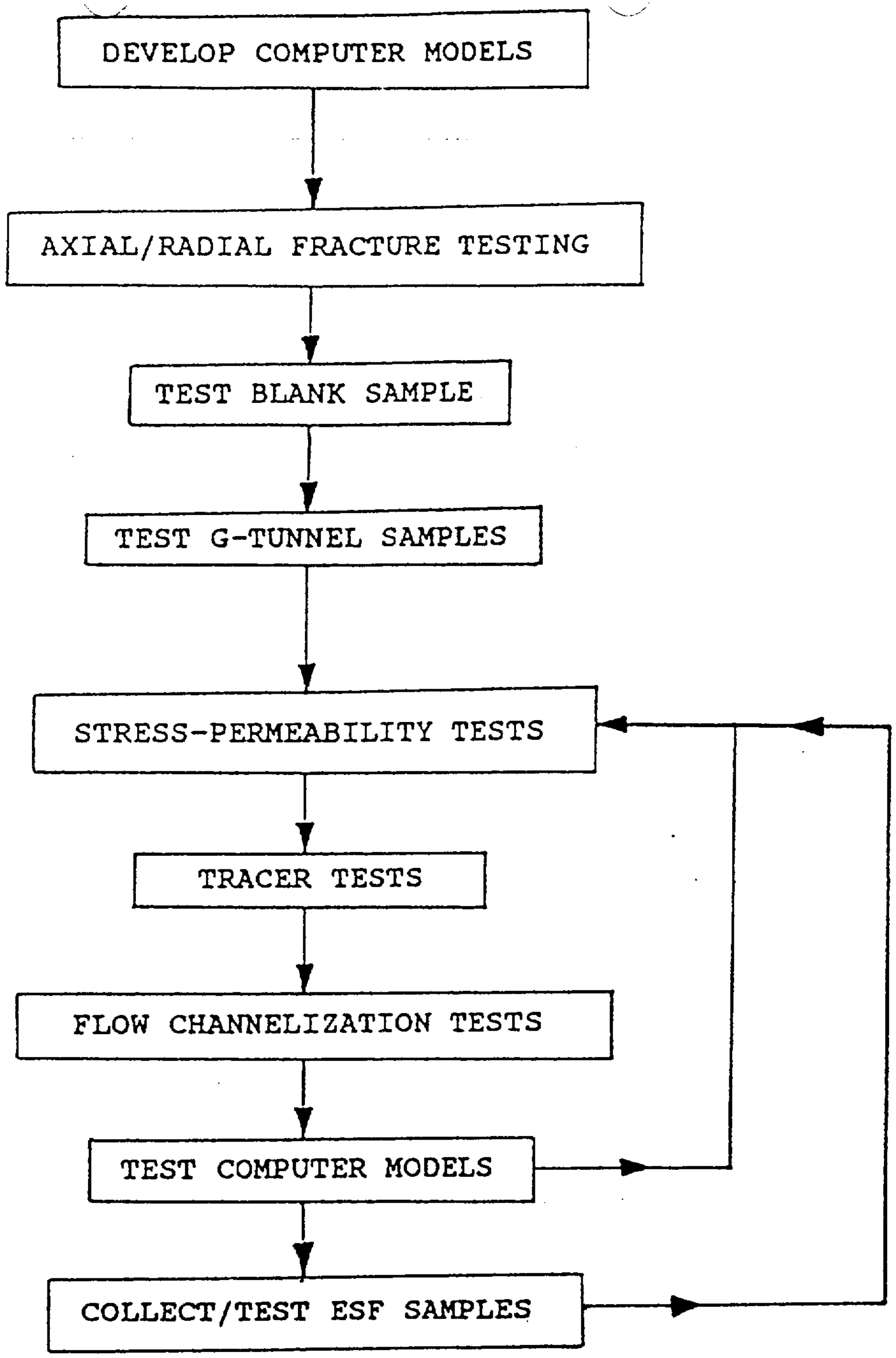

Figure 3.1-1. Intact fracture test configuration.

samples collected from the ESF will be tested and the results used to test the preliminary models of fluid flow in unsaturated rock.

3.1.7.2 Sample Collection

Drilling and excavation activities disturb the natural state of fractured rock and hamper the collection of undisturbed, intact-fracture samples. Success in obtaining a minimally disturbed fracture depends on rock type and the nature and extent of the fractures in the sample. Preliminary testing of the sampling procedures was performed in the G-Tunnel, Nevada Test Site, NV, with similar rock types (Severson and Boernge, 1991). Fracture samples in the ESF will be selected based on the results of fracture mapping in the ESF and visual inspections. Three-dimensional projections of individual fractures will be determined from the two-dimensional fracture maps and fracture-orientation data provided as part of the Underground Geologic Mapping Study during ESF construction.

Core samples will be collected from numerous locations in the following five informal hydrogeologic units in the ESF: 1) the Tiva Canyon welded (the North and/or South ramp), 2) the Paintbrush nonwelded (the North and/or South ramp), 3) the Topopah Spring welded (main test level), 4) the vitric Calico Hills nonwelded, and 5) the zeolitized Calico Hills nonwelded. Sample locations will be chosen by the PI using detailed mapping information if available. Samples will be selected that contain a single fracture exhibiting as little mechanical disturbance as possible and that are visually representative of the range of fractures observed regarding aperture, roughness, and shape. It is important to emphasize that specific requirements of the field-phase activities will be developed in subsequent, detailed test planning documents.

When possible, these cores will be collected in coordination with the following tests: a) Overcore Stress Test, b) Excavation Effects Test, c) Fracture Mineralogy Test, and d) Radial Boreholes Test, and e) Major Faults Test. The core samples will be collected so that data collected from the three previously mentioned tests can be used to interpret, collaborate, or bound the laboratory tests conducted on the collected core samples. The core can be collected wherever competent, single fractures occur.

3.1.7.2.1 Radial Fracture Sampling

Radial fracture sampling will progress in a step-wise manner as summarized here. A fracture will be considered suitable for sampling if it has a minimal number of intersections with other fractures and is oriented so that it can be intersected by a pilot hole perpendicular or approximately perpendicular to the plane of the fracture. A 25.4-cm (10-inch), inside diameter core barrel will be started 15.2 to 25.4 cm (6 to 10 inches) into the rock face to pass initial surface irregularities. The pilot hole then will be drilled with a 1.9-cm (0.75 in) outside diameter core barrel using a centering template.

The pilot hole will be drilled, the core barrel removed and a downhole video camera will be used to inspect and locate the fracture. When a possible fracture is identified with the video camera, the length from the top to the bottom of the planned core sample and pilot hole will be calculated and the corehole will be cored with the 25.4-cm (10-inch) core barrel to the top of sample depth.

Next the pilot hole will be extended to the calculated bottom of the pilot hole dimension. The video camera will again verify the condition of the pilot hole. If the pilot hole does not have additional fractures or unacceptable geologic conditions, the anchoring system (comprised of a rock bolt, three mechanical anchors, spacer, nuts, and washers) will be installed, holding the fracture in compression.

Securing the fracture is followed by overcoring to 5.1 cm (2 inches) beyond the bottom of the pilot hole. A wedge tool is used to separate the core from the rock mass near the bottom of the corehole. The core sample is removed from the corehole, labeled, measured, waxed, wrapped, placed in a shipping crate, and then shipped to the USGS Denver laboratory for testing.

3.1.7.2.2 Axial fracture sampling

The clamp-core method was included as a core sampling technique per recommendations by Lawrence Livermore National Laboratory to obtain fracture core samples with less disturbance than the rock bolt-overcore method (Yow, 1986). This sampling method provides core samples necessary to study axial fluid flow in fractured rock.

Axial fracture core samples are collected by coring parallel to the centerline of a fracture perpendicular or approximately perpendicular to the mined surface. A 25.4-cm (10-in) diameter coring bit is used to core the rock on the centerline of the fracture. After full depth coring is completed, several circumferential straps are placed around the core after the core barrel is removed and tightened using tools that can be used in the core annulus. The sample is broken off at the bottom of the coring depth using a wedge tool that fits in the core annulus. The core is then removed with a core shovel and packaged for shipping.

3.1.7.3 Sample Preparation

The core samples will be examined closely for small fractures and mineralogical discontinuities. Initial laboratory procedures will prepare the fracture samples for the two vessel types, a hydrostatic pressure vessel for axial fractures and a uniaxial pressure vessel for radial fractures. The core samples will be trimmed to size. The matrix properties for each core will be obtained from the trimmings. In addition, fracture coating material and the rock matrix will be analyzed using x-ray diffraction techniques. Small access holes will be cored to install thermocouple psychrometers and tensiometers (pressure transducer-type) in the core sample.

The radial core samples will be instrumented with linear variable differential transformers (LVDTs). The LVDTs will be placed approximately every 120 degrees on the circumference of the core and across the fracture plane. The deformation of the matrix material of the core samples will also be measured using LVDTs. The LVDTs will be used to collect measurements of the changes in the mean fracture aperture and the mean overall sample deformation.

The core will also be instrumented with pressure transducer-tensiometers (PTTs), electrical resistivity electrodes, and thermocouple psychrometers (TPs) as shown in Figure 3.1-2. The TPs and PTTs will be placed in small drillholes at different locations within the core to differentiate between matrix and fracture properties. The TPs and PTTs will measure the energy status of the water (matric plus osmotic and matric water potentials, respectively) and electrode pairs will monitor changes in the electrical resistivity of the core. Both surface area and point of attachment of the electrical resistivity electrodes will be varied to obtain an optimal configuration. Electrode pairs for electrical resistance measurements will be evenly spaced on opposite sides of the core/fracture plane so that the electrical current is perpendicular to the sample axis. The number of instruments will vary from sample to sample, depending on the fracture roughness properties and the location and frequency of physical and/or mineralogical discontinuities located on the core surface or within the core.

Similar instruments will monitor the axial fracture samples which will be confined in a hydrostatic test vessel to maintain core integrity (Figure 3.1-3). Fracture movement will be measured with LVDTs mounted across the axial fracture near the ends of the core sample. Two LVDTs will be mounted diametrically opposed to each other on each side of the fracture. Overall sample deformation (i.e., length of the

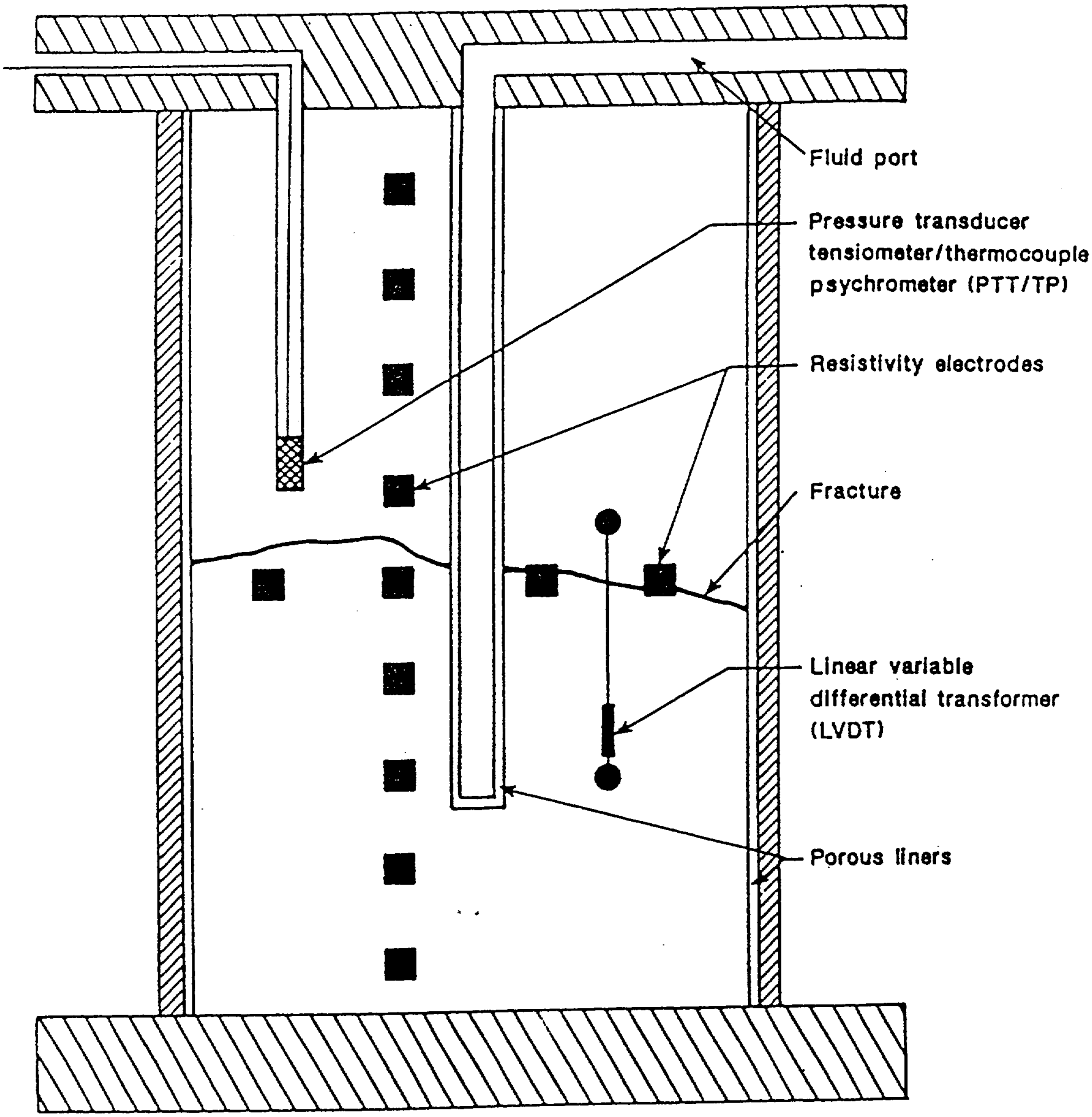

Figure 3.1-2. Stylized diagram of the test vessel for the radial fracture permeability studies.

axial fracture core) will also be measured with LVDTs mounted on each "half-cylinder" of the core.

3.1.7.4 Stress-Permeability tests

Stress-permeability studies will provide hydraulic parameter measurements under a range of mechanical conditions. Both single- and two-phase permeability tests will be conducted in the laboratory. These tests will be conducted in the laboratory by injecting liquids and gases into the core sample under varying, applied stress conditions using a hydrostatic test apparatus (axial fractures) or a loading frame apparatus (radial fractures). Nitrogen will be used for the air permeability tests. The fluid for the liquid permeability tests will be water from well J-13 from the Nevada Test Site. This well water is formation water but would be adjusted to be similar to the pore water in the unit the samples are collected. Particular attention would be paid to the SAR of the fluid used. The UZ Hydrochemistry Test, activity 8.3.1.2.2.4.8, results will be used to ensure the liquid used has the same SAR to avoid dispersion or chemical changes to the fracture coatings present.

The loading frame or test apparatus, in which the intact fracture samples will be mounted, will be equipped with a control unit capable of loading, displacement, or strain rate control. Following a preliminary check for system leaks, a local data acquisition system (DAS), will be connected to the various instruments to record the measurements to be taken.

Laboratory determinations will be made of the hydraulic properties of the rock matrix of each intact fracture sample collected. This test will study fluid flow in fractured rock core samples. The matrix properties of these samples must be well-defined to correctly interpret the tests conducted. The matrix parameters to be determined include bulk density (liquid displacement), porosity, liquid and gas permeability (steady state), relative permeability (diffusivity), unconfined compressive strength, Young's modulus, and Poisson's ratio. The samples for matrix testing will be rock material from the corehole the sample is collected from, and/or material remaining after the core is trimmed for the confining vessel.

When any sample (rock, soil, gas, water, etc.) is removed from its in situ environment it is expected that the physical and chemical equilibrium of the sample has been altered. In general, when collecting a sample from the physical environment it is desirable to minimize the extent of this disturbance as much as possible. In situ disturbance assessment during fracture sampling has very little precedent

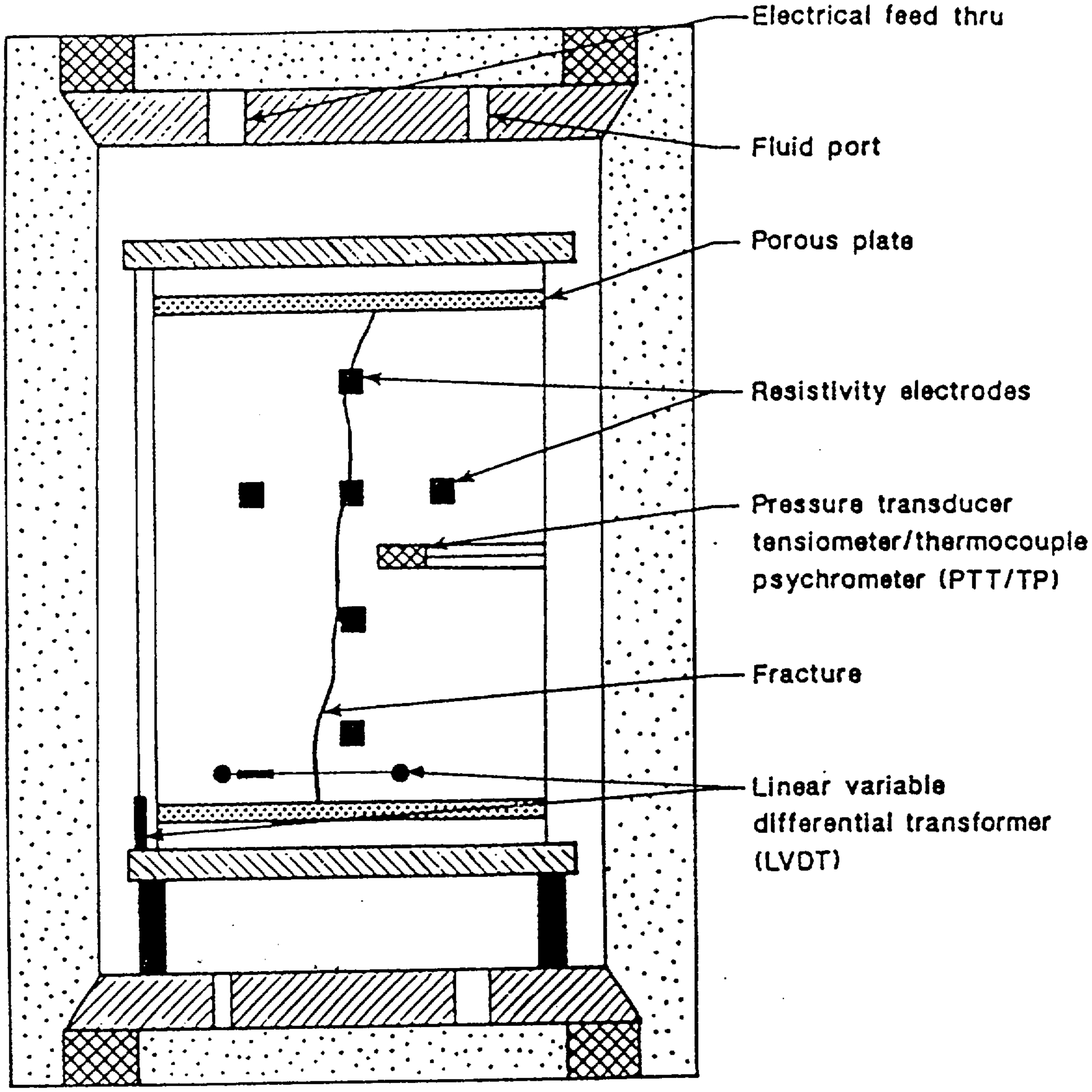

Figure 3.1-3. Stylized diagram of the confining vessel for the axial fracture permeability studies.

in the scientific literature and is usually regarded as a formidable technical challenge to field investigators. However, under controlled laboratory conditions the samples may be subjected to a relatively standardized load-cycling procedure which is designed to regain a natural load condition and a reasonable approximation of the original fracture aperture geometry. A brief review of disturbance assessment as it has been addressed in the scientific literature is described below. The effects of sampling disturbance on the axial and radial intact fracture core samples will be minimized in the laboratory by a load-cycling procedure described in this section.

Applied hydrostatic pressures to axial fractures will be similar to the in situ stresses expected at various levels in the ESF and in the proposed repository. Each load increment will be maintained until flow, pressure, fracture aperture, and overall sample deformation have achieved steady-state conditions. Steady-state conditions may take greater than 30 days depending on the desired water potential/water content. Bulk moisture content (as determined by electrical resistivity), water potential, pressure, and flow will be monitored and their interactions defined. Computer codes necessary to account for unsaturated hysteretic effects (Niemi and Bodvarsson, 1991) will be incorporated into the computer models that will simulate fluid flow through variably saturated discrete fractures under varied stresses.

Water will be introduced into the center hole of the radial fractures under constant loading. Applied loads will be determined by the in situ stresses expected (or by those measured in the Overcore Stress Test) at various elevations in the ESF and in the proposed repository. Each load increment will be maintained until steady-state conditions of flow, rock strain, and fracture aperture have been achieved. It is expected that 1 to 10 days will be required to achieve steady-state conditions; hence, one test will be run about every two weeks, excluding setting up and dismantling the confining cell. Water potential, pressure, resistivity, and flow will be monitored.

This basic procedure will be repeated with three variations. First, the initial saturation of the sample will be varied during liquid and gas injection so the complete scanning curves of the water characteristic relations curves can be constructed. Secondly, incremental loading variations will be made while flow rates are held constant, indicating how permeability is affected by stress-induced aperture changes. Flow rates, fracture displacement, overall sample deformation, and water/gas pressures (air-entry values for capillary pressures) will be monitored at each loading step up to the maximum and every unloading step back to zero. The data collected will include water potential values for the rock matrix and the fracture plane. The third variation will include a load applied and removed as many as 2-3 times during each test run so that hysteresis due to repeated applied loads may be evaluated.

The permeability of fractured rock core analyzed in the laboratory typically decreases with applied load and then returns to a permeability which is often less than the original starting value as the load is reduced to its initial level. This hysteretic phenomena is usually attributed to stress-induced, permanent deformation of the fracture aperture by asperity crushing (Iwai, 1976; Engelder and Scholz, 1981). Hysteresis is indicated when the elastic stress-strain curve derived from a loading test returns to an original strain value of zero by a different path during the subsequent unloading phase. Thus, perfect elasticity is not evident in most load-cycling investigations (Jaeger and Cook, 1979). Both fracture-deformation and fracture-flow rate curves during loading and unloading can be nonlinear with pronounced hysteresis. This has been observed with both natural and induced fractures (Jones, 1975; Kranz et al, 1979; Nelson and Handin, 1977; Raven and Gale, 1985).

Stress-induced hysteresis poses an obvious problem when measuring permeabilities in the laboratory where it is often desirable to analyze fluid-flow processes on fractures that are ideally undisturbed and not subject to re-seating and asperity crushing. This general desire has been brought about in part by the recognition that fluid flow in fractures is a very sensitive function of normal stress (Iwai, 1976; Gangi, 1978). Witherspoon et al. (1979) observed that the standard equation describing fluid flow in idealized parallel plate fractures, the so-called "cubic law", generally applies to natural rough fractures because the magnitude of the aperture is the dominant controlling factor in determining permeability. A slight change in aperture can easily mask out the effects of other changes in the aperture geometry.

Stress-induced hysteretic effects are generally most evident during the initial loading cycles (Reda and Hadley, 1985). Studies by Bandis et al. (1983) also show that repeated load cycles can be used to obtain single, reproducible stress-closure curves that are void of this stress-induced hysteretic phenomena. In their investigations, extensive stress-closure data was obtained for rock joints subjected to three cycles of loading and unloading using 64 samples selected from a variety of rock types. If it is assumed that rock joints in the natural in situ stress environment have undergone repeated closures throughout their history, one would expect a "hardening" effect to minimize hysteresis in totally undisturbed samples. However, since disturbance is considered to be inevitable during the sampling process, investigators have frequently subjected the samples to repeated load cycling in the laboratory in order to consolidate joints at loads comparable to those in the in situ environment.

Raven and Gale (1985) observed that larger samples (i.e., 0.245-m (9.65-in) diameter) undergo less deformation than smaller samples under the same loading conditions and are, therefore, less subject to stress-induced hysteresis. This was attributed to the larger samples having more asperities in contact and therefore lower contact point stresses and more tortuous flow channels.

Due to the uncertainties and limitations of disturbance minimization techniques in the field, it is anticipated that all fracture samples used in laboratory permeability tests will be initially cycled through a minimum of three loading-unloading intervals. These loading cycles will not exceed the in situ stresses present. A sample will be selected at the beginning of the laboratory analyses for a preliminary determination of the load cycling requirements (i.e., number of cycles required, load ranges, etc.). In addition, relatively large-diameter (0.254 m [10-in]) core will be obtained in order to further minimize hysteretic effects.

It is accepted that the resulting fracture geometry will not be identical to the original in situ geometry. However, it is believed that load-cycling will ensure that the fracture surface will be representative of natural, undisturbed fractures. In addition, it is emphasized again that the reliability and interpretation of these laboratory analyses is not contingent on the acquisition of undisturbed fractured core. Fractures that have a reasonable similarity in both load and aperture conditions to natural fractures are adequate and appropriate for the scope of the laboratory investigations.

Testing efficiency will be increased using preliminary computer models (developed under SP 8.3.1.2.2.8) for simple one-dimensional, single- and dual-phase flow to predict the hydraulic response of the fracture samples. These preliminary models will be tested and revised based on the tests conducted under this activity. Models that demonstrate the highest accuracy in simulating single-fracture flow under controlled laboratory conditions will be used to assist in the design of other subsequent SCP activity field tests and in the preliminary estimation of flow properties.

3.1.7.4.1 Tracer tests

The tracer tests will be performed as an integral part of the stress-permeability tests. Conservative tracers (bromide, iodide, and/or meta-(trifluoromethyl) benzoic acid (m-TFMBA) will be introduced during these hydraulic tests. Samples of the injected fluid will be collected as outflow from the fracture at predesignated time increments, and the tracer concentration determined.

Tracers will be injected into the fracture samples and their concentrations will be monitored during the steady-state flow tests. The data collected will be used to construct breakthrough curves and to obtain values for effective porosities and dispersivities. Small sample sizes and anticipated uncertainties in measurement accuracy may limit the direct application of the tracer test results. However, a significant gain in the understanding of the fluid flow and transport processes will be obtained. Preliminary computer models developed under SP 8.3.1.2.2.8 will be used to predict experimental results and to design the conditions for each test run. These simulations will also serve to evaluate model efficiency and applicability for subsequent larger-scale field tests.

3.1.7.4.2 Single-Phase permeability tests

The single-phase liquid permeability tests are similar to methods cited in both the soil physics and petroleum literature. Porous ceramic plates will be used on each end of the core sample. The water flow regime will be controlled by a water reservoir system to obtain different head values. Positive pressures at the inlet may be required for outlet hydraulic gradients greater than approximately -152 cm of water. In situ water potential measurements and inflow and outflow measurements will be used to determine when steady state conditions are achieved or approached. Electrical resistivity measurements will also be used to evaluate in situ moisture redistribution in the sample. A series of unsaturated permeability determinations will be made over the full range of imposed suctions during both the wetting and drying cycles to evaluate the magnitude of hysteresis effects in the fracture sample. A conservative tracer will be injected into the flow system at various steady state intervals and breakthrough curves will be constructed based on the tracer concentration measured from the outflow collected. While determining a gas permeability, the phase saturation within the fracture plane and possibly the fracture saturation will change. Water potential, resistivity, and linear displacement (LVDTs) measurements will continue to be collected.

The water reservoir system will hold the pressure heads constant. Changes in applied stresses will indicate how permeability is affected by stress-induced aperture variations for the permeability tests. Flow rates and fracture displacement (LVDT measurements) will be measured at each loading step up to a maximum load and then every unloading step back to zero. Loading-unloading cycles will be repeated so that permeability hysteresis attributed to asperity deformation can be evaluated.

3.1.7.4.3 Two-Phase permeability tests

Laboratory permeability tests will also evaluate simultaneous two-phase flow properties, i.e., the permeability to water and air at varying stages of saturation. The steady-state outflow of the gas and liquid phases will be monitored for each constant loading condition applied. Saturations will be changed during simultaneous flow by changing the ratio of the gas and liquid flow rates.

Flow rates of injected liquids and gases will be held constant to indicate how permeability is affected by stress-induced aperture variations. Flow rates, fracture displacement, and overall sample deformation will be measured at each loading step up to the maximum and then every unloading step back to zero. Loading-unloading cycles will be repeated so that permeability hysteresis attributed to asperity deformation can be evaluated. Hysteresis due to applied loads is previously discussed in section 3.1.7.4, Stress-Permeability tests.

3.1.7.4.4 Flow-channelization tests

In addition to obtaining permeabilities of radial and axial intact fractures under applied stress and variably saturated conditions, it is proposed to collect fracture plane geometry data. Flow-channelization in the fracture plane will be described using several laboratory methods during the final phase of laboratory testing. Fracture plane geometry data collected would include aperture, surface roughness, flow path tortuosity, asperity height and distribution, and contact area. It has been shown that fracture permeability is a function of both contact area (Iwai, 1976) and surface roughness (Kranz et al., 1979). Iwai showed both numerically and experimentally that permeabilities lower than those predicted by the cubic law occurred as a result of increasing fracture contact area because the available flow paths decreased and the flow-path tortuosity increased. Tracer experiments conducted both in situ (Abelin et al., 1984) and under laboratory conditions (Neretnieks et al., 1982) indicate that flow through natural fissures occurs along preferred channels.

The fracture plane geometry data will be obtained using the fracture surfaces and casts collected using a low-melting point metal injection technique and a resin impregnation technique. The digital contours of the fracture surfaces/casts will be obtained using a moire projection technique described below. The fracture geometry data collected will be used to physically verify an aperture-generator algorithm used in a numerical, single-fracture characteristic curve program developed under SCP Activity 8.3.1.2.2.8.

3.1.7.4.4.1 Moire projection method

The moire projection method will allow three-dimensional, adjustable resolution contouring of variably-sized fracture plane surfaces (Cardenas-Garcia et al, 1991) and/or fracture plane casts. The moire projection method uses a white light source and gratings to generate an interference pattern corresponding to contours of elevation on the fracture surface. A schematic diagram of the optical arrangement is shown in Figure 3.1-4. The method is totally non-destructive and permits resolving contours to less than 0.01 mm, as the system is currently designed. The projection system can be configured so that it can be taken to the field if desired. The optical record will include still photographs as well as video tape. When a rock surface is scanned the system will digitize the frames obtained. This data can then be displayed in various forms, to a monitor screen, as a graphical representation (plotter), photographs, etc. However, the principle use of the digital files will be to provide fracture plane geometry data for analyzing and interpreting the permeability results of the Intact Fracture Test.

3.1.7.4.4.2 Low-Melting point metal injection

Similar low-melting point metal injection methods have been used previously (Pyrak et al., 1985; Swanson, 1979; Yadav et al., 1984) to obtain casts of fracture planes to determine void shapes, contact area, and flow paths. Dullien and Dhawan (1975) obtained pore casts primarily at very high saturations. Swanson (1979) was able to modify the technique so that casts could be obtained at various nonwetting phase saturations.

After Pyrak et al. (1985), the non-wetting material used is Wood's metal, an alloy of lead, tin, bismuth, and cadmium. The Wood's metal is melted in a double boiler at 90 deg. C. and the core confining vessel is flooded with it. Approximately 10 MPa of positive pressure is necessary to push the alloy into a 0.1 micron aperture and 1 Mpa for a 2.0 micron aperture in granitic rock. After the metal cools, the fracture is taken apart and a cast of the flow channels is

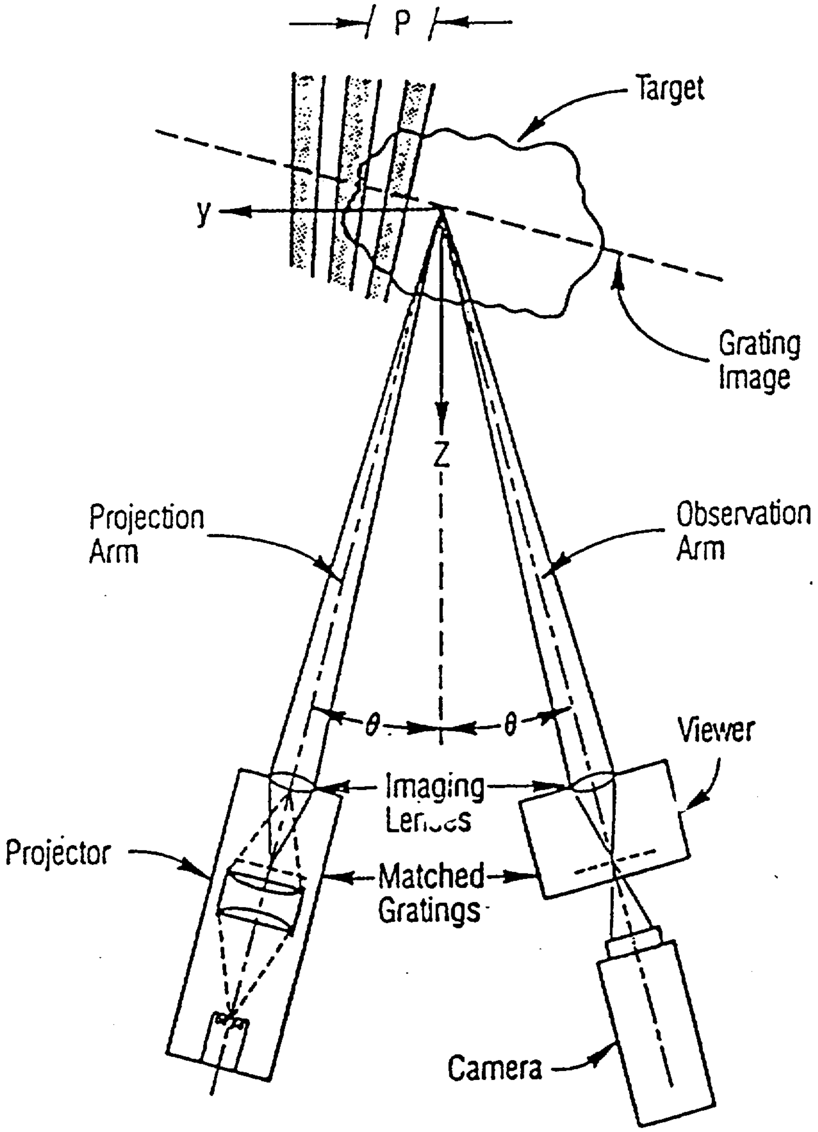

Figure 3.1-4. Schematic diagram of optical arrangement for the projection moire technique.

obtained which can be used to determine the void shapes, contact area, and flow paths in the fracture plane.

Observations under scanning electron microscope (SEM) reveal damage to the cast when broken away from the rock is limited to only several microns (Nolte et al., 1989). Apertures of 0.2 microns appear to be the smallest pores which can be penetrated at 2 MPa of confining pressure. An image analyzer was used to obtain contact area fractions from the work by Pyrak et al. (1985). This study proposes to use moire projection methods (section 3.1.7.4.4.1) to digitize the topography of the fracture casts obtained using low-melting point injections.

3.1.7.4.4.3 Resin impregnation

The resin impregnation method offers the added benefit of measuring surface roughness on both sides of the fracture plane. This technique is conducted on a fracture sample contained within a confining vessel. When the permeability tests are complete. i.e., the final load cycle complete; the stress level is constant; the fracture plane drained; and the sample flushed with carbon dioxide and nitrogen (Gale, 1987). The fracture plane is then placed under vacuum and injected with a room-curing resin. The fracture cast can then be studied to obtain a direct measure of fracture aperture distribution, contact area, resin thickness (aperture width), and roughness. These surfaces will be studied using the moire projection methods (section 3.1.7.4.4.1). This impregnation method differs somewhat from previous resin studies such as those conducted by Yadav et al. (1984).

3.1.7.5 Computer Modeling

A preliminary computer model(s) (developed under SP 8.3.1.2.2.8) of fluid flow in discrete fractures will be used to design and predict the results of the intact fracture tests. More than one model may be used to predict the hydraulic response of the fracture samples to single- and two-phase flow. The codes developed will assist in determining the conditions necessary to optimize the test procedures. The preliminary model(s) will be evaluated during the initial stages of testing and modified, if necessary, for greater efficiency and accuracy.

The preliminary discrete fracture model (SP 8.3.1.2.2.8) is a semi-analytical flow model for a single rough fracture that combines the equations for capillary rise and the cubic law to predict the relative permeability of a fracture at various saturations (Kwicklis and Healy, 1993). The model accounts for the capillary-controlled distribution of the liquid phase. The model assumes that the water is supplied to the fracture at the contact points between the fracture walls.

The aperture-generating algorithm uses a digitized representation of a real or artificial fracture wall. The fracture wall is replicated numerically and laterally offset to simulate an aperture. The walls can be manipulated in a compressional or shear sense to create the simulated in situ fracture. The aperture is then discretized in three dimensions and coupled with the flow portion of the computer code.

The measured fracture aperture geometrical properties obtained from the flow-channelization experiments will be compared with those predicted by the aperture generator contained within the single-fracture flow model. An assessment will then be made as to the adequacy of the aperture generator that has been conditioned by the measured fracture geometry data. The specific geometrical parameters will be compared for both measured and predicted values and uncertainties in the aperture generator estimations will be established.

The measured unsaturated permeability values will be compared and regressed against predicted values obtained from the model (which has been conditioned by measured fracture geometry data). These permeability values will also be compared and regressed against semi-empirically derived estimates of the unsaturated permeability values obtained from the pore-size distribution data and/or the moisture retention data.

Meaningful estimates of transport parameters such as mechanical dispersion (in the fracture domain) or diffusion (in the matrix domain) may not be possible to determine due to the small size of the samples and the fact that the core sample will probably not represent the rock mass as a whole. However, the breakthrough curves constructed using laboratory-collected data will be compared with the predicted curves from numerical models with transport capabilities. These comparisons will be made to better understand the nature of the transport mechanisms at the microscale and to evaluate the applicability of transport modeling approaches in a larger scale, fracture-dominated flow system.

When sufficient data has been obtained from the previously described tests (i.e., single-, two-phase permeability, and flow-channelization), the results of the laboratory tests will then be used to test models used in subsequent larger-scale tests (Percolation and Bulk Permeability/Radial Boreholes Tests as described in Sections 8.3.1.2.2.4.2 and 8.3.1.2.2.4.3) where fracture flow properties will also be studied. Study Plan 8.3.1.2.2.8 (Characterization of Fluid Flow in Unsaturated, Fractured Rock) describes the relationship between the scale-based tests (i.e., the Intact Fracture, Percolation, and Bulk

Permeability/Radial Boreholes Tests) and associated conceptual and numerical models.

3.1.8 Data analysis

Two types of data analysis will be performed during the Intact-Fracture Test. The first type will analyze data collected directly from the tests e.g., determining the relations between incremental loading and fracture permeability, tracer concentration versus time or distance traveled, and critical saturations to initiate fracture flow. These results will be useful in determining characteristic relations and responses. The results will also be used to test and calibrate preliminary numerical models for fluid flow in fractured rock. In addition, the data will help choose initial and boundary conditions for modeling efforts applied to the hydrologic system at Yucca Mountain.

The second type of data analysis will be computer modeling (developed under SP 8.3.1.2.2.8) at various stages of the testing. Initially, discrete fracture flow models (variable aperture model, see Study Plan, YMP-USGS-SP 8.3.1.2.2.8, R1) will be used to design the test and to predict its results so that independent parameters may be selected for optimum test performance. These models will also be used to evaluate test results from both prototype and ESF versions of the test procedures. Models will be calibrated and probably altered for more efficient applicability and accuracy during this phase. This process of modeling and testing is shown schematically in Figure 3.1-1.

3.1.9 Application of Results

The experimental results will be used to test unsaturated flow models developed under SP 8.3.1.2.2.8. From the known fracture and matrix properties, boundary conditions, and potential distribution within a sample, a flux will be calculated. The calculated flux will be compared with the measure flux. The comparisons will indicate model accuracy in predicting the flux at different boundary conditions under applied stresses.

3.1.10 Materials and equipment for the intact-fracture test

A list of the equipment necessary to perform the Intact-Fracture Test is provided in Table 3.1-1. The equipment listed is for the Intact Fracture Test in and ESF and for developmental and prototype work.

ble 3.1-1. Instrumentation, equipment, and material for the Intact-
cture Test.

Item
Drill rig for core collection.
Dust collection unit, an Atlas-Copco model 220 or equivalent.
Air compressor; capable of supplying sufficient air volume for drill rig.
Diamond-impregnated, Norton Christiansen yellow matrix or equivalent, core bits with an inside diameter of 10 inches (welded rock material).
Carbide core bits with an inside diameter of 10 inches (nonwelded rock material).
Surface-set, diamond core bits with an outside diameter of 0.75 inches (welded rock material).
Carbide core bits with an outside diameter of 0.75 inches (nonwelded rock material).
Rock bolts with a 0.375-inch outside diameter, flat washers to 2-1/2 hes diameter, and hexagonal nuts (9/16-inch).
Downhole videoprobe, 12-mm outside diameter.
Wedge tool.
Core shovel for 10-inch core.
Slab saw.
High capacity loading frame.
Hydrostatic confining cells and confining assembly.
Uniaxial load confining cells.
Mass flow meters and monitor for gas injection.
Flow meter apparatus for liquid injection (these include flow tanks, pressure transducers, N2 supply, servovalves, and orifice meters) and outflow collection.
Linear variable differential transformers (LVDTs).

ble 3.1-1 (continued) . Instrumentation, equipment, and material for e Intact-Fracture Test.

Item
Thermocouple psychrometers and tensiometer equipment (including packers for instrumenting cores).
Moire projection equipment and accessories for flow channelization topography.
Electrical resistivity equipment (electrodes, LRC meter).
Isothermal bath.
Balances.
Vacuum oven.
Vacuum saturation table.
Programmable DC voltage sources.
Digital multimeters.

3.1.11 Schedules and milestones

A tentative schedule for the tests to be conducted under the Intact Fracture Test activity is presented in Figure 3.1-5. These figures illustrate the approximate durations and interrelations of the tasks that will be accomplished under this activity.

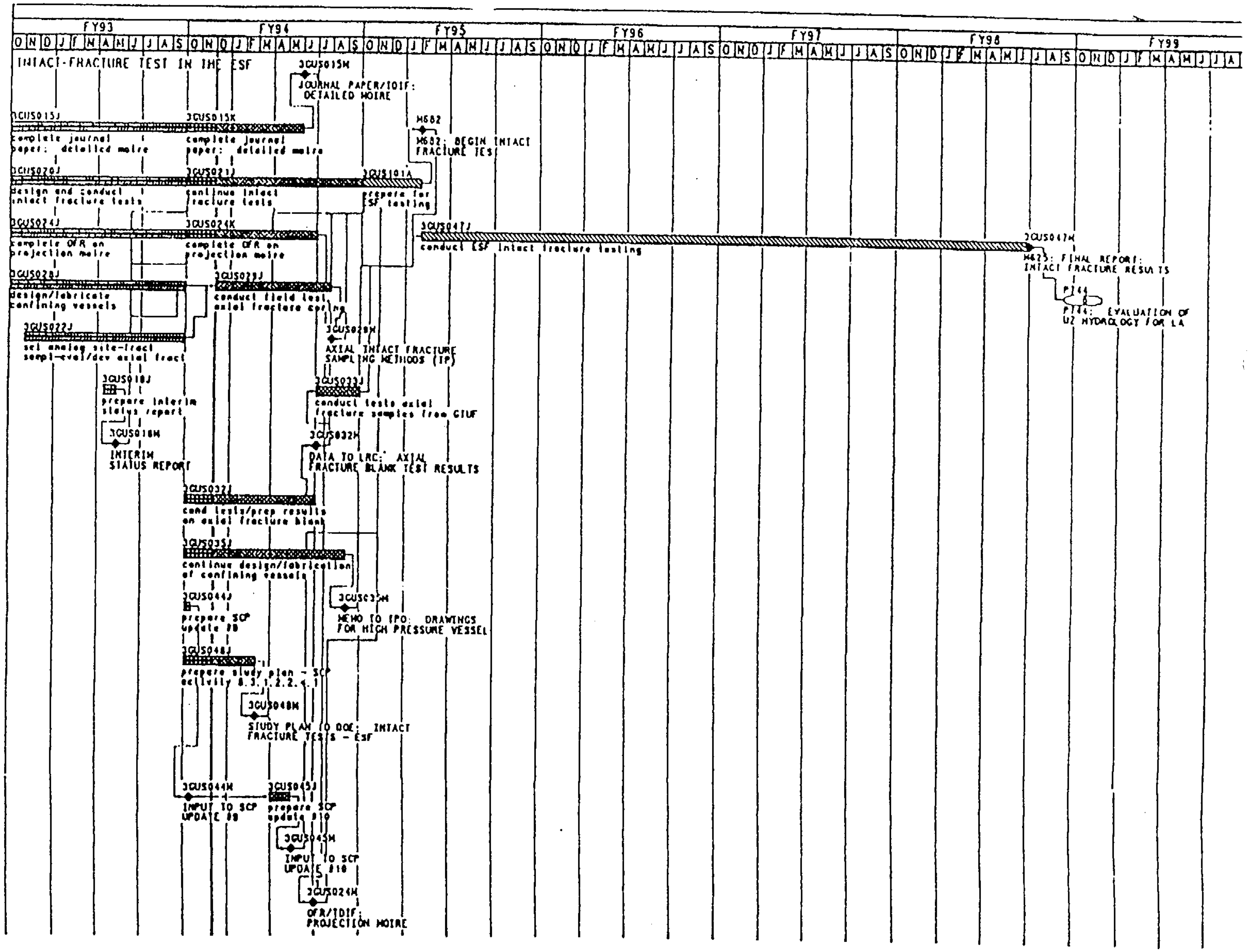

Figure 3.1-5. Summary of schedule and milestones for the Intact Fracture Test in the ESF.

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PERCOLATION TESTS IN THE ESF

YMP-USGS SP 8.3.1.2.2.4.2

This is a part of the Unsaturated Zone Percolation Study
YMP-USGS SP 8.3.1.2.2.4

August, 1994

ABSTRACT

This study plan is a supporting activity for SP 8.3.1.2.2.8, Development of Conceptual and Numerical Models of Flow in Unsaturated, Fractured Rock. The objective is to provide data that can be used in SP 8.3.1.2.2.8 to test models of fluid flow in variably saturated and fractured rock. Flow experiments will be performed in the ESF on blocks of fractured rock. Experiments will be repeated at several locations where matrix and/or fracture properties are expected to significantly vary.

Blocks with well characterized matrix and fracture properties will be instrumented. Boundary conditions will be controlled. Inflow and outflow rates will be measured at different boundary conditions. The measured flow rates will be compared with calculated flow rates. The comparison will indicate model accuracy in predicting flux at different conditions.

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3.2.1 Objective and rationale of activity

3.2.1.1 objective

This activity is a supporting test for SP 8.3.1.2.2.8, Development of Conceptual and Numerical Models of Flow in Unsaturated, Fractured Rock. The objective is to provide field data from well characterized systems that can be used in SP 8.3.1.2.2.8 to develop and test conceptual and numerical models of fluid flow and transport in variably saturated and fractured rock at the proposed repository site. Since the permeability of the fractured system at Yucca Mountain is expected to be spatially variable, the limited number of experiments as proposed in this activity is not expected to yield hydrologic properties that are statistically reliable.

3.2.1.2 rationale

Field measurements are required for SP 8.3.1.2.2.8 to examine existing hypotheses and generate alternative hypotheses, if necessary, to explain the behavior of fluid flow in unsaturated, fractured rock. The hypotheses will be used to develop and test conceptual and numerical models of fluid flow and transport in variably saturated and fractured rock. The models will later be used in SP 8.3.1.2.2.9, Unsaturated-Zone Modelling and Synthesis, to predict long-term behavior of the proposed repository.

Models in SP 8.3.1.2.2.8 will be tested at different scales. Activity 8.3.1.2.2.4.1, Intact Fracture Test, will provide samples at the laboratory scale. Activity 8.3.1.2.2.4.2, this activity, will provide samples at a larger scale.

3.2.2 Constraints on activity

3.2.2.1 timing

This activity is not a construction-phase test. It may be started any time after access is available to the desired testing locations. Results from this test are required for SP 8.3.1.2.2.8 milestone "RPT, INTERMED. FRACTURE-FLOW MODEL OF YM", due in September 1996. A minimum of 1 year of testing time is required for each test site.

3.2.2.2 initiation of field work

Field work may not be started until an approved Job Package is completed in accordance with AP-5.21Q, Field Work Activation. The testing procedure as described in this study plan may be changed to meet field conditions not yet identified. Changes may be made provided the test objectives will be met.

3.2.2.3 interference with and impacts on other field tests

This test may be conducted in (a) locations specifically excavated for this activity, or (b) locations shared with existing or planned ESF tests. Sharing test locations with other activities will be considered if it becomes cost effective, and the other activities will not interfere with this test. This test will be conducted away from the main access tunnel in rooms that will be constructed using drilling and blasting. A wire saw will be used to cut blocks as will be explained in sec. 3.2.4.3. Water will be used for cooling the wire saw cable during sample cutting. Therefore, test locations should be such that blast effects and cooling water will not interfere with or affect other neighbouring activities.

3.2.3 Scope of work

3.2.3.1 data required from this test

As explained earlier, this activity is a supporting test for SP 8.3.1.2.2.8. The information required from this test will help resolve some of the technical issues listed in SP 8.3.1.2.2.8, section no. 3.1.4. Sufficient experimental measurements are required to minimize parameter guessing and unsupported model adjustments during the modelling phase in SP 8.3.1.2.2.8. The measurements include:

(a) well-defined fracture networks and fracture properties, including fracture maps, equivalent pneumatic apertures, and fracture fillings (mineral types and areal distribution);

(b) well-defined matrix hydrologic properties, such as porosity, permeability, and moisture characteristic curves;

(c) known boundary conditions, such as inflow and outflow water rates, boundary matric potential, atmospheric pressure, and temperature;

(d) water and matric potential distribution within the tested samples in both the fractures and the matrix.

In addition to the above mentioned measurements, fracture samples will be prepared and tested according to SP 8.3.1.2.2.4.1, Intact Fracture Test in the ESF.

3.2.3.2 test locations

The objective of this test is to gather information that will be used to test the performance of unsaturated flow models in fractured rock. Experiments will be conducted at several locations in the ESF. The locations will reflect the different horizons where hydrologic properties are expected to significantly change. If the properties show sharp changes between unit contacts, then at least one block will be cut to include such a contact. The preliminary test repetitions and locations are:

(a) one at the geologic contact of the Tiva Canyon welded unit (TCw) - Paintbrush Tuff nonwelded unit (PTn);

(b) one at the contact of the Paintbrush Tuff nonwelded unit (PTn) - Topopah Spring Welded unit 1 (TSw1);

(c) two in the Main Test Level at the Core Test Area;

(d) two in the Calico Hills formation, if excavated.

The first two locations will be in the North Ramp Alcoves where the above mentioned geologic contacts are sighted.

If it is cost effective, the tested samples may be removed from the ESF and tested in a laboratory.

3.2.3.3 test configuration

The objective of this study is to make water flow measurements in well-defined systems. The test measurements as listed in section 3.2.3.1 need to be made. The following experimental requirements will be needed to meet the test objectives:

(a) minimization of flow uncertainties: to minimize uncertainties in the outflow water measurements, all potential hydraulic paths between a sample and its surrounding need to be identified. All inflow and outflow amounts need to be measured. This will necessitate sealing or isolating all potential paths between sample faces and the surrounding.

(b) access for visual fracture mapping: fractures in the tested samples need to be fully identified to minimize uncertainties in flow paths. Fractures can be mapped along the sample faces. Three-dimensional fracture maps can be constructed if all sample faces are exposed and mapped; however, uncertainties in the spatial extent of some fractures can not be avoided. Such fractures include those that are visible along a face and end inside a tested block, or those that start and end inside a block without intersecting any of the exposed surfaces. Video camera logging through instrumentation holes will clarify some fracture uncertainty.

(c) access for instrumentation: access for instrumentation is required to install devices that will be used to measure pneumatic apertures, water and matric potentials, and inflow and outflow rates. Aperture and water and matric potential measurements will be done with devices installed in holes that intersect fractures or matrix. To drill the instrumentation holes, access from some or all the sides will be required. Sufficient clearance will be needed for the drill and saw used to drill holes and cut the samples. Access to the top and bottom faces of a sample is also required to control the inflow and outflow rates.

3.2.3.4 sample size

The hydrologic properties of fractured rock are extremely heterogeneous (SP 8.3.1.2.2.8, sec. 3.1.7.5). The size of a field sample needs to be large enough to include sufficient variations in properties, and small enough to instrument and monitor. A preliminary estimate of the sample size is 2-m (6.6-ft) cube. Such a size will be large enough to include several fractures, and small enough to be manageable for drilling and instrumentation. Preliminary modelling will be done under SP 8.3.1.2.2.8 to select a proper sample size. Subsequent samples may vary in size depending on results from the first experiment.

3.2.4 Detailed test description

The experimental design given here is preliminary. It may be changed following evaluation studies which will be conducted under SP 8.3.1.2.2.8. Furthermore, the experimental design may be changed following the first field experiment to account for any changes that may improve the design of successive tests.

3.2.4.1 sample location and access

Based on fracture maps, a preliminary sample location will be identified. A location is required where a continuous path through fractures exists since fracture flow measurements between the top and bottom of fractured blocks will be made during this study.

All excavations will be done with methods that will minimize damage, e.g. controlled blasting. After a test location is identified along a main drift, two parallel drifts will be excavated as shown in Figure 3.2-1, plan view. They will provide access to a pillar from which a sample will be cut. The drifts need to extend beyond the sample location to provide sufficient space for a drill that will later be used to drill the back face of the sample. Drift dimensions will depend on the space required to fit and operate the drilling and cutting machines; they will be determined by the organization responsible for drilling. The pillar width will depend on the sample size plus thickness of the two end slabs.

3.2.4.2 initial examination and supporting

initial examination

Several holes between the two drifts will be drilled to examine the interior part of the pillar. The pillar will be examined to choose a block that will include fractures that appear conductive and continuous between the top and bottom. The examination will be achieved with a video camera and gas injection probes. Hole diameter will be determined shortly before excavation. The hole size should be sufficient to fit the instruments and proper for anchoring rock bolts as described below.

installation of initial support system

After removing the gas injection probes, rock bolts will be installed in the same holes to hold the identified sample together while it is cut. This is required to prevent sample breakage along fractures that are continuous through a sample. To avoid fracture plugging, grout, if used with rock bolts, should be prevented from intruding extensively into fractures. It will be difficult to enforce fractures parallel to section B-B as shown in Figure 3.2-1. Therefore, a sample has to be chosen such that fractures parallel to section B-B are less likely to occur. This can be achieved after mapping the surface fractures along the two access drifts.

3.2.4.3 sample cutting

The identified sample block will be cut from the pillar. All six faces of a sample will successively be exposed by removing slabs from the pillar between the two access drifts using a wire saw (see Figure 3.2-1). Except the end slabs, all other slabs will be tapered to facilitate their removal.

The slabs may be cut with a wire saw. Cooling water will be required to operate a wire saw. Water will be tagged with a tracer (see section 3.2.4.10 for a list of tracers) to estimate the amount that may go in the matrix and fractures. Excessive cooling water may need to be collected if it affects other neighbouring tests.

Holes will first be drilled to outline the tapered slabs that will be cut with the wire saw. Ten holes will initially be required as shown in Figure 3.2-1, section A-A. The diameter of the holes will depend on the size of the wire saw that will be used for this operation. The saw cable will be threaded through a pair of holes that define a cutting plane. After a cut is finished, the tapered slab will be pushed into the drift adjacent to the wider end. Bottom cuts should first be made to prevent a slab from falling on and jamming the saw cable.

The bottom slab will first be cut so that a support system can be installed. Holes C2, C3, D2, and D3 in Figure 3.2-1, section A-A, outline the bottom slab. Planes D2-D3, C2-D2, C3-D3, and C2-C3 will successively be cut. The four cuts will free the bottom slab. Hydraulic rams or chain hoists may be used to remove the slab. A Jack hammer may also be used to break the slab and remove it in pieces. The bottom face will be mapped for fractures using a video camera.

A support system will be installed beneath the block. The support system needs to be mobile such that the sample can be maneuvered between the two access drifts. Maneuverability is required to provide access for cutting the side slabs and to drill and instrument the front and back faces. Tracks may be used to support the block after leveling the ground between the two drifts.

Next, the top slab will be cut. This stage will be the most difficult since the top slab will rest on the block and not on the floor as with the bottom and side slabs. It is preferred to cut the top slab before the side slabs to preserve the integrity of the block while removing the top slab. Planes B1-B4, A1-A4, A1-B1,and A4-B4 will successively be cut. Slab removal will be similar to that of the bottom slab.

Next, the side slabs will be cut to free the block from its surrounding. Planes D1-D2, B2-C2, and B1-D1 for one slab, and planes D3-D4, B3-C3 and B4-D4 for the other slab will be cut.

The end slabs will be last to cut. Holes B6, B7, C6, and C7 will first be drilled (Figure 3.2-1, section B-B). Cuts along planes B6-C6, and B7-C7 will free the end slabs. After they are free, the slabs will rest on the bottom support system. They may be broken with jack hammers and removed in pieces. Access to drilling and cutting the side slabs will be possible by moving the block between the two access drifts.

3.2.4.4 preliminary fracture mapping

After exposing the six faces of a block, all surface fractures will be mapped. A preliminary three-dimensional map of the fracture planes will be created. This map will be used to determine locations for instrumentation boreholes. Fracture filling (mineralogy and extent) will be examined from the cut side slabs.

3.2.4.5 borehole drilling

Based on the preliminary fracture map, boreholes will be drilled to intersect fractures where the water and matric potentials will be monitored (number of holes has not yet been determined and will vary with different samples). While drilling these holes, they will be examined with a borehole video camera to detect fractures not visible along the outer faces of the block. The fracture data from this examination will be used to supplement the preliminary fracture map and complete it. Based on the updated map, other instrumentation boreholes may be drilled.

3.2.4.6 fracture permeability measurements

After drilling is completed, the permeability of the intersected fractures will be measured using packer gas-injection strings. Zones with identified fractures will be isolated and tested at several injection pressures. Both inflow rate and injection pressure will be monitored. Pressure will also be monitored in several surrounding holes to detect fracture interconnectedness. Method of estimating equivalent fracture aperture will be similar to the method outlined by Thamir et al. (1994).

3.2.4.7 borehole instrumentation

Following permeability measurements, the holes will be instrumented with thermocouple psychrometers and tensiometers. The choice will depend on the initial water and matric potentials of the block matrix. Thermocouple psychrometers will be used if the water potential in the block is between -7000 kPa and -100 kPa. Tensiometers will be used if the matric potential in the block is above -100 kPa. Thermocouple psychrometer and tensiometer probe design was described by Thamir et al. (1993).

3.2.4.8 infiltrometer design

The matric potential along the top and, if possible, the bottom faces will be controlled. Sand layers along these two faces will be used to evenly distribute the water pressure along the sample surfaces. Tensiometers will be installed in the upper sand layer to evaluate the matric potential along the top boundary as was the case in a previously conducted prototype test (Thamir et al., 1993, 1994). A water spraying system with controllable flow rate will be installed above the block to regulate the matric potential along the upper face. A water collection and measuring system will be installed below the block. Scales will be used to measure the inflow and outflow. The proposed system will be similar to a prototype system described by Thamir et al. (1994). It will allow the application of controllable inflow rates or matric potentials along the top boundary.

3.2.4.9 data acquisition system

All sensors will be connected to a data acquisition system which will be used to control the experiments and collect the data. Control functions will be required to (a) apply constant flow rates or constant matric potential along the top boundary, and (b) apply heating and cooling currents to the thermocouple psychrometers. Data collection will be required to record sensor readings from all instruments.

The ESF IDS will not be used to collect data from this test. The data acquisition system for this test will be supplied and operated by the PI's organization because the following features, which will not be offered by the ESF IDS, are required:

(a) control functions: control functions will be required to operate the thermocouple psychrometers and to regulate water flow rate and matric potential; and

(b) low voltage measurements: the thermocouple psychrometers require a data acquisition system with accuracy of at least 0.5 µVDC.

These features were incorporated in the data acquisition system for the Prototype Percolation Test (Thamir et al., 1993). A similar system can be used for the ESF field test.

The following additional information, not needed for the data acquisition system of the laboratory prototype experiment, will be required from the ESF IDS group:

(a) wiring methods: methods for wiring and shielding in the ESF to minimize measurement error in what may be an electrically noisy environment will be required;

(b) equipment housing methods: computer and data acquisition system housing specifications will be required to minimize ESF environmental effects on the equipment;

(c) interfacing methods: interfacing methods and specifications, for software and hardware, will be required to connect the data acquisition system to the ESF IDS. The format of the data collected by this test will need to conform to the format required by the organization responsible for data archiving and distribution (currently LANL). Such conformance will minimize accidental changes to data files by reducing the number of stages through which data have to go through before archiving. The data will be transferred to the ESF IDS for archiving and distribution. Facilities for data transfer, e.g. networking, need to be provided by the IDS group; and

(d) calibration responsibility: the group responsible for calibrating the measuring equipment, e.g. voltmeters and scanners, needs to be identified; it will be the IDS group or the PI. This responsibility must be identified before the test starts. Sensor calibration will be the PI responsibility.

3.2.4.10 experimental procedure

The experimental procedure will be similar to a previously conducted prototype laboratory test (Thamir et al., 1993, 1994). Water will be applied at the top of a block. Inflow and outflow water rates, water and matric potential of the boundaries, and water and matric potential distribution in the block will be measured. Water will be tagged with tracers of known concentrations, e.g. iodide, bromide, and borate. The tracers will be used to track each batch of water and to estimate the travel time at different boundary conditions through each block. To be able to account for all inflow and outflow amounts, the block sides will be isolated from the surrounding atmosphere to minimize water evaporation. Flow rate through each block, at different boundary matric pressures, will be measured. Lateral flow between the top and each side may be measured if a water collection system along the bottom of each face proves to be successful; otherwise, the sides will be sealed to prevent lateral flow.

Matrix properties such as porosity, permeability, and moisture characteristic curves, will be measured from samples that will be retrieved from the side slabs of each sample block. Fracture properties such as coatings and areal distribution of filling will also be estimated from the side slabs. Fracture samples will also be taken from the side slabs; the sampling and testing procedure will be according to SP 8.3.1.2.2.4.1, Intact Fracture Test in the ESF.

Bacterial growth is expected to occur in the tested blocks as it did during the prototype test (Thamir et al., 1994). The bacterial concentration in both the input and output water will be measured. Clean water needs to be used while preparing and testing the blocks to insure that new bacteria or nutrients are not added to the blocks. If the bacterial effect appears to significantly alter fracture permeability, then further studies need to be made since they are a part of the natural system.

3.2.4.11 factors that may affect experimental duration

From the previously run laboratory prototype test (Thamir et al., 1993, 1994), trapped gas may impede water movement in fractures. Initially, water pressure along the top of a block may need to be increased to values above 0.2 kPa (20 cm of water) to flush gas out of fractures and initiate flow. The outflow may periodically and temporarily stop after flow through the block is established; however, the stoppage may depend on the experimental design rather than being a property of fracture flow.

Steady state may not be achieved in a reasonable time. Output flow rate may not stabilize under a constant boundary pressure (Thamir et al. 1994). There are two possibilities for an unstable flow rate to happen: (1) continuous trend (increasing or decreasing), and (2) continuous fluctuation (increasing and decreasing). With a continuous trend, other factors will need to be investigated, eg. air entrapment and bacterial growth. With a continuous fluctuation, the definition of steady state may need to be revised to be considered over longer periods. With either case, naturally occurring effects will need to be differentiated from experimental artifacts.

3.2.5 Application of results

Several field tests will successively be conducted under this activity. The experimental results will be used to test unsaturated flow models under SP 8.3.1.2.2.8. From the known fracture and matrix properties, boundary conditions, and potential distribution within a sample, a flux will be calculated. The calculated flux will be compared with the measured flux. The comparison will indicate model accuracy in predicting flux at different conditions.

3.2.6 Schedule

All dates are based on the ESF excavation schedule prepared in June, 1994.

Initial results from this test are required for SP 8.3.1.2.2.8 milestone "RPT, INTERMED. FRACTURE-FLOW MODEL OF YM", which is due in September 1996. To meet this requirement, an initial data report will need to be finished 3 months earlier, i.e. in May 1996. Data for this milestone will be from tests in the North Ramp Alcoves.

Final results from this test will be required to prepare the final report of fracture flow model under SP 8.3.1.2.2.8. This report will be due between 1997 and 2000 (date has not yet been determined). Results for this milestone will be from all block tests as listed in section 3.2.3.2.

The laboratory prototype test took approximately one year to conduct after water went through the block. Therefore, it is estimated that at least one year will be required to conduct each of the ESF block tests since the ESF blocks are larger than the prototype test block. Test preparation will take about 3 months; it will include block cutting, fracture mapping, drilling of instrumentation holes, permeability measurements, and instrumentation. Sufficient time needs to be given to purchase and calibrate sensors and data acquisition systems.

To meet the May 1996 date, block testing in the North Ramp Alcoves needs to start at the beginning of 1995. Tests in the main test level will start when the core test area is prepared. Currently, this area is scheduled to be ready for testing during the first quarter of 1996.

3.2.7 References

Thamir, F., E.M. Kwicklis, and S. Anderton, 1993, "Laboratory Study of Water Infiltration into a Block of Welded Tuff", Proceedings of the 4th Annual International Conference on High Level Radioactive Waste Management, American Nuclear Society, April 26-30, p. 2071-2080.

Thamir, F., E.M. Kwicklis, D. Hampson, and S. Anderton, 1994, "Observations of Water

Movement in a Block of Fractured Welded Tuff", Proceedings of the 5th Annual International Conference on High Level Radioactive Waste Management, American Nuclear Society, May 22-26, p. 2020-2029.

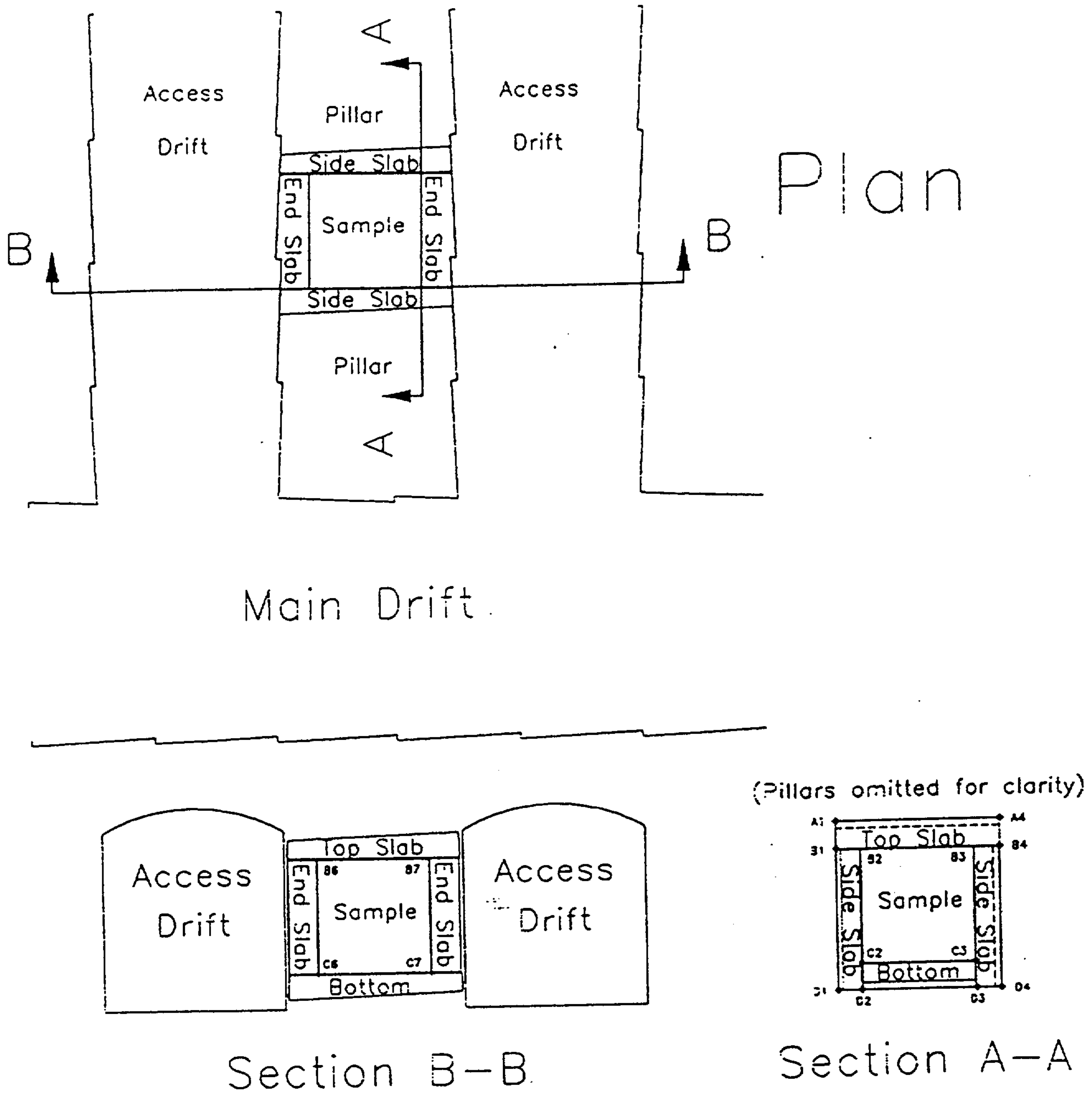

Figure 3.2-1 Plan and section views of a test location showing access to a test block and cutting sequence.

USGS-SP-8.3.1.2.2.4, R3

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5/5/93

YUCCA MC ITAIN SITE CHARACTERIZATIC PROJECT
STUDY PLAN APPROVAL FORM

Study Pla Number 8.3.1.2.2.4

Study lan Title Characterization of the Yucca Mountain Unsaturated Zone in the Exploratory Studies Facility

Revision Number 2

Prepared by: U.S. Geological Survey

Date: May 26, 1994

Approved:

6/2/94
Director, Regulatory and Site Evaluation Division / Date

R. E. Spence 6/2/94
Director, Quality Assurance Division / Date

Effective Date: 6/14/94

AP-1.10Q

ABSTRACT

This study plan describes the plans for four of the five unsaturated-zone hydrologic site-characterization activities to be performed in and adjacent to the Yucca Mountain exploratory-studies facility (ESF) during construction. These USGS underground activities are expected to contribute to an understanding of the *in-situ* hydrologic characteristics of the unsaturated zone, to provide an understanding of the impacts of the ramps and drifts construction on the *in-situ* characteristics, and to provide hydrologic-parameter input for the resolution of design and performance issues. The four activities include:

- Radial-borehole tests,
- Perched-water tests,
- Hydrochemistry tests, and
- Excavation-effects tests.

Plans for the fifth activity, hydrologic properties of major faults, will be included in a subsequent revision of the study plan.

The plans for *in-situ* hydrologic testing in the ramps and drifts of the ESF will be included in a subsequent revision of the study plan. These three activities include:

- Intact fracture tests,
- Percolation tests, and
- Bulk-permeability tests.

The rationale of the overall unsaturated-zone ESF study is described in Sections 1 (regulatory rationale) and 2 (technical rationale). Section 3 describes the specific activity plans, including the tests and analyses to be performed, the selected and alternate methods considered, and the technical procedures to be used. Section 4 summarizes the application of the study results and Section 5 presents the schedules and associated milestones.

RECORD OF REVISIONS

REVISION NUMBER	REVISION	DATE
R0	Study rationale and plans for four construction-phase activities Radial-borehole tests (Section 3.4) Excavation-effects tests (Section 3.5) Perched-water tests (Section 3.7) Hydrochemistry tests (Section 3.8)	3-24-88
	Addition of plans for multipurpose-borehole activity (Section 3.9); revision of radial-borehole activity in response to addition of multipurpose-borehole activity. Revisions in response to SCP statutory draft changes.	1-03-89
R1	Study rationale and plans for four construction-phase activities Radial-borehole tests (Section 3.4) Excavation-effects tests (Section 3.5) Perched-water tests (Section 3.7) Hydrochemistry tests (Section 3.8) Deletion of Calico Hills tests and multipurpose-borehole tests	12-92

CHARACTERIZATION OF THE YUCCA MOUNTAIN UNSATURATED ZONE IN THE EXPLORATORY STUDIES FACILITY

YMP - USGS - SP 8.3.1.2.2.4, R1

STUDY PLAN

DECEMBER 1992

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1 PURPOSE AND OBJECTIVES OF STUDY

1.1 Purpose of the study plan

The U.S. Geological Survey (USGS) is conducting studies at Yucca Mountain, Nevada, as part of the Yucca Mountain Project (YMP). The purposes of the USGS studies are to provide geologic and hydrologic information to evaluate the suitability of Yucca Mountain for development of a geologic high-level nuclear-waste repository and the ability of the mined geologic-disposal system (MGDS) to isolate the waste in compliance with regulatory requirements. In particular, the project is designed to acquire information necessary for the U.S. Department of Energy (DOE) to demonstrate in its environmental-impact statement and license application that the MGDS can meet the requirements of federal regulations 10 CFR Part 60, 10 CFR Part 960, and 40 CFR Part 191.

This study plan describes the USGS plans for *in-situ* hydrologic characterization of Yucca Mountain from the ramps, drifts, and associated boreholes of the exploratory-studies facility (ESF). The study is now organized into eight activities:

- 8.3.1.2.2.4.1 - Intact-fracture test,
- 8.3.1.2.2.4.2 - Percolation test,
- 8.3.1.2.2.4.3 - Bulk-permeability test
- 8.3.1.2.2.4.4 - Radial-borehole test,
- 8.3.1.2.2.4.5 - Excavation-effects test,
- 8.3.1.2.2.4.6 - Calico Hills test (ACTIVITY DELETED)
- 8.3.1.2.2.4.7 - Perched-water test,
- 8.3.1.2.2.4.8 - Hydrochemistry tests,
- 8.3.1.2.2.4.9 - Multipurpose-boreholes testing near the exploratory shafts (ACTIVITY DELETED), and
- 8.3.1.2.2.4.10 - Hydrologic properties of major faults encountered in the ESF.

Note that the numbers (e.g., 8.3.1.2.2.4.1) used throughout this plan provide references to specific sections of the YMP Site Characterization Plan (SCP) (U.S. DOE, 1988). The SCP describes the technical rationale of the overall site-characterization program and provides general descriptions of the activities described in detail in Section 3 of this study plan.

Figure 1.1-1 illustrates the location of the study within the SCP Geohydrology Program. This study in the ESF is one of nine studies planned to characterize the unsaturated zone at Yucca Mountain; the

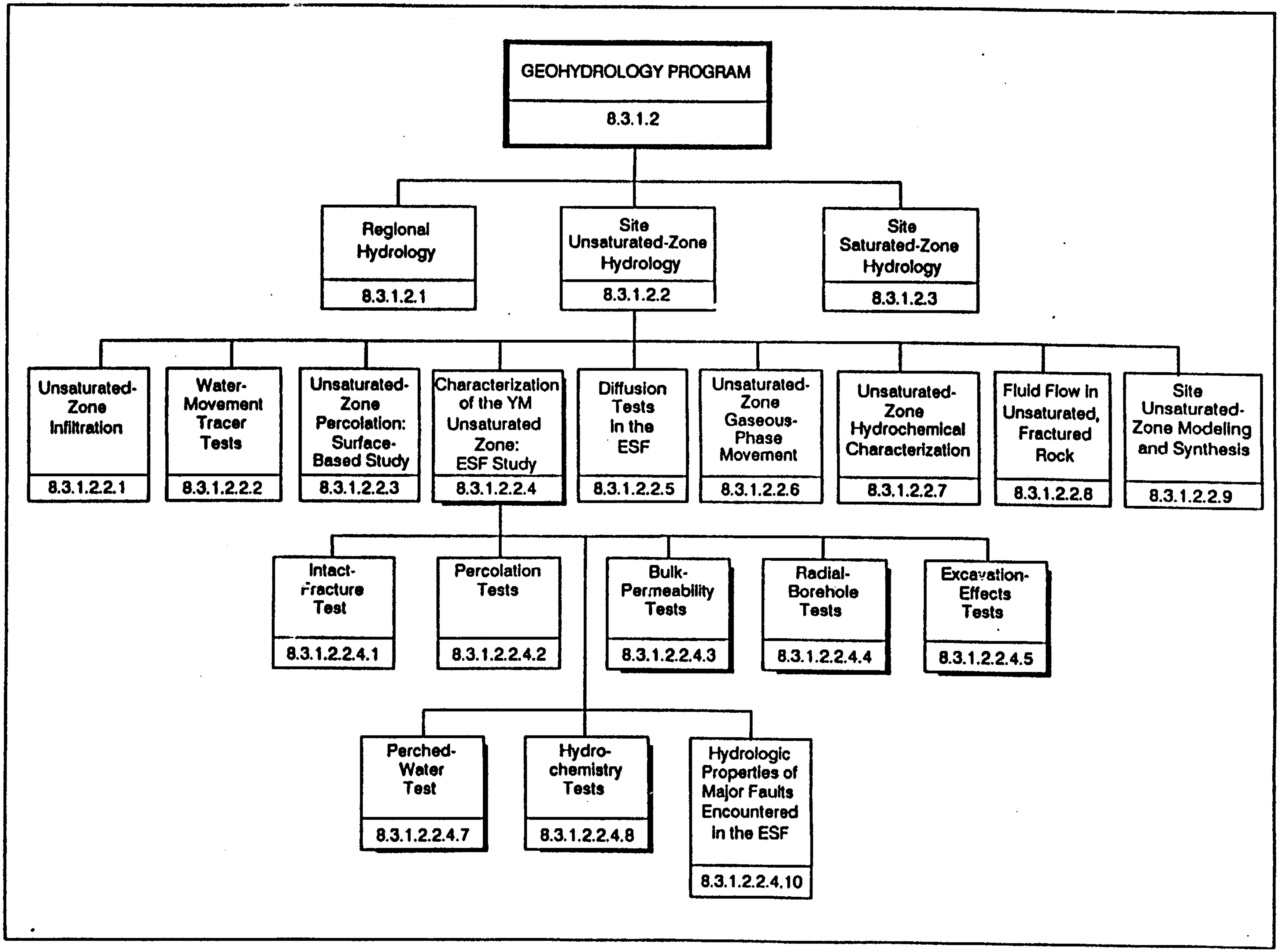


Figure 1.1-1. Diagram showing the location of the ESF characterization of the YM unsaturated zone study within the unsaturated-zone investigation and the Geohydrology Program.

others are part of the surface-based evaluations. The eight activities in the study were selected on the basis of various factors. Time and schedule requirements were considered in determining the number and types of tests chosen to obtain the required data. Tests were designed on the basis of design and performance parameter needs, available test and analysis methods, and test scale and interference. These factors are described in Sections 2 and 3.

The descriptions and plans for each activity are presented in Section 3. The descriptions include (a) objectives and parameters, (b) technical rationale, and (c) tests and analyses. Alternate test and analysis methods are summarized, and cross references are provided for technical procedures.

Five hydrologic test activities are planned during the ESF construction phase. They are the radial-borehole tests (Activity 8.3.1.2.2.4.4), excavation-effects tests (Activity 8.3.1.2.2.4.5), perched-water tests (Activity 8.3.1.2.2.4.7), hydrochemistry tests (Activity 8.3.1.2.2.4.8), and hydrologic properties of major faults (Activity 8.3.1.2.2.4.10). Revised plans for the first four of these activities were included in Revision 1 of the study plan, in Sections 3.4, 3.5, 3.7, and 3.8, respectively. Plans for the major-faults activity is included in this revision of the study plan. Three other activities will be conducted as part of the *in-situ* testing in the drifts of the ESF: the intact-fracture tests (Activity 8.3.1.2.2.4.1), percolation tests (8.3.1.2.2.4.2), and bulk-permeability tests (Activity 8.3.1.2.2.4.3). The plans for these activities will also be presented in a subsequent revision.

The Calico Hills tests (Activity 8.3.1.2.2.4.6) and the multipurpose-borehole testing (Activity 8.3.1.2.2.4.9) have been dropped from the study, for reasons presented in Sections 3.6 and 3.9, respectively.

Application of the study results is summarized in Sections 1.3 and 4, schedules and milestones are presented in Section 5, and a study-plan reference list is presented in Section 6.

1.1.1 Objectives of the study

Hydrologic evaluation of the unsaturated zone will be conducted as an integrated set of surface-based and ESF activities with a common objective to provide an understanding of the past, present, and future fluid flow characteristics in the unsaturated zone at Yucca Mountain.

Surface-based testing will be conducted on the land surface and in vertical and horizontal holes drilled into the repository host rock and surrounding units. Surface-based borehole studies designed to investigate the deep unsaturated zone are described in YMP-USGS SP 8.3.1.2.2.3 (Unsaturated-zone percolation - surface-based studies), and are integrated with the ESF activities (described in this plan) in terms of technical objectives, spatial locations, and parameter determinations. (Parameter is used in this plan to mean a property, characteristic, and/or the numerical value of a constant that is used to describe the unsaturated-zone hydrologic system).

The north and south ramps, underground drifts, and associated boreholes of the ESF will provide (1) an opportunity to evaluate the *in-situ* unsaturated-zone hydrologic properties in orientations not achievable from surface-based boreholes, (2) an opportunity to directly inspect the structure and stratigraphy of the rock walls of the ramps and drifts, and (3) an opportunity to evaluate the rock-matrix and fracture-hydrologic parameters for a wide range of test scales. Figure 1.1-2 illustrates the map location of the ESF at Yucca Mountain. Figure 1.1-3 illustrates the conceptual layout of the ESF.

The objective of this ESF unsaturated-zone study is to understand the spatial distribution of present water flow within the unsaturated zone. Plans for studies of past and future unsaturated-zone flow characteristics are described in YMP-USGS SP 8.3.1.2.2.7 (Unsaturated-zone hydrochemistry) and YMP-USGS SP 8.3.1.2.2.9 (Unsaturated-zone modeling and synthesis). Hydrologic studies of infiltration from the land surface (YMP-USGS SP 8.3.1.2.2.1), and site-saturated zone studies (YMP-USGS SP 8.3.1.2.3.1), provide boundary condition information for models of unsaturated-zone percolation. A more detailed discussion regarding the modeling activities associated with this study can be found in the "Characterization of fuild flow in unsaturated, fractured rock" study plan (YMP-USGS-8.3.1.2.2.8). The site-scale unsaturated-zone modeling activities are in study plan YMP-USGS-8.3.1.2.2.9.

The salient conditions to be characterized in the unsaturated zone include the hydraulic and matric potential gradients that extend from the land surface to the water table (350 to 750 m; 1,150 to 2,460 ft beneath Yucca Mountain). These potential gradients may vary discontinuously between geohydrologic units. Figure 1.1-4 shows the relation between the stratigraphic and geohydrologic units at Yucca Mountain. The characterization of flow beneath Yucca Mountain must include, for all geohydrologic units, the determination of flow distribution under a variety of conditions. As flux is difficult to measure at either the infiltration boundary (land surface) or the water table, it must be estimated from either the potential water distribution and the conductive properties of the rocks or by other indirect methods.

From the viewpoint of waste isolation, the most significant site-characterization findings will be to predict the transport of radionuclides from the repository, beneath Yucca Mountain, to the water table. SCP Sections 8.3.5.12 (Ground-water travel time) and 8.3.5.13 (Total-system performance) describe the need for this essential information. The hydraulic-properties data that will be used for these unsaturated-flux calculations will be collected by the USGS in the surface-based and ESF unsaturated-zone percolation studies.

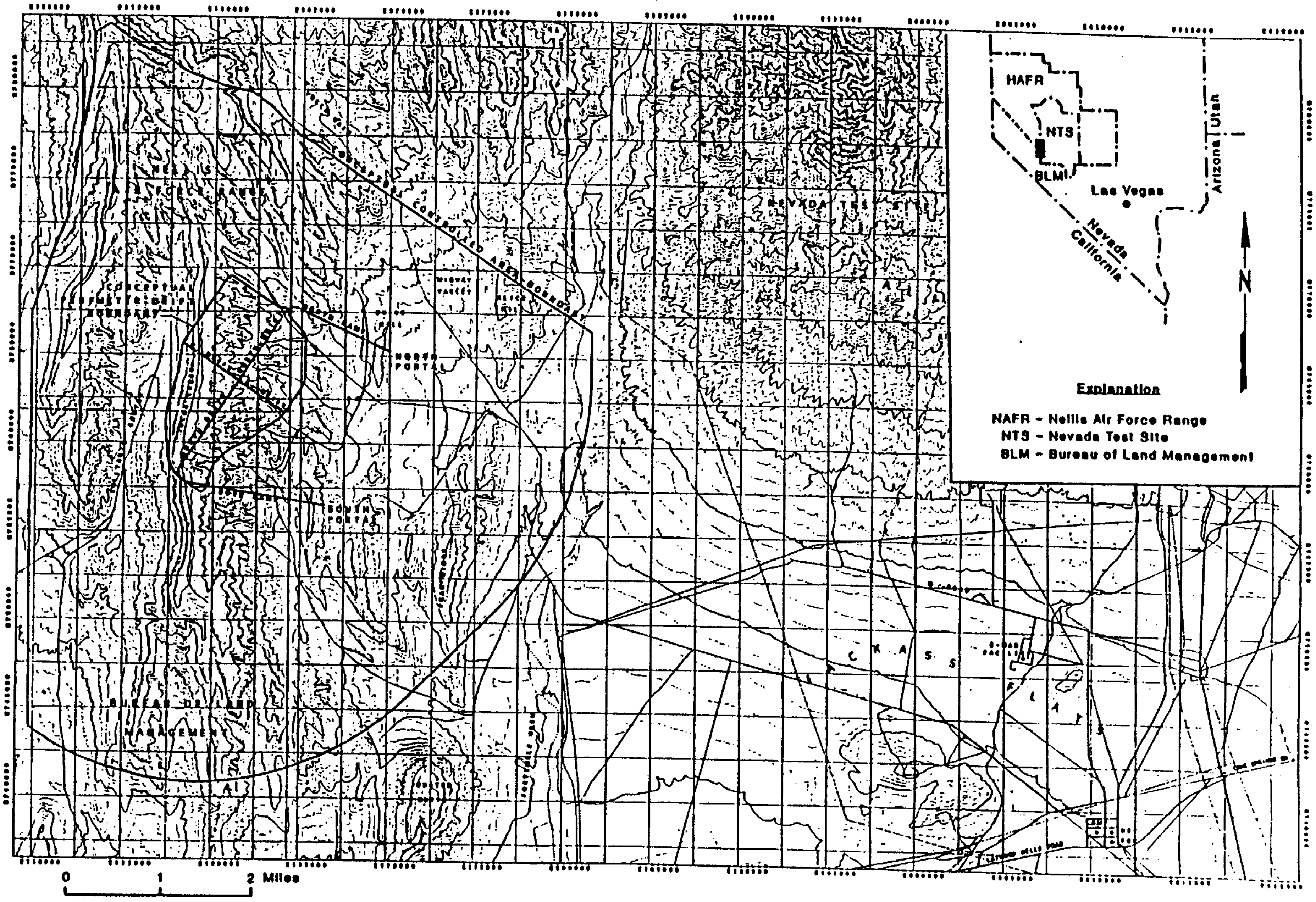


Figure 1.1-2
Map Showing Location of Exploratory Studies Facility at Yucca Mountain

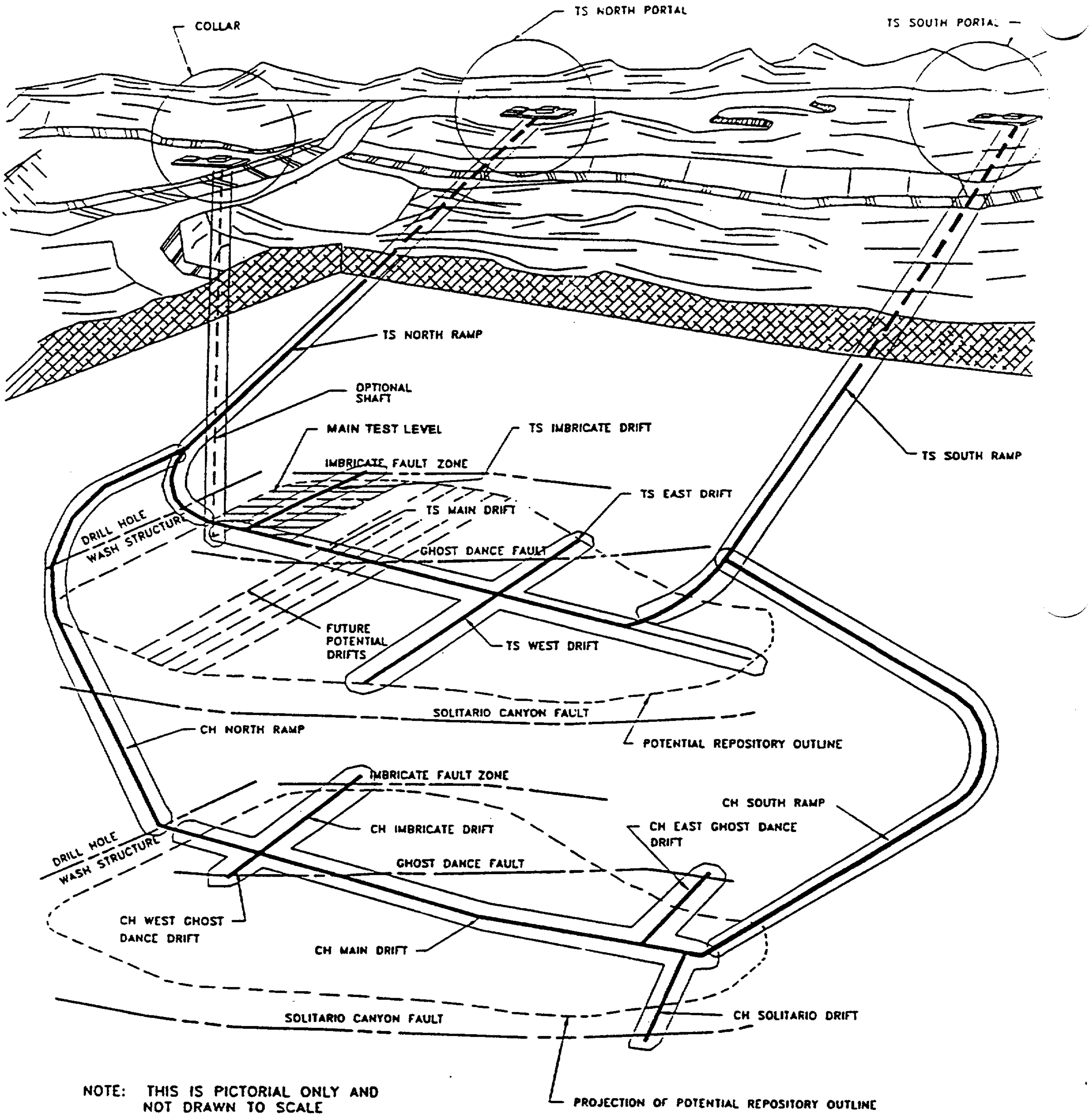
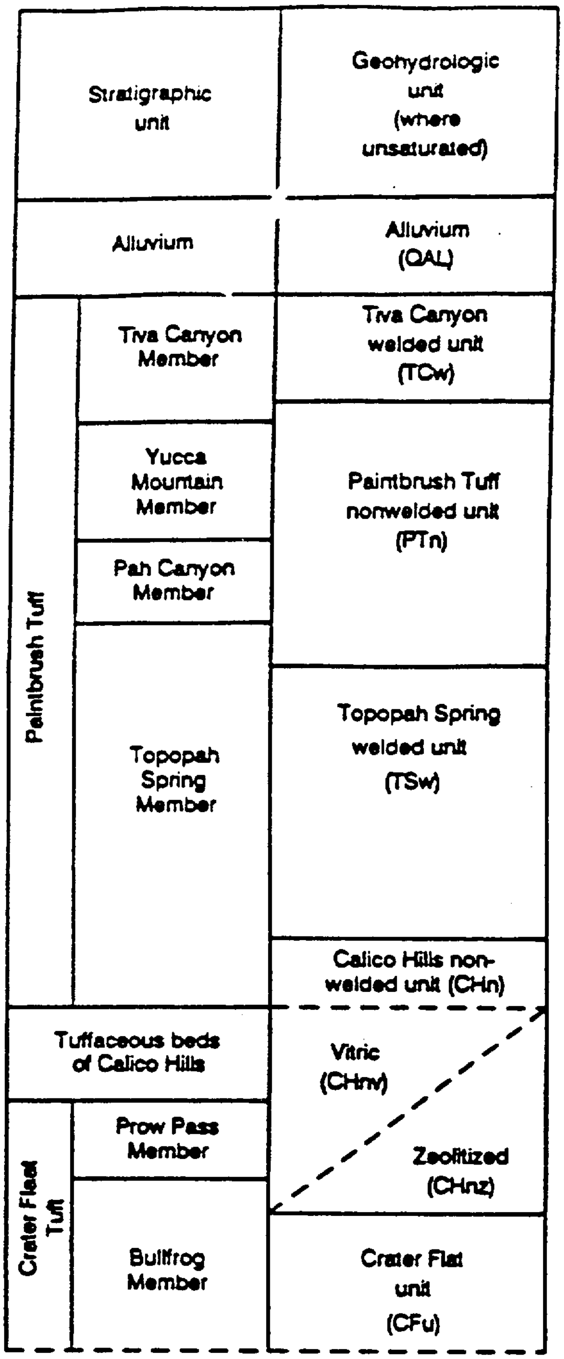


Figure 1.1-3. Conceptual illustration of the exploratory studies facility.



Note: Figure not to scale

Figure 1.1-4. Diagram showing the relation of geohydrologic units to stratigraphic units (modified from Montazer and Wilson, 1984).

Gas flow in the unsaturated zone has an important hydrologic role, as well as providing a mechanism for transport of gaseous radionuclides to the accessible environment. Whereas the coexisting matrix pores and fractures greatly complicate computations of total-system behavior under present or estimated future conditions, the possible existence of large-aperture fractures provides for large relative gas permeability. Natural gas-phase flow is driven by seasonal atmospheric-density differences between the mountain slopes and mountain summit, and by geothermal heat. Vapor discharges from the air-filled fractures may inhibit water percolation from rain and snow melt because of convective and diffusive vapor discharge to the land surface. If air flow reduces the matrix water content, by drying the matrix immediately adjacent to the fractures, the resulting increased water tension would aid in damping infiltration pulses that may be channeled in fractures. It is important to be able to quantify vapor flow because it may be opposite in direction to liquid flow, and of similar flux. Current knowledge of and site-characterization efforts for unsaturated-zone gas flow appear in YMP-USGS SP 8.3.1.2.2.6 (Yucca Mountain unsaturated-zone gaseous-phase movement).

Hydraulic, pneumatic, and hydrochemical testing and analysis will be conducted as part of this ESF unsaturated-zone study to provide an understanding of the conditions and processes described above. Integration of this information with the results of other hydrologic studies (Figure 1.1-1) will provide the basis for the development of the unsaturated-zone hydrologic model described in Section 2.

1.2 Regulatory rationale and justification

The results of unsaturated-zone testing conducted in the ESF ramps and drifts will provide hydrologic data for calculations of the unsaturated-zone ground-water travel time and the predictions of radionuclide releases to the accessible environment. Hydrologic properties determined in the study will be used in design analyses of the underground facility, repository seals, and waste packages.

The overall regulatory-technical relations between the SCP design and performance information needs and the data collected in this study are presented in the geohydrology testing strategy presented in SCP Section 8.3.1.2 and the issue-resolution strategies (repository, seals, waste package, and performance assessment) presented in SCP Sections 8.3.2 through 8.3.5. The description presented below provides a more specific identification of these relations as they apply to this study.

Project-organization interfaces between this ESF unsaturated-zone study and the YMP performance and design issues are illustrated in Figure 1.2-1. The figure also indicates project interfaces with other site studies; these relations are described further in Section 4.2. The relations between the design and performance issues noted below and the regulatory requirements of 10 CFR 60 and 10 CFR 960 are described in Section 8.2.1 of the SCP.

Information derived from the study will principally support the determinations of pre-waste-emplacement, ground-water travel time (Issue 1.6) and the predictions of radionuclide releases to the accessible environment (Issue 1.1). Study results will also provide information for the resolution of the issues concerned with the near-field hydrologic environment of the waste-package emplacement holes (Issue 1.4) and releases from the repository engineered-barrier system (Issue 1.5).

Physical, hydrologic, and hydrochemical information about the unsaturated-zone rocks obtained from this study will be used in the analyses for repository design (Issue 4.4) and in the assessments of repository post-closure performance (Issue 1.11). Unsaturated-zone information on fracture characteristics and hydrologic conditions will be used in developing the design requirements for ramp and borehole seals (Issue 1.12). Information on the moisture conditions and chemistry of the unsaturated-zone water will be used in the analyses of waste-package performance (Issue 1.10).

The following portion of this section summarizes from the SCP the study-level interfaces between this study and the performance and design issues. The discussion of the uses of site-characterization data from this study in resolving those issues is based upon performance measures and performance parameters identified in SCP Sections 8.3.2 through 8.3.5.

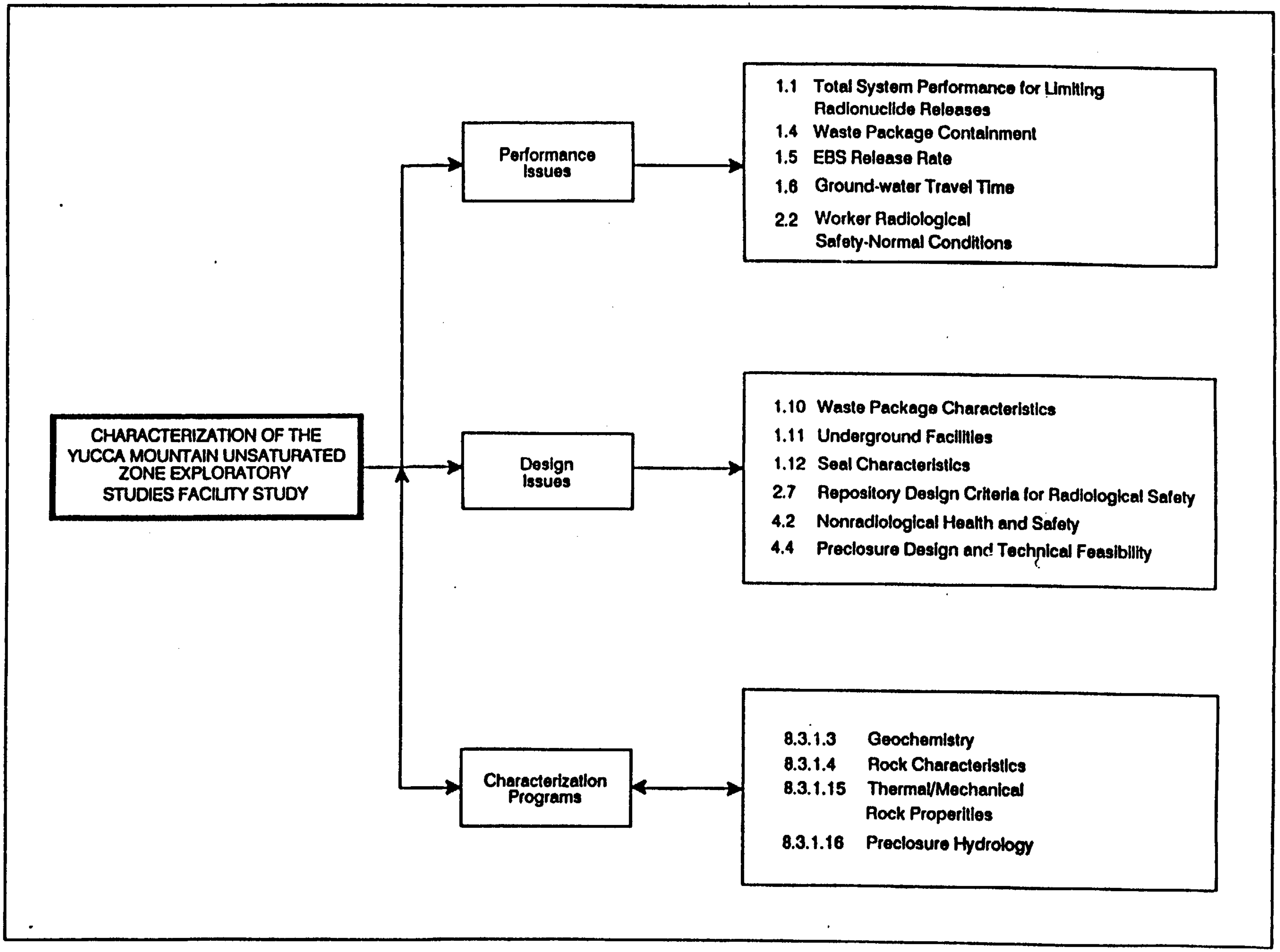


Figure 1.2-1. Diagram showing interfaces of the ESF characterization of the YM unsaturated-zone study with YMP performance and design issues and other site-characterization programs.

Performance Issue 1.1

(Total-system radionuclide release to the accessible environment;
10 CFR 60.112 and 40 CFR 191.13)

In calculating the complementary cumulative distribution function (CCDF) for estimating radionuclide releases after repository closure, the DOE intends to take into account all those natural processes and events that are sufficiently credible to warrant consideration. Impacts of processes and events initiated by human activities will also be considered in the system-performance assessments for Issue 1.1. Selection of processes and events considered credible enough to affect future repository performance has resulted in the identification of a set of scenarios grouped in scenario classes, according to features which the scenarios have in common. The expected partial-performance measure (EPPM) for a scenarios class is a term that expresses the probability of occurrence of that scenario class. Significant scenario classes are those which have the highest EPPM values. (A detailed treatment of scenario classes and the EPPM concept appears in SCP Section 8.3.5.13.)

Scenario Class E, also called the nominal case, describes the undisturbed performance of the repository; it takes into account the legitimate, distinguishable alternative conceptual models that are supported by the available information. This class is associated with anticipated or expected conditions, and it describes the predicted behavior of the repository and the uncertainties in predicted behavior, considering only likely natural events.

Disruptive scenario classes (disturbed cases) are also developed in Issue 1.1. These classes are considered sufficiently credible to warrant consideration, but are outside the range of probability considered for the nominal case.

Site information resulting from this study will be used to satisfy the requirements of numerous supporting parameters needed to evaluate the nominal case of Scenario Class E of the issue-resolution strategy for total system performance. The study results will also provide baseline data for the disturbed cases. These supporting parameters (e.g., hydrologic characteristics of the rock matrix, fracture network, or fault zones specific to the repository area) are used in calculations of the performance parameters for the different scenarios.

In Scenario Class E, the unsaturated and saturated zones are considered the primary barriers to radionuclide migration, and the engineered barrier system is considered as a backup. SCP Table 8.3.5.13-9 is a description of the performance parameters for this scenario. Examples of performance parameters for the nominal case to which site-characterization data from the present study can contribute include average flux and average effective porosity in the unsaturated zone in the repository area. Supporting performance parameters needed to evaluate the nominal case and to serve as baseline data for the disturbed cases are listed in SCP Table 8.3.5.13-17. Supporting parameters pertaining to the unsaturated zone include effective porosity, relative liquid permeability, and saturated permeability. Site data from the present study also contribute to these supporting parameters.

Unsaturated-zone hydrologic properties measured in this study (e.g., matrix and fracture permeability, porosity, and water content), as well as altitudes of stratigraphic contacts, contribute to the Issue 1.1 supporting parameters employed in the following calculations.

- Calculation of the specific-discharge field in the unsaturated zone, moisture content of unsaturated-zone units, and hydrodynamic response times in the overburden units.
- Calculation of the specific-discharge field in fault zones in the unsaturated zone, moisture content in fault zones, and hydrodynamic response times of fault zones.
- Calculation of coupling factors and radionuclide retardation factors in the unsaturated zone.
- Calculation of model validation coupling factors in the unsaturated zone.
- Calculation of gas-phase carbon-14 transport in the overburden units.
- Model calibration and validation of gas-phase carbon-14 transport in the unsaturated-zone overburden units.

Performance Issue 1.6
(Pre-waste-emplacement ground-water travel time; 10 CFR 60.113)

Issue 1.6 addresses the question of whether or not the candidate repository site can meet the Nuclear Regulatory Commission (NRC) performance objective for ground-water travel time. The performance objective is that the geologic repository shall be located so that the pre-waste-emplacement ground-water travel time along the fastest path of likely radionuclide travel from the disturbed zone to the accessible environment shall be at least 1,000 yr (or such other time approved or specified by the NRC). Briefly, the qualitative description of the disturbed zone is the part of the controlled area where physical and chemical properties are expected to change due to underground facilities construction or the effects of waste-generated heat, such that the properties changed may have a significant effect on repository performance. The controlled area is a location which on the surface encompasses no more than 100 km^2 and extends no further than 5 km from the outer boundary of the radioactive wastes, and which includes the subsurface underlying the area defined by these limits. The accessible environment is the atmosphere, the land surface, surface water, oceans, and the portion of the lithosphere that is outside the controlled area.

As in Issue 1.1, site information from the study will be used to satisfy numerous supporting performance parameters needed to assess ground-water travel time in individual unsaturated-zone units. These supporting parameters (e.g., unsaturated-zone rock matrix permeability in the repository area) are used to define various aspects of the unsaturated-zone model, spatial correlation structure model, and fracture-hydrologic-characteristics model. These aspects include initial and boundary conditions, material properties, system geometry, and validation of model concepts. The results of the ground-water travel-time model calculations yield performance parameters for each of the unsaturated-zone units. Examples of these performance parameters are discharge and distances along flow paths; these are applied to the performance measure of ground-water travel time for each of the hydrogeologic components of the ground-water regime.

Rock hydrologic and physical properties (e.g., rock matrix bulk density, bulk permeability), altitudes of geohydrologic-unit contacts, and water chemistry measured in this study are required as input for the supporting parameters for the unsaturated-zone ground-water travel-time model initial and boundary conditions, material properties, and system geometry. Porosity and fracture properties (e.g., fracture orientation, fracture distribution) are required in the fracture-hydrologic-properties model for supporting parameters for validation, material properties, and system geometry.

Performance Issues 1.8 and 1.9
(Favorable and potentially adverse conditions; 10 CFR 60.122)
(Qualifying and disqualifying conditions; 10 CFR 960.3-1-5)

The results of this study have indirect applications to the NRC siting criteria - Favorable Condition 7 (pre-waste-emplacement, ground-water travel time) through Issue 1.6, and Favorable Condition 8 (unsaturated-zone hydrogeologic conditions) through Issue 1.1. The study also has indirect applications to the higher-level findings for the geohydrology qualifying and disqualifying conditions through Issues 1.1 and 1.6.

Design Issue 1.10
(Characteristics and configuration of the waste package; 10 CFR 60.135)

Unsaturated-zone water chemistry, transmissive properties (e.g, transmissivity, hydraulic conductivity), and water-content information obtained from this study will be used to characterize the near-field (pre-waste-emplacement) environment of the waste packages.

Information on the quantity and quality of unsaturated-zone water obtained from this study will be used in assessing the performance of the engineered-barrier system in limiting the release of radionuclides. Hydrologic properties data (e.g., bulk permeability) of the Topopah Spring welded unit will be obtained from this study and will be used in calculating the flow and transport in the near-field host rock. The applicable performance measures are concentrations of radionuclide species in the gas phase, liquid water, and adsorbed to solid phases within the near-field host rock. The performance parameters receiving site information are host-rock hydrologic properties.

The results of the this study will also support (indirectly through Issue 1.10) resolution of performance issues concerned with releases from the engineered-barrier system (Issue 1.5) and the performance of the waste package (Issue 1.4), where the applicable performance measure is the quality of water that can contact the waste container. The water-chemistry data collected in the study will apply to the hydrochemical performance parameters of the issue.

Design Issue 1.11
(Characteristics and configurations of repository and engineered barriers - post closure; 10 CFR 60.133)

The characteristics and configurations of the repository underground openings will rely, in part, on the rock physical, thermal, mechanical, and hydrologic properties information derived from this study. These information will be used in (a) assessments of the layout of the underground facility and the thermal-mechanical stability of the repository underground openings and (b) drainage and moisture control plans.

The rock physical (e.g, fracture aperture, fracture weathering), thermal (e.g., fractured-rock temperature), mechanical (e.g., fracture deformation), and hydrologic (e.g., volumetric rock matrix water content) properties derived from the matrix-properties testing for the radial-boreholes tests (Activity 8.3.1.2.2.4.4) and excavation-effects tests (Activity 8.3.1.2.2.4.5) will support assessments of the usable underground area for waste emplacement. Water-seepage and perched-water testing parameters (e.g, flow rates in the perched-water zones, discharge in the perched-water zones) in the ramps, drifts, and boreholes (Activity 8.3.1.2.2.4.7) and hydrologic-properties testing of major faults (Activity 8.3.1.2.2.4.10) will support the design of drainage and moisture-control systems for the repository underground facilities. Information (e.g., fracture orientation, fracture deformation) derived from the excavation-effects tests (Activity 8.3.1.2.2.4.5) will be used in evaluations of design constraints to limit excavation-induced changes in the rock-mass permeability.

Unsaturated-zone physical and hydrologic properties (e.g, rock matrix bulk density, rock matrix gravimetric water content) derived from this study indirectly support the assessment of the underground safety of the repository workers (Issue 2.2 and 4.2) and repository design criteria (Issue 2.7).

Design Issue 1.12
(Characteristics and configuration of repository and borehole seals; 10 CFR 60.134)

Unsaturated-zone information derived from this study will be used in the design of repository seals. Information on rock-hydrologic properties (e.g., hydraulic conductivity), *in-situ* stress, rock-mechanical properties (e.g., bulk permeability), fracture characteristics, and water chemistry will be obtained from ramp and drift construction-phase testing and borehole testing within the ESF.

Bulk-rock conductivity, extent and conductivity of the modified-permeability zone around the ramps and drifts , rock-mass fracture characteristics, and hydrogeologic contact information will be obtained from the radial-borehole tests (Activity 8.3.1.2.2.4.4). Information obtained about the extent and hydraulic conductivity of permeability zones in tuff units in the repository will be used for the design of borehole and ramp seals.

The excavation-effects tests (Activity 8.3.1.2.2.4.5) will provide information on the *in-situ* stress, the modified-permeability zones around the ramps and drifts, and the unsaturated hydraulic conductivity and fracture characteristics of the rock mass around the openings. These data will be used in the design of ramp and drift seals.

Results of water-sample analysis (Activity 8.3.1.2.2.4.8) from perched-water zones or from fractures and faults will provide hydrochemical information needed for ramp, drift, and borehole seal design. Discharge rates from perched-water zone tests results (Activity 8.3.1.2.2.4.7) will also be used in designing repository seals.

Design Issue 4.4
(Repository design and technical feasibility)

The altitudes of rock-unit contacts derived from the geologic mapping in the ramps and drifts (Activity 8.3.1.4.2.2.4) will provide information to assess the thickness of the rock units. This information will be used to determine the underground space available for repository construction and waste emplacement.

In-situ stresses, rock-mechanical properties, and fracture geometry and deformation information obtained in the excavation-effects tests (Activity 8.3.1.2.2.4.5) will support the assessments of developing usable repository underground openings (ramps, drifts, emplacement rooms, and boreholes) of required size under normal and credible abnormal conditions. Information from this activity will be used in evaluating the rock-mechanical and rock-hydrologic property changes in the disturbed rock around the underground openings and the impacts of these changes on the repository design.

Condensate from seeps and natural water inflow from perched-water zones (if encountered) will be evaluated in the ramps, drifts, and boreholes (Activity 8.3.1.2.2.4.7), and the radial boreholes (Activity 8.3.1.2.2.4.4). Water-flow rate information (e.g., discharge in perched-water zones) will be used in the design of systems for water control in the ramps, drifts, boreholes and repository openings. Water-chemistry data (Activity 8.3.1.2.2.4.8) will also be used in underground facility design.

It should be noted that the principal data on rock-deformation properties for the resolution of design and performance issues are taken from Investigation 8.3.1.15.1 (Spatial distribution of rock thermal and mechanical properties), from Investigation 8.3.1.15.2 (Spatial distribution of ambient stress and thermal conditions), and for rock-unit contacts and fracture geometry and properties from Investigation 8.3.1.4.2 (Geologic framework of Yucca Mountain). Data acquired in Study 8.3.1.2.2.4 are primarily for the understanding of unsaturated-zone hydrologic properties and have a secondary utility in supplementing data needs outside the study. For example, in-situ stress data gathered in Activity 8.3.1.2.2.4.5 (Excavation-effects tests) are measured mainly to estimate permeability changes caused by repository construction; however, these data will also contribute to Study 8.3.1.15.2.1 (Site ambient stress conditions).

The following briefly summarizes the information to be obtained by the activities of this study. More detailed descriptions of information to be obtained are presented in Section 3.

The intact-fracture tests (Activity 8.3.1.2.2.4.1) will provide an understanding of fracture-flow processes at an *in-situ* scale of one to two fracture spacings. These determinations will be used to improve on estimates of matrix-fracture flow transition and flux needed for ground-water model validation.

The percolation tests (Activity 8.3.1.2.2.4.2) will provide direct evidence of water-percolation rates at an intermediate *in-situ* scale at several locations in the Topopah Spring welded unit (TSw). These determinations will have application to ground-water flow path and travel-time determinations.

The bulk-permeability tests (Activity 8.3.1.2.2.4.3) will provide intermediate *in-situ* scale measurements of the Topopah Spring welded unit conductivity. These determinations will have application to water-vapor and gas-flux calculations in the assessments of ground-water and gas travel times in the TSw. The radial-borehole tests (Activity 8.3.1.2.2.4.4) will provide cross-hole test information within each of the tuff units in the unsaturated zone and across selected contacts between these units. The permeability measurements obtained from the radial boreholes will provide, with similar scale information obtained from the bulk-permeability tests (Activity 8.3.1.2.2.4.3) and surface-based boreholes testing (Activity 8.3.1.2.2.3.2), broad spatial coverage of the hydrogeologic properties of Yucca Mountain.

The excavation-effects tests (Activity 8.3.1.2.2.4.5) will provide an estimate of stress-induced changes on permeability as a result of ramp excavation. These changes will provide estimates of flow-path adjustments for ground-water travel-time calculations as a result of excavation of the underground openings.

Perched-water zones (if encountered) will be monitored and tested (Activity 8.3.1.2.2.4.7) to determine flow paths and rates. Test results will be applicable to ground-water travel-time calculations and repository-design analyses.

Chemical testing of water and gas samples obtained from core samples and from boreholes drilled in the ESF (Activity 8.3.1.2.2.4.8) will provide independent data (from the hydraulic characteristics) of flow paths and travel times. The chemical and isotopic data will be used as means of confirming conceptual models and validating numerical models of ground-water and gas-flow paths and travel times.

The major-fault hydrologic-properties activity (Activity 8.3.1.2.2.4.10) will collect matrix, rock-mass, and chemical data to evaluate the permeability and flow conditions of principal faults encountered in the ramps and drifts of the exploratory-studies facility.

2 RATIONALE FOR STUDY

2.1 Technical rationale and justification

Section 3 of this plan provides additional detail for the specific activities, tests and analyses, and methods of this study. This section provides an overview and justification of the overall study.

2.1.1 Statement of problem and test justification

Understanding the unsaturated-zone flow system at Yucca Mountain is essential to the site-characterization program because it is within this interval of partially saturated rocks that the repository is proposed to be constructed. The geologic evaluation of the site is a multi-discipline effort. Programs and investigations are planned to study the geochemical and geologic characteristics (SCP Section 8.3.1.3, Geochemistry; 8.3.1.4.2, Stratigraphy and structure; and 8.3.1.15.1, Thermal and mechanical properties). It is not within the scope of this study plan, however, to discuss the geologic and rock-characteristics studies. The reader is referred to the SCP and associated study plans for descriptions pertaining to the particular studies or activities of interest. This study plan discusses only the unsaturated-zone hydrologic tests in the exploratory-studies facility.

In the unsaturated zone, water is presumed to be present both in liquid and vapor phases within the interstitial, fracture, and lithophysal openings. It is important to evaluate water flow and storage within the repository block because water is the expected major medium for any transport of radionuclides to the accessible environment. Water flow and storage is envisioned to be complexly three dimensional, controlled by the structural, stratigraphic, and climatological settings, and, in general, liquid-water flow is expected to occur within interconnected pores and fractures, as well as advective and diffusive vapor-phase flow within interconnected air-filled fracture openings.

In addition to understanding water movement within the repository block, there is a need to consider and account for the occurrence of dissolved constituents in both the liquid and gas phases. The concentrations and transport of solutes within the unsaturated zone are coupled to the occurrence and movement of water (liquid and vapor) and may also be affected by chemical interactions with the surrounding rock matrix. Furthermore, because liquid-water and vapor are expected to be in local thermodynamic phase equilibrium, liquid-water saturation and water-vapor and solute concentrations are coupled through the prevailing geothermal regime. Consequently, the hydrologic evaluation of the site constitutes a problem of two-phase, multi-component, coupled heat (geothermal) and water flow within a layered sequence of tilted, faulted and fractured, variably saturated tuffaceous geohydrologic units.

Hydrologic testing in the ramps, underground drifts, and underground boreholes will (1) supplement and complement surface-based hydrologic information with *in-situ* hydrologic characterization of the rock mass, (2) provide an opportunity for directly inspecting the structure and stratigraphy of the rock walls, and (3) provide an opportunity to evaluate rock-matrix and fracture-hydrologic parameters for a wide range of test scales. The ESF unsaturated-zone tests are designed with the objective of ultimately providing an understanding of the spatial and temporal water movement within the unsaturated zone.

The ESF unsaturated-zone tests will provide hydrologic information that is not readily obtainable from surface-based boreholes. The ESF provides a testing environment that is suitable for three-dimensional characterization of the rock mass, and the percolation tests are designed to study hydraulic parameters in multiple directions. Lateral variations will be studied through horizontal drifts and boreholes and by careful mapping of underground rock exposures. Excavation of the ramps and drifts will produce large volumes of rock that can be used for determination of water chemistry (Activity 8.3.1.2.2.4.8, Hydrochemistry tests) and for laboratory analysis of rock/hydraulic properties. Samples of rocks containing intact fractures can be readily obtained from within the ramps and drifts. Results of hydraulic tests (Activity 8.3.1.2.2.4.1, Intact-fracture tests) on such samples will be more representative of *in-situ* conditions, thereby increasing confidence in correlations between hydrologic and geologic data and, ultimately, *in-situ* characterization. Percolation tests can be conducted in a rock mass that has not been disturbed by recent weathering and is representative of the repository host rock.

In addition to determination of specific hydrologic parameters and relations, the effects of excavation on the host rock can be studied directly in the ESF. The radial-boreholes (Activity 8.3.1.2.2.4.4), percolation (Activity 8.3.1.2.2.4.2), bulk-permeability (Activity 8.3.1.2.2.4.3), and perched-water (Activity 8.3.1.2.2.4.7) tests will indirectly provide multi-scale information on geohydrologic properties invaluable to the analysis of the design and performance of the repository. The excavation-effects tests (Activity 8.3.1.2.2.4.5) will directly estimate the magnitude and extent of the modification of the TSw geohydrologic unit caused by excavation. The major-fault hydrologic properties test (Activity 8.3.1.2.2.4.10) will provide data on permeability and flow conditions of discrete major fault zones.

The ESF will provide an ideal environment for *in-situ* hydrologic tests of the unsaturated zone beneath Yucca Mountain, the objective of the tests being to quantitatively define geohydrologic parameters influencing water flow in the TSw and CHn. Because the spatial and temporal extrapolation of water flow within the unsaturated zone involves complex interactions that can only be described with the aid of hydrologic models, preliminary data from the ESF hydrologic tests will be used as a basis for multiscale, numerical modeling of the unsaturated zone. These models will provide a description of the important components of the geohydrologic system and will reflect an understanding of the hydrologic parameters, the initial and boundary hydrologic conditions and processes, and their relations.

The geohydrologic program will develop two hydrologic models that will describe two distinct zones of the hydrologic system: the unsaturated zone and the saturated zone (Figure 2.1-1). A surface-water hydrologic model will be developed to provide input to these two hydrologic models. The hydrologic models will be used at many stages of site characterization to perform preliminary analyses, to design and analyze tests and experiments, and to analyze and interpret field data. The principal hydrologic modeling effort is to construct mathematical representations to simulate the natural geohydrologic system and its components.

The ESF unsaturated-zone tests and corresponding hydrologic model concentrate on the deep part of the unsaturated zone. The unsaturated-zone hydrologic model will be developed at site scale, whereas the surface-water and saturated-zone hydrologic models will be developed at both site and regional scales. The hydrologic zones described by these models are those that significantly affect the resolution of hydrologic-related design and performance issues; these zones therefore are the principal subjects of hydrologic investigations. The logic diagram of Figure 2.1-1 shows the relations among the hydrologic models and the overall geohydrologic program. The diagram expands the unsaturated-zone hydrologic model to show the components and parameters categories that are used in that model. The diagram shows that the unsaturated-zone model consists of numerical and conceptual models, which in combination will provide a hydrologic description of the unsaturated zone.

The unsaturated-zone hydrologic model consists of three major components: (1) the geohydrologic framework, (2) rock properties, and (3) initial and boundary conditions. The geohydrologic framework establishes the unsaturated-zone system geometry. Rock properties include unsaturated-zone hydraulic and gaseous-phase properties. Boundary conditions include hydrologic infiltration (land surface) and water-table boundaries. These components form the basis for developing the numerical models that quantitatively describe various aspects of the zone and are used as a basis for developing the technical rationale for the planned work.

2.1.2 Parameters and testing strategies

In SCP usage (U.S. Department of Energy, 1988) activity parameters are those parameters that are generated by testing and analysis in the field, laboratory, or office; they represent the most basic measurements that will be used to characterize the geohydrology of Yucca Mountain and vicinity. Many of the activity parameters are building blocks to support various aspects of the project. Some, such as hydraulic conductivity, support design and performance issues directly. Others primarily provide bases for analyses and evaluations to be conducted within the Geohydrology Program or within other characterization programs.

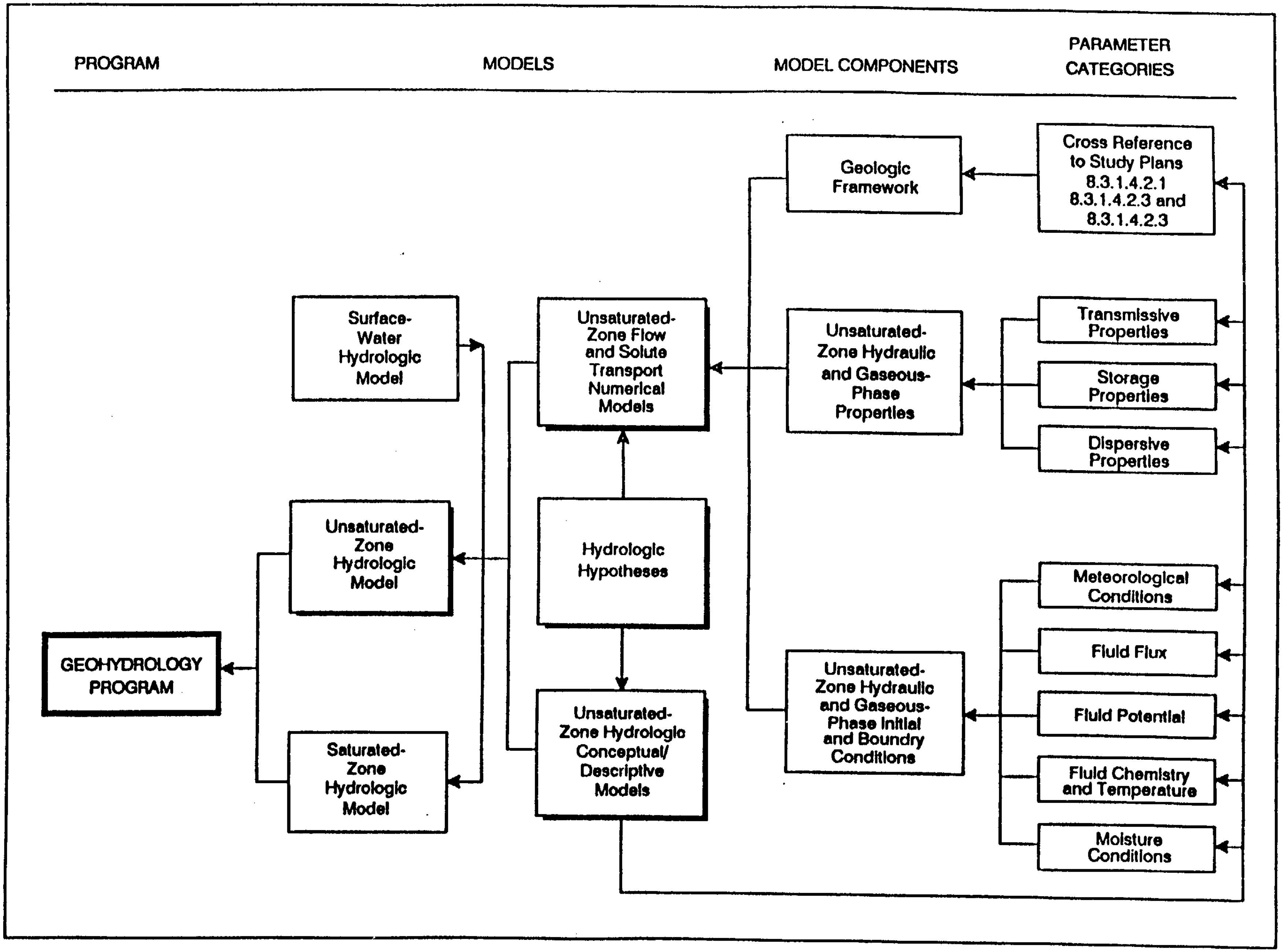


Figure 2.1-1. Logic diagram of Geohydrology Program, including model components and parameter categories.

In SCP Table 8.3.1.2-1, activity parameters for the Geohydrology Program are grouped according to parameter categories. The activity parameters associated with activities of this study also appear in the figures and tables of Section 3 of this study plan. Parameter categories serve to group similar types of performance and design parameters supporting performance-assessment and design issues resolutions (SCP Sections 8.3.2 through 8.3.5) and match them with groups of similar types of activity or characterization parameters to be obtained during site characterization. Parameter categories in the SCP were introduced as a classification scheme to aid in assessing the appropriateness and completeness of the data collection program. In Figure 2.1-1, the parameter categories are shown supporting specific model components that make up the site unsaturated-zone model. This figure corresponds to SCP Figure 8.3.1.2-3, and in that document is accompanied by parallel logic diagrams for the surface-water and saturated-zone components of the Geohydrology Program.

In SCP usage, a characterization parameter is a parameter, obtained by a characterization program, that has a logical, direct tie to a performance or design parameter, and for which a testing basis can be defined. Most characterization parameters will be developed from some combination of activity parameters, and will be the products of data reduction, tests and analyses, and modeling. Hydrologic analyses generated in this study can be traced from activity parameters through characterization parameters and to their intended use in satisfying performance-assessment requirements for issues resolutions.

In this and other study plans, it has been useful to group the measured or calculated parameters of the various activities (activity parameters) into a limited set of characterization parameters, more broadly defined parameters that encompass activity parameter data collected in the field and laboratory, or generated by modeling. By introducing these parameters, it becomes easier to understand how the study relates to satisfying the information requirements of parameters in the design and performance issues. The grouping of activity parameters according to characterization parameters is given in Table 2.1-1. Characterization parameters also appear in the logic diagrams accompanying the activity descriptions of Sections 3.4, 3.5, 3.7, and 3.8.

Characterization parameters will be expressed as functions of space and (or) time and will be presented in formats that will facilitate use of the data in resolving design and performance issues. In future SCP progress reports, a testing basis will be developed for each characterization parameter, and will consist of some means of expressing the goals, confidence limits, and accuracy associated with each characterization parameter, so that requirements of performance parameters can be satisfied. An example of a testing basis could be that some statistical measure of the parameter, such as the mean, be known to a specific degree of accuracy.

Table 2.1-1. <u>Association of activity parameters with site characterization parameters</u>

Activity	Characterization Parameter	Activity Parameters Associated with Characterization Parameter
Activity 8.3.1.2.2.4.4 - Radial-borehole tests	Hydraulic conductivity	Permeability, water
	Gas permeability	Permeability, relative, gas, rock matrix Permeability, saturated, gas, rock matrix Pneumatic permeability, bulk, fractured rock Permeability, pneumatic Fault permeability Gas permeability, excavation effects Porosity pore-size distribution, matrix Porosity, bulk, fractured rock Porosity, matrix Porosity Bulk density, rock matrix Grain density, rock matrix Fault characteristics: distribution, aperture, weathering Anisotropy
	Water permeability	Moisture retention, rock matrix Water content, gravimetric, rock matrix Water content, volumetric, rock matrix Permeability, relative, water, rock matrix Porosity pore-size distribution, matrix Porosity, bulk, fractured rock Porosity, matrix Porosity Bulk density, rock matrix Grain density, rock matrix Anisotropy Fracture aperture Fracture permeability
	Hydraulic gradient	Water potential, distribution and fluctuation Water potential, rock matrix, and total fractured rock Pneumatic potential, distribution and fluctuation Pore-gas composition Radioactive isotopes Stable isotopes
	Gaseous diffusion	Gaseous diffusion coefficient, fractured rock units Diffusive tortuosity, fractured rock and rock mass Temperature, distribution and fluctuations

Table 2.1-1. Association of activity parameters with site-characterization parameters (continued)

Activity	Characterization Parameter	Activity Parameters Associated with Characterization Parameter
Activity 8.3.1.2.2.4.5 - Excavation-effects tests	Fracture permeability	Initial fracture permeability around excavations Changes in fracture permeability due to excavation effects Changes in rock stress due to excavation effects Fracture locations Fracture characteristics In-situ rock stress and mechanical property measurements In-situ stress changes, magnitude and direction Fracture deformation Changes in rock stress due to excavation effects Effects of stress changes on fracture aperture Fracture aperture Fracture distribution Fracture orientation Fracture roughness
	Fracture effective porosity	Changes in fracture effective porosity due to excavation effects Rock density Rock porosity Fracture locations Fracture characteristics In-situ rock stress and mechanical property measurements Changes in rock stress due to excavation effects Effects of stress changes on fracture aperture Fracture aperture Fracture distribution Fracture orientation Fracture roughness
	Fracture saturation	Moisture content, in-situ degree of saturation Changes in fracture saturation due to excavation effects Fracture locations Fracture aperture Fracture distribution Fracture orientation Fracture roughness
Activity 8.3.1.2.2.4.7 - Perched-water tests	Hydraulic conductivity	Hydraulic conductivity, perched-water zones Transmissivity Porosity, rock units near ramps and drifts

Table 2.1-1. Association of activity parameters with site-characterization parameters (continued)

Activity	Characterization Parameter	Activity Parameters Associated with Characterization Parameter
Activity 8.3.1.2.2.4.7 - Perched-water tests	Hydraulic gradient	Water potential (total), perched-water zones Hydraulic head, perched-water zones Radioactive isotopes Stable isotopes Water quality Potential
	Ground-water flux	Infiltration rate Discharge rate Flow rates, perched-water zones
	Storage coefficient	Storage coefficient, perched-water zones
Activity 8.3.1.2.2.4.8 - Hydrochemistry tests	Flow paths, ground water and gas	Radioactive-isotope activity Stable isotopes Pore-gas composition Water quality, cations and anions Flow paths, hydrochemical determination
	Travel times, ground water and gas	Radioactive-isotope activity Stable isotopes Pore-gas composition Water quality, cations and anions Travel times, hydrochemical determination
Activity 8.3.1.2.2.4.10 - Hydrologic properties of major faults encountered in the ESF	Hydraulic conductivity	Permeability, water
	Gas permeability	Permeability, relative, gas, rock matrix Permeability, saturated, gas, rock matrix Pneumatic permeability, bulk, fractured rock Permeability, pneumatic Fault permeability Gas permeability, excavation effects Porosity pore-size distribution, matrix Porosity, bulk, fractured rock Porosity, matrix Porosity Bulk density, rock matrix Grain density, rock matrix Fault characteristics: distribution, aperture, weathering Anisotropy

Table 2.1-1. Association of activity parameters with site-characterization parameters (continued)

Activity	Characterization Parameter	Activity Parameters Associated with Characterization Parameter
Activity 8.3.1.2.2.4.10 - Hydrologic properties of major faults encountered in the ESF	Water permeability	Moisture retention, rock matrix Water content, gravimetric, rock matrix Water content, volumetric, rock matrix Permeability, relative, water, rock matrix Porosity pore-size distribution, matrix Porosity, bulk, fractured rock Porosity, matrix Porosity Bulk density, rock matrix Grain density, rock matrix Anisotropy Fracture aperture Fracture permeability
	Hydraulic gradient	Water potential, distribution and fluctuation Water potential, rock matrix, and total fractured rock Pneumatic potential, distribution and fluctuation Pore-gas composition Radioactive isotopes Stable isotopes
	Gaseous diffusion	Gaseous diffusion coefficient, fractured rock units Diffusive tortuosity, fractured rock and rock mass Temperature, distribution and fluctuations

A common requirement of the activity parameters is that sufficient confidence can be placed in their numerical values and in the understanding of their relations for hydrologic modeling and hypothesis testing. That is, confidence in the calibration of a model to a given level is dependent on the extent to which the input data and observations are well characterized and credible. These empirical data are affected by uncertainties due to measurement errors and to presence of both random and correlated large-scale spatial variability (heterogeneities). The presence of these uncertainties must be considered in order to assess the accuracy with which numerical hydrologic models simulate the natural geohydrologic system. The sensitivity of the performance measure to various parameters can, nevertheless, be investigated, and such models can be used as tools to improve understanding of the functioning of each zone, to test hypotheses, and to further guide data collection.

Some of the specific parameters listed in Table 2.1-1, although not required directly for resolving performance and design issues, are required to accomplish satisfactory hydrologic modeling, which in turn increases confidence in the accuracy of the parameters that are required for performance and design analyses. Because model parameters cannot be known explicitly everywhere throughout the modeled area, the input parameters must be expressed as statistical distribution functions. Numerical models will be used as a principal approach to assess whether the data collected to describe the present and expected geohydrologic characteristics provide the information required by the performance and design issues.

A principal testing strategy of the study, therefore, is to utilize approaches that minimize uncertainty of the activity parameters and in the understanding of their relations within the constraints of available resources. Some degree of uncertainty is inevitable, because parameters vary in space and time, measurements contain errors, and hydrologic processes are slow and difficult to measure. As described below, however, the strategy of the study is to increase confidence by utilizing multiple approaches for determining parameters not readily amenable to measurement or analysis, by testing hypotheses, and by developing acceptable models.

A major advantage to using multiple approaches for determining parameters is that, in general, reliance is not placed only on one test to determine a parameter. Some tests will provide only partial information, whereas others will provide extensive information necessary for determination of a hydrologic parameter. By combining the test results and studying their relations, a greater understanding and confidence of any particular parameter can be achieved. For example, the estimation of fluid-travel times (a critical issue) can be addressed with multiple approaches. Fluid travel time can be estimated by calculating the residence of environmental tracers in the pore water or by calculating the velocity at which fluid flows through the rock from the bulk hydrologic parameters. The hydrochemistry tests will provide residence times for pore and fracture fluids at the repository site. The combination of intact-fracture, bulk-permeability, percolation, radial-borehole, and major-fault hydrologic properties tests will provide data on permeability, effective porosity, and pore-size distribution necessary for the calculation of travel time. In addition, the percolation tests will provide velocities at various steady-state infiltration rates in small volumes of rock. Fluid potential distributions will be obtained from the radial-borehole and major-fault hydrologic-properties tests, and if perched water is encountered, hydrologic tests and hydrochemical tests will be conducted to evaluate water flux, flow paths and travel times.

Because of the nonstandard nature of some of the tests, the possibility that one or more tests may fail in achieving the desired objectives is recognized. The use of multiple approaches for determining parameters increases confidence that the failure or the partial failure of one or more tests will not severely inhibit the ability of the characterization activities in providing the information required. Prototype tests for site characterization, especially those related to characterization of the unsaturated zone, have been performed (see Dennis, 1991) which has increased the confidence level that test objectives can be achieved.

For some activity parameters, it is necessary to measure them at different scales. For example, various tests are designed to measure unsaturated fracture hydraulic conductivity, from the conductivity of discrete fractures to that of increasingly more extensive fracture networks. The smallest-scale test is the intact-fracture tests which entails direct observation and measurement of fluid and mass transport within a single fracture. The purpose of the small-scale testing is to develop an empirical foundation for modeling flow and transport through single fractures. When this discrete-fracture model is evaluated (calibrated and validated), it can be used to simulate a larger network of discrete fractures. The percolation tests will then be used to evaluate the fracture-network model. In turn, another numerical model, based on this fracture-network approach, will be applied to simulate the percolation tests. The error in evaluating flow through the percolation test block by the fracture-network modeling approach may be large, because the percolation-tests scale may not be representative of the entire rock mass. For this reason, the bulk-permeability and radial-borehole tests will be conducted to evaluate the effect of size on variations of hydrologic properties. In the bulk-permeability tests, the pneumatic permeabilities of different volumes of rock will be evaluated directly from cross-hole tests, data that will then be used to estimate the scale at which the continuum approach is valid. The variable-scale discrete model developed from intact-fracture tests will be used to predict the hydrologic properties of a large volume of rock that will be tested later in the main test level of the ESF. Results from this model will be compared with results using the fracture-network model developed from percolation tests. If predictions prove to have insignificant error, the technique can be used to extend results of the bulk-permeability tests to other parts of the ESF and repository block. In turn, the validity of this extrapolation method will be tested directly by the radial-borehole tests (Activity 8.3.1.2.2.4.4), the surface-based vertical- and horizontal-borehole tests (Study 8.3.1.2.2.3), and gaseous-phase movement study (Study 8.3.1.2.2.6) which averages permeabilities for very large volumes of rock by recording pressure changes at various levels in boreholes caused by barometric fluctuations.

The process of variable-scale testing and modeling will delineate the scale at which the continuum approach can be used with minimum error as well as provide large-scale understanding of the host rock. The results will increase confidence that an understanding has been gained of the relations between hydraulic conductivity and fracture characteristics, and that the appropriate scale has been selected for modeling and testing of the hydrologic hypotheses. The testing and refinement of hydrologic hypotheses provide a logical and systematic approach to improving our understanding of how the geohydrologic system functions. The result will be an improved conceptual model which, in turn, leads to increased confidence in the hydrologic models and, ultimately, in the geohydrologic program (Figure 2.1-1). In turn, results of the study will provide a basis for updating and revising the hypotheses.

2.1.3 Hydrologic hypotheses

The unsaturated-zone hydrologic hypotheses describe in general terms the manner in which fluids (water and gas) may move through the unsaturated zone. The testing and refinement of hypotheses provide a logical and systematic approach to the ultimate definition of how the geohydrologic system functions. The results will be an improved conceptual model which, in turn, leads to increased confidence in the geohydrologic evaluation of the repository site.

The hypothesis component shown in Figure 2.1-1 is tied to Table 2.1-2, which lists current hypotheses for the unsaturated zone. The table also shows objectives and approaches of the activities that are directly involved in testing these hypotheses.

In conducting preliminary performance and design analyses, assumptions must be made regarding parameters and hydrologic processes and conditions. These preliminary analyses may include assumptions involving parameters such as flow paths, velocities, fluxes, gradients, conductivities, anisotropies, boundary conditions, and structural and geohydrologic-unit controls on unsaturated flow. Concepts that may affect these aspects of the hydrologic system include the potential for lateral flow and capillary barriers in the unsaturated zone, conditions under which matrix and fracture flow occur, and accumulation of perched water. The ongoing process of hypothesis testing helps to increase confidence that the assumptions made in preliminary analyses are reasonable.

2.1.4 Hydrologic modeling

In assuming that the overall hydrologic system within the unsaturated zone at Yucca Mountain can be described by conventional theories of fluid storage and movement in porous and fractured media,

Table 2.1-2. Relations between unsaturated-zone hydrologic conceptual model hypotheses and the activity objectives of Study 8.3.1.2.2.4

Hypothesis	SCP number	Activity objectives
Fractures and fracture systems and barriers to or conduits for liquid-water flow, depending on ambient matrix saturation.	8.3.1.2.2.4.1	To evaluate fluid-flow and chemical-transport properties of single, relatively undisturbed fractures.
	8.3.1.2.2.4.2	To determine the hydrologic conditions that control the occurrence of fluid flow within fractures and matrix and to provide experimental data against which the validity of numerical models can be tested.
Discrete fractures and fracture networks can be modeled as equivalent porous media.	8.3.1.2.2.4.1	See above objectives.
Orientation of fractures and faults influences degree of transmissiveness, thereby introducing a fundamental system anisotropy.	8.3.1.2.2.4.2	See above objectives.
	8.3.1.2.2.4.3	To determine the scale at which the host rock behaves as an equivalent anisotropic porous medium.
	8.3.1.2.2.4.3	To compare hydraulic test results against a distribution of simulated results calculated from a large number of realizations of the possible fracture networks conditioned on average fracture orientation and/or fracture density data.
	8.3.1.2.2.4.3	To use a numerical fracture-flow model to establish the minimum dimensions at which other rock masses with the same fracture characteristics behave as equivalent porous media and to examine the dependence of rock-mass dimensions on changing saturation.
	8.3.1.2.2.4.4	To evaluate the potential for lateral flow of water within dipping units.
	8.3.1.2.2.4.4	To evaluate the potential for lateral flow of water along geohydrologic-unit contacts.

Table 2.1-2. Relations between unsaturated-zone hydrologic conceptual model hypotheses and the activity objectives of Study 8.3.1.2.2.4 (continued)

Hypothesis	SCP number	Activity objectives
	8.3.1.2.2.4.4	To detect vertical flows of water, as both vapor and liquid, in the unsaturated zone.
Hydrologically interconnected fracture systems and rock matrix define a macroscopic composite or equivalent porous medium.	8.3.1.2.2.4.2	See above objectives.
	8.3.1.2.2.4.3	See above objectives.
Unsaturated lateral flow can occur at the contact between the Tiva Canyon welded (TCw) and Paintbrush nonwelded (PTn) units, depending on the flux and the permeability contrast across the contact.	8.3.1.2.2.4.4, 8.3.1.2.2.4.8	To evaluate the potential for lateral flow of water along geohydrologic-unit contacts, using radial borehole tests in the ESF, and to evaluate hydrochemical-isotopic data from any gas and pore water collected.
Lateral flow can occur within the PTn, because of intercalation of layers with contrasting hydraulic properties within the unit.	8.3.1.2.2.4.4	To evaluate the potential for lateral flow of water within dipping units, using radial borehole tests in the ESF.
Flow in the Topopah Spring welded unit (TSw) is downward and occurs under steady-state conditions. Flow is primarily in the matrix when the flux is less than some value related to the saturated matrix hydraulic conductivity, and flow is primarily in fractures at fluxes larger than that value.	8.3.1.2.2.4.4	To detect vertical flow of water, as both vapor and liquid, in the unsaturated zone using radial borehole tests in the ESF.
The nearly vertically oriented fault zones and their associated fractures can be highly effective pathways for vertical liquid-water flow with large flux, especially in the competent TCw and TSw. Under some conditions, faults can impede lateral flow and thus produce perched-water bodies where the faults intercept significant lateral flow.	8.3.1.2.2.4.7, 8.3.1.2.2.4.10	To detect the occurrence of any perched water, estimate the hydraulic properties of the zones, and determine the implication of existence of such zones of flux, flow paths, and travel times.
Perched-water bodies and capillary-barriers may be temporarily present within the UZ system.	8.3.1.2.2.4.7	To detect the occurrence of any perched-water zones.
	8.3.1.2.2.4.7	To estimate the hydraulic properties of the zones.
	8.3.1.2.2.4.7	To determine the implications of the existence of such zones on flux, flow paths, and travel times.

Table 2.1-2. Relations between unsaturated-zone hydrologic conceptual model hypotheses and the activity objectives of Study 8.3.1.2.2.4 (continued)

Hypothesis	SCP number	Activity objectives
Volumes containing many pores and fractures are definable such that changes in boundary fluxes equal changes in internal moisture storage.	8.3.1.2.2.4.8	To understand the gas transport processes within the unsaturated zone and to provide independent evidence of flow direction, flux, and travel time of gas.
	8.3.1.2.2.4.8	To design and implement methods for extracting uncontaminated pore fluid from rock excavated during ramp construction.
	8.3.1.2.2.4.8	To determine the flow direction, flux, and travel time of water in the unsaturated zone by isotopic geochemistry techniques.
	8.3.1.2.2.4.8	To determine the extent of water-rock interaction so that geochemical modeling can be performed to deduce the flow path and to understand the geochemical evolution of the unsaturated zone water.

the present and probable future spatial distribution and magnitude of hydrologic parameters can be predicted from appropriately constructed hydrologic models. The successful development of calibrated numerical models of the hydrologic system will increase confidence that the geohydrologic framework, distribution of input parameters, and nature of initial and boundary conditions are appropriate for utilization in performance and design analyses.

Hydrologic modeling produces the velocity field essential for defining flow paths and computing ground-water travel time. Such modeling requires sufficiently detailed knowledge of the geohydrologic framework and the three-dimensional distribution of hydrologic parameters. The importance of these ESF unsaturated-zone tests for determining the magnitude and distribution of these hydrologic parameters is emphasized. *In-situ*, underground, multiple-approach, variable-scale testing is necessary for developing a complete and accurate geohydrologic program of the repository block under Yucca Mountain.

2.2 Constraints on the study

2.2.1 Prototype testing

The USGS investigators responsible for the activities described in Section 3 have chosen and proposed testing procedures that they expect will work as planned. The investigators recognize, however, that there is a degree of risk associated with many of the tests that have not been previously tried and have therefore planned and conducted prototype tests to validate the performance of the proposed testing methods. For a summary of results of prototype tests, see Dennis (1991).

Prototype testing serves several purposes, including the development of reasonable and adequate quality-assurance procedures and an assessment of the data-acquisition and storage needs of individual tests. Primarily, prototype testing provides an opportunity to understand, implement, refine, and practice testing procedures prior to the actual testing. For example, certain hydrology tests (bulk permeability, percolation, and excavation effects) have never been performed at the proposed scales. Similarly, many of the proposed testing methods have never been applied to unsaturated, densely welded, fractured tuffs, such as the Topopah Spring welded unit at Yucca Mountain (Figure 1.1-4).

Equipment selection and development is a major objective of the prototype testing. As such, specification of equipment to be used during site characterization cannot be completely defined until this testing is done. For standard testing methods, equipment lists may be found in the technical procedures noted for each activity described in Section 3 of this plan.

Because the underground facilities have not been constructed at Yucca Mountain, geologic and hydrologic prototype testing has been conducted at G-tunnel in Rainier Mesa, which is located at the Nevada Test Site (NTS) about 60 kilometers (40 miles) from Mercury, Nevada. Prototype testing and equipment development for the air permeability testing activity was conducted at the Apache Leap Tuff site near Superior, Arizona. Prototype drilling, instrumentation, and testing established procedures that will be needed for site-characterization tests to provide quality-assured data for the licensing process.

References are made to specific prototype tests in each of the activity descriptions of Section 3.

2.2.2 Representativeness of repository-scale and correlation to repository conditions

The ESF is located within the repository area and will penetrate the same geohydrologic units as does the repository. Because of this, the environment in which ESF tests will be conducted is an approximate representation of the repository area and representativeness should be enhanced by the current ramp-based rather than shaft-based design. How well each test will represent future or present conditions of the repository at the scale of the repository depends on a number of factors relating to the particulars of the test.

The ESF hydrologic-test results will be extrapolated across the site on the basis of an integrated drilling plan (SCP Section 8.3.1.4.1, Development of an integrated drilling program) and an integrated geologic- and hydrologic-characterization program. Geologic studies (Study 8.3.1.4.2.1, Vertical and lateral distribution of stratigraphic units within the site area; 8.3.1.4.2.2, Structural features within the site area; and 8.3.1.4.2.3, Development of a three-dimensional geologic model of the site area) will provide larger-scale models that will allow ESF-scale test results to be extrapolated across the site surface-based hydrologic testing in boreholes (Activity 8.3.1.2.2.3.2, Site vertical-borehole studies) and will also increase confidence in the ability to extrapolate across the repository site.

The representativeness of the current testing plans is considered to be much more representative than what was described in the SCP Section 8.4.2.1.5 (Representativeness of planned testing) for tests in a vertical shaft. The current ESF will have a minimum of two ramps with drifts in the TSw2, with an option for two additional ramps and drifts in the CHn. Drifts will extend from the ramps to the Ghost Dance Fault, Solitario Canyon Fault, and Imbricate Fault zone. Figure 1.1-3 illustrates the appropriate locations of where the ramps and drifts will cross major geologic structures that will allow for a visual and a hands-on inspection for geologic and hydrologic rock properties.

2.2.3 Accuracy and precision of methods

Selected and alternate methods for testing in each activity are summarized in tables at the end of each activity description (Section 3). These methods were selected on a basis of their precision and accuracy, duration, and interference with other tests and analyses. The accuracy and precision of the exploratory-studies facility hydrologic tests is difficult to quantify prior to testing and implementation of the methodology. The degree of accuracy and/or precision of each method within activities is a qualitative, relative judgement based on current knowledge and familiarity with, and understanding of, the method. Prototype testing was also helpful in assessing the accuracy and precision of the methods proposed for collecting site characterization data. For selected methods, if values for accuracy and precision exist, they will be listed in the USGS technical procedures which are referenced in the activity descriptions of Section 3.

2.2.4 Potential impacts of activities on the site

The current ESF design consists of the following:

1. Two ramps: Designated as the North and South Ramps, will extend from the surface and connect underground with the Main Drift;

2. Main Drift in the TSw2 that connects the North and South Ramps;

3. Core test area of the Main Test Level: Principal area in the Topopah Spring Member where the majority of testing will be conducted;

4. Calico Hills Ramps: Ramps that provide access from the Topopah Spring Member to the Calico Hills geologic barrier and provide access to the Imbricate, Ghost Dance, and Solitario Canyon fault zones;

5. Calico Hills Main Drift: A lateral drift through the Calico Hills unit that will provide access for the exploratory drifts to the Imbricate, Ghost Dance, and Solitario Canyon fault zones;

6. Lateral Drift Extension from Main Drift: A drift constructed by the drill and blast method. The diameter has not yet been determined;

7. East-West Drift to test Ghost Dance Fault;

8. Drifts from ramps to test Ghost Dance Fault, Solitario Canyon Fault, and Imbricate Fault zone (see Figure 1.1-3).

Surface facilities will include a power substation, sewage treatment lagoons, construction and testing-support buildings, various trailers, and an access road.

After construction is completed, additional *in-situ* tests will be conducted, principally in the Main Test Level. The *in-situ* test activities described in this plan will have relatively little impact on the natural-state site conditions. Hydrologic disturbances from ESF testing activities could potentially impact site performance by increasing the water flux at the repository horizon, changing the hydrologic properties of the unsaturated zone, and creating preferential pathways for liquid and gaseous transport of radionuclides. The only tests that currently have been identified to be performed in the ESF that may introduce water into the unsaturated zone are the percolation and the hydrologic properties of major faults tests. Since the test blocks for the percolation test will be separated from the rock mass and isolated within the drift, the water added to the rock can be recovered. If the decision to use water following air injection tests in fault zones is made, the quantity of water used will be tagged with a tracer and kept to a minimum. Test areas will be limited to fault zones away from other tests. Therefore, there is no indication that the testing activities will introduce a significant amount of water to the unsaturated zone or that the use of water will result in permanent changes to the *in-situ* hydrologic properties of the rocks.

2.2.5 Time required versus time available

The *in-situ* hydrologic tests described in this study plan are constrained by the schedule for the start and completion of the ramps and drifts. The ESF testing is also constrained by the need to complete the *in-situ* tests for input to the YMP environmental impact statement-performance assessment and license application. Section 5.1 presents current schedules for the four activities described in this plan.

2.2.6 Limits of analytical methods

Although numerical modeling of tests planned in this study will be performed, the problem remains of identifying parameters in a distributed system with many degrees of freedom available. Measurements in the tests will be made at a few locations in a system in which the numerical mesh of the model may have thousands of unknowns. The use of all available data can reduce uncertainty, but some uncertainty will remain. Uncertainty analyses may be considered as an alternative to the solution of those problems that incorporate the unknown features of the system.

2.2.7 Potential for interference among activities, and from ESF construction

YMP requires that all construction and testing must go through analysis to evaluate test interference due to construction and interference from other tests. Such analysis will ensure that interference has been eliminated or minimized. Generally, the selected tests of this study will have little or no interference with other planned tests. In cases where tests do interfere, the USGS investigators have planned the testing sequence accordingly, in order to maximize data collection and minimize interference. All of the water that will be used in hydrologic tests will be tagged with a tracer to determine if any interference is occurring in adjacent test areas. The decision as to which tracers are to be used will be made on a case-by-case basis as part of the test planning process.

SCP Section 8.4.2.3.1, Exploratory studies facility testing operations, layout constraints, and zones of influence, discusses the constraints imposed on the underground layout by each experiment and the estimated zone of influence of each experiment. The design requirements generally arise from requirements that the *in-situ* conditions such as stress state, degree of saturation, and temperature in the region where the experiment is to be conducted not be altered by other activities in the ESF. Flexibility in choosing the final location and orientation of an experiment may also be an important constraint because of local variations in geology and fracture orientation. The zone of influence is intended to describe the extent to which each experiment alters or influences the surrounding region. In the conduct of each test, it is vital to insure that the data derived from the test are not influenced by other experiments that may be underway at the same time. The criteria for determining if a potential interference existed was taken to be whether the zone of influence of one experiment impinged on another experimental area to such a degree that the results of the experiment could be affected. To insure conservatism in this approach, the potential for interference was considered high if the zones of influence of two experiments overlapped. Because the maximum zones of influence of each test were overlaid onto a layout to check for potential interference, timing of the test was not taken into consideration during the analysis. If interference concerns showed up during the analysis, timing of the tests involved was considered to determine if the tests were separated sufficiently in time to preclude the interference problem (i.e., one test may have been completed, leaving no permanent alteration of the rock, before the second was begun). If potential interferences were found during the analysis, the adjustments to the timing of the experiments or the layout were considered.

The test-to-test interferences concerns were evaluated (SCP Section 8.4.2.3.1) as outlined above only for the experiments proposed for the Main Test Level. Experiments and observational activities planned for the underground excavations were evaluated with regard to potential zones of influence, but further evaluation was not considered necessary due to the nature of the tests (primarily observational and sample collection) or the limited amount of rock affected, or the large physical separation between these tests and others.

The interference analysis of all experiments proposed for the Main Test Level was performed based on the current test definitions, available analysis results, and prototype test data. The designs of several of the experiments may change as site evaluation proceeds. These changes will require a reevaluation of potential interferences among the applicable tests.

On the basis of analyses presented in the SCP Section 8.4.2.3.6.1 (Potential for interference between tests), the locations and separation distances between tests are considered to be acceptable. Hydrologic interference between drifts is not likely to be observed, although the possibility of flow in large-aperture fractures from one drift to another cannot be ruled out. Additionally, no mechanical interference or unacceptable vibratory interference is expected. A portion of the hydrochemistry testing is expected to be performed at the same location as the radial boreholes tests, the use of an air tracer will enable recognition of potential interferences between these tests.

3 DESCRIPTION OF ACTIVITIES

The study is organized into ten activities:

- 8.3.1.2.2.4.1 - Intact-fracture tests
- 8.3.1.2.2.4.2 - Percolation tests
- 8.3.1.2.2.4.3 - Bulk-permeability tests
- 8.3.1.2.2.4.4 - Radial-borehole tests
- 8.3.1.2.2.4.5 - Excavation-effects tests
- 8.3.1.2.2.4.6 - Calico Hills tests (ACTIVITY DELETED)
- 8.3.1.2.2.4.7 - Perched-water tests
- 8.3.1.2.2.4.8 - Hydrochemistry tests
- 8.3.1.2.2.4.9 - Multipurpose-boreholes testing near the exploratory shafts (ACTIVITY DELETED), and
- 8.3.1.2.2.4.10 - Hydrologic properties of major faults encountered in the ESF.

Five test activities are planned during the ESF construction phase: radial borehole, excavation effects, perched water, hydrochemistry, and hydrologic properties of major faults. This study plan includes the plans for radial-borehole, excavation-effects, perched-water, and hydrochemistry; which are described in Sections 3.4, 3.5, 3.7, and 3.8, respectively. The plans for hydrologic properties of major faults will be described in Section 3.10 in a subsequent revision of this plan. Three other activities will be conducted as a part of the *in-situ* testing in the ramps and drifts of the ESF: intact fracture, percolation, and bulk permeability. The plans for these activities will be described in a subsequent revision of this plan.

3.1 Intact-fracture test

The intact-fracture tests will be conducted in a USGS laboratory. The rock samples for this test will be obtained from the ESF. Because the test is not a part of the ESF construction-phase testing, the plan for this activity will be presented in a subsequent revision of this study plan.

3.2 Percolation test

The percolation tests will be conducted in ramps and drifts of the ESF. Because the tests are not part of the ESF construction-phase testing, the plan for this activity will be presented in a subsequent revision of this study plan.

3.3 Bulk permeability tests

The bulk permeability tests will be conducted in the ramps and drifts of the ESF. Because these tests are not part of the ESF construction-phase testing, the plan for this activity will be presented in a subsequent revision of this study plan.

3.4 Radial-borehole tests

3.4.1 Objectives

The objectives of this activity are to:

1. quantify the gas permeability and anisotropy of the geohydrologic units within the unsaturated zone.
2. evaluate the effects of excavation in the ramps and drifts on hydrologic properties of unsaturated-zone geohydrologic units.
3. estimate tortuosity and effective porosity of the drained pore spaces of the unsaturated geohydrologic units;
4. quantify the boundary effects at the geohydrologic unit contacts;
5. compare pneumatic and hydraulic test results especially at the geohydrologic unit contacts; and
6. monitor for flow of water, as both vapor and liquid, in the unsaturated zone;

3.4.2 Rationale for activity selection

It is hypothesized that most fractures in the unsaturated zone beneath Yucca Mountain probably are drained and devoid of significant liquid water (Montazer and Wilson, 1984; Wang and Narasimhan, 1985). The air in these fractures, as well as within the unsaturated pores, is nearly saturated with water vapor. This vapor-saturated air probably is mobile in the more extensively fractured tuffs and, to a lesser degree, in the moderately to nonfractured tuffs. Two mechanisms cause flow of the vapor-saturated air: the natural geothermal gradient and the transient pneumatic-potential gradient that results from atmospheric-pressure fluctuations.

Two simplified cases of water flow in the unsaturated zone include upward movement of water vapor and downward migration of liquid water. Upward migration of vapor-saturated air may indicate the potential for upward migration of gaseous radionuclides. In addition, downward water movement may be indicative of potential radionuclide-solute transport. In both cases, the natural vapor and liquid-water fluxes may be influenced by the thermal field created after emplacement of high-level radioactive waste.

Although water vapor in the unsaturated zone probably cannot transport significant amounts of radionuclides, the transport of gaseous radionuclides in the vapor-saturated air is a concern. Gaseous radionuclides, such as tritium and carbon-14, may be transported to the atmospheric environment by natural gradients or disturbed gradients imposed by repository emplacement. Therefore, permeabilities, anisotropy, porosities, travel time, and transport mechanism in the air-filled voids of the unsaturated zone are important in assessing the performance of a potential repository. Tortuosity, air-filled effective porosity, and air permeability should be determined in order to evaluate the potential transport rate of the gaseous radionuclides. Tortuosity and air-filled effective porosity are needed to calculate the effective coefficient of diffusion of the gases through the rock and thus to evaluate diffusive transport. Gas permeability is needed to calculate flow velocity so that convective transport can be evaluated. Porosity, tortuosity, air permeability and anisotropy will be determined by testing (gas injection into the rock), passive monitoring of pneumatic pressure, and gas sampling and analysis. These activities are described in greater detail in Section 3.4.3.

Flow of liquid water in the unsaturated zone is expected to be downward; however, heterogeneity in tuff properties could result in deviation of flow from the vertical. Two situations could cause this deviation: (1) anisotropy in permeability within geohydrologic units and (2) contrasts in permeability between adjacent geohydrologic units. In the latter case, if a large contrast in permeability exists between units, then perched-water or capillary-barrier conditions may form. If these conditions occur along dipping geohydrologic-unit contacts, water may flow laterally. The existence of major structural features, such as faults, may result in diversion of water. The case of water diversion caused by marked contrasts in permeability of different geohydrologic units will be investigated by the hydrologic properties of major faults tests (Activity 8.3.1.2.2.4.10).

Understanding the potential for lateral flow of water along geohydrologic-unit contacts is crucial in calculating the rate at which water may percolate through the repository host rock and the travel time to the accessible environment. Large contrasts in hydrologic properties exist at the TCw-PTn and PTn-TSw1 contacts. The potential for a capillary barrier between the matrix of the TCw and the matrix of the PTn and a potential barrier between the matrix of the PTn and the fractures of the TSw1 will be investigated. In addition, the potential for perched water and lateral flow at the PTn-TSw1 contact and at contacts in the layered anisotropic PTn unit will be examined on both small and large scales. Diversion of downward flow by the welded unit could significantly reduce the downward flow of water to the proposed repository. The upper and lower contacts of the PTn have been identified as test sites; ramp construction may identify additional contacts of highly variable permeabilities in the PTn that will require testing. Initial testing will consist of injecting gas across the contacts followed by long term monitoring and ultimately water will be injected across the geohydrologic contact during the final phase of testing.

Free drainage of the repository host rock is considered a favorable condition for a repository in the unsaturated zone. Free drainage will assure that, with wetter climatic conditions, saturated conditions may not develop within the repository host rock. Air-filled pore and fracture space is available to transmit any recharge pulse; hence, air permeability is an indicator of the potential for free drainage in the unsaturated zone.

Excavation of underground openings alters the natural state of stress within rock. Stress redistribution will cause fractures and pores to open or close depending upon their location in the newly established stress field. In turn, bulk permeability and porosity of the rock will change as a result of changes in fracture and pore sizes. Changes in porosity directly affect the saturation level of the rock; therefore, saturation also is sensitive to stress changes. The effects of excavation on tuff hydrologic parameters are important for two reasons: (1) the excavation of ramps and drifts may affect the interpretation of hydrologic information obtained from the radial boreholes, and (2) the disturbed zone surrounding the ramps may create new pathways for radionuclide migration and thus may require corrective measures. Gas-injection packer tests will quantify the hydrologic characteristic changes around ramps and drifts.

In order to develop a standard cross-hole pneumatic and hydraulic test system that can be used in the ESF hydrologic tests (radial-borehole tests, bulk-permeability tests, and excavation-effects tests) and also can be applicable to the surface-based air permeability testing, prototype testing was conducted at the University of Arizona's Apache Leap Tuff site located near Superior, Arizona. The test system was made up of several components, including testing and preparation of hardware, software, technical procedures, data analyses, and field-test configuration. The prototype testing identified both strong and weak components of the system. In summary, the measurement instruments, pressure transducers, thermistors, thermocouple psychrometers (TCPs), mass flow controllers, etc. all functioned well while the packer system, used to isolate test intervals, had some deficiencies. The constant-rate test methods and pressures-squared differences analysis methods (Brar, 1975) were found to work well and a Scientific Notebook Plan (HP-241T) for conducting surface-based air permeability testing has been written and approved.

3.4.3 General approach and summary of tests and analyses

The radial-borehole tests were originally conceived as construction-phase tests designed to quantify the effects of vertical shaft excavation; however, the tests have undergone several modifications in design since they were first envisioned.

The radial boreholes testing configured for two ramps, (see Figure 3.4-1), consists of four test Programs: 1) air permeability-anisotropy testing of the geohydrologic units using a three-borehole arrangement, 2) air-injection testing across the geohydrologic contacts using a four-borehole arrangement, 3) long-term monitoring of selected intervals in one or more boreholes at each site, and 4) water-injection testing at the contact sites following completion of the long-term monitoring. Because the two ramps offer some duplication of tests, one or more of the contact sites may be

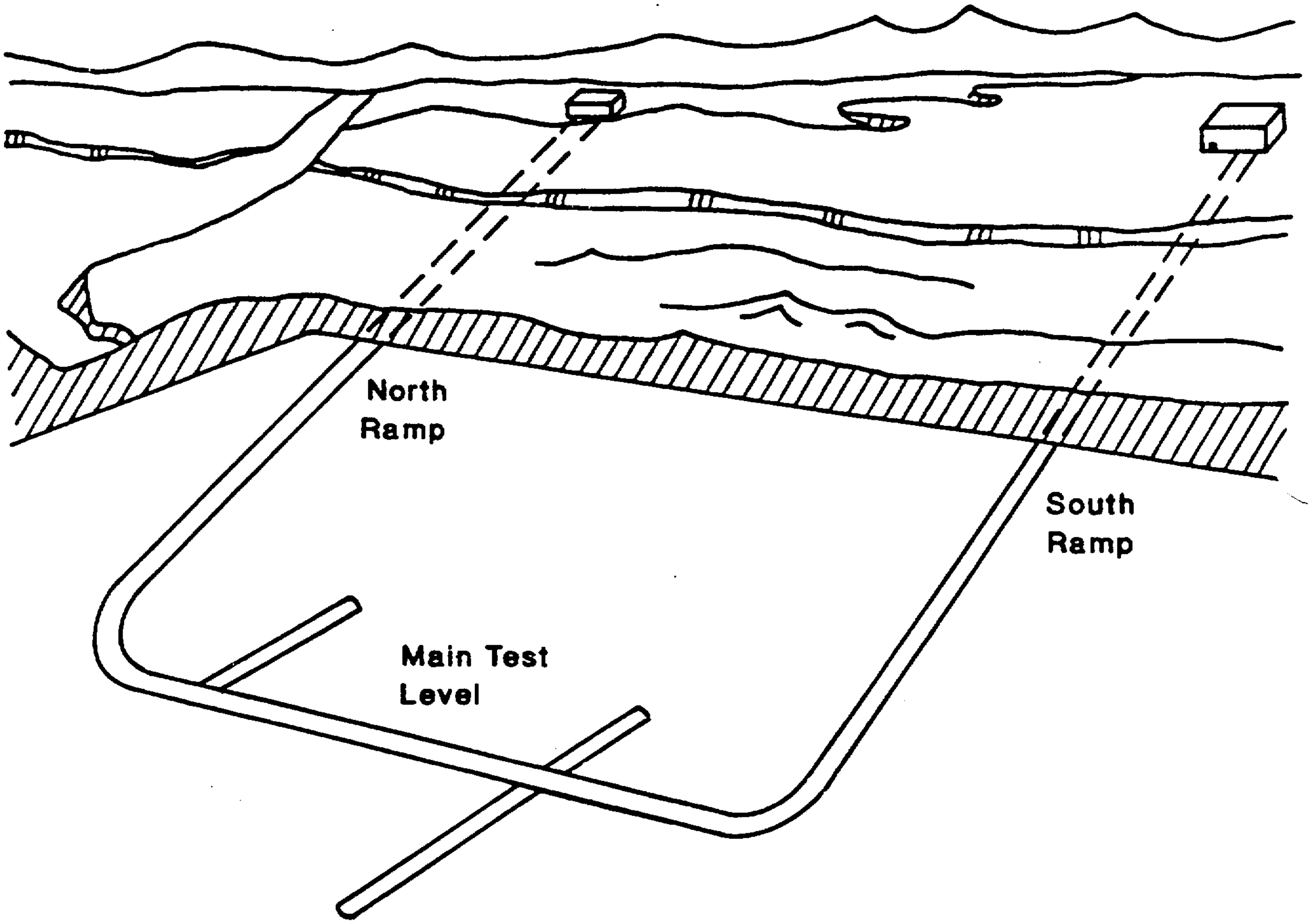


Figure 3.4-1. ESF configuration

selected for hydraulic testing before long-term monitoring. This would supply data on possible perched-lateral flow and capillary barriers sooner than originally proposed. In addition, it will allow long-term monitoring of the drying process.

Air permeability-anisotropy testing of the geohydrologic units will be conducted in a alcove perpendicular to the ramp. The alcove will contain three 30-m HQ boreholes also orientated quasi-perpendicular to the ramp. The actual location and drill angle of the boreholes will be determined after the fracture-mapping data is reviewed. The three boreholes will be instrumented with pneumatic packers and/or downhole liner system and sensors. Single and cross-hole air injection testing and cross-hole tracer testing will be conducted. The goals of the testing are to quantify the: 1) permeability, 2) anisotropy, 3) effective porosity, and 4) tortuosity of the geohydrologic units. Testing will be conducted in alcoves located in the north and south ramps (see Figure 3.4-2). The following is a list of alcove stratigraphic locations.

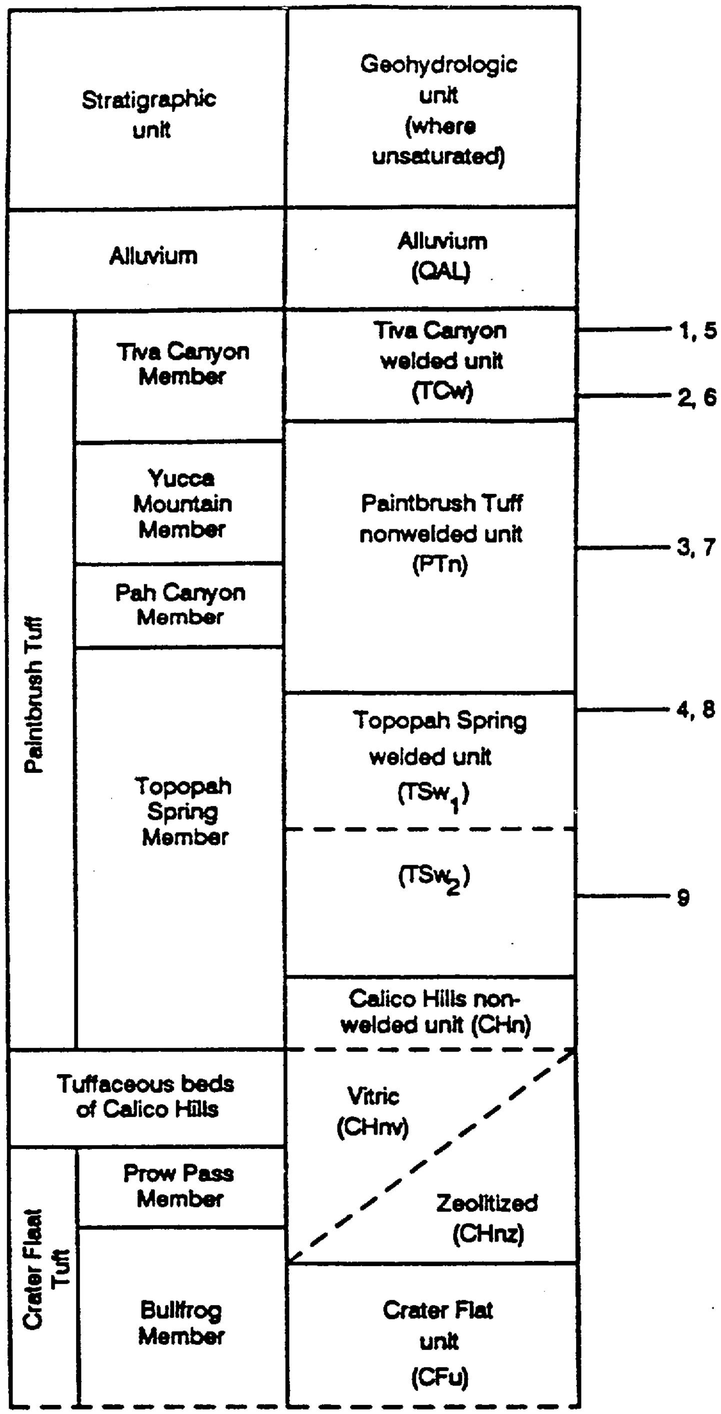
NORTH RAMP

1. Alcove in upper TCw
2. Alcove in lower TCw
3. Alcove in middle PTn
4. Alcove in TSw1

SOUTH RAMP

5. Alcove in upper TCw
6. Alcove in lower TCw
7. Alcove in middle PTn
8. Alcove in TSw1
9. Alcove in TSw2

Air and water injection testing across and along the geohydrologic contacts will also be conducted in alcoves perpendicular to the ramp. Testing will require four 30-m boreholes, two on each side of the contact, also drilled perpendicular to the ramp. The boreholes will be instrumented with pneumatic packers and/or a downhole liner system and sensors. Following installation, single and cross-hole air-injection testing, and possibly a limited number of water injection tests, will be conducted. At the completion of the testing all or some of the boreholes will be instrumented for long-term monitoring. The long-term monitoring instrumentation will consist of pneumatic packers, pressure transducers, thermistors, and thermocouple psychrometers (TCPs). The isolated intervals will also have surface gas lines so that gas samples can be taken. The long-term monitoring program is expected to last approximately 5 years. Following completion of the long-term monitoring program, single and cross-hole water injection tests will be conducted at all sites. The goals of the geohydrologic unit contact testing are to: 1) quantify the boundary effects of the contacts on air flow, 2) monitor for any long-term change in



Note: Figure not to scale

Figure 3.4-2. Stratigraphic locations of permeability-anisotropy test sites.

pressure, temperature, or water potential at the contacts,and 3) quantify the boundary effects of the contacts on water flow. Testing will be conducted in the north and south ramps at but not limited to the following locations (see Figure 3.4-3):

NORTH RAMP

1. Alcove at TCw-PTn contact
2. Alcove at PTn-TSw1 contact

SOUTH RAMP

3. Alcove at TCw-PTn contact
4. Alcove at PTn-TSW1 contact

Because the ramp is expected to be generally unlined it will influence the moisture content, temperature, and pneumatic pressure of the surrounding rock. In order to quantify these influences on the pneumatic testing and long-term monitoring, pneumatic testing and long-term instrumentation must be conducted as soon as possible following the ramp reaching an identified test level. This early baseline data is required in order to ascertain the degree to which the moisture and temperature state of the rock is impacted by the ramps.

Figure 3.4-4 summarizes the organization of the radial-borehole activity. A descriptive heading for each test and analysis appears in the boxes of the second and fourth rows. Below each test/analysis are the individual methods that will be utilized during testing. Figure 3.4-5 summarizes the objectives of the activity, site-characterization parameters, and activity parameters. Cross-references to other study plans which provide input to the radial-borehole tests also appear in both figures.

The two figures summarize the overall structure of the planned activity in terms of methods to be employed and measurements to be made. The descriptions of the following sections are organized on the basis of these charts. Methodology and parameter information are tabulated as a means of summarizing the pertinent relations among (1) the activity parameters to be determined, (2) the information needs of the performance and design issues, (3) the technical objectives of the activity, and (4) the methods to be used.

The exact scheduling of the radial borehole testing and associated activities is dependent on the ramp construction schedule and the access provided during ramp construction.

3.4.3.1 Borehole drilling and coring

3.4.3.1.1 Permeability-anisotropy boreholes

The permeability-anisotropy borehole test sites will consist of three 30-m HQ boreholes. The boreholes will be

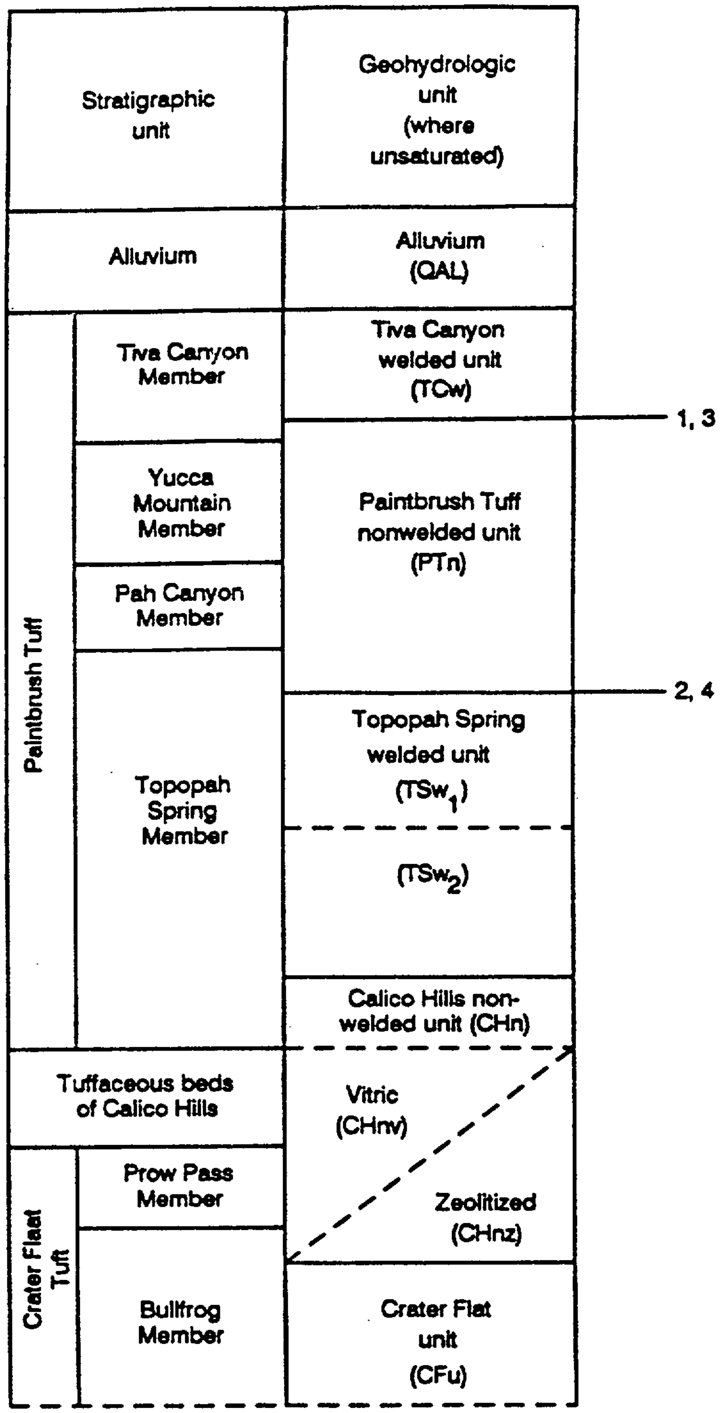


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Figure 3.4-3. Stratigraphic locations of geohydrologic contact test sites.

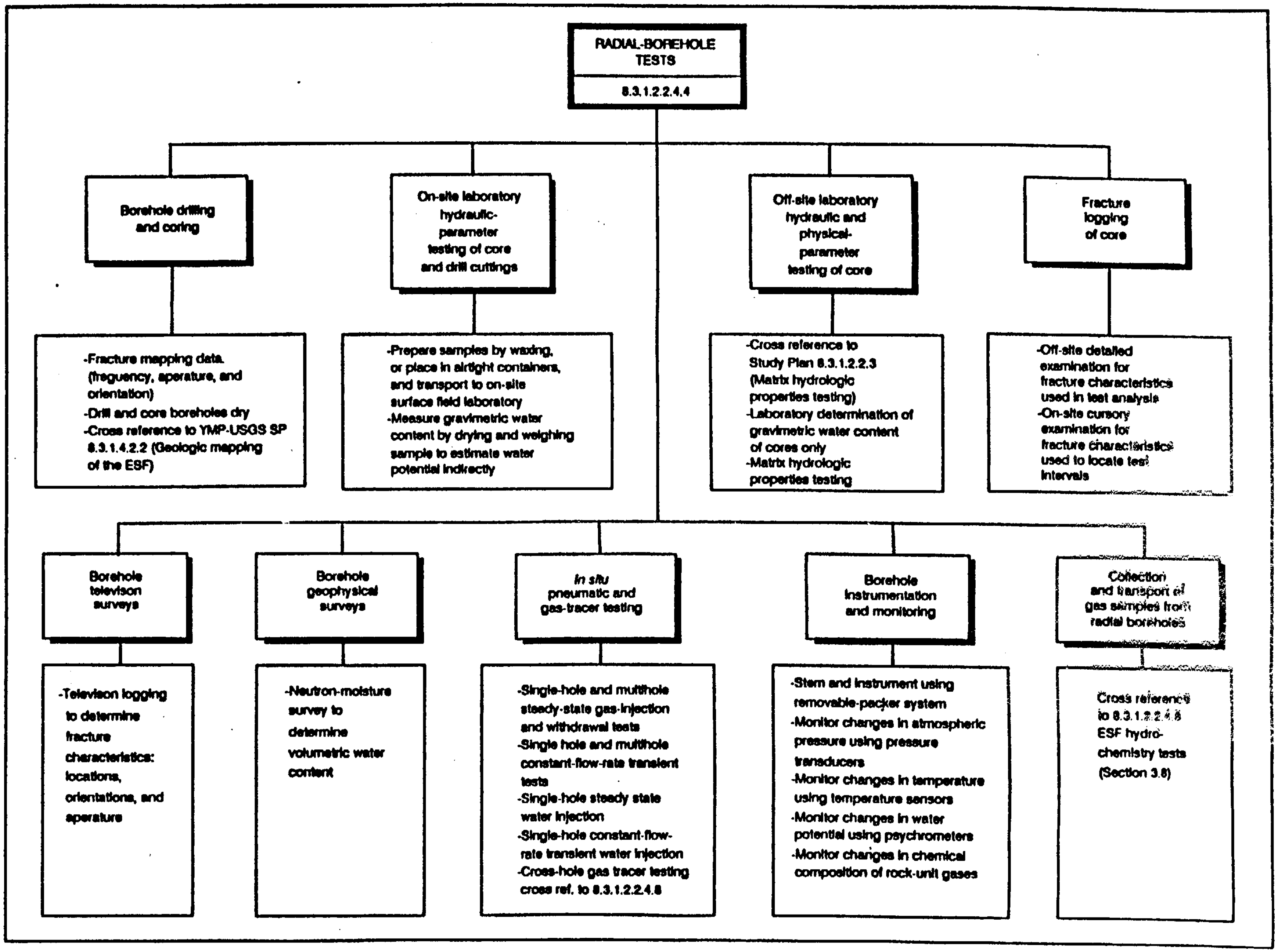


Figure 3.4-4. Organization of the radial-borehole activity, showing tests, analyses, and methods.

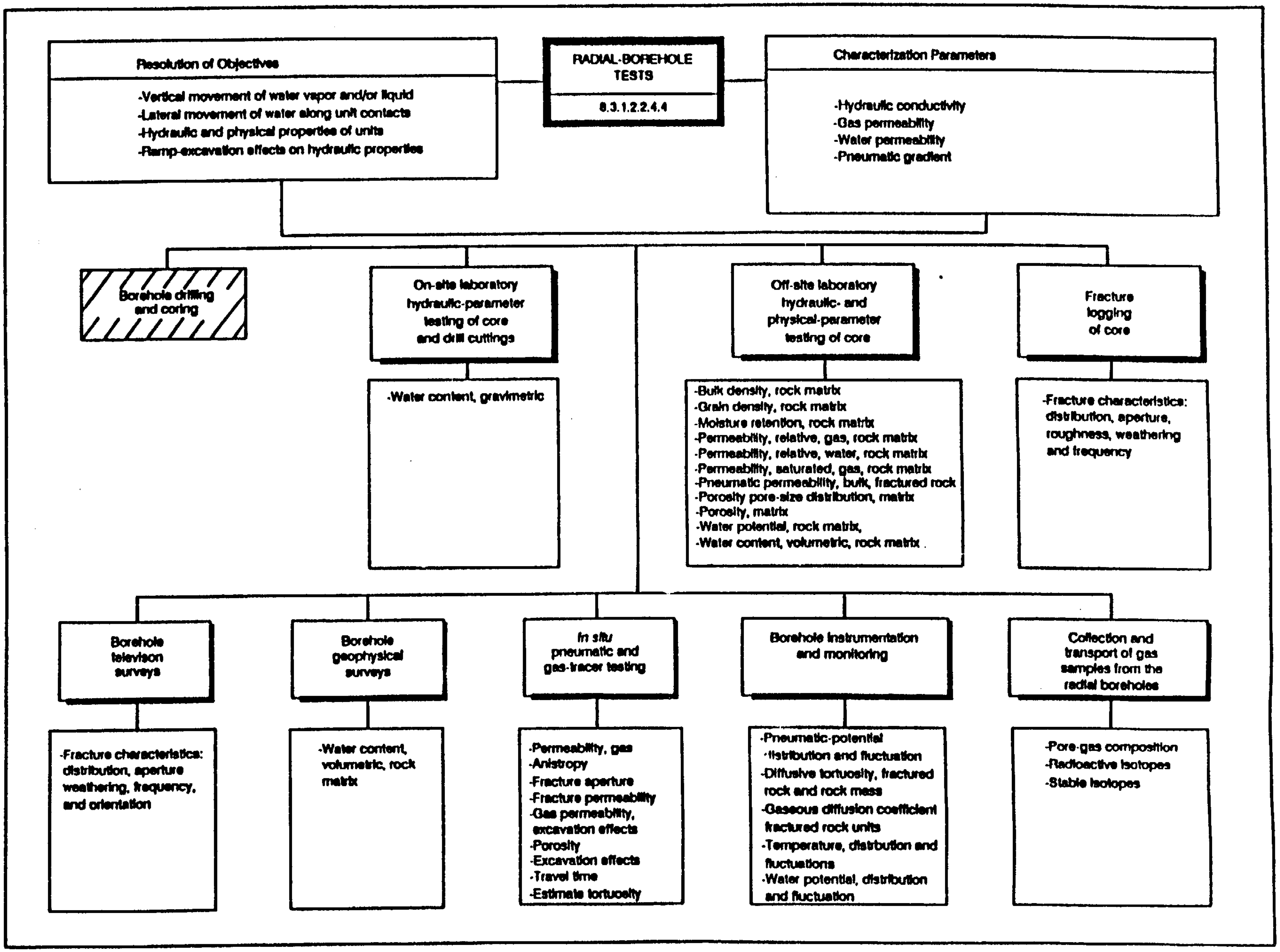


Figure 3.4-5. Organization of the radial-borehole activity, showing tests, analyses, activity parameters, and characterization parameters. (The cross-hatched box indicates that no activity parameter will be generated.)

located in alcoves off the main ramps. Each alcove will be perpendicular to the ramp and the boreholes will be drilled in the far end of the alcove. The boreholes will be drilled in a conical configuration based on an expanding triangle as shown in Figure 3.4-6. The borehole drill locations are configured in an equilateral triangle with 2-m sides. The boreholes are then drilled at an 8-degree angle off perpendicular of the triangle and away from the center of the triangle. This drilling will expand the equilateral triangle so that the equilateral sides will measure 9.3 m when the boreholes are 30 m in length. However, this configuration may be modified based on future information on fracture orientation, etc. obtained in the ramps. The boreholes will be dry drilled with tracer-tagged compressed air. The HQ core will be collected, packaged, labeled, and transported to an off-site laboratory for hydrologic analysis. The alcove must be large enough to allow the drilling operations and sample handling operations to proceed concurrently. Following drilling the boreholes will be logged. Nine preliminary test sites for permeability-anisotropy testing have been selected (see Figure 3.4-2). The final test site locations will be selected during ramp construction.

The length of the radial boreholes was chosen to insure that the testing is conducted in both the zone of stress redistribution associated with the ramps and in the undisturbed zone outside the stress redistribution zone. The stress redistribution zone is predicted to extend for two ramp diameters from the ramp wall into the surrounding rock. This prediction is based on the solution derived from the theory of elasticity for a circular opening. The borehole length of 30 m extends well beyond the predicted disturbed zone of 16 m and will allow testing of both disturbed and undisturbed rock.

3.4.3.1.2 Geohydrologic unit contact boreholes

The geohydrologic unit contact testing borehole test sites will consist of four 30-m HQ boreholes arranged in a rectangle straddling the contact (see Figure 3.4-7). The boreholes will be drilled in alcoves off the main ramps. The alcoves will intersect the geohydrologic contacts and be perpendicular to the ramps. The alcove size will depend on the angle at which the ramp intersects the contact. The boreholes will be drilled perpendicular to the ramps, parallel to the contact, and parallel to each other (see Figure 3.4-7). Two of the boreholes will be located approximately 1.5 m above the contact and separated by 2 m, and two boreholes will be located approximately 1.5 m below the contact and separated by 2 m. These dimensions will probably be altered based on geologic and hydrologic information obtained at the contact test sites. Four preliminary test sites for contact testing have been selected

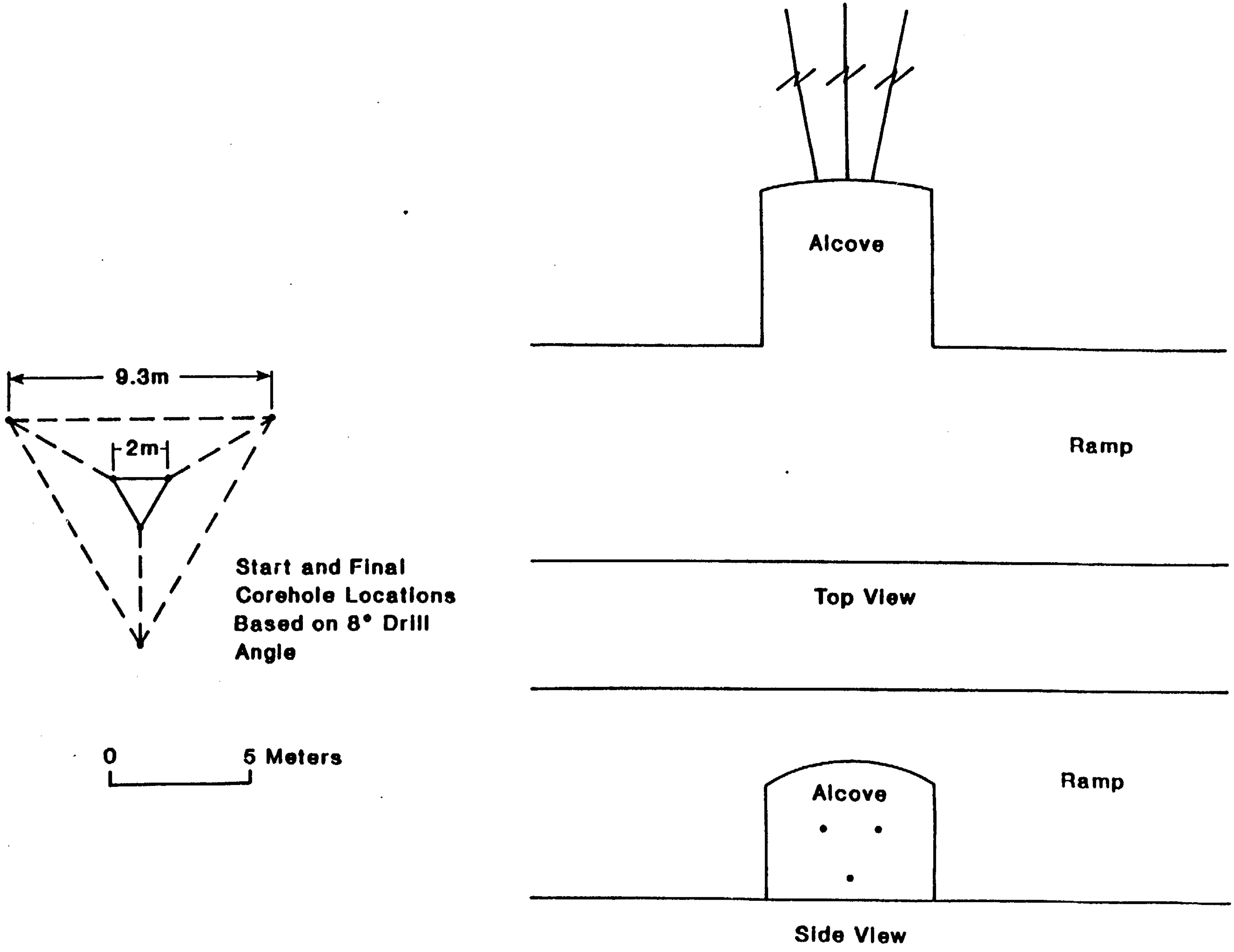


Figure 3.4-6. Schematic of permeability - anisotropy borehole configuration.

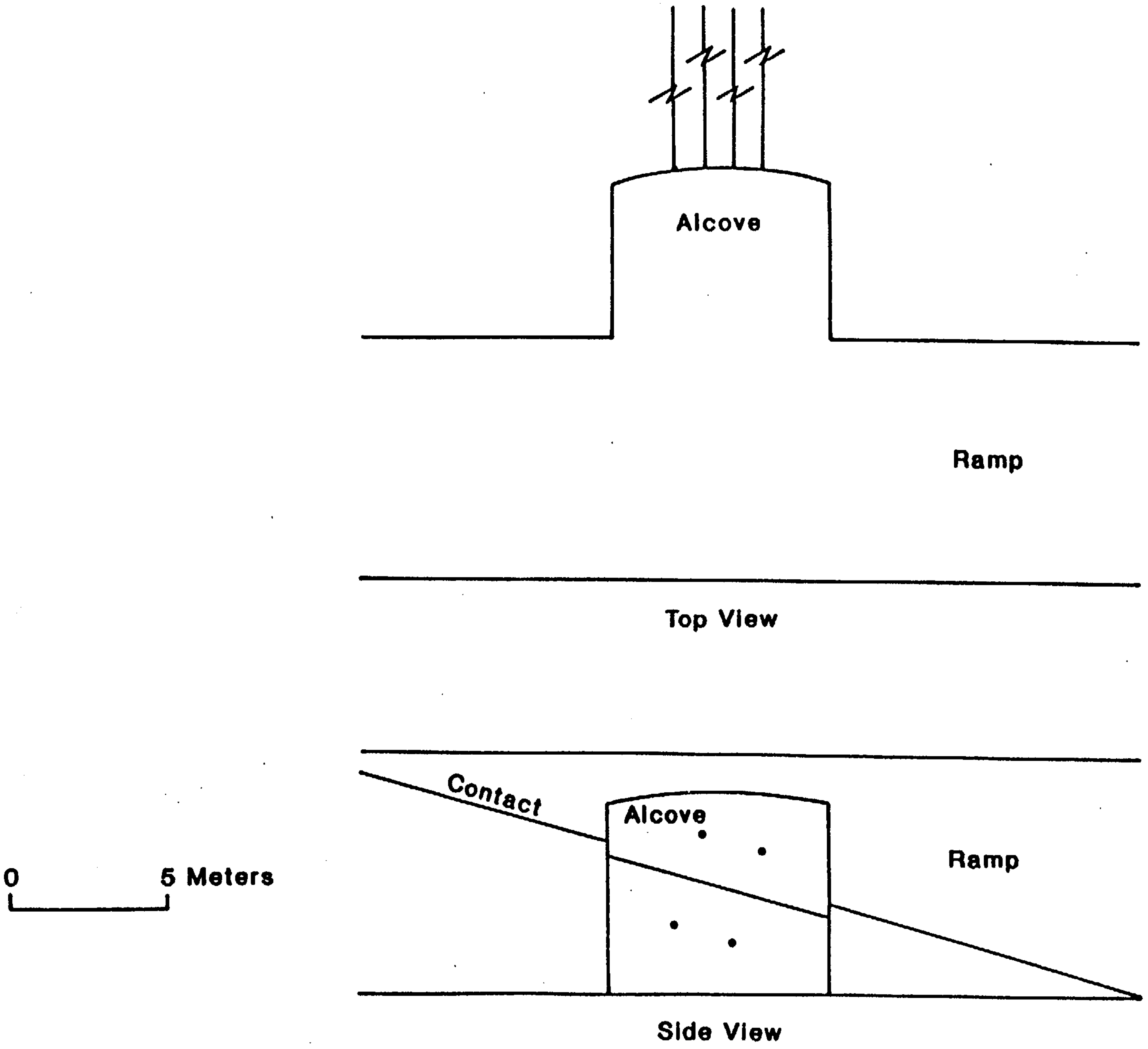


Figure 3.4-7. Schematic of geohydrologic contact borehole configuration.

(see Figure 3.4-3). However, information obtained during ramp construction, such as identification of zones with large changes in permeability and/or porosity within geohydrologic units, may require addition of test sites. Following drilling the boreholes will be logged.

Like the permeability-anisotropy boreholes, the contact boreholes also will be dry drilled using tracer-tagged compressed air as the drilling medium to provide bit cooling and removal of cuttings. The length selection for these holes is also based on the same stress redistribution rationale as in the permeability-anisotropy boreholes. The HQ core will be collected, packaged, labeled, and transported for off-site hydrologic analysis.

3.4.3.2 On-site laboratory hydraulic-parameter testing of core and drill cuttings.

Core and drill-cutting samples obtained during the drilling process will immediately be sealed in wax, or placed in air-tight canisters and transported to a field laboratory, where gravimetric-water content of selected core and cuttings will be determined. Information obtained by this method will be used in the interpretation of gas-injection tests and will serve as baseline data for the newly drilled boreholes.

Table 3.4-1 indicates that an alternative to waxing or sealing the samples in containers is to transport the samples to the laboratory without preparing or preserving them first. Drilling and sampling downtime could be reduced if this practice were adopted, but the samples also could begin to dry out if they were not quickly processed and analyzed.

3.4.3.3 Off-site laboratory hydraulic- and physical-parameter testing of core

Core and cutting samples not utilized during on-site hydrologic testing will be sent off site to laboratories for testing the following properties: volumetric water content, grain density, porosity, bulk density, water potential, water retention, saturated-water permeability, and relative water and gas permeability. The information obtained from these tests will be used in the interpretation of gas injection tests and will serve as baseline data for the newly drilled boreholes. Methods used to measure these important hydrologic parameters are described in the matrix hydrologic properties testing activity (Activity 8.3.1.2.2.3.1) in YMP-USGS SP 8.3.1.2.2.3, (Unsaturated-zone percolation - surface-based studies), along with possible alternatives. Table 3.4-1 gives the activity parameters addressed by these tests.

Table 3.4-1. Summary of tests and methods for the radial-boreholes activity (SCP 8.3.1.2.2.4.4) (continued)

Methods (selected and alternate)	Activity parameter
Fracture logging of core	
Off-site detailed examination for fracture characteristics used in test analysis (selected)	Fracture characteristics: distribution, aperture, weathering, roughness, and frequency
On-site cursory examination for fracture characteristics used to locate test intervals (selected)	"
Borehole television surveys	
Television logging to determine fracture characteristics (selected)	Fracture characteristics: distribution, aperture, weathering, frequency, and orientation
Borehole geophysical surveys	
Neutron-moisture survey to determine volumetric water content (selected)	Water content, volumetric, rock matrix
In-situ pneumatic and gas-tracer testing	
Single-hole and multihole, steady-state, gas-injection and -withdrawal tests (selected)	Permeability, Gas
"	Anistropy
"	Fracture aperture
"	Fracture permeability
"	Excavation effects
Single-hole and multihole, gas-injection, constant-flow rate, transient tests (selected)	Permeability, Gas
"	Anistropy
"	Porosity
"	Gas permeability, excavation effects
Single-hole and multihole, gas-injection, constant-pressure, transient tests (alternate)	Permeability, Gas

Table 3.4-1. Summary of tests and methods for the radial-boreholes activity (SCP 8.3.1.2.2.4.4)

Methods (selected and alternate)	Activity parameter
Borehole drilling and coring	
Drill and core boreholes dry (selected)	(No activity parameters)
Cross-reference to YMP-USGS SP 8.3.1.4.2.2 (Geologic mapping in the ESF)	(See YMP-USGS SP 8.3.1.4.2.2)
On-site laboratory hydraulic-parameter testing of core and drill cuttings	
Prepare samples by waxing, or place in airtight containers, and transport to on-site surface field laboratory (selected)	(No activity parameters)
Measure gravimetric water content by drying and weighing preserved sample to estimate water potential indirectly (selected)	Water content, gravimetric, rock matrix
Measure gravimetric water content by drying and weighing non-preserved sample (alternate)	"
Off-site laboratory hydraulic- and physical-parameter testing of core	
Matrix hydrologic properties testing (selected)	Bulk density, rock matrix
"	Grain density, rock matrix
"	Moisture retention, rock matrix
"	Permeability, relative, gas, rock matrix
"	Permeability, relative, water, rock matrix
"	Permeability, saturated, water, rock matrix
"	Permeability, saturated, gas, rock matrix
"	Pneumatic permeability, bulk, fractured rock
"	Porosity pore-size distribution, matrix
"	Porosity, matrix
"	Water potential, rock matrix
Laboratory determination of gravimetric water content of cores only (selected)	Water content, volumetric, rock matrix

Table 3.4-1. Summary of tests and methods for the radial-boreholes activity (SCP 8.3.1.2.2.4.4) (continued)

Methods (selected and alternate)	Activity parameter
In-situ pneumatic and gas-tracer testing (continued)	
Single-hole and multihole, gas injection, constant-pressure, transient tests (alternate)	Anistropy
"	Porosity
"	Gas permeability, excavation effects
Cross-hole gas tracer testing, cross reference to 8.3.1.2.2.4.8 (selected)	Travel time
"	Estimate tortuosity
Borehole instrumentation and monitoring	
Stem and instrument using removable-packer system (selected)	(No activity parameters)
Monitor atmospheric pressure changes within test intervals using pressure transducers (selected)	Pneumatic-potential distribution and fluctuation
Monitor changes in chemical composition of rock-unit gases (selected)	Diffusive tortuosity, fractured rock and rock mass
"	Gaseous diffusion coefficient, fractured rock units
Monitor changes in temperature within borehole using temperature sensors (selected)	Temperature, distribution and fluctuations
Monitor changes in water potential within boreholes using psychrometer (selected)	Water potential, distribution and fluctuation
Collection and transport of gas samples from the radial boreholes	
Cross reference to 8.3.1.2.2.4.8 ESF hydrochemistry tests (selected)	Pore-gas composition
"	Radioactive isotopes
"	Stable isotopes

3.4.3.4 Fracture logs of core

If continuous coring is possible, a cursory examination of the core for fracture characteristics (i.e., type of fracture, frequency, depth to fracture, etc.) will be made on-site during drilling. In the laboratory, a more detailed examination of the core will be made to develop detailed fracture-characteristic logs. Fracture data from boreholes will be used in conducting the permeability-anisotropy and geohydrologic contact testing along with selection of the long-term monitoring zones. No alternative methods for this activity were identified, although borehole-television cameras will also be used to view fractures *in situ*.

3.4.3.5 Borehole television surveys

Following completion of drilling, all boreholes will be logged with an oriented television camera for fracture characteristics and lithology. The survey will be used for fracture orientation and to determine whether the fractures intersecting the borehole are open or closed. The fracture data will be used to supplement geologic mapping in the ESF and to determine the location of test intervals and long-term monitoring zones. An alternative to borehole-television surveys is to maintain orientation of the core during drilling. This would require a special oriented-core barrel. The oriented core could be used to determine fracture orientation; however, it is often difficult to determine from core whether fractures are open or closed, and if they are drilling-induced or natural, especially at greater depths where weathering is not as prominent.

3.4.3.6 Borehole geophysical surveys

Following television logging all boreholes will be neutron-logged. Neutron surveys also will be conducted in the permeability-anisotropy boreholes on a periodic basis. These data will be used to look at long-term drying trends in the far-field environment.

3.4.3.7 *In-situ* pneumatic and gas-tracer tests

Single and cross-hole gas injection tests will be conducted at the permeability-anisotropy and geohydrologic unit contact sites. Testing will use a downhole liner to isolate numerous sections of each borehole. These isolated sections can then be used as monitoring or injection zones. The fracture-log data obtained from the drill core and video-camera surveys will be used to select the test zones. The early test site boreholes will probably have their full lengths tested. After some experience and initial analysis, the testing density can probably be reduced.

Fluid-injection or -withdrawal (production) field tests are used to evaluate the *in-situ* permeability and storativity of rock subjected to natural overburdening and confining stresses. Laboratory testing of core is another method commonly used to evaluate rock permeability and porosity. Unfortunately, laboratory permeability tests require subjecting the drill core to stress conditions expected in the field in order to accurately determine *in-situ* permeabilities; this requires prior knowledge of the stress conditions, including stress directions and magnitudes. In addition, the *in-situ* permeability of fractured rocks with large fracture permeability would be grossly underestimated if laboratory-test results on core, which usually represent matrix permeabilities, were used exclusively.

Another alternative to measuring permeability directly from cores or *in-situ* field tests is to use a fracture model to estimate permeability indirectly (Dershowitz, 1991; Van Golf-Racht, 1982; Rissler, 1978; Snow, 1965). Fracture data, including fracture orientations, surface roughness, densities, and apertures, are collected from drill-hole video, core, and geophysical logs and then used directly in a fracture model to compute rock permeability. This method is somewhat restrictive because a large fracture data base is required to characterize the rock and determine permeability; there is a great deal of uncertainty associated with measuring *in-situ* fracture apertures accurately because borehole unloading can result in near-borehole fracture deformation, and fracture lengths are very difficult to determine if only one drill hole is present or the distance between multiple holes is large. Due to the inherent problems associated with using fracture models and laboratory permeabilities to determine *in-situ* rock permeability, fluid-injection or -production field tests provide the most effective method of determining this important parameter.

Prototype testing has determined that several gas-injection and -withdrawal methods will be utilized during the testing program. They include: (1) single-hole, constant-flow-rate, transient tests; (2) single-hole steady-state, gas-injection and -withdrawal tests; (3) cross-hole constant-flow-rate transient tests; and (4) cross-hole steady-state gas injection and withdrawal tests.

Single-hole fluid injection or withdrawal (production) field tests are commonly used to evaluate reservoir or aquifer permeability. These tests utilize only one active well and no observation wells. Rock parameters are evaluated from data (flow rates, pressure, and temperatures) collected from a single borehole (Earlougher, 1977). The two single-hole methods listed above and in Table 3.4-1 are briefly described below. A thorough treatise on each method can be found in the references accompanying each description.

Steady-state, gas-injection and -withdrawal tests will be used to determine the permeability of individual fractures.

Steady-state tests consist of injecting gas into or withdrawing gas from the rock until the downhole pressure and uphole measured injection (withdrawal) flow rates remain constant. Trautz (1984) used this method to characterize fractures in unsaturated fractured tuffs. Schrauf and Evans (1984) also used this method to evaluate the relation between the gas conductivity and geometry of natural fractures in the laboratory.

The single-hole constant-rate transient test consists of injecting gas into the rock at a constant rate and at the same time monitoring the transient pressure response (i.e., change in pressure with time). Constant-production-rate, transient tests are commonly used in the oil industry to evaluate gas-reservoir parameters (Earlougher, 1977). An alternative to this method, which is listed in Table 3.4-1, is a constant-pressure, transient test. As the name implies, gas is injected or produced from the rock at a constant pressure while the change in gas-flow rate is monitored with time. Such a test is seldom made because it is much easier to measure pressure accurately than it is to accurately measure flow rate (Earlougher, 1977). Constant-rate tests, however, may inadvertently become constant-pressure tests, and so it is desirable to be able to analyze both types of tests.

Cross-hole pneumatic and hydraulic field tests, commonly referred to as "interference tests" in the petroleum industry, are used to evaluate reservoir properties such as permeability and storativity, determine the location of structural features such as faults, no-flow and recharge boundaries, and evaluate isotropic versus anisotropic conditions in reservoirs (Earlougher, 1977) and fractured aquifers (Hsieh and Neuman, 1985; and Hsieh and others, 1985). Cross-hole testing is a descriptive phrase used to describe a multiple-well test. Multiple-well tests require at least one active (producing or injecting) well and at least one observation well; however, only one active well will be utilized at any given location and time during this study. Gas will be injected or produced from an isolated test interval in one of the boreholes and the response of the formation to the change in fluid pressure will be monitored in numerous nearby observation intervals located in the other boreholes. The test results, namely active- and observation-well fluid pressures, and injection or production-flow rates, are used to calculate reservoir aquifer parameters. Analysis of the test results is dependent upon flow-domain boundary conditions, the type of fluid injected into the formation, the saturation state of the formation, and the type of test conducted (e.g., steady-state or transient).

The methods described with regard to single-hole tests apply equally to cross-hole testing. The greatest difference between the two test configurations is the quality of results that can be determined from the test data. Single-hole test results can be heavily influenced by wellbore conditions (i.e., skin effects caused by wellbore damage or improvement), making it difficult or impossible to calculate reservoir parameters. In addition, it is impossible to characterize the anisotropic nature of a reservoir using a single-hole test. The cross-hole tests provide a convenient test configuration for gaining important hydraulic information about the geohydrologic units penetrated by the ramps, information that could not be obtained from single-hole testing methods alone. Types of cross-hole tests to be conducted include: (1) constant-rate transient gas-injection tests; and (2) steady-state, gas injection and withdrawal. A possible alternative to these methods could be constant-pressure, gas-injection tests.

3.4.3.7.1 Permeability-anisotropy pneumatic testing

Single and cross-hole gas injection tests will be conducted at the permeability-anisotropy test sites. During single-hole testing, intervals will be tested and analyzed for spatial correlations (Winberg, 1991). During cross-hole testing, two boreholes will be used as monitoring boreholes. They will be fitted with downhole liners isolating up to 30 intervals in each borehole. These intervals will be connected to the alcove by small-diameter tubes. The tubes can be attached to pressure transducers and used to monitor the pressure in the downhole interval or attached to pumps to obtain gas samples. The third borehole will be fitted with a liner with a single large-capacity injection zone. The injection zone is adjustable and can be moved throughout the borehole. The single large-capacity injection zone will be connected to the surface with a large-diameter tube through which gas can be injected or pumped. The tube will be connected to a surface gas source and used to conduct pneumatic tests. Each of the three boreholes will be used as the injection borehole while the remaining two boreholes are monitored.

Cross-hole pneumatic tests between the permeability-anisotropy boreholes will be used to define the three-dimensional permeability tensor in the same manner that Hsieh and Neuman (1985) used cross-hole hydraulic tests to determine the hydraulic-conductivity tensor of saturated, fractured rock. Hsieh and Neuman's (1985) method will be modified to account for gas flow. An important feature of Hsieh and others' (1985) method is that it allows the investigator to determine the anisotropic nature of the medium without prior knowledge of principal-permeability directions or magnitudes. Virtually all of the previously proposed methods required that one or more principal directions be known prior to the test (Papadopulos, 1965; Hantush, 1966; Snow, 1965).

3.4.3.7.2 Geohydrologic unit contact pneumatic testing

Single and cross-hole gas injection tests will be conducted at the geohydrologic contact test sites. During single-hole testing, intervals will be tested and analyzed for spatial correlations (Winberg, 1991). During cross-hole testing, three of the boreholes will be fitted with downhole liners isolating up to 30 intervals in each borehole. These intervals will be connected to the alcove by small-diameter tubes. The tubes can be attached to pressure transducers and used to monitor the pressure in the downhole interval or attached to pumps to obtain gas samples. The fourth borehole will be fitted with a downhole liner with one large-capacity injection interval. The large-capacity injection interval is adjustable and can be moved throughout the boreholes. A single larger-diameter tube will connect the large-capacity injection interval to an alcove gas source and will be used to inject or pump gas. Each of the four boreholes will be used as injection boreholes while the remaining three are used as monitoring boreholes.

Cross-hole pneumatic tests between the geohydrologic unit contact boreholes will be used to quantify the hydrologic characteristics of the geohydrologic contacts. Compressed air will be injected into an isolated interval in one borehole and the pressure response monitored in numerous intervals in monitoring boreholes on both sides of the contact. The boreholes will be placed so the influence of the contact on the injection zone and monitoring zones in boreholes on the same side of the contact will yield information as to what type of boundary the contact represents. Numerous isolated intervals in all four boreholes will be used as the injection zone. Use of numerous injection intervals over the full lengths of all the boreholes will evaluate contact characteristics over a large area and evaluate the geohydrologic units' near-contact permeability and effective porosity over a large area.

3.4.3.7.3 Gas tracer testing

Following pneumatic testing, cross-hole tracer testing will be conducted at both the permeability-anisotropy and geohydrologic unit contact test sites. Tracer travel times between selected intervals can be compared to velocities calculated from pneumatic testing and used to estimate tortuosity. Tracer testing will be conducted in cooperation and under guidelines of the geochemistry staff using methods referenced in Section 3.8.

3.4.3.8 *In-situ* hydraulic testing

Following pneumatic and tracer testing, one or more of the permeability-anisotropy and geohydrologic unit contact test sites may be selected for hydraulic testing. Pneumatic and hydraulic test results will differ due to gravity, air entrapment, Klinkenberg effect, and other possible influences. However, an opportunity to compare pneumatic and hydraulic test results is an important need in the site characterization program. If reliable techniques can be derived for estimating permeability (and hydraulic conductivity) from air- and water-injection test data at the field-scale (that scale which corresponds to the zone which is evaluated in the air- or water-phase testing), then pneumatic testing results may be more efficient and provide a more comprehensive assessment of the permeability of the formations. It will be necessary to perform single and cross-hole hydraulic tests at select locations in order to determine the usefulness of effective air permeability in calculating hydraulic conductivity, and may provide some insight into questions on water flow across geohydrologic unit contacts.

Obviously, sites chosen for a comparative analysis of hydraulic and pneumatic testing should be representative of other locations in both welded and nonwelded units. However, they should also be situated away from areas where water might interfere with other test activities. The selected hydraulic test sites should provide the confidence needed for correlating pneumatic and hydraulic parameters. All water will be tagged to facilitate identification.

Hydraulic testing will also allow for long-term monitoring following water injection. Because the two ramps provide matching test sites, this will allow long-term monitoring of the same formation following air versus water injection.

Those sites not tested before long-term monitoring will be tested following the long-term monitoring program.

Figure 3.4-4 lists the types of cross-hole pneumatic and hydraulic tests that will be conducted during cross-contact testing. Constant flow-rate transient tests and steady-state tests will be utilized.

3.4.3.9 Borehole instrumentation and monitoring

The second phase of the tests consists of instrumenting and monitoring selected intervals in one or more boreholes at all radial borehole sites and periodically withdrawing rock-gas samples. Permanent instrumentation will be installed in selected boreholes and continuously monitored for *in-situ* water potential, pneumatic pressure, and temperature changes for a period up to 5 years.

Long-term monitoring of the radial boreholes will enable detection of changes in the water potential, pneumatic pressure, and temperature associated with possible water pulses, barometric influences, or ramp influences that are occurring in the unsaturated zone. During infiltration events, percolation of water will disturb the *in-situ* water potential and temperature. Water potential will be monitored with thermocouple psychrometers that measure relative humidity in the unsaturated zone. This is related to water potential in the voids by Kelvin's equation

(Hillel, 1971). Prototype testing by the USGS has shown that thermocouple psychrometers can be calibrated with salt solutions to a sensitivity of 0.05 bars and accuracy of 0.7 bars over a range of -1 to -75 bars. Prototype thermistor testing has developed thermistors with sensitivity of 0.001 deg C, and accuracies of 0.005 deg C over a range of 10 to 50 deg C. Prototype pressure transducer testing and development has resulted in units with sensitivities of 10.0 Pascals, and accuracies of 20.0 Pascals over a range of 0.5 to 1.5 atms.

A preliminary data analysis of the pneumatic tests and borehole television logs will be used to determine optimal emplacement of the long-term monitoring stations. At least three stations will be installed in each selected borehole. Each station will be instrumented with a thermocouple psychrometer, pressure transducer, thermistor, and access tube for gas sampling. Sensor leads will be connected to a local data-acquisition system (DAS) located near the collar of the borehole in the ramps or drifts. The DAS will convert analog to digital signals which will be sent to the integrated data system (IDS). The design and operation of the system is based on the prototype systems developed in G-tunnel and during the Hydrologic Research Facility prototype boreholes work.

After the sensors and data-acquisition system are installed, data monitoring will continue throughout the *in-situ* phase tests being conducted throughout the ramps and Main Test Level. No alternatives were identified for the methods presented in Table 3.4-1.

3.4.3.10 Collection and transport of gas samples from radial boreholes

Gas sampling (collecting, transporting, and analyzing gas samples) will be conducted as part of the plans described in Section 3.8 (Hydrochemistry tests). A brief description of activities is presented here so that the reader has a better understanding of the interface between the radial-borehole tests and the hydrochemistry tests.

Two sets of gas samples will be taken from the radial boreholes. The first will be for analysis of the general composition of air in the unsaturated zone, including nitrogen, oxygen, argon, and carbon dioxide. Drilling and injected gas will be identified by the tracers. This sampling will be conducted approximately every three months and will continue throughout the *in-situ* phase tests. The second set will be for analysis of gaseous radioactive and stable isotopes: carbon-14, carbon-13, tritium, oxygen-18, and deuterium. Sampling for the second set is complicated and may last about five weeks. For this reason, this sampling will be repeated only annually but will continue throughout the duration of the *in-situ* phase testing.

3.4.3.11 Methods summary

The activity parameters to be determined by the tests and analyses described in the above sections are summarized in Table 3.4-1. Also listed are the selected and alternate methods for determining the parameters. The alternate methods will be utilized only if the primary (selected) method is impractical to measure the parameter(s) of interest. In some cases, there are many approaches to conducting the test. In those cases, only the most common methods are included in the tables. The selected methods in Table 3.4-1 were chosen wholly or in part on the basis of accuracy, precision, duration of methods, expected range, and interference with other tests and analyses.

The USGS investigators have selected methods that they believe are suitable to provide accurate data within the expected range of the activity characterization parameter. Models and analytical techniques have been or will be developed to be consistent with test results.

3.4.4 Quality assurance requirements

The USGS Quality Assurance Program Plan for the YMP (USGS, 1989) requires technical procedures for all technical activities that require quality assurance.

Table 3.4-2 provides a tabulation of technical procedures applicable to this activity. Approved procedures are identified with a hydrologic procedure number. Procedures identified as "TBD" will be approved prior to being needed for use in site characterization.

Equipment requirements and instrument calibration are described in the technical procedures. Lists of equipment and stepwise procedures for the use and calibration of equipment, limits, accuracy, handling, and calibration needs, quantitative or qualitative acceptance criteria of results, description of data documentation, identification, treatment and control of samples, and records requirements are included in these documents.

Table 3.4-2. Technical procedures for the radial-borehole activity (SCP 8.3.1.2.2.4.4)

Technical procedure number (YMP-USGS-)	Technical Procedure
	Borehole drilling and coring
HP-12	Method for collection, processing, and handling of drill cuttings and core from unsaturated-zone boreholes at the well site, NTS
HP-38	Method for measuring humidity, pressure, and temperature of intake and exhaust air during vacuum drilling
TBD	Borehole cleaning and verification techniques
TBD	Borehole drilling and coring horizontal holes dry
	On-site laboratory hydraulic-parameter testing of core and drill cuttings
HP-32	Method for monitoring moisture content of drill-bit cuttings from the unsaturated zone
HP-73	Calibration and use of the Sartorius Electronic Toploader (balance) Model 1507 MP8
	Off-site laboratory hydraulic- and physical-parameter testing of core
HP-28	Laboratory procedures for the determination of moisture-retention curves on rock core
TBD	Procedures for the measurement of (1) volumetric water content, (2) bulk density, (3) porosity, (4) saturated water and gas permeability, (5) relative permeability
TBD	Cross-reference to 8.3.1.2.2.3.1 for a complete listing of matrix hydrologic-properties technical procedures
	Fracture logging of core
GP-11	Logging fractures in core
TBD	On-site fracture logging of core

Table 3.4-2. Technical procedures for the radial-borehole activity (SCP 8.3.1.2.2.4.4) (continued)

Technical procedure number (YMP-USGS-)	Technical Procedure
	Borehole television surveys
GP-10	Borehole video fracture logging
TBD	Borehole video logging in horizontal boreholes
TBD	Operation of borehole television
TBD	Method for cleaning borehole walls prior to television camera survey
	Borehole geophysical surveys
HP-62	Method for measuring subsurface moisture content, using a neutron moisture meter
	In situ pneumatic and gas-tracer testing
TBD	Air permeability testing in the ESF
TBD	Operation of borehole liner system in ESF
TBD	Calibration of pressure transducers for air permeability testing
TBD	Calibration of thermistors for air permeability testing
TBD	Calibration of TCPs for air permeability testing
	Borehole instrumentation and monitoring
HP-14	Method for calibrating Peltier-type thermocouple psychrometer for measuring water potential of partially saturated media
HP-17	Method of calibration and testing for operation of pressure transducers for air-permeability studies in the unsaturated zone

Table 3.4-2. Technical procedures for the radial-borehole activity (SCP 8.3.1.2.2.4.4) (continued)

Technical procedure number (YMP-USGS-)	Technical Procedure
	<u>Borehole instrumentation and monitoring (continued)</u>
TBD	Data-acquisition system operations check
TBD	Field procedure for connection of sensor leads and initializing data-acquisition system
TBD	Field procedure for in situ calibration of pressure transducers
TBD	Field procedure for in situ evaluation of thermocouple psychrometer sensor performance
TBD	Field procedure for stemming and instrumentation boreholes
TBD	Flow-test data identification, shipping, handling, and archiving
TBD	Laboratory procedures for calibration of thermal sensors
TBD	Final checkout and acceptance of instrumentation packages and emplacement into radial test holes, exploratory studies facility NTS (preliminary plan)
	<u>Collection and transport of gas samples from the radial boreholes</u>
HP-56	Gas and water-vapor sampling from unsaturated-zone test holes
HP-131	Methods for handling and transporting unsaturated-core and rubble samples for hydrochemical analysis
TBD	Procedure for shipping and handling gas samples

3.5 Excavation-effects test

3.5.1 Objective of activity

The objective of this activity is to estimate the magnitude and extent of modification to the Topopah Spring welded unit (TSw) hydrologic properties caused by excavation and the mechanical supports of the ESF openings.

3.5.2 Rationale for activity selection

Permeability before and after excavation is a parameter required in SCP Table 8.3.1.2-1. This parameter is required to estimate errors that may be introduced in evaluating hydrologic properties in other tests in the ESF. Data from the percolation (Section 3.2), bulk-permeability (Section 3.3), and radial-borehole (Section 3.4) tests may be influenced by hydrologic properties of the rock around openings constructed to conduct the tests. Therefore an evaluation is needed to determine the significance of excavation effects and to develop methods to correct for changes in physical properties that may be introduced by modification of the rock hydrologic properties near these openings.

3.5.2.1 Theoretical background

Excavation in fractured rocks can significantly alter the physical properties of the rock near an underground opening (Montazer, 1982). Olsson (1992) reported a factor of eight in the reduction of water flow rate through a fractured zone into one drift after excavation using blasting. The location was at the Swedish Stripa project site, which is in the saturated zone.

These changes are a concern because modification of the hydrologic properties, such as permeability, may alter existing pathways or introduce new pathways for gas and liquid flow. The travel time of liquids and gases along these changed or new pathways may be significantly different from those along natural pathways. If travel time is significantly changed, then the effects of excavation will have to be considered during other hydrologic tests.

The magnitude of changes in fracture permeability, effective porosity, and saturation depends on the excavation method, *in-situ* stress tensors, and fracture orientation around the opening. Fracture permeability may increase or decrease, depending on the orientation of the excavation with respect to fractures and to *in-situ* stress. Fractures that are parallel to the long axis of the opening (but not radial from this axis) and in close proximity to the walls are expected to open due to the stress relaxation in the radial direction. However, radial fractures are expected to close due to stress increase in the tangential direction. In addition, deformation of fracture apertures may significantly change saturation within the fractures, so that some fractures attain larger water saturation. These complex relative permeability relations may be evaluated by monitoring fracture deformation, saturation, stress changes, and permeability during construction.

3.5.2.2 Parameters required for evaluation

To evaluate the excavation effects, some or all of the following parameters will be required. The choice will depend on the approach that will be followed as described in Section 3.5.3. The parameters are:

(a) pre-mining fracture permeability around the excavation,
(b) pre-mining state of rock stress,
(c) pre-mining water saturation,
(d) mechanical properties of the *in-situ* rock,
(e) stress changes after the opening is made,
(f) fracture deformation, and
(g) permeability changes due to excavation.

3.5.3 General approach

In order for the excavation effects to be considered significant, the changes in fracture permeability around underground openings need to be measurable and the final permeability values statistically different from the initial values, as well as, those of the surrounding vicinity.

There are two approaches that may be utilized to evaluate the excavation effects. The first approach is a deterministic one where the physics of the process is investigated. It is achieved by measuring all the parameters mentioned above in Section 3.5.2.2 and using them to support a geomechanical model. The model may allow prediction of excavation effects at other locations within the ESF where rock stress and properties are different. This approach will need to be evaluated at least twice at two locations where the stress and rock properties are different. It will be desirable to measure parameters (e) through (g) in Section 3.5.2.2 during and after excavation. This will give more case studies to verify the geomechanical model to predict changes in the study vicinity. An advantage to this approach is that a physical model may be applied to predict changes in permeabilities where conditions are different.

The second approach is a statistical one. The changes in fracture permeability before and after an excavation is made are measured. The same set of measurements is repeated at several other locations to gather enough data to minimize uncertainty levels in predicting permeability changes at different locations. An important restriction to this approach is that predictions will be valid only to areas where the physical properties and stresses of the *in-situ* rock are similar to those where the measurements were made, provided that the same excavation method is used. The number of repetitions required to achieve a given uncertainty level can be estimated after making a few initial *in-situ* measurements at two or more locations. This approach will have little interference with construction and will not require an extensive instrumentation scheme.

3.5.4 Test approaches

Figure 3.5-1 summarizes the objectives and organization of the excavation-effects tests. Cross-references to other study plans which provide input to the excavation-effects tests also appear in Figure 3.5-1. Figure 3.5-2 lists the test procedures. A brief description of each method appears in the boxes below each procedure.

Figures 3.5-1 and -2 summarize the overall structure of the planned activity in terms of approaches and procedures to be employed and measurements to be made. The descriptions of the following sections are organized on the basis of these figures. Methodology and parameter information are tabulated as a means of summarizing the pertinent relations among (1) the activity parameters to be determined, (2) the information needs of the performance and design issues, (3) the technical objectives of the activity, and (4) the methods to be used.

3.5.4.1 Initial evaluation

Since a prototype to this test has not been made, at least one statistical test is required to verify that (a) changes in permeability are measurable, and (b) that the final permeabilities are statistically different from the initial values as well as those of the surrounding vicinity. If either condition is shown not to be true, then the tests will not be continued. However, if both conditions are shown to be true, then either approach, as listed above in Section 3.5.3, or a combination of the two approaches, can be employed. The choice will depend on the cost and interference with construction involved with each approach.

This stage will be accomplished by conducting a comparison of air-permeability profiles around a planned opening before and after its excavation. The measurements will be made in the ESF from boreholes drilled parallel to a proposed opening.

The test will be conducted from two alcoves excavated along both sides of a planned excavation as shown in Figure 3.5-3. The location of the site will be determined based on drift-wall mapping such that the opening will intersect many fractures. Although this selection will result in a biased sample, it will be a sample that may indica e worst-case scenarios.

Following the completion of each alcove, up to twelve boreholes, six on each side, will be drilled for permeability measurements. These boreholes will have a maximum length of 30 m (100 ft) and be parallel to the planned excavation with a minimum length of 25 m (80 ft). The boreholes will be within one excavation diameter (or width) from the wall of the planned excavation. This interval is chosen because the stress redistribution, and hence, expected permeability changes around circular openings is mostly effective within two radii. If

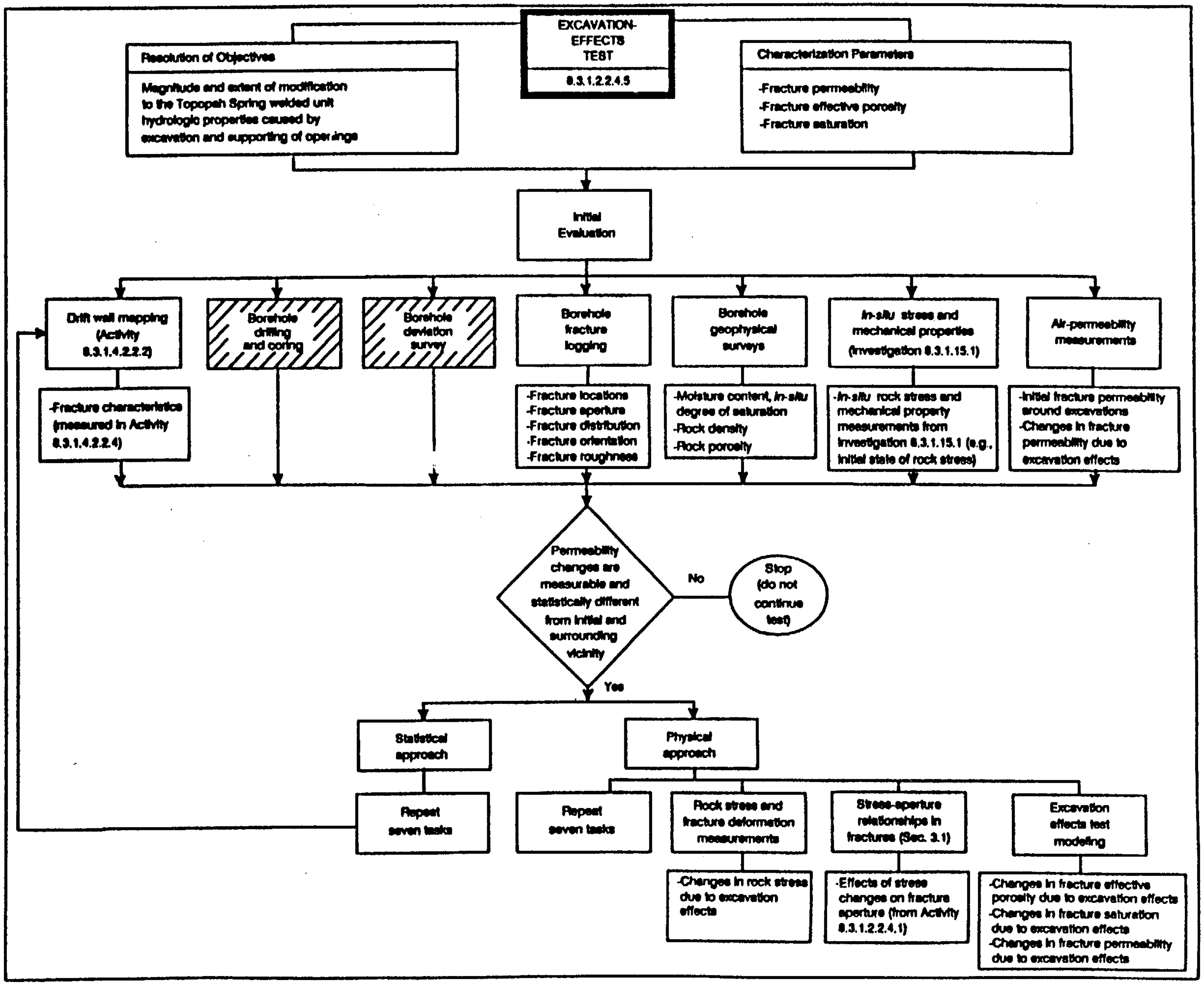


Figure 3.5-1. Organization of the excavation effects activity showing objectives, methods, activity parameters, and characterization parameters. (The cross-hatched box indicates that no activity parameters will be generated)

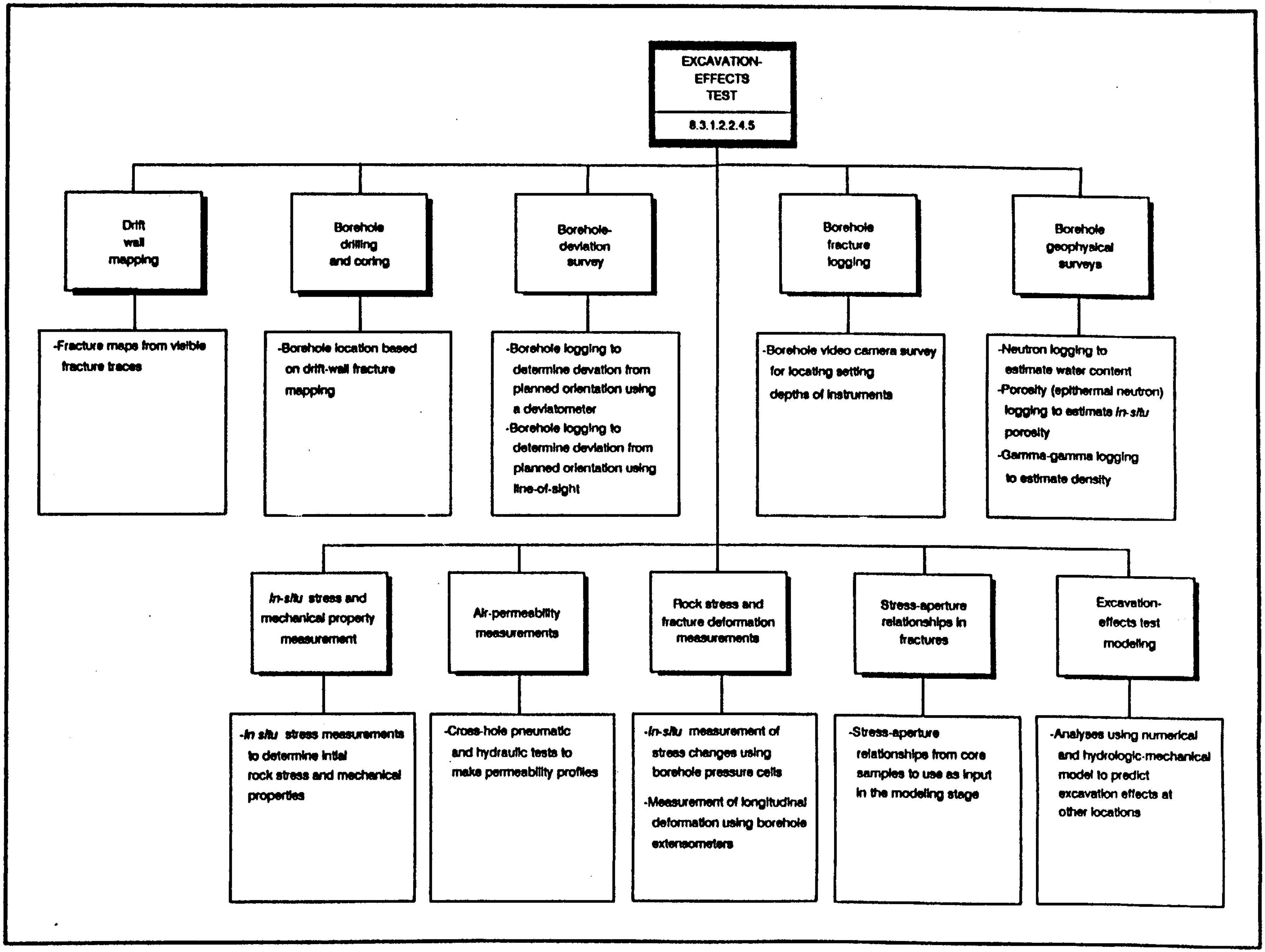
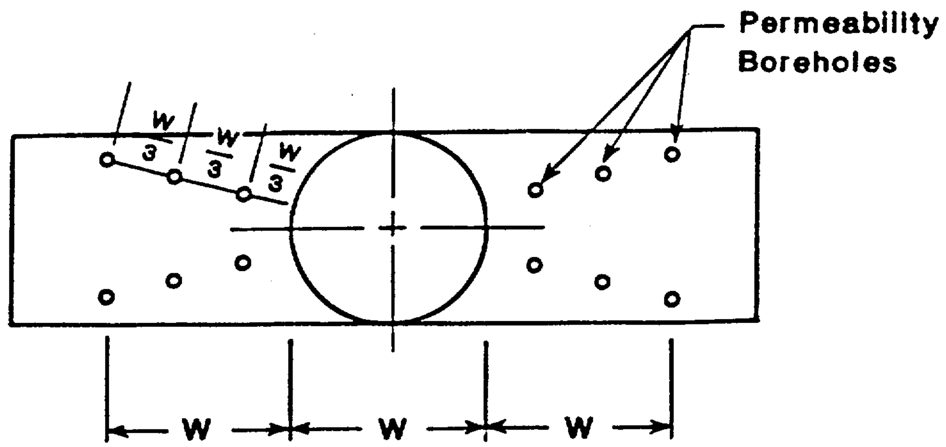
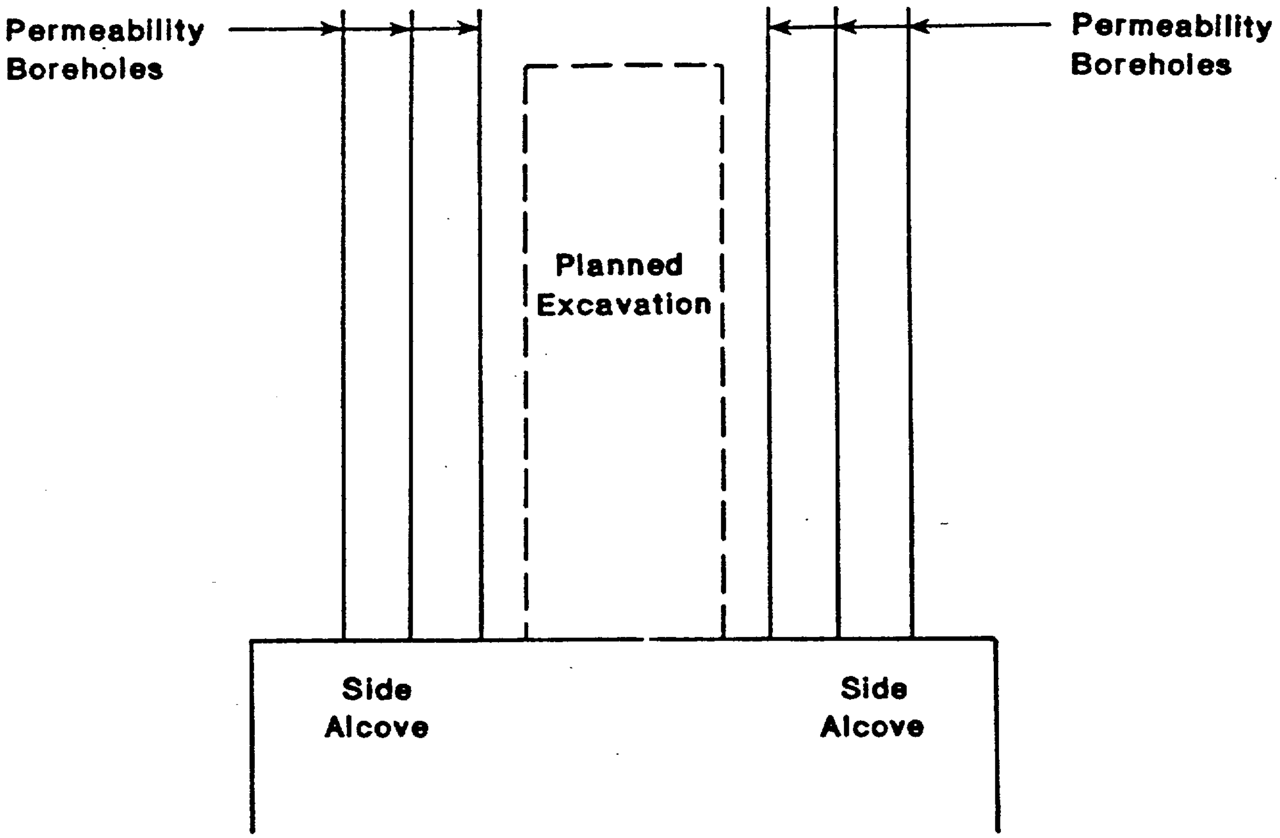


Figure 3.5-2. Organization of the excavation-effects activity showing tests and methods.



W = Excavation Diameter (Or Width)

Front View



Plan View

Figure 3.5-3. Excavation effects test plan for the initial evaluation and statistical approach.

required, additional undisturbed zone permeability estimates beyond the two-radii zone will be estimated in the radial-boreholes tests (Section 3.4).

After the boreholes are drilled, they will be logged with geophysical surveying devices to estimate the water saturation, density, and porosity in the vicinity of the proposed excavation. Then an initial permeability profile along the boreholes will be measured. Rock excavation will proceed until it is past the depth of the boreholes. A second geophysical log, using the neutron moisture and epithermal neutron tools, will be run in the boreholes prior to additional permeability tests. Finally, a second permeability profile will be made in the same boreholes.

If it can be demonstrated that permeability changes are measurable and that the final values can be differentiated from the initial values as well as those of the surrounding vicinity, then either of the following approaches can be followed to complete this test.

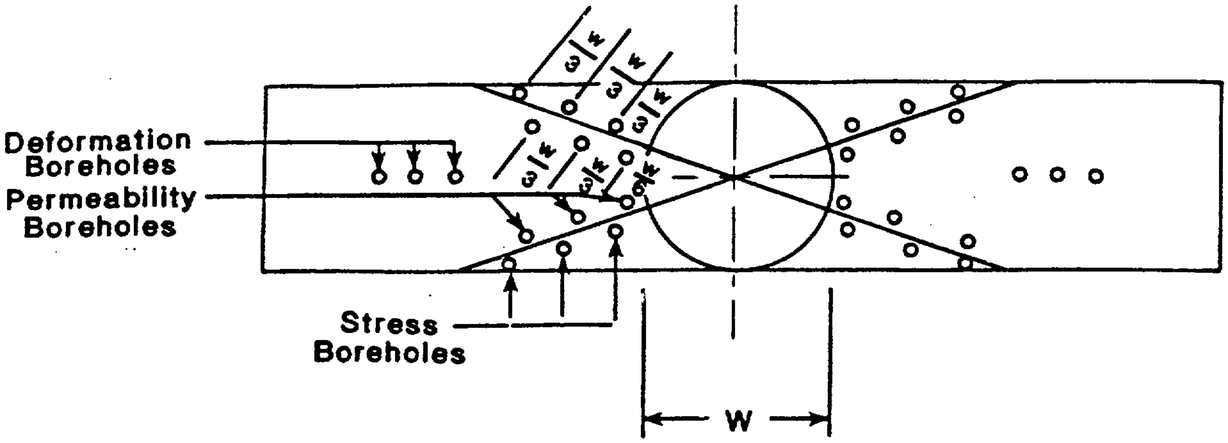
3.5.4.2 Physical approach

After verifying that the effects are significant, and if this approach is chosen, calibrated instruments will be installed around another planned excavation to measure all the parameters listed above in Section 3.5.2.2. Initial fracture permeability, state of stress, water saturation, and mechanical properties of the *in-situ* rock will be measured. Rock stress and permeability changes, and fracture deformation during and after the excavation, also will be measured. These measurements will be conducted from up to 30 boreholes drilled around a proposed opening in the ESF as shown in Figure 3.5-4. However, since this approach requires extra instrumentation, the decision to implement it needs to be made at least six months in advance so that enough time is allowed for stress and deformation instrument procurement and calibration.

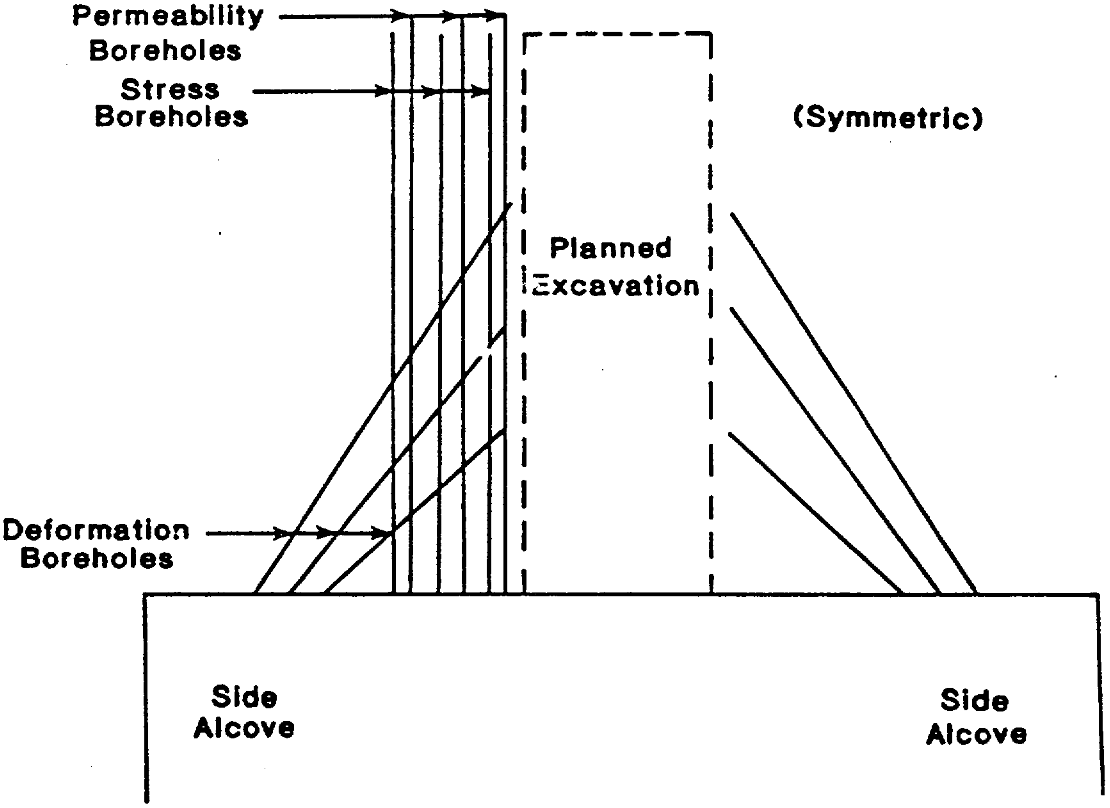
A coupled hydrologic-mechanical model will be used to analyze the results and predict excavation effects at other locations within the ESF where rock stress and properties are different. Uncertainty will be associated with the *in-situ* measurements. This uncertainty will propagate to the predicted results. It is yet to be determined whether the level of uncertainty from physical models is different from that resulting from statistical models to justify one approach over the other.

Although the borehole density in this approach seems high, the stress disturbance caused by the drill holes is expected to be very small compared to the disturbance that will be caused by the excavation. This is based on the assumption that if the rock behaves as a linear elastic material then most of the stress redistribution will take place within two radii (one diameter) of a circular opening. Since the biggest borehole is not expected to be larger than 150 mm (6 in) in diameter, the disturbed zone

W = Excavation Diameter (or width)



FRONT VIEW



PLAN VIEW

Figure 3.5-4. Excavation effects test plan for the physical approach around these boreholes is not expected to extend beyond one diameter from the borehole wall.

3.5.4.3 Statistical approach

If the statistical approach is chosen to complete the test, then the experimental procedure will be similar to that described earlier in the section on initial evaluation (Section 3.5.4.1 and Figure 3.5-3). No extra instrumentation will be needed. The number of repetitions will depend on the required level of uncertainty which has not yet been defined.

3.5.5 Test procedures

All boreholes will be instrumented after they are logged for fractures with a video camera. This will allow instrument installation to be more precise such that the measurements will reflect values in fractured zones. The following procedures will be utilized during this test. The first seven procedures will be required for both approaches. The latter three will be required only if the physical approach is implemented.

3.5.5.1 Drift-wall mapping

Locations of the proposed testing sites will be based on fracture maps which are a part of Activity 8.3.1.4.2.2.4, (Geologic mapping of the ESF) in Study 8.3.1.4.2.2 (Structural features in the site area).

3.5.5.2 Borehole drilling and coring

Boreholes will be drilled following the completion of side alcoves, if needed. The tentative borehole locations are shown in Figures 3.5-3 and 3.5-4. A predetermined drilling scheme, rather than a random one, will be used for this study. A random drilling scheme will not be used since a limited and small number of boreholes will be drilled. A few boreholes will not have a uniform distribution to cover the area surrounding the opening.

3.5.5.3 Borehole-deviation survey

All boreholes will be logged using a deviatometer. This is essential for the analysis stage of this test where the locations of the instruments, which will be installed later, relative to the opening are required. The line-of-sight method will be used for boreholes that appear to be straight.

3.5.5.4 Borehole fracture logging

All boreholes will be logged with a video camera to locate the fractures and possibly fractured or damaged zones. USGS personnel will log the cores of the same boreholes for sections that cannot be viewed clearly with the video camera. This is required in order to determine the depth settings of the different instruments needed for this test and for updating the fracture map which is required for the analysis stage. The television log is preferred over the core-logging method where wall smoothness can be observed. Additionally, some of the fractures seen on cores may be induced by drilling rather than being natural fractures.

3.5.5.5 Borehole geophysical surveys

All boreholes will be logged using neutron-moisture, epithermal neutron (porosity), and gamma-gamma tools before and after excavation. These parameters will be needed for the analysis stage of this test. Laboratory methods will be used to determine more accurate estimates for porosity and density. Laboratory determination of water content is another alternative to geophysical surveying, although not as accurate.

3.5.5.6 *In-situ* stress and mechanical property measurements

The *in-situ* stress and mechanical property measurements will be required in the vicinity of the proposed testing locations. This information will be performed under Investigation 8.3.1.15.1 (Spatial distribution of thermal and mechanical rock properties).

3.5.5.7 Air-permeability measurements

Permeability boreholes will be drilled after completing the side alcoves as shown in Figures 3.5-3 and 3.5-4. Based on borehole fracture logging, the depth settings of the packers will be determined. This is done in order to monitor fracture permeability in the permeability boreholes. Permeability will be measured before excavation is started to gather baseline values. Another set of measurements will be taken after the opening is complete, i.e., past the permeability boreholes. If the physical approach is chosen, then measurements during excavation will be desirable. The testing methods are described in Section 3.4 (Radial borehole tests).

3.5.5.8 Rock stress and fracture deformation measurements

Boreholes for monitoring stress changes and fracture deformations will be instrumented after the completion of the side alcoves. Stress changes and axial borehole deformation are required for the modeling stage of this test. The borehole pressure cell (Haramy and Kneisley, 1991) will be considered for measuring changes in rock stress. The U.S. Bureau of Mines three-component borehole deformation gage (Bickel, 1978) is another alternative provided that one gage is used in a borehole located in an area where vibrations will not affect gage sensitivity. Borehole extensometers will be utilized to monitor axial deformation (strain) in the angled boreholes (Figure 3.5-4). All instruments will be connected to a data-acquisition system for continuous monitoring.

3.5.5.9 Stress-aperture relationship of fractures

Since fracture aperture is stress-dependent (Olsson, 1992), a relationship between fracture aperture, which is related to permeability, and stress will be required to model fractured rock behavior. This information will be collected under the Intact-fracture test in the exploratory studies facility (SCP Volume IV, Part B, Section 8.3.1.2.2.4.1).

3.5.5.10 Excavation-effects test modeling

Fracture data (statistical and mechanical parameters), permeability profiles, fracture deformation, stress-aperture relationships, and rock mechanical properties will be utilized to validate coupled hydrologic-mechanical models to predict permeability changes around different underground openings in the potential repository. There are several models that may be used to simulate such a behavior. Examples of such models are reported by Olsson (1992).

3.5.5.11 Methods summary

The activity parameters to be determined by the tests and analyses described in the above sections are summarized in Table 3.5-1. Tests that are part of other studies are not included in this table.

The table lists selected as well as alternate methods for determining the parameters. The alternate methods will be utilized only if the primary (selected) method is impractical to measure the parameter(s) of interest. In some cases, there are many approaches to conducting the test. In those cases, only the most common methods are included in the tables. The selected methods in Table 3.5-1 were chosen wholly or in part on the basis of accuracy, resolution, duration of methods, expected range, and interference with other tests.

The USGS investigators have selected methods which they believe are suitable to provide accurate data within the expected range of the activity parameter. Models and analytical techniques have been or will be developed to be consistent with test results.

3.5.6 Quality assurance requirements

The USGS Quality Assurance Program Plan for the YMP (USGS, 1989) requires technical procedures for all technical activities that require quality assurance.

Table 3.5-2 provides a tabulation of technical procedures applicable to this activity. Approved procedures are identified with a hydrologic procedure number. Procedures identified as "TBD" will be approved prior to being needed for use in site characterization. Technical procedures that belong to tests that are part of other studies are not included in this table.

Table 3.5-1. Summary of tests and methods for the excavation-effects activity (SCP 8.3.1.2.2.4.5)

Methods (selected and alternate)	Activity parameter
Drift-wall mapping (Activity 8.3.1.4.2.2.2)	
Drift-wall mapping	Fracture characteristics
Borehole fracture logging	
Borehole deviation survey using a deviatometer (selected)	--
Using the line-of-sight method (alternate)	--
Borehole television survey for locating setting depths of instruments (selected)	Fracture aperture
"	Fracture distribution
"	Fracture orientation
Oriented-core for locating setting depths of instruments (alternate)	Fracture distribution
"	Fracture orientation
"	Fracture roughness
Borehole geophysical surveys	
Neutron logging to estimate water content (selected)	Moisture content, in situ degree of saturation
Laboratory determination of water content from cores ((alternate)	"
Porosity (epithermal neutron) logging to estimate in situ porosity (selected)	Rock porosity
Laboratory determination of porosity (alternate)	"

Table 3.5.1. Summary of tests and methods for the excavation-effects activity (SCP 8.3.1.2.2.4.5) (continued)

Methods (selected and alternate)	Activity parameter
Borehole geophysical surveys (continued)	
Gamma-gamma (density) logging (selected)	Rock density
Density determination from laboratory measurements (alternate)	"
In-situ stress and mechanical properties (Investigation 8.3.1.15.1)	
In-situ stress and mechanical properties measurements	In-situ stress and mechanical properties
Air permeability measurements	
Cross-hole pneumatic and hydrologic tests (selected)	Initial fracture permeability around excavations
"	Changes in fracture permeability due to excavation effects
Rock stress and fracture deformation measurements	
In situ measurements of stress, using borehole pressure cells (selected)	In situ stress changes, magnitude and orientation
"	Changes in rock stress due to excavation effects
In situ measurements of stress, using U.S. Bureau of Mines 3-component borehole deformation gage (alternate)	In-situ stress changes, magnitude and direction
"	Changes in rock stress due to excavation effects

Table 3.5.1. Summary of tests and methods for the excavation-effects activity (SCP 8.3.1.2.2.4.5) (continued)

Methods (selected and alternate)	Activity parameter
Rock stress and fracture deformation measurements (continued)	
Measurement of longitudinal deformation using borehole extensometers (selected)	Fracture deformation
"	Changes in rock stress due to excavation effects
Stress-aperture relationships in fractures (Sec. 3.1)	
Stress-aperture relationships from core samples	Effects of stress changes on fracture aperture
Excavation-effects test modeling	
Test using numerical hydrologic-mechanical model (selected)	Changes in fracture effective porosity due to excavation effects
"	Changes in fracture saturation due to excavation effects
"	Changes in fracture permeability due to excavation effects

Table 3.5-2. Technical procedures for the excavation-effects activity (SCP 8.3.1.2.2.4.5)

Technical procedure number (YMP-USGS-)	Technical procedure
	<u>Borehole drilling and coring</u>
HP-12	Method for collection, processing, and handling of drill cuttings and core from unsaturated-zone boreholes
TBD	Method for measuring humidity, pressure, and temperature of intake and exhaust air during vacuum drilling
	<u>Borehole-deviation surveys</u>
TBD	Borehole deviation surveys
TBD	Oriented core logging
	<u>Borehole fracture logging</u>
GP-10	Borehole video fracture logging
TBD	Borehole fracture logging from oriented cores
	<u>Borehole geophysical surveys</u>
TBD	Method for measuring in situ porosity, using porosity (epithermal neutron) logs
TBD	Method for measuring in situ density, using gamma-gamma logs
HP-62	Method for measuring subsurface moisture content, using a neutron moisture meter
	<u>Rock stress and fracture deformation measurements</u>
TBD	Method for assembling, calibrating, installing, and using rock stress gages in boreholes
TBD	Method of assembling, calibrating, installing, and using extensometers
	<u>Excavation-effects test modeling</u>
TBD	Method for evaluating the correctness of a coupled-hydraulic-mechanical finite-element model (bench-mark problems)

Equipment requirements and instrument calibration are described in the technical procedures. Lists of equipment and stepwise procedures for the use and calibration of equipment, limits, accuracy, handling, quantitative or qualitative acceptance criteria of results, description of data documentation, identification, treatment and control of samples, and records requirements are included in these documents.

3.6 Calico Hills test

The Calico Hills test has been deleted from this current ESF unsaturated-zone study. If the YMPO decides to expand ESF testing to include the Calico Hills geologic unit, the following tests will include tests in this unit: Radial boreholes, Perched water, Hydrochemistry, Excavation effects, Hydrologic properties of major faults, Intact fracture, Percolation, and Bulk permeability. Preliminary test locations have been selected in the Calico Hills for *in-situ* hydrologic characterization tests for these eight tests.

3.7 Perched-water test

3.7.1 Objectives of activity

The objectives of this activity are to:

1. detect the occurrence of any perched water;
2. estimate the hydraulic properties of perched-water zones; and
3. determine the implication of the existence of such zones on water flux, flow paths, and travel times.

3.7.2 Rationale for activity selection

Perched water in the hydrogeologic system may imply a particular flow path for water (Montazer and Wilson, 1984). In addition, temporal variations in occurrence and characteristics of such perched water could indicate dynamic or static conditions of the unsaturated zone. Therefore, analysis of the spatial and temporal occurrence of perched water would help identify various flow paths of water. When the flow paths are identified, calculations of flux and travel time become possible. The Darcian flux is determined by dividing the flow rate by the cross-sectional area that is perpendicular to the direction of flow (Freeze and Cherry, 1979). Travel time is estimated by dividing the length of the flow path by the flux and estimated effective porosity. Direct estimation of the travel time from land surface to the perched water is also possible through analysis of the ages of pore, fracture, and perched water at known depths. The age-dating methods are described in hydrochemistry tests in Section 3.8.3.

The activity is designed to detect and estimate properties of any perched-water zones in the part of the unsaturated zone penetrated by the ESF. This evaluation is needed to understand the hydrogeologic conditions causing accumulation of perched water; the implication of such a zone on flux, flow paths, and travel time; and whether perched water is a transient or permanent feature.

Surface boreholes, drilled in advance of construction of the North and the South Ramps, may encounter perched water. If perched water is detected in any of the North or South Ramp geology boreholes, it will allow full preparation for sample collection and testing in the ramps. If perched water has not been detected in the North or South Ramp geology boreholes, it will be necessary to visually inspect ramp walls for indications of perched water, and to sample and test, if any is encountered. All ramp and drift walls will be visually inspected for the occurrence of perched water during ESF construction.

At the Nevada Test Site and vicinity, perched water is known to occur principally within or above the tuff and lava-flow aquitards, as described by Winograd and Thordarson (1975). In the underground workings beneath Rainier Mesa, the perched water occurs only within the tuff aquitard. Nine perched springs occur within the tuff aquitard and lava-flow aquitard. Perched water has not been positively identified in the bedded- or welded-tuff aquifers. Perched water within or above the tuff aquitard generally occurs in poorly connected fractures. The general absence of perched water in the welded-tuff aquifer is attributed to both abundant hydraulically connected fractures and absence of a perching bed; these prevent accumulation of perched water.

Beneath Yucca Mountain, man-induced or natural perched water has been encountered during drilling of test well USW H-1 (Rush and others, 1984) and during drilling of test hole USW UZ-1 (Whitfield, 1985). In test well USW H-1, water was perched above an underlying 5-m-thick bedded or reworked ash-flow tuff at the base of the Topopah Spring Member of the Paintbrush Tuff. This may have been contaminated water resulting from the large amount of water used during drilling, with water and detergent as the circulating media. In test hole USW UZ-1, drilling in the Topopah Spring Member was discontinued at a depth of 387 m (1,269 ft) because a large volume of water was encountered, and the water level could not be lowered significantly. All or part of this water may be contamination from geologic test hole USW G-1 located 305 m (1,000 ft) to the southeast of test hole USW UZ-1.

The conceptual model of flow in the unsaturated zone indicates that perched water may occur within or immediately above the Paintbrush Tuff nonwelded unit (PTn) and the Calico Hills nonwelded unit (CHn) (Montazer and Wilson, 1984). This water could occur where displacement along faults has created permeability contrasts on opposite sides of the fault. The occurrence of perched water would probably be by percolation downward into underlying units, by flow down the fault planes or zones, by lateral flow along contacts, or by combinations of these pathways.

No perched water is expected in the host rock, except perhaps immediately above the CHn. The presence or potential for future perching of water in the host rock, however, might interfere with construction, operation, and ultimate performance of a repository at Yucca Mountain. In addition, perched water could cause substantial modification of geochemical interactions, transport processes, flow paths, and travel times. For example, inflow of perched water during construction of the ESF or repository might substantially affect construction techniques, schedules, and safety concerns because of the potential for flooding. Perched water in the PTn, above the host rock, could affect the spatial and temporal distribution of flow in the host rock by modulating pulses of infiltration and by diverting flow laterally to faults. Perching of water beneath the host rock in the CHn could affect travel times and flow paths to the accessible environment. Perched-water zones could result from barriers obstructing flow, which could increase travel time, or from barriers creating shorter preferential pathways, which would decrease travel time.

Because the ESF has not been constructed at Yucca Mountain, geologic and hydrologic prototype testing has been conducted at G-tunnel in Rainier Mesa, which is located at the Nevada Test Site about 60 km (40 mi) from Mercury, Nevada. This prototype testing has helped to develop and test hydraulic methods for determining the rate of flow, hydraulic head, and procedures for collecting representative water samples from a mined ramp or drift wall. In addition, instrumentation needed to provide long-term hydrogeologic data in perched-water zones has been identified.

3.7.3 General approach and summary of tests and analyses

The perched-water test will be conducted only if perched water is encountered during construction of the ESF. As the tunnel boring machine (TBM) advances, prior to the walls being prepared for geologic mapping, seeps or saturated zones will be looked for in conjunction with mapping activities. If the inflow of appreciable quantities of perched water is reported, hydraulic tests will be initiated as soon as the ramp or drift becomes accessible. If perched water or fracture flow is observed, boreholes will be drilled laterally into the ESF walls to test and sample the zone. A flow-rate measurement will precede the borehole drilling if the flow rate into the ESF is sufficiently large.

Data from hydraulic tests of the perched-water zone will be analyzed in the field to determine the hydraulic characteristics of the zone and to estimate its lateral extent. These hydraulic tests will help to define the occurrence and to estimate the hydraulic properties of the zone so that the hydrologic conditions and flow characteristics of the perched-water zone can be modeled. Various conditions occur under which water may perch in the unsaturated zone beneath Yucca Mountain. Two possibilities are (1) as saturated zones within porous nonwelded tuffs and (2) within isolated single fractures or fracture networks that are poorly connected or are truncated against some network overlying relatively impermeable material. Depending on the hydrogeologic characteristics of each zone, the rate of discharge into the ESF may vary significantly; in fact, this rate of discharge will determine the type of hydraulic tests required. For example, a saturated zone within a porous nonwelded tuff and an isolated single fracture may yield only seeps or wet zones that require boreholes and piezometers for hydraulic tests. A saturated zone in a well-connected fracture network may yield appreciable flows of water and can be tested by pumping.

Excavation of the ESF may affect the interpretation of the hydrogeology of the perched-water test. The disturbed zone around the ESF and the stress changes caused by excavation and drilling that alter the bulk permeability and porosity of the rock may create new pathways for flow, thereby altering the performance and results of the pumping and *in-situ* borehole tests. In addition to excavation effects, the possibility of lining portions of the ESF with concrete may modify the hydrogeologic properties of the rocks surrounding the ESF. Water from the wet concrete may enter fractures in the ESF walls and may invade fractures, altering flow paths.

Uncertainties and limitations which effect interpretation of data may result from perched-water zones of limited areal extent and/or loss of early-time data because of drainage into the ESF before access can be gained to the perched-water zone. The limited access afforded by the TBM could enhance these uncertainties and limitations. It will be necessary to assess the magnitude of these effects during analysis and interpretation of test results.

The perched-water test, conducted with either pumping or borehole tests, will determine both the type of occurrence of any perched water and the hydraulic properties necessary to predict flux, flow paths, and travel times through the unsaturated zone as influenced by intervening perched water. The effects of perched-water bodies on the construction and operation of a repository would be estimated, as would the potential for existing or future perched water near the repository. In addition, the possibility of a small-conductivity unit above the repository, directing water away from the repository, would be evaluated. The perched-water data would also be important in formulating mathematical models of the flow in the unsaturated zone.

Any perched water encountered by the ESF will be sampled and analyzed for water quality and for stable and radioactive isotopes. Relative ages of pore and fracture water will be estimated from these data in the hydrochemistry tests. These data will help determine flow paths, flux, and travel times, as described in Section 3.8.3.

Figure 3.7-1 summarizes the organization of the perched-water test. A descriptive heading for each test and analysis appears in the shadowed boxes of the second and fourth rows. Below each test/analysis are the individual methods that will be utilized during testing. Cross-references to other study plans which provide input to the perched-water tests also appear in Figure 3.7.1. Figure 3.7-2 summarizes the objectives of the activity, site-characterization parameters, and activity parameters. These appear in the boxes in the top left side, top right side, and below the shadowed test/analysis boxes, respectively, in Figure 3.7-2.

The two figures summarize the overall structure of the planned activity in terms of methods to be employed and measurements to be made. The descriptions of the following sections are organized on the basis of these charts. Methodology and parameter information are tabulated as a means of summarizing the pertinent relations among (1) the activity parameters to be determined, (2) the information needs of the performance and design issues, (3) the technical objectives of the activity, and (4) the methods to be used.

The methods utilized in this activity will provide information that is approximately representative of the repository area. The spatial variabilities of existing conditions within the repository block, and the correlations to present and potential future repository conditions are represented by the perched-water tests.

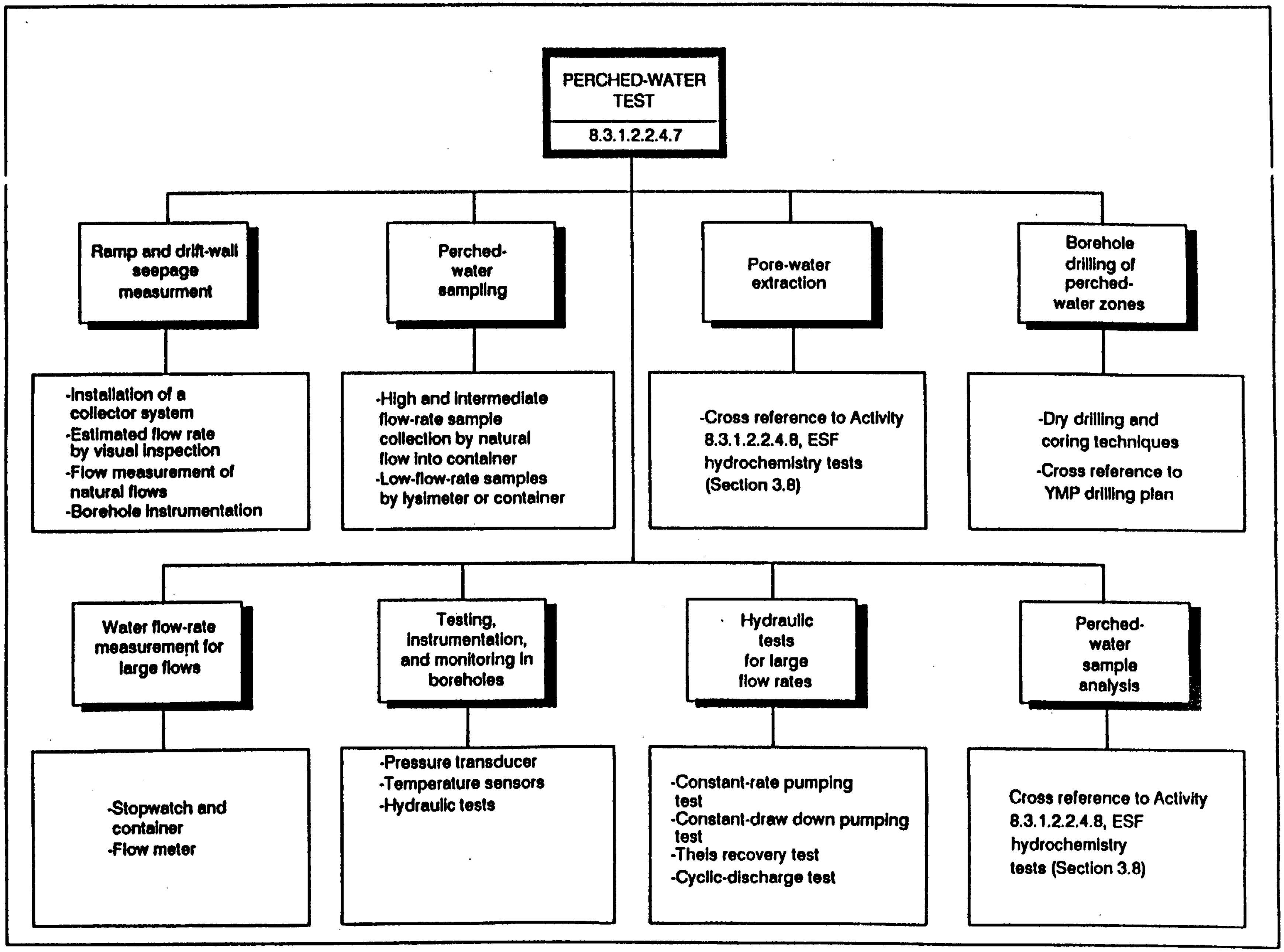


Figure 3.7-1. Organization of the perched-water activity, showing tests, analyses, and methods.

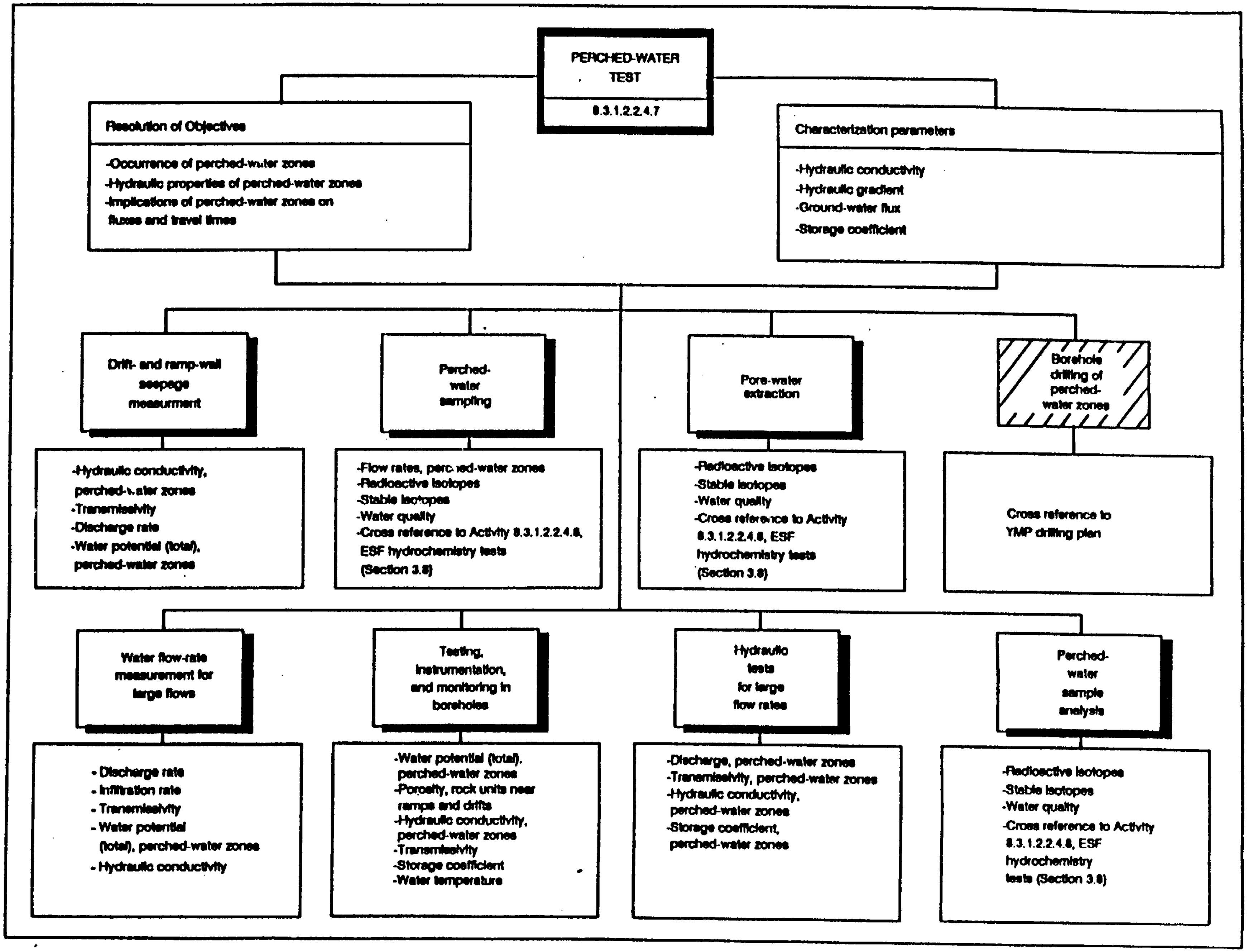


Figure 3.7-2. Organization of the perched-water activity, showing tests, analyses, activity parameters, and characterization parameters. (The cross-hatched box indicates that no activity parameters will be generated.)

The perched-water tests will be conducted in the ESF, which will penetrate the same hydrogeologic units as the repository. Because of this, the environment in which these tests will be conducted is an approximate representation of the repository area. The perched-water tests will help identify various flow paths of water in the repository block. When the flow paths are identified, calculations of the spatial and temporal occurrence of perched water and travel times within the repository become possible. Furthermore, an understanding of the TSw hydrogeologic conditions causing the accumulation of perched water, whether perched water is a permanent or transient feature, and the implications of such a zone on flux, flow paths, and travel times will be useful in predicting potential future hydrologic conditions within the repository.

3.7.3.1 Ramp- and drift-wall seepage measurement

In the event that perched water is encountered during construction, the rate of seepage from ramp- and drift-walls will be measured or estimated before any holes are drilled. One method of seepage measurement is installation of a small collector system such as a small inclined ledge to concentrate small flows of water in order to facilitate measurements with a container. A second method of seepage measurement is estimation of flow rate that is made by visual inspection. Boreholes drilled into perched-water zones will allow access for instrumentation and seepage or flow measurements. In lined portions of the ESF, block-outs and subsequent boreholes will allow easy access for later instrumentation and seepage or flow measurements. No viable alternatives are available in place of the three methods that were selected. A summary of the tests, analyses, and methods is presented in Table 3.7-1 (Section 3.7.3.9).

3.7.3.2 Perched-water sampling

Any perched water found in the ESF will be sampled. These samples will be analyzed for water quality and for stable and radioactive isotopes. Relative ages of pore and fracture water will be estimated from these data in the hydrochemistry tests. These data will help determine flow paths, flux, and travel times, as described in Section 3.8.3.

One method is perched-water sample collection by natural large or intermediate flow into a container. A second method is small-flow-rate sample collection by lysimeter or container. The third, fourth, and fifth tests are to use methods to sample water quality, radioactive isotopes, and stable isotopes by cross reference to Section 3.8.3. As in Section 3.7.3.1, there are no viable alternate methods to use in place of the five methods that were selected. The five selected methods are presented in Table 3.7-1 in Section 3.7.3.9.

3.7.3.3 Pore-water extraction

Pore-water samples will be obtained from core. The pore water will be extracted from the core by methods indicated by cross reference to Section 3.8.3.6. There are no alternate methods to the methods selected. The selected methods are presented in Table 3.7-1 in Section 3.7.3.9.

3.7.3.4 Borehole drilling of perched-water zones

The drilling of holes into perched-water zones will be accomplished using dry-drilling methods. These dry-drilling and coring methods have been developed during prototype testing. Dry drilling and coring is the selected method because representative rock samples and cores that are uncontaminated by drilling liquid can be obtained and because positive identification of perched-water zones is obtainable.

3.7.3.5 Measurement of large flows

The selected methods of measuring the rate of perched water flowing from either the drift or ramp wall or a borehole are using a stopwatch and container, flow meter, or a weir. These data will be used to estimate hydraulic conductivity and transmissivity. There are no viable alternate methods to use in place of the three methods selected. The three selected methods are presented in Table 3.7-1 in Section 3.7.3.9.

3.7.3.6 Testing, instrumentation, and monitoring in boreholes

If a wet zone or seep is encountered, and if the amount of water is inadequate to justify a pumping test, a hole will be drilled into it to increase flow; this hole will penetrate beyond the region disturbed by ESF construction and will be cased to the outer edge of the disturbed zone. If an isolated water-bearing fracture is encountered, holes will be drilled to intersect the fracture and possibly along and perpendicular to the fracture plane.

Following any pumping test, two to four lateral holes will be drilled and completed with borehole instrumentation packages to further test and sample the perched-water zone. If the amount of water is inadequate to justify a pumping test, short boreholes will be drilled into the walls of the ESF for testing of the water-bearing zone.

In addition to easily measurable yields of perched water, wet zones or seeps may be encountered, or the water saturation in the rock may be so large (for example, 95 or 100 percent water saturation) that a search for perched water of small yield may be necessary. If a wet zone or seep of small discharge is found, a long or short borehole will be drilled in the general direction of production in an effort to develop and concentrate the flow. The length of the hole will depend on the width of the disturbed zone as determined by other tests (Sections 3.4 and 3.5). Long lateral boreholes may be drilled and completed with borehole instrumentation packages for long-term monitoring. The diameter of the borehole will be small, but will still allow installation of a borehole instrumentation package, such as piezometers. The borehole instrumentation will be designed to enable monitoring of the *in-situ* pressure, sampling of the water, and testing of the perched-water zone. The decision on whether to drill a borehole will be made on site by a USGS hydrologist. The direction of the borehole will be guided by the direction of the apparent fracture system from which water is being produced. The borehole should penetrate beyond the disturbed zone and be cased to its outer edge. If the developed water flow is sufficiently large, it will be sampled upon completion of the lateral borehole; if not, it will be plugged and sampled later. The casing will be capped and will protrude through any concrete lining for later sampling. In the event that the borehole is in a lined portion of the ESF, a special block-out will be necessary to protect the casing and allow access to the casing cap.

The selected methods for testing boreholes include using instruments to monitor saturated and unsaturated conditions to ensure the detection of transient boundaries. These may include (1) pressure transducers to measure hydraulic head; (2) lysimeters for collecting water samples; (3) tensiometers to measure matric potential; (4) hydraulic tests similar to those used in Section 3.7.3.7 to determine hydraulic conductivity, transmissivity, and storage coefficient; (5) geophysical logging; and (6) temperature sensors. There are two alternate methods. The first alternate method involves using thermocouple psychrometers, but this was not selected because it is used to measure matric potential in rocks that contain less water than would be present in a perched-water zone. The second alternate method consists of periodic visual observations of the borehole, but this is less satisfactory than using borehole instruments. The selected methods and the alternate methods are presented in Table 3.7-1 in Section 3.7.3.9.

The boreholes will be especially useful if pumping tests of long duration are not practical during ESF excavation. All boreholes will be subjected to long-term hydraulic tests and monitoring in order to estimate the extent and hydraulic properties of the perched-water zones. Monitoring of the boreholes may also be useful in measuring temporal changes in a perched-water zone due to changes in percolation rates. Although the infiltration rate is estimated to range from 0.5 to 4.5 mm/yr (Montazer and Wilson, 1984), temporal changes that might occur due to locally large infiltration along a fault zone may cause increased hydraulic head in a borehole after heavy rainfall or snowmelt. This probably would indicate that a perched-water zone is directly influenced by recharge. If the perched-water zone in a borehole decreased in hydraulic head during a period of drought, a possible change of the flow path, flux, and travel time through the unsaturated zone might be determined.

Hydraulic-head data from boreholes may provide information on the vertical component of percolation within a perched-water zone. This measurement may be accomplished by horizontal boreholes spaced vertically throughout a perched-water zone (Figure 3.7-3).

All tests will provide water samples for chemical and isotopic analyses. Boreholes that are cased will be capped for later sampling; a special block-out will be used to protect the casing and allow later access to the casing cap in portions of the ESF where a liner is installed. All boreholes will be subjected to long-term hydraulic monitoring to estimate the extent and hydrologic properties of the perched-water zone.

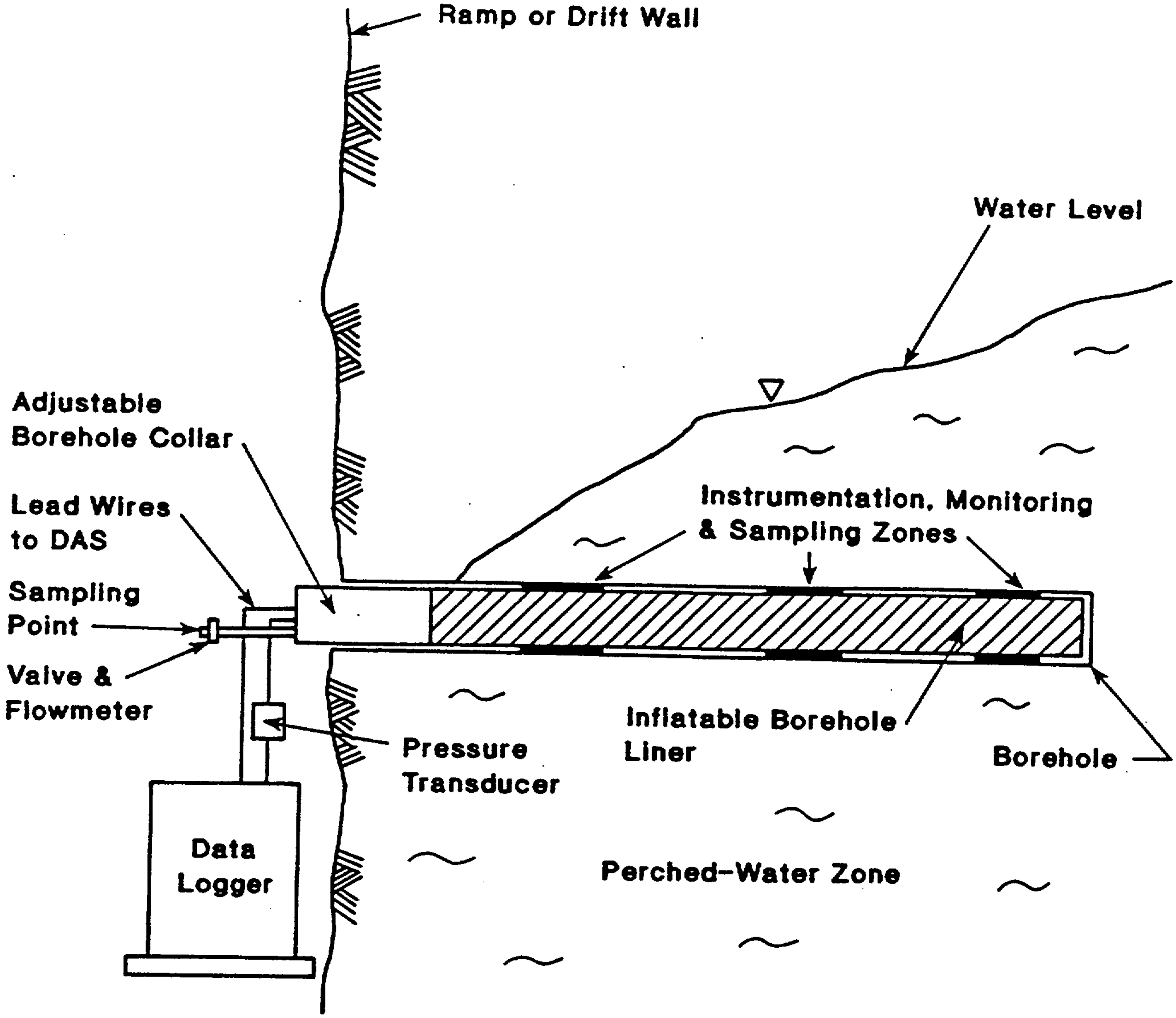
3.7.3.7 Hydraulic tests for large flow rates

Pumping tests will be conducted in the ESF if water flows at a sufficient rate into the underground openings. Pumping tests will be designed to determine the yield of the perched water. Extent of perched-water zones will be determined by a combination of surface and subsurface testing. For example, a long-term test might detect a decreasing rate of inflow, with a change in chemical constituents in the water; or a decline in static water level after repeated pumping might indicate that the perched water is of limited extent. If pumping tests show a constant rate of inflow and a constant static water level, a perched-water zone of great extent would be indicated. These pumping tests must be conducted with great care because a pumping rate that is too large might flush out sediment or clay from a weak zone or form a clay gouge within a fault; thus, hydraulic properties such as transmissivity and the storage coefficient would be increased or decreased artificially, as noted by Stuart (1955). A pumping rate that is too small, however, might indicate only storage of water within the ESF due to its large diameter, which is similar to the effects of well-bore storage. Following any pumping test, two to four lateral boreholes will be drilled and completed with piezometers and/or lysimeters to further test and sample for perched water at a later time.

Inflows to the ESF may not be analyzable by standard hydraulic-test methods. Hydrologic assessment will need to be planned and formed on a case-by-case basis.

3.7.3.8 Perched-water sample analysis

Any perched water encountered in the ESF will be sampled. These samples will be analyzed for major anions and cations, and for stable and radioactive isotopes. The water quality methods of analysis of the hydrochemical and age-dating data will be done as part of the perched-water test. Relative ages of pore and fracture water will be estimated in the hydrochemistry tests. These data will help determine flow paths, flux, and travel times (Section 3.8.2).



Note: Figure Not to Scale

Figure 3.7-3. Schematic diagram of instrumentation of a perched-water zone within the ESF.

There are no viable alternate methods to use in place of the selected methods which are presented in Table 3.7-1 in Section 3.7.3.9.

3.7.3.9 Methods summary

The activity parameters to be determined by the tests and analyses described in the above sections are summarized in Table 3.7-1. Also listed are the selected and alternate methods for determining the parameters. The alternate methods will be utilized only if the primary (selected) method is impractical to measure the parameter(s) of interest. In some cases, there are many approaches to conducting the test. In those cases, only the most common methods are included in the tables. The selected methods in Table 3.7-1 were chosen wholly or in part on the basis of accuracy, precision, duration of methods, expected range, and interference with other tests and analyses.

The USGS investigators have selected methods that they believe are suitable to provide accurate data within the expected range of the activity parameter. Models and analytical techniques have been or will be developed to be consistent with test results.

3.7.4 Quality assurance requirements

The USGS Quality Assurance Program Plan for the YMP (USGS, 1989) requires procedures for all technical activities that require quality assurance.

Table 3.7-2 provides a tabulation of technical procedures applicable to this activity. Approved procedures are identified with a hydrologic procedure number. Procedures identified as "TBD" will be approved prior to being needed for use in site characterization. Many of the needed technical procedures depend on the selection and procurement of borehole instrumentation and cannot be completed until that is accomplished.

Equipment requirements and instrument calibration are described in the technical procedures. Lists of equipment and stepwise procedures for the use and calibration of equipment, limits, accuracy, handling, calibration needs, quantitative or qualitative acceptance criteria of results, description of data documentation, identification, treatment and control of samples, and records requirements are included in these documents.

Table 3.7-1. Summary of tests and methods for the perched-water activity (SCP 8.3.1.2.2.4.7)

Methods (selected and alternate)	Activity parameter
Ramp- and drift-wall seepage measurement	
Installation of collector system (selected)	Hydraulic conductivity, perched-water zones
"	Transmissivity
"	Discharge rate
"	Water potential (total), perched-water zones
Estimate flow rate by visual inspection (selected)	Hydraulic conductivity, perched-water zones
"	Transmissivity
"	Discharge rate
"	Water potential (total), perched-water zones
Measurement of natural flows by borehole instrumentation (selected)	Hydraulic conductivity, perched-water zones
"	Transmissivity
"	Discharge rate
"	Water potential (total), perched-water zones
Perched-water sampling	
Large-flow- and intermediate-flow-rate sample collection by natural flow into container (selected)	Flow rates, perched-water zones
Small-flow-rate samples by lysimeter or container (selected)	"
Cross reference to 8 3.1.2.2.4.8 ESF hydrochemistry test (selected)	Radioactive isotopes
Cross reference to 8.3.1.2.2.4.8 ESF hydrochemistry tests (selected)	Stable isotopes
Cross reference to 8.3.1.2.2.4.8 ESF hydrochemistry tests (selected)	Water quality

Table 3.7-1. Summary of tests and methods for the perched-water activity (SCP 8.3.1.2.2.4.7) (continu

Methods (selected and alternate)	Activity parameter
Pore-water extraction	
Cross reference to 8.3.1.2.2.4.8 ESF hydrochemistry tests (selected)	Radioactive isotopes
Cross reference to 8.3.1.2.2.4.8 ESF hydrochemistry tests (selected)	Stable isotopes
Cross reference to 8.3.1.2.2.4.8 ESF hydrochemistry tests (selected)	Water quality
Borehole drilling of perched-water zones	
Dry drilling and coring (selected)	--
Wet drilling and coring (alternate)	--
Measurement of large flows	
Stopwatch and a container (selected)	Discharge, perched-water zones
"	Infiltration rate
"	Transmissivity
"	Water potential (total), perched-water zones
"	Hydraulic conductivity
Flow meter (selected)	"
"	Infiltration rate
"	Transmissivity
"	Water potential (total), perched-water zones
"	Hydraulic conductivity

Table 3.7-1. Summary of tests and methods for the perched-water activity (SCP 8.3.1.2.2.4.7) (continued)

Methods (selected and alternate)	Activity parameter
<u>Testing, instrumentation, and monitoring of boreholes</u>	
Pressure transducer (selected)	Water potential, total, perched-water zones
Hydraulic tests (selected)	Hydraulic conductivity, perched-water zones
"	Storage coefficient, perched-water zones
"	Transmissivity, perched-water zones
Periodic visual inspection (alternate)	Water potential, total, perched-water zones
<u>Hydraulic tests for large flow rates</u>	
Theis recovery test (selected)	Discharge, perched-water zones
"	Hydraulic conductivity, perched-water zones
	Storage coefficient, perched-water zones
"	Transmissivity, perched-water zones
Cyclic-discharge test (selected)	Discharge, perched-water zones
Cyclic-discharge test (selected)	Hydraulic conductivity, perched-water zones
"	Storage coefficient, perched-water zones
"	Transmissivity, perched-water zones
Constant-drawdown pumping test (selected)	Discharge, perched-water zones
"	Hydraulic conductivity, perched-water zones
"	Storage coefficient, perched-water zones
"	Transmissivity, perched-water zones
Constant-rate pumping test (selected)	Discharge, perched-water zones
"	Hydraulic conductivity, perched-water zones
Constant-rate pumping test	Transmissivity, perched-water zones

Table 3.7-1. Summary of tests and methods for the perched-water activity (SCP 8.3.1.2.2.4.7) (continu

Methods (selected and alternate)	Activity parameter
Perched-water sample analysis	
Cross reference to 8.3.1.2.2.4.8 ESF hydrochemistry tests (selected)	Radioactive isotopes
Cross reference to 8.3.1.2.2.4.8 ESF hydrochemistry tests (selected)	Stable isotopes
Cross reference to 8.3.1.2.2.4.8 ESF hydrochemistry tests (alternate)	Water quality

Table 3.7-2. Technical procedures for the perched-water activity (SCP 8.3.1.2.2.4.7)

Technical Procedure Number	Technical Procedure
TBD	Sampling, testing, and monitoring perched-water seepage in the exploratory studies facility
TBD	Sampling, testing, and monitoring perched-water zones in boreholes in the exploratory studies facility
HP-06	Hydrologic pumping test
HP-53	Method for calibrating digital and analog watches
HP-17	Method of calibration and testing for operation of pressure transducers for air-permeability studies in the unsaturated zone
HP-108	Long-term monitoring of boreholes in perched-water zones in the exploratory studies facility
HP-103	Pumping tests of perched water in the exploratory studies facility

3.8 Hydrochemistry tests

3.8.1 Objectives of activity

The objectives of this activity are:

1. to extract unaltered pore water and gas samples from core samples, and gas and water vapor samples from boreholes;
2. to obtain hydrochemical and isotopic data that will help in understanding the transport mechanism, flow direction, and travel time of gas and water in the unsaturated zone; and
3. to determine the geochemical evolution of unsaturated- zone water by hydrochemical and isotopic techniques.

3.8.2 Rationale for activity selection

Understanding the unsaturated-zone flow system at Yucca Mountain is essential to the site-characterization program because it is within this interval of rocks that the proposed repository is to be constructed. It is important to evaluate the flow and storage of gas, vapor, and water within the repository block because moisture (vapor and liquid) is the expected major medium for any transport of radionuclides to the accessible environment. Furthermore, a chemical evaluation of gaseous and liquid constituents is important in understanding hydrologic processes, water/rock interactions, geochemical evolution of ground water, and transport mechanisms in the unsaturated zone.

In the unsaturated zone, water is presumed to be present both in liquid and vapor phases. Water flow and storage is envisioned to be complexly three dimensional, controlled by structural, textural, stratigraphic, and climatological factors. In general, liquid-water flow is expected to occur within interconnected pores and fractures, together with advective and diffusive vapor-phase flow within interconnected air-filled fractures. In the geohydrologic units beneath Yucca Mountain, flow paths and fluxes are not clearly understood, and the movement of moisture (gas and liquid) between surficial units and the repository block has not been directly quantified. Because liquid water and water vapor are expected to be in local thermodynamic phase equilibrium, liquid-water saturation, water-vapor, and solute concentrations are coupled through the prevailing geothermal regime. Consequently, hydrologic evaluation of the site constitutes a problem of two-phase, multi-component, coupled heat (geothermal) and moisture flow within alluvium and a layered sequence of variably-saturated, tuffaceous, geohydrologic units which have been tilted, faulted, and fractured. Thus, a hydrochemical evaluation of the unsaturated zone constitutes a study in which the liquid and gaseous chemical interactions must be considered within an already complicated hydrologic scenario.

A study of unsaturated-zone chemistry and distribution of gases will help evaluate chemical transport and flow processes within the repository block. ^{14}C and tritium concentration measurements will determine the residence time of gases in the unsaturated zone. $^{13}C/^{12}C$ isotopic data will also be used in support of ^{14}C age estimates. Stable-isotope ratios ($^{18}O/^{16}O$ and D/H), which might indicate the climatic and evaporative history of moisture, will provide information on flow paths of gases through the unsaturated zone as well as interactions with other minerals or transport properties.

The inorganic composition of Yucca Mountain unsaturated-zone water indicates the types of chemical processes within the unsaturated zone. The chemistry of pore water reflects the results of rock-water interactions within the matrix of the rock, and the chemistry of fracture water reflects the results of chemical processes along the rock-water interface. If fracture and matrix water have similar chemical constituents, the amounts of dissolved species may be different due to different lengths of contact time.

A progressive change in pore-water inorganic composition is expected with depth in the unsaturated zone. This compositional variation probably can be related to variations in the types and compositions of primary minerals with which the pore water may come in contact and to the duration of contact time. The composition of fracture water may be useful in determining the degree of interconnectivity of the fractures. Certain fractures may not extend over long distances and hence may not intersect major water pathways. The water composition in such fractures may be similar to adjacent pore water, which has had long periods of rock/water interaction. Water within interconnected fractures, however, probably has had relatively short residence times and could be relatively dilute compared with water from poorly interconnected fractures. A dilute chemical concentration in water at great depths combined with a young ^{14}C age of water would imply a relatively fast travel time in the unsaturated zone, and possibly periods of intense recharge at the land surface. Conversely, nondilute concentrations at a great depth and old ^{14}C age of water would imply a slow travel time or overall minor recharge at the site. Hydrochemical data and interpretations will be used as a cross-check on travel times computed from hydraulic parameters.

Pore-water chemistry data and mineralogic data for the matrix and fractures in the unsaturated zone will be input to geochemical models to provide additional information from which to infer the water-rock reactions occurring in the unsaturated zone. For example, the degree to which a theoretical water composition (calculated to be in equilibrium with a known mineral assemblage) matches the measured data can be used to infer the extent of mineral/ground-water reactions operating in the system. A close match implies an approach to equilibrium, and possibly a long contact time (long residence time), whereas a poor match indicates the relative importance of reaction kinetics in controlling vadose-zone water composition.

Rock-water interaction affects the transport behavior of radionuclides leached from the waste package. Processes and conditions that may affect the precipitation, sorption, and mobility of radionuclides can, therefore, be inferred from the inorganic composition of the unsaturated-zone water. Rock-water interaction parameters, such as ionic strength and ranges of Eh/pH, will also provide information on solubility and reactivity of the natural geochemical environment beneath Yucca Mountain and of the artificial environment created by the engineered-barrier systems.

Isotopic composition data can be used to interpret paleohydrologic conditions, including sources, times, and climate of recharge. When ocean water evaporates, the lighter $H_2{}^{16}O$ water molecules are preferentially evaporated compared with $H_2{}^{18}O$ or $HD^{16}O$, and the atmosphere becomes relatively depleted in the heavy isotopes. When poleward- or landward-driven water condenses, the first precipitation is enriched in the more condensable heavy isotopes. The remaining water becomes further depleted of heavy isotopes, which causes successive precipitation water to be progressively lighter. As a result, precipitation is lighter farther inland and higher in the mountains, and also lighter toward both poles. Thus, precipitation at various distances from the coast and at various altitudes and latitudes can be differentiated by the stable hydrogen- and oxygen-isotope compositions. Isotopic variations resulting from these effects can provide input to interpretations of a variety of hydrologic processes at Yucca Mountain, as discussed below.

Although individual precipitation at the same location varies greatly in composition with time due to local weather fluctuations (temperature, humidity, and wind), water infiltrating the ground may have relatively small isotopic compositional variation with time due to an averaging effect. Thus, long-term climatic changes might be inferred from significant differences in isotopic composition of unsaturated-zone water. Precipitation at the Nevada Test Site during a cooler climate should be comparatively more depleted in heavy isotopes than that from a warmer climate. Therefore, by analyzing the compositions of oxygen-18 and deuterium in the unsaturated-zone water, it might be possible to identify the climate at the time of recharge (that is, recharged during the warm- or cold-climatic regime). Hydrologic processes on a shorter time scale might also be inferred from stable isotopes of hydrogen and oxygen. The possible sources of Yucca Mountain's precipitation are the Pacific Northwest, California coast, Gulf of California, and the Gulf of Mexico. Each is probably tagged with different stable oxygen- and hydrogen-isotope ratios. When the isotopic composition of unsaturated-zone waters is compared with precipitation collected at Yucca Mountain from these four sources, the water source possibly can be inferred. Furthermore, from the age of water determined by ^{14}C and ^{3}H methods, it is possible to identify the time of recharge, travel, and residence time (Yang and others, 1985).

Tritium ^3H analyses will be used to determine the residence time of pore and fracture water up to about 100 yr; ^{14}C analyses will extend the determination range from 100 to 40,000 yr, and ^{36}Cl yields dates from 50,000 to about 900,000 yr. Obtaining age estimates from each of these isotopic analyses requires, at a minimum, evaluation of all sources and sinks of the elements, and the isotopic signature of each. To the degree that this is possible, four relative-age scenarios will be tested:

(a) Very young (<200 yr) fracture water and near-fracture water, and relatively old (>5,000 yr) pore water. This scenario implies a short residence time for fracture water and that most of the flow through the unsaturated zone is through the fracture network.

(b) Relatively young (<1,000 yr) pore water and relatively old (>5,000 yr) fracture and near-fracture water, and most fractures are air filled. This unlikely situation implies that most of the flow is through the matrix network and that the fractures are poorly connected.

(c) Pore-water, fracture-water, and near-fracture-water samples having the same age at a common depth, and age increasing with depth. This situation implies that fractures are poorly connected and behave as enlarged pores.

(d) General absence of fracture and near-fracture water, and the occurrence of relatively old (>5,000 yr) pore water. This scenario implies that the residence time of water entering the fracture system is extremely short or that all water transported by fractures is drawn into the matrix system by capillary action.

If enough pore water can be extracted from unsaturated-rock samples (in addition to the amount required for hydrochemistry tests, as described herein), pore-water samples will be sent to Los Alamos National Laboratory (LANL), and in turn sent to an outside contract laboratory, for $^{36}Cl/Cl$ ratio analysis (YMP-LANL-SP 8.3.1.2.2.2, water-movement test).

When water percolates primarily downward, travel time can be estimated from the ages of pore, fracture, near-fracture, and perched water at known depths. In more complicated scenarios, when water moves tortuously, assessment of flow paths will require input from mineralogy, stable isotopes, and reaction modeling. After this flow path information is combined with estimates of water age, travel time can be calculated and compared with the value calculated from hydraulic parameters.

The Calico Hills nonwelded unit (CHn) is a nearly saturated zeolitized geohydrologic unit that probably functions as a porous medium. The water table is in this unit beneath some parts of Yucca Mountain. This unit probably retards the downward movement of pore and fracture water. Radiocarbon ages of water determined for this zone will allow an estimation of the residence time of water in the deepest part of the unsaturated zone.

Three prototype tests were undertaken prior to the ESF hydrochemistry tests to design and validate methods of pore-water and gas collection. The optimal rubble size test and the dry coring of rubble tests are not described here because mining rubble will not be available from the ramp and drift construction. The pore-water extraction by compression testing is described in more detail in Section 3.8.3.5. The pore water extraction prototype test has indicated the potential of one-dimensional compression to obtain water from nonwelded core samples, with a degree of saturation greater than 16 percent and from welded core samples with a degree of saturation greater than 37 percent. Additional research is being attempted to determine if water can be obtained from welded core having smaller degrees of saturation using fragmented core samples.

3.8.3 General approach and summary of tests and analyses

The activity is designed to collect gas and unaltered pore, near-fracture, fracture, and perched water from long (45.7 m; 150 ft) boreholes and borehole cores located in all geologic units, and near significant geologic features throughout the ESF (Figure 3.8-1). These long boreholes will be constructed from alcoves off of the main drift. The alcoves will be perpendicular to the ramp/drift, and the boreholes will be drilled in the far end of the alcove. The alcove approximate dimensions are: width, 6 m; height, 5 m; and depth, 6 m. The boreholes should be drilled as soon as the alcoves are completed. Short (1-2 m) small diameter (2.5-5 cm) boreholes will be hammer-drilled as close as practicable behind the tunnel boring machine (TBM) using a jackleg. These short boreholes will be situated along the wall of the 61-m (200-ft) starter tunnel and at the locations of the long boreholes, prior to construction of the alcoves, to provide a sample as nearly representative of pre-mining conditions as possible. If it can be shown during initial testing that short borehole analytical results are similar to long borehole results the short borehole construction and testing will be discontinued. If initial testing indicates the borehole length is too short to escape effects of mining, then these short boreholes will be drilled deeper.

Core samples will be collected continuously during borehole coring, and gas samples will be collected twice a year for three years from the radial boreholes (Section 3.4), from most of the bulk-permeability holes (Section 3.3), from most of the major fault holes (Section 3.10), and from boreholes cored specifically for the hydrochemistry tests. The possibility of construction of the Calico Hills north and south ramps and exploratory drifts could provide access for drilling hydrochemistry-test boreholes that would provide critical information on water residence time in the Calico Hills nonwelded unit and direction of water flow in this unit. Collection of gas and core samples to determine these parameters is of paramount importance to the site characterization for waste isolation. These boreholes will be generally located as described in Table 3.8-1, and

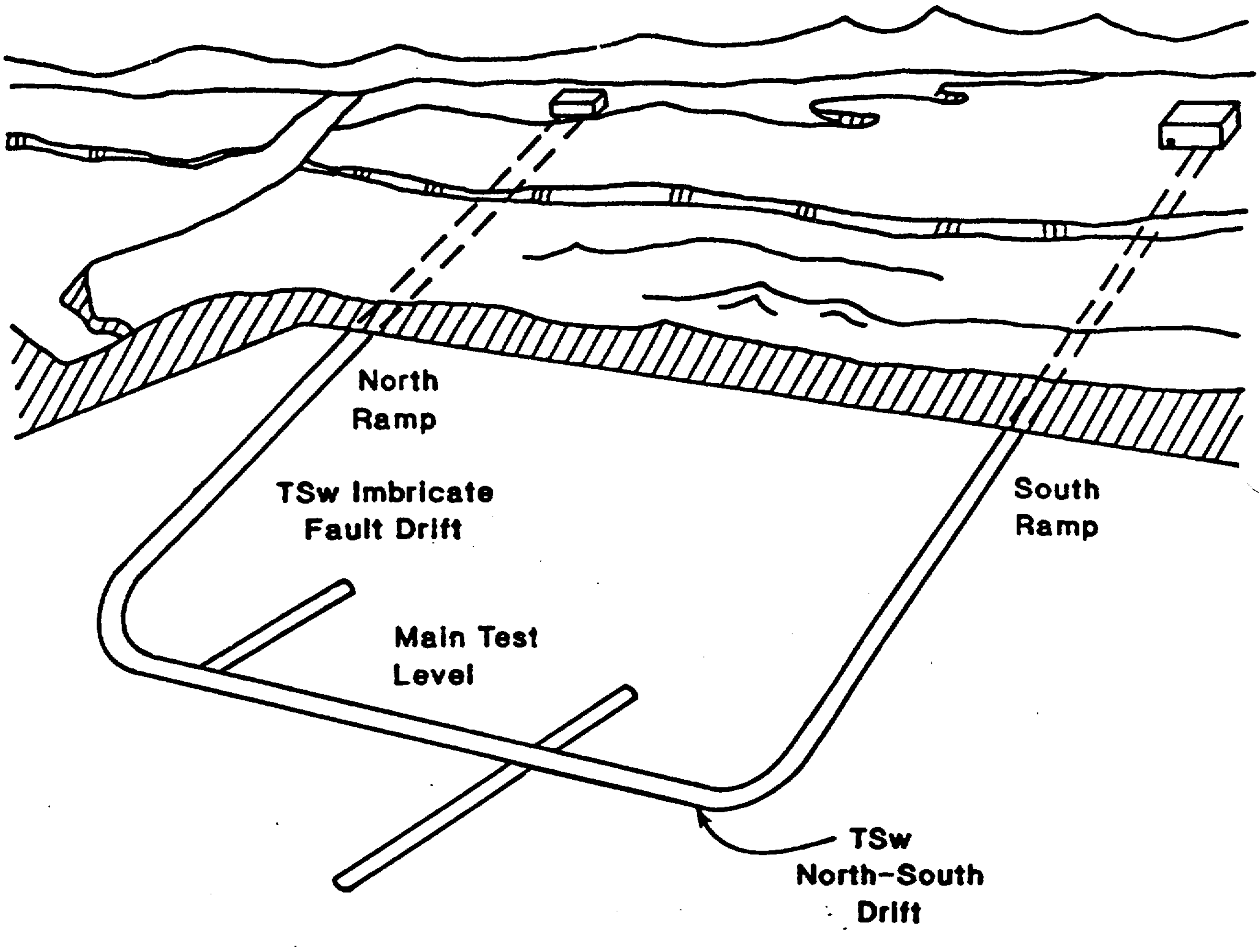


Figure 3.8-1. ESF Option 30 configuration.

Table 3.8-1. Generalized locations of boreholes for use in ESF UZ Hydrochemistry testing

North Ramp

ESF-NR-1	Alcove upper TCw	(Radial Boreholes Anisotropy Test)
ESF-NR-2	Alcove Bow Ridge Fault	(Major Faults Test)
ESF-NR-3	Alcove lower TCw	(Radial Boreholes Anisotropy Test)
ESF-NR-4	Alcove TCw-PTn Contact	(Radial Boreholes Contact Test)
ESF-NR-5	Alcove middle PTn	(Radial Boreholes Anisotropy Test)
ESF-NR-6	Alcove Imbricate Fault	(Major Faults Test)
ESF-NR-7	Alcove $PTn-TSw_1$	(Radial Boreholes Contact Test)
ESF-NR-8	Alcove TSw_1	(Radial Boreholes Anisotropy Test)
ESF-NR-9	Alcove Drill Hole Wash Fault	(Major Faults Test)
ESF-NR-10	Alcove TSw_1	(Hydrochemistry Test)

South Ramp

ESF-SR-1	Alcove Upper TCw	(Radial Boreholes Anisotropy Test)
ESF-SR-2	Alcove Dune Wash Fault	(Major Faults Test)
ESF-SR-3	Alcove Lower TCw	(Radial Boreholes Anisotropy Test)
ESF-SR-4	Alcove TCw-PTn	(Radial Boreholes Contact Test)
ESF-SR-5	Alcove middle PTn	(Radial Boreholes Anisotropy Test)
ESF-SR-6	Alcove Imbrigate Fault	(Major Faults Test)
ESF-SR-7	Alcove PTn-TSw, Contact	(Major Faults Test)
ESF-SR-8	Alcove TSw_1	(Radial Boreholes Anisotropy Test)
ESF-SR-9	Alcove Abandon Wash Fault	(Major Faults Test)
ESF-SR-10	Alcove TSw_2	(Radial Boreholes Anisotropy Test)
ESF-SR-11	Alcove Yucca Ridge Fault	(Major Faults Test)

Topopah Spring Drifts

TSw North-South Drift

ESF-TSD-1	Alcove TSw_1 Horizontal	(Hydrochemistry Test)
ESF-TSD-2	Alcove TSw_1 Vertical	(Hydrochemistry Test)
ESF-TSD-3	Alcove TSw_2 Horizontal	(Hydrochemistry Test)

Table 3.8-1. Generalized locations of boreholes for use in ESF UZ Hydrochemistry testing (continued)

	TSw East-West Drift	
ESF-TSD-4	Alcove TSw_3 Horizontal	(Hydrochemistry Test)
ESF-TSD-5	Alcove Ghost Dance Fault	(Major Faults Test)
ESF-TSD-6	Alcove Solitario Canyon Fault	(Major Faults Test)
	TSw Imbrigate Fault Drift	
ESF-TSD-7	Alcove Imbricate Fault	(Major Faults Test)

as shown in Figures 3.8-1, 3.8-2, 3.8-3, and 3.8-4. A stratigraphic column indicating the location of anticipated geologic units in the exploratory studies facility is shown in Figure 3.8-5.

Due to limited hydrologic and geologic data available at the present, the geological locations of the boreholes may need to be changed, or additional holes may be required as more information becomes available.

A location for short-term core storage, measuring 3 m deep, 3 m high and 3 m wide must be provided underground, out of traffic areas.

During gas sampling no other hydrologic testing should be done within 25 m of the intervals being sampled.

Matrix pore water will be removed from borehole cores (collected from the long boreholes) by one-dimensional compression. Near-fracture matrix water samples will be extracted by compression of fracture intersections from long borehole cores. Fracture water will be collected in the short and long boreholes using absorbent pads. Perched water will be pumped out of the short and long boreholes or collected in the borehole using a borehole liner system.

These gas and water samples will be analyzed for their major ions, and stable and radioactive isotope compositions. Table 3.8-2 summarizes chemical and isotope analyses. The information that can be derived from these tests and how they can help to resolve issues of site characterization have been described in detail in Section 3.8.2 (Rationale for activity selection) or 3.8.3 (General approach and summary of tests and analyses).

The activity will be performed throughout the construction phase of the North and South ramps, the Topopah Spring north-south drift, the Topopah Spring east drift, the Topopah Spring west drift, and the Imbricate Fault drift (see Figures 3.8-1, 3.8-2, 3.8-3, and 3.8-4). Testing will continue for a period of as long as three years after completion of the drifting. When wet zones (water content of >50 percent) are encountered as the drifts are being mined, additional samples will be collected. Core samples collected from the long boreholes will be immediately sealed (according to technical procedure HP-237T) for shipment (according to technical procedure HP-131) to the USGS UZ Hydrochemistry Laboratory in Denver, Colorado, or to the Raytheon Services Nevada (RSN) Materials Testing Laboratory (MTL) in Mercury, Nevada.

A tracer gas (SF_6) will be added to the compressed air during borehole drilling to determine if contamination from ramp and drift ventilation or compressed drilling air has occurred. The residual SF_6 background will be checked before the data from core samples will be used for site characterization. Any water used at the ESF site will be tagged with a tracer. The universal water tracer will be lithium bromide. Samples of any water, and samples of other

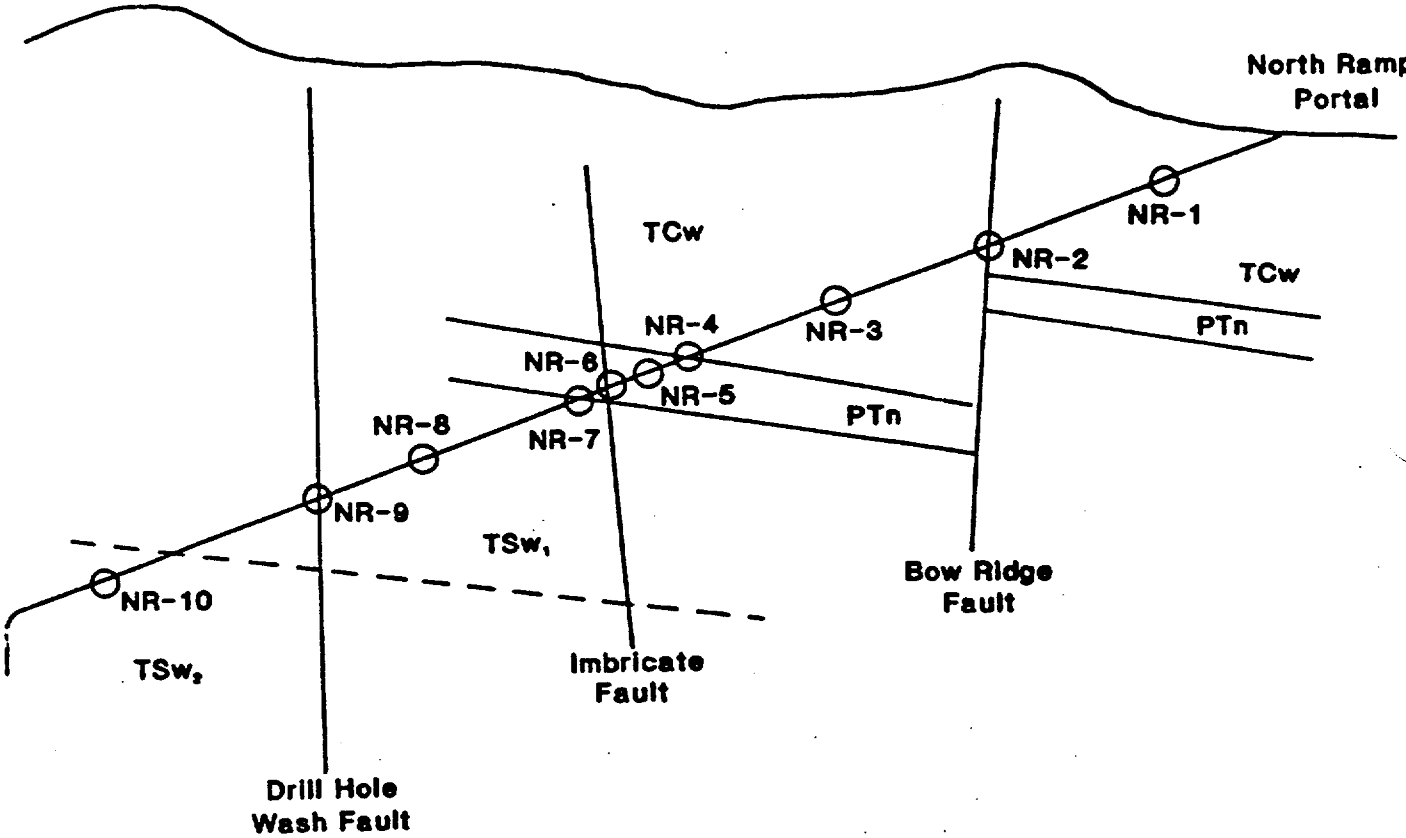


Figure 3.8-2 Generalized location of boreholes in the North Ramp for use in the ESF hydrochemistry test

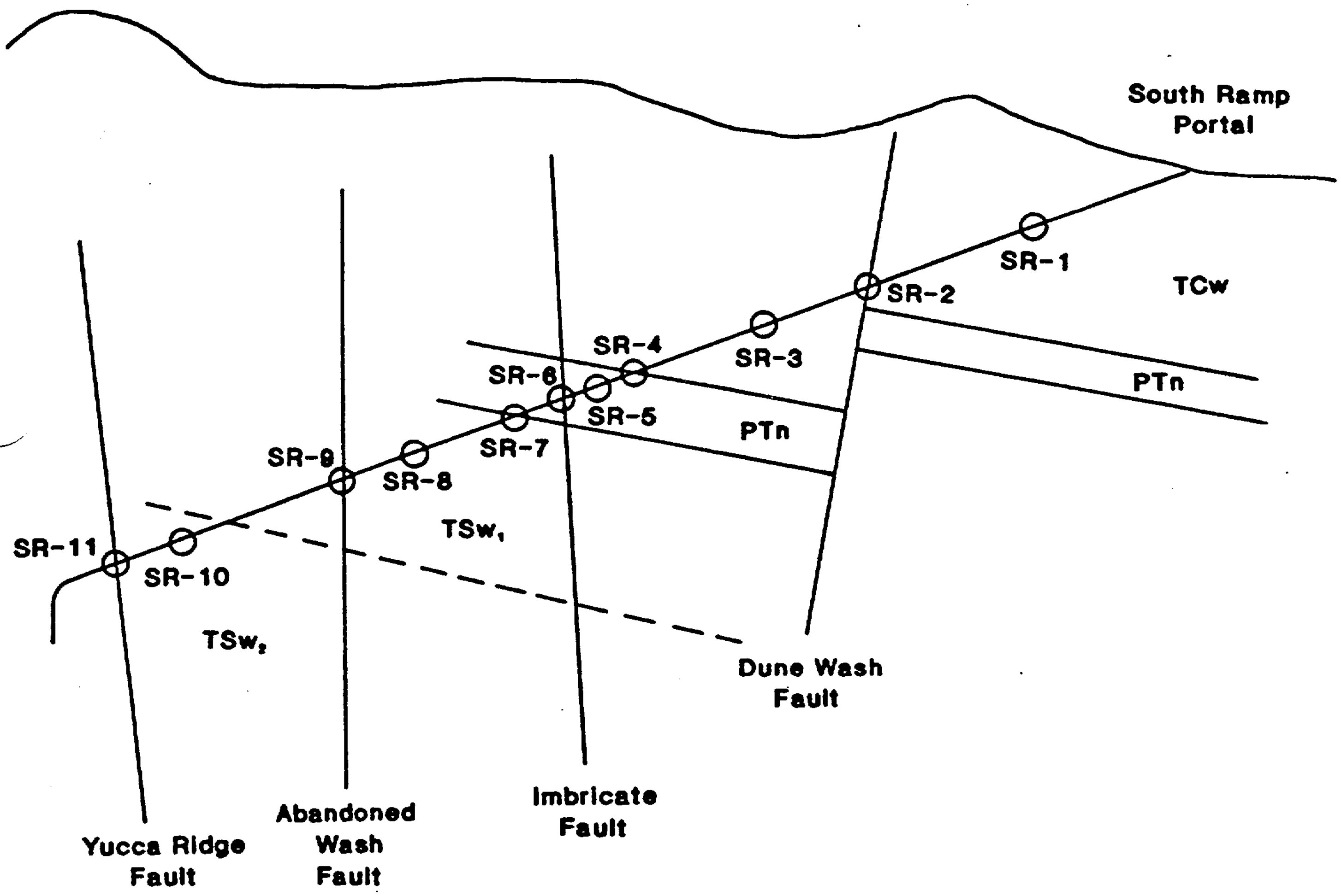


Figure 3.8-3 Generalized location of boreholes in the South Ramp for use in the ESF hydrochemistry test

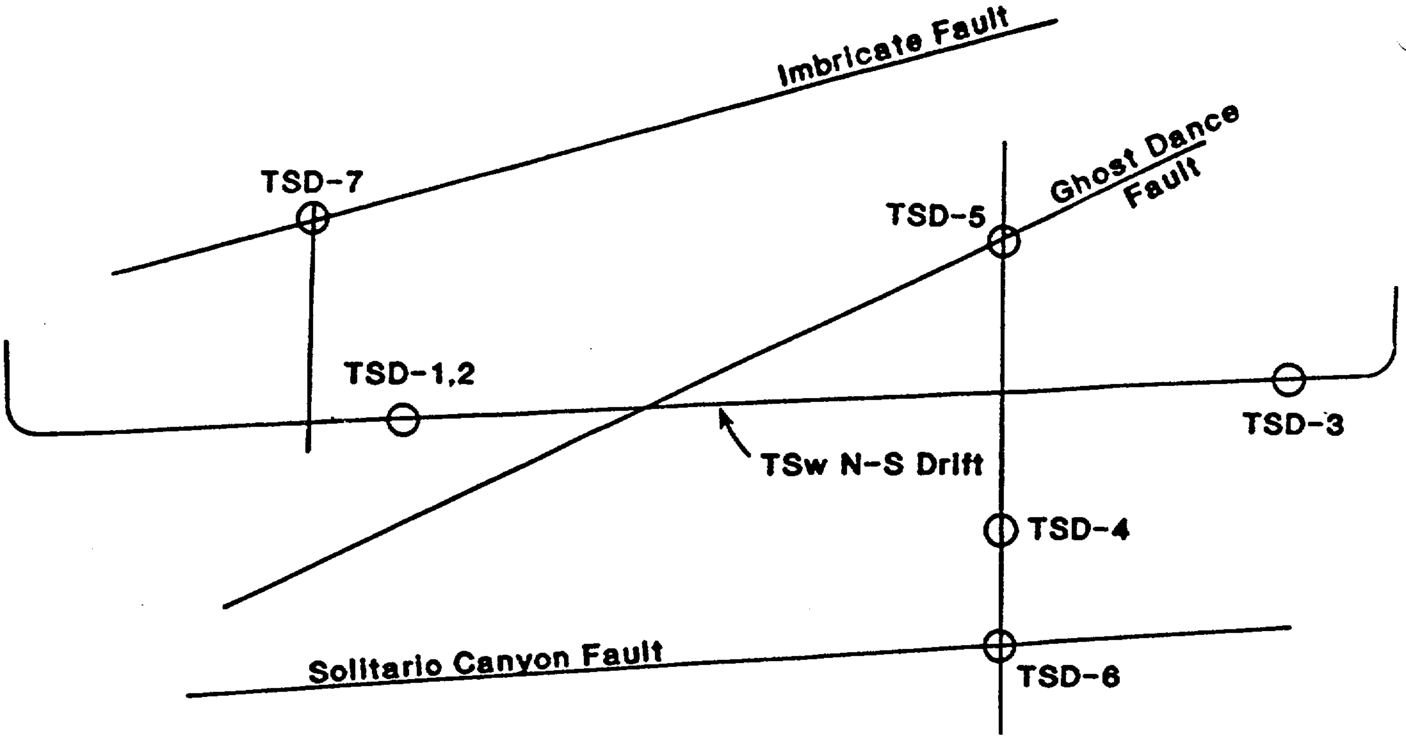
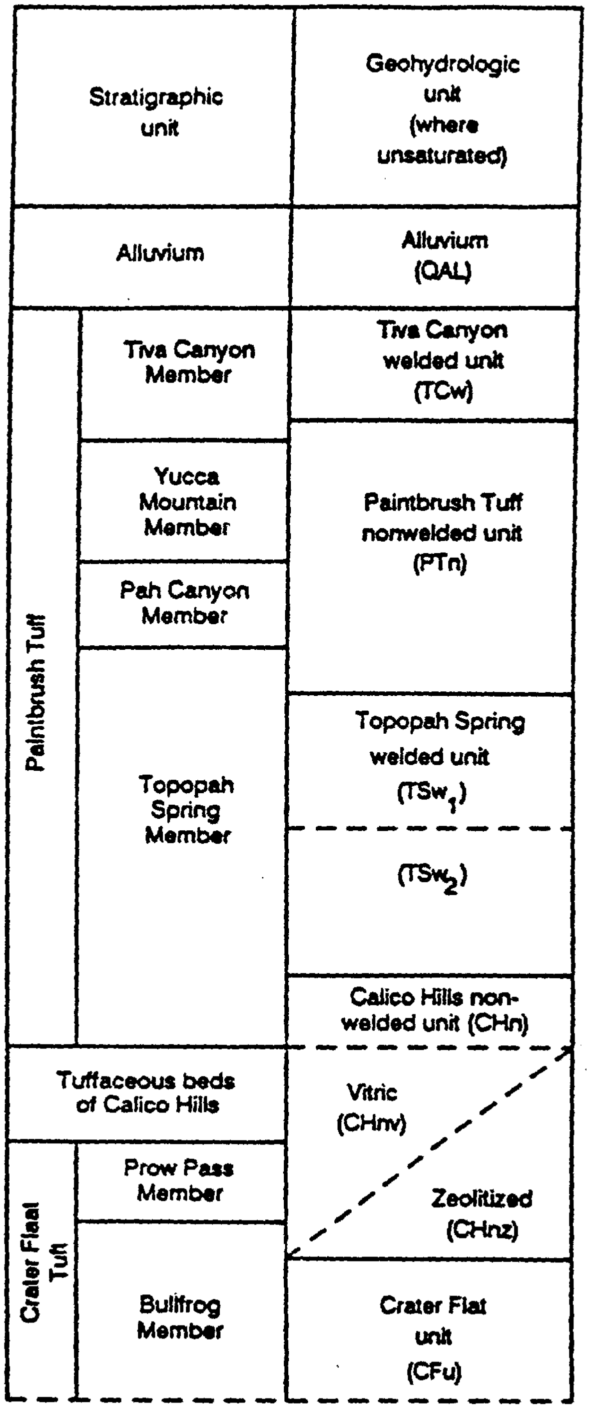


Figure 3.8-4. Generalized location of boreholes in the Topopah Spring drifts for use in the ESF hydrochemistry test.



Note: Figure not to scale

Figure 3.8-5 Stratigraphic column of anticipated geologic units in the ESF

Table 3.8-2. Chemical and isotopic analyses

Parameter	Chemical Species	Information
Inorganic cations and anions	Na, Ca, Mg, K, HCO_3, SO_4, Cl, SiO_2, Mn, Fe, Al, pH, SC	Types of ongoing chemical reactions. Residence times of fracture fluids.
Organic compounds	Organic compounds (trace amounts)	Forming of organometallic complexes that change the mobility of radionuclides.
Stable isotopes	$^{18}O/^{16}O$ and D/H ratios	Timing of major recharge events.
Age dating	^{14}C, ^{3}H, $^{13}C/^{12}C$ ratio, ^{36}Cl	Age and travel time of unsaturated zone waters. Style and pattern of fluid flow in the unsaturated zone.
Gas diffusion	CO_2, CH_4, Ar, O_2, N_2, SF_6, fluorocarbons	Diffusion of gases (^{14}C, ^{3}H) into the unsaturated zone.
Contamination check	Li, Br, I, NO_3, BO_3	Washdown of tracers.

Note: Temperature and redox parameters will be determined for perched water occurrences but are not applicable to extracted pore water.

materials (grout, concrete, etc.) used in the ESF should be provided to the UZ hydrochemistry test Principal Investigator (PI) for analysis.

Figure 3.8-6 summarizes the organization of the activity. A descriptive heading for each test and analysis appears in the shadowed boxes of the second and fourth rows. Below each test/analysis are the individual methods that will be utilized. Figure 3.8-7 summarizes the objectives of the activity, site-characterization parameters which are addressed by the activity, and the activity parameters measured during testing. These appear in the boxes in the top left side, top right side, and below the shadowed test/analysis boxes, respectively, in Figure 3.8-7.

The two figures summarize the overall structure of the planned activity in terms of methods to be employed and measurements to be made. The descriptions of the following sections are organized on the basis of these charts. Methodology and parameter information are tabulated as a means of summarizing the pertinent relations among (1) the activity parameters to be determined, (2) the information needs of the performance and design issues, (3) the technical objectives of the activity, and (4) the methods to be used.

The hydrochemistry tests will be conducted in the ESF, which will penetrate the same geohydrologic units as will the repository. Because of this, the environment in which these tests will be conducted is an approximate representation of the repository area. Furthermore, gaseous and aqueous chemical samples will be collected from boreholes throughout the lateral extent of the drifting, to provide information on horizontal variability of the host-rock hydrochemistry around the ESF. The methods utilized in this activity will provide information that is approximately representative of the repository area. The spatial variability of existing conditions within the repository block, and the correlations to present and potential future repository conditions are represented by the activity. Data from the hydrochemistry tests will be used to model (1) the geochemical evolution of ground water, (2) the gas-transport mechanisms and water (liquid and vapor) movement within the repository host rock, and (3) residence time of water and directions of water flow.

3.8.3.1 Collection and transport of gas samples from boreholes

Collection of gas samples from short boreholes will be collected according to a technical procedure to be prepared at a future date. Four types of gas samples will be collected from long boreholes cored as part of the hydrochemistry, bulk-permeability, radial-borehole, and major-fault tests: (1) gas-composition samples, (2) $^{13}C/^{12}C$ ratio samples, (3) ^{14}C samples, and (4) water-vapor samples. The dimensions, orientations, and instrumentation configurations are discussed in Sections 3.3, 3.4, and 3.10 and illustrated in Figures 3.4-6, 3.4-7, 3.8-2, 3.8-3, and 3.8-4. All boreholes will be cored (HQ3 size) and

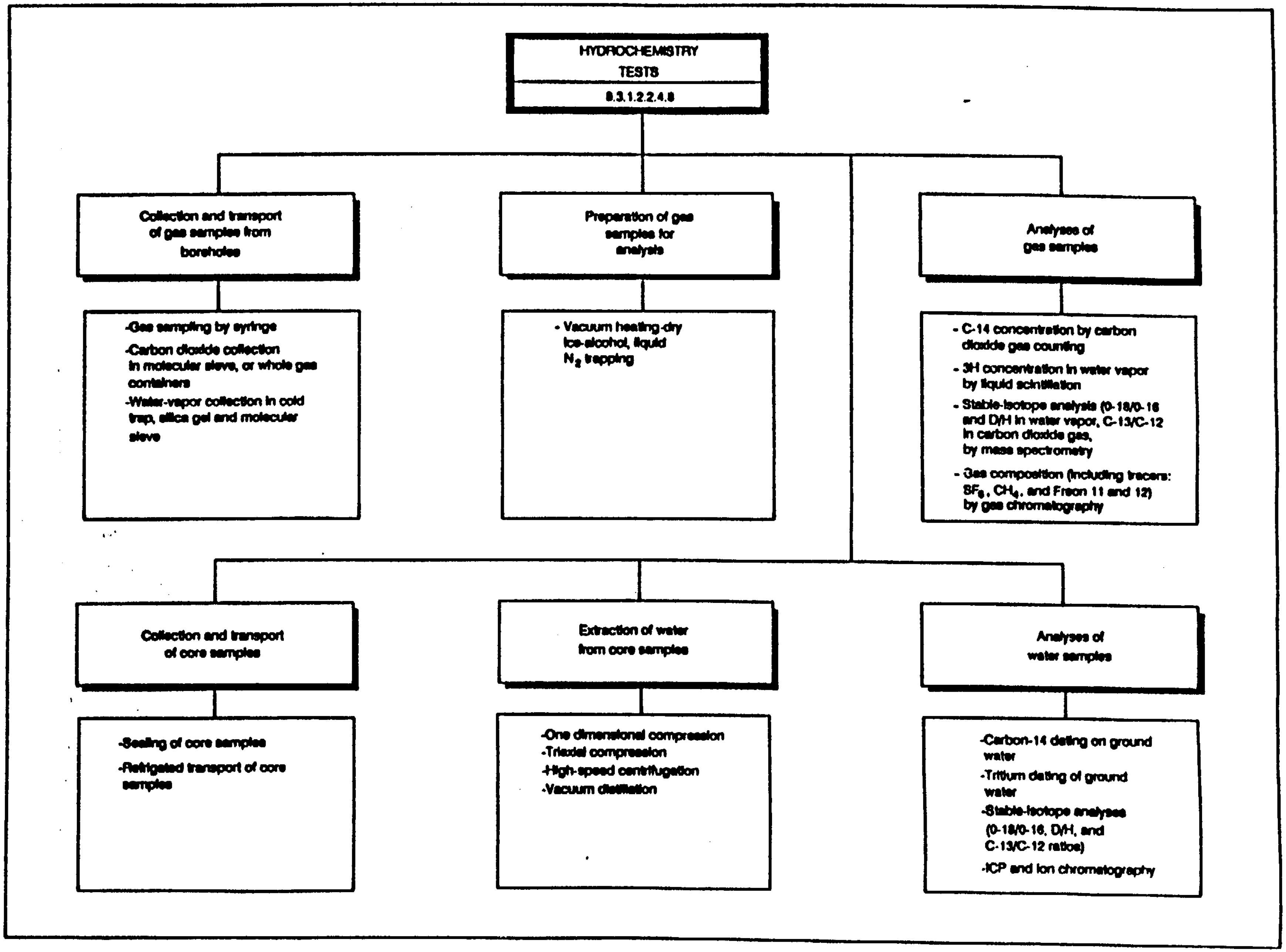


Figure 3.8-6. Organization of the hydrochemistry activity, showing tests, analyses, and methods.

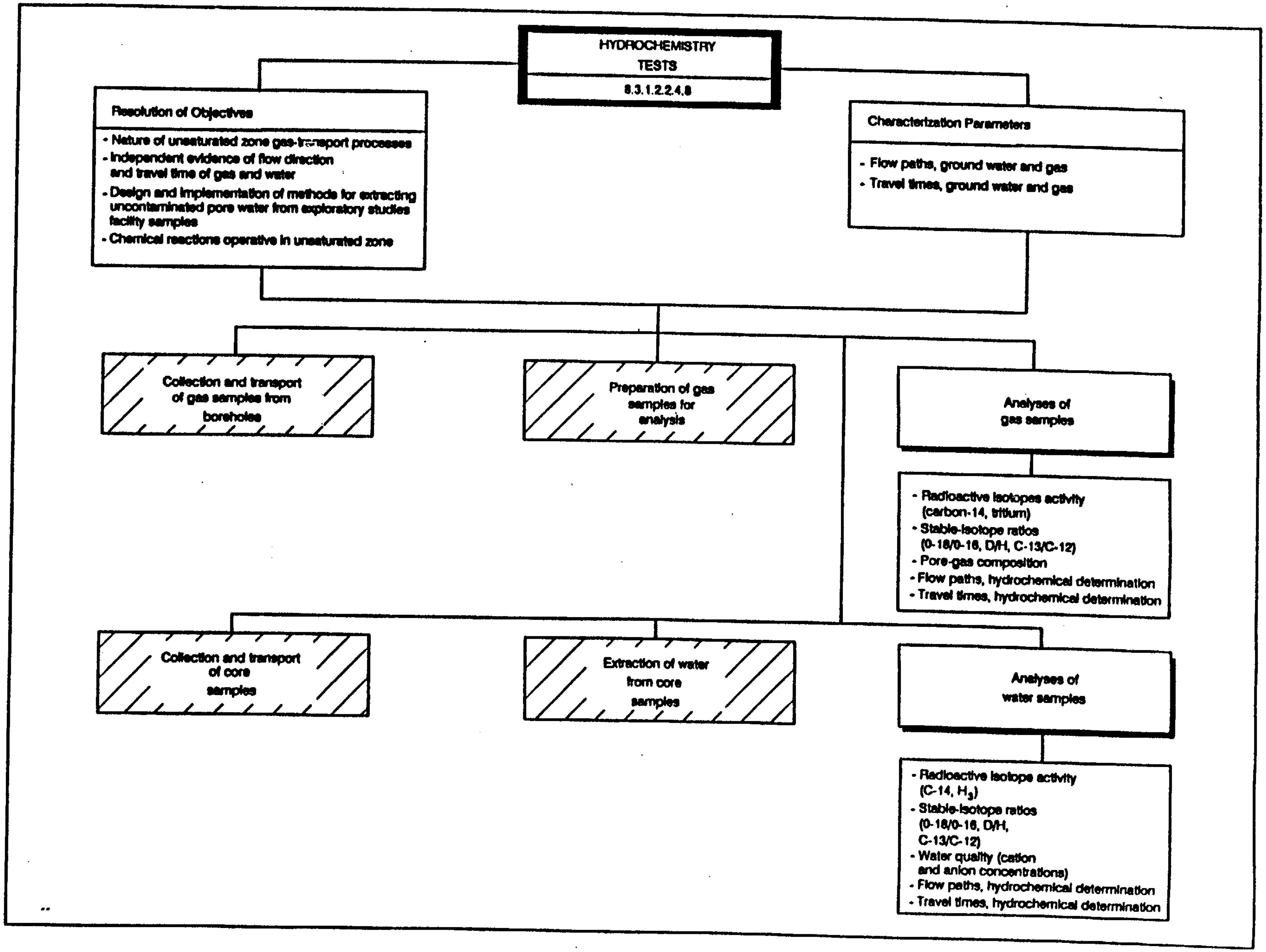


Figure 3.8-7. Organization of the hydrochemistry activity, showing tests, analyses, activity parameters, and characterization parameters. (The cross-hatched boxes indicate that no activity parameter will be generated).

sulfur hexafluoride (SF_6) will be used as a trace gas for drilling air.

Gas samples will be collected from boreholes using a full borehole liner that inverts down and up hole, horizontally or vertically, and is capable of transporting gas sampling tubes from the collar to ported sampling locations downhole. Sampling tubes will be pumped before sample collection to purge the tubes of any atmospheric air that might have been introduced while connecting the pumps to the system. Gases sampled from the ESF boreholes will be analyzed for gas tracers introduced during the construction phase. Sample collection will not begin until drilling air tracer levels have been significantly reduced. During sample collection, the sample gas will be pumped at a flow rate of 500 mL/minute. (See Figure 3.8-8 for system apparatus.)

(1) Gas composition samples -- Two methods will be used for gas-composition sample collection. The first method uses a syringe inserted in the line of gas tubing pumped by the peristaltic pump; gas is allowed to flow directly into the syringe. The second method involves pumping the gas sample into a 250-ml flow-through glass container. Gas-composition sampling by syringe is preferred over collection in a flow-through cylinder; the syringe method is easier to perform and allows the sample to be injected directly from the syringe into a gas chromatograph for analysis (according to technical procedure HP-160). Gas-composition samples require no tracking because they are immediately analyzed in the field.

(2) $^{13}C/^{12}C$ ratio samples -- Two methods will be used. The first method uses 5Å molecular-sieve pellets to trap the CO_2 gas. The gas sample is allowed to flow into a 300-ml stainless-steel cylinder containing the 5Å molecular-sieve pellets which trap the CO_2. The second method involves allowing the CO_2 gas to flow into a 250-ml or 500-ml flow-through glass container, 3- or 10-liter Tedlar bags, or 2.1-liter aluminum cylinders.

(3) ^{14}C samples -- Two methods will be used for ^{14}C sample collection. The first method employs a 5Å molecular sieve as discussed in (2) above. The second method (KOH method) allows the gas to disperse through a fritted plate and bubble into a container of 5 molar KOH solution. The KOH solution traps the CO_2 by converting it to potassium carbonate (K_2CO_3). The principal advantage of the molecular-sieve method of ^{14}C sampling over the KOH method is its simple design and insured, nonbreakable transport between the sampling site and the laboratory.

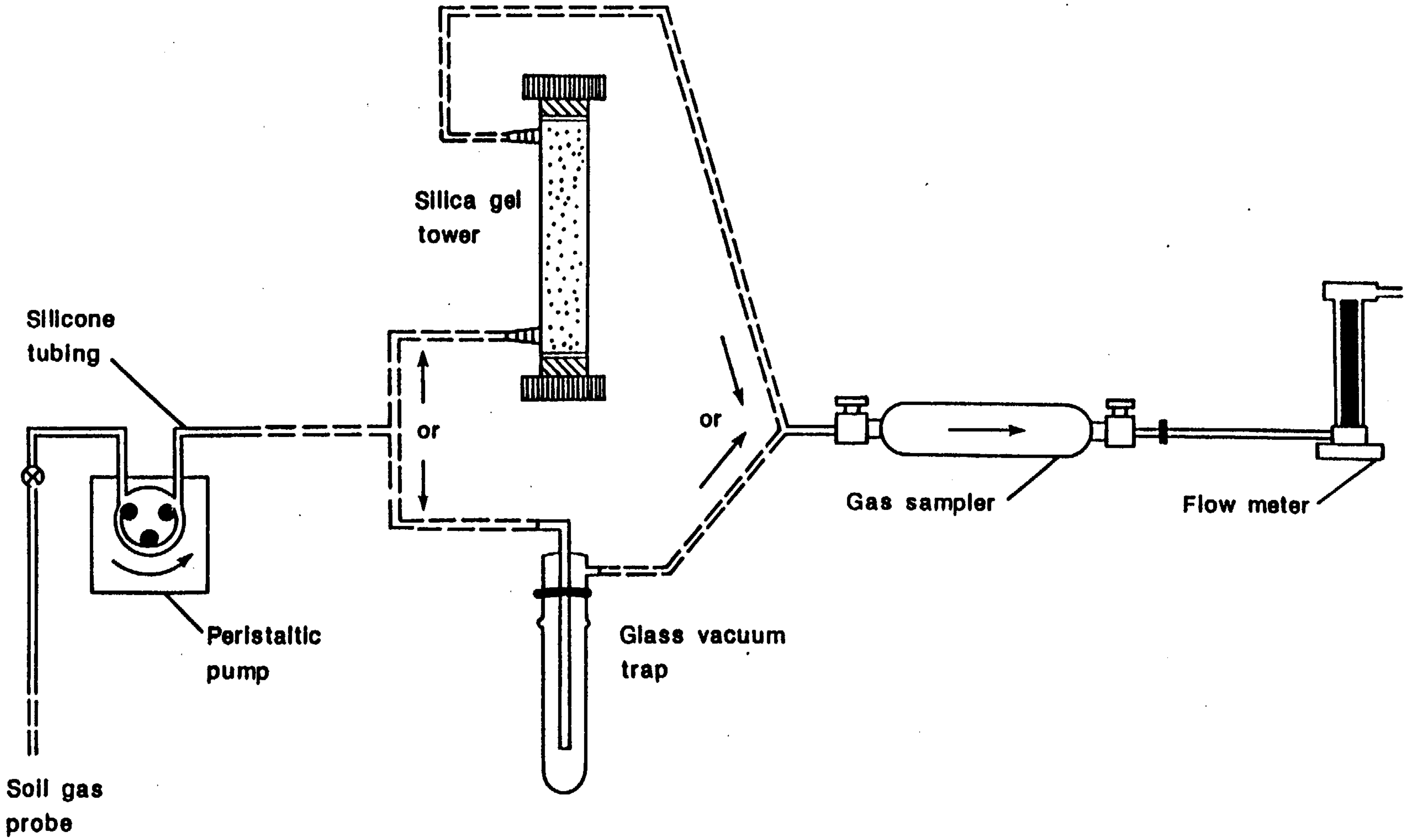


Figure 3.8-8. Diagram showing apparatus for on-site soil-gas collection for hydrochemistry tests.

^{14}C and $^{13}C/^{12}C$ ratio samples will be packed in cardboard boxes and mailed directly from the field to the USGS UZ Hydrochemistry Laboratory at the Denver Federal Center in Colorado or hand-carried to the Hydrologic Research Facility (HRF) laboratory for processing.

(4) Water-vapor samples -- Three methods will be used: cold trap, silica gel, and 5Å molecular sieve. The first method involves pumping the gas sample through a glass cold trap cooled by a dry-ice-alcohol slurry to remove the water vapor. The second method allows the gas to flow through a tower filled with silica gel to remove the water vapor. The third method uses a 5Å molecular sieve similar to (2) above to collect the water vapor. All three methods provide water volume measurements, however, water-vapor sampling using a cold trap is preferred over collection by silica gel tower or molecular sieve because the water can be used for isotopic determinations. The degas heating of the water vapor from the silica gel or molecular sieve causes exchange of oxygen atoms in the water vapor with oxygen atoms in the silicate minerals of the silica gel and molecular sieve, causing errors in oxygen-isotope measurements; the cold trap method is not subject to this problem. Condensed water-vapor samples (in vials) are hand-carried to the USGS Hydrochemistry Laboratory.

All data obtained by each group of methods (selected or alternate) should be compared to insure the validity of the selected method. Gas sample collection methods are detailed in technical procedure HP-56.

3.8.3.2 Preparation of gas samples for analysis

Two methods are available for preparing gas samples for analysis: (1) degassing of CO_2 samples trapped in molecular sieve by heating under a vacuum and collecting the released gases in cold traps using liquid nitrogen, and (2) adding acid to a potassium hydroxide (KOH) solution containing CO_2 to release the CO_2 gas from potassium carbonate (K_2CO_3). The first method is detailed in technical procedure HP-86, and involves heating the molecular sieve gas-collection cylinder to 300° C to drive off the captured gases, collecting the water vapor as ice in a cold trap cooled to -78° C by a dry-ice/alcohol slurry, collecting the CO_2 as a solid in a cold trap cooled by liquid nitrogen and storing the warm-up CO_2 gas in a storage cylinder. A simplified diagram of the degassing system is shown in Figure 3.8-9. The CO_2 collected in the KOH solution is released by acidification

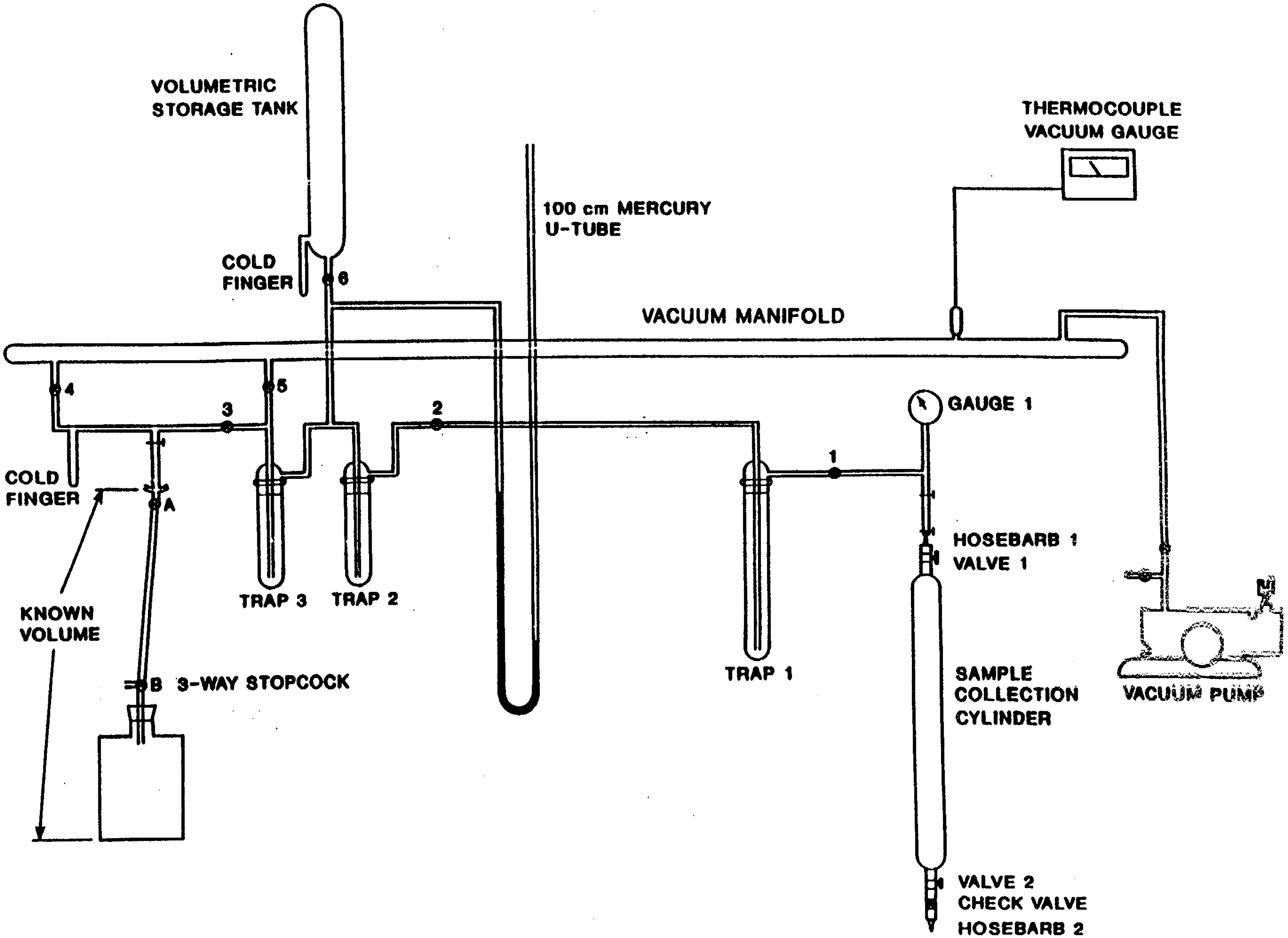


Figure 3.8-9. Diagram showing degassing system for hydrochemistry tests.

and converted into benzene for ^{14}C analysis by scintillation counting. Water vapor collected using a glass cold trap requires no further preparation. Water vapor collected on molecular sieve or silica gel is removed by heating, then collected in a cold trap immersed in a dry-ice/alcohol slurry.

Internal checks assure release of all of the CO_2 gas. For example, near the end of the degassing procedure, the liquid-nitrogen level is raised around the CO_2 cold trap. This exposes a clean section of the collection tube in the trap to liquid nitrogen; any CO_2 still solidifying in the trap will form a ring of new white solid on this section of the tube - indicating that the degassing process is not yet complete. No formation of new CO_2 solid ensures that all of the CO_2 has been trapped.

3.8.3.3 Analyses of gas samples

Stable-isotope ratios ($^{18}O/^{16}O$, $^{13}C/^{12}C$, and D/H) will be analyzed using mass spectrometry by the USGS Research Laboratory, Reston, Virginia, or by the USGS, Geologic Division, Branch of Petroleum Geology, Organic Geochemistry Lab, Denver, Colorado. Low-level gas counters will be used to determine ^{3}H activity in water vapor at the University of Miami, Miami, Florida and at the USGS UZ Hydrochemistry Laboratory. Large ^{14}C samples ($^{14}CO_2$ gas) will be analyzed using conventional gas-counting methods by Geochron, Inc. in Boston, Massachusetts. Small ^{14}C samples will be analyzed by tandem accelerator mass spectrometry (TAMS) at the University of Arizona, Tucson, Arizona. Gas composition samples will occasionally be analyzed for the presence of construction-phase tracers (SF_6 and fluorocarbons), using gas chromatography.

3.8.3.4 Collection and transport of core samples

Core samples will be collected by dry coring into the face of the alcoves constructed adjacent to the ramps and drifts. These samples should be collected at least 6.1 m (20 ft) from the line of the ramp or drift to ensure that they are unaffected by the drift and ramp mining. The samples for this activity will be obtained by a dry-coring technique using traced (SF_6) drilling air, and will be HQ3 core with diameter of 6.1 cm (2.4 in). Borehole core samples will be collected and sealed according to technical procedure HP-237T.

The core will be transported to the Sample Management Facility (SMF) to be stored in a refrigerated room as soon as possible after collection. Portions of the core will be released to the PI or his designate to be transferred to the RSN Materials Testing Laboratory (MTL), Mercury, Nevada, or to the UZ Hydrochemistry Laboratory.

The sealed core samples will be transported to the laboratory in Denver in an air-conditioned vehicle to insure core-water preservation during the movement of the core from the Nevada Test Site to the permanent storage facility in Denver. The methods for transportation are detailed in technical procedure HP-131. Coordination with the sample overview committee is required in order to preclude sample-handling and sample-custody conflicts in the ESF and SMF.

3.8.3.5 Extraction of water from core samples

Five methods are available to extract water from unsaturated tuffs: (1) one-dimensional compression (technical procedures HP-223, HP-248T, and HP-249), (2) triaxial compression (technical procedure HP-125), (3) high-speed centrifugation, (4) vacuum distillation, and (5) immiscible displacement. One-dimensional and triaxial compression involve placing a core sample in a compression chamber and applying axial pressure in step increases to force water and air from the pore space (see Figure 3.8-10). Using a sequence of step increases allows a maximum amount of water to be recovered with a minimum potential for rock/water interactions which might alter the original pore-water composition. The centrifugation method (technical procedure HP-110) uses the large centrifugal force developed in a high-speed (8,000 to 18,000 rpm) centrifuge to drive pore water out of a core (see Figure 3.8-11). The removal process can be simple drainage, or an immiscible fluid can be introduced to displace the pore water during centrifugation. The distillation method (technical procedure HP-126) involves heating the core under a vacuum and capturing the vaporized pore water in a low-temperature (-78 °C) cold trap. The immiscible-displacement method uses an immiscible fluid (usually a halogenated hydrocarbon) to displace pore water from the core by a leaching process.

In extracting pore water from tuff samples, several of the above methods can be used in sequence to achieve maximum water recovery. A progression from one-dimensional compression to vacuum distillation for a single sample ensures optimum water removal. One-dimensional compression is favored over centrifugation for two major reasons.

(1) The forces acting on the core are much better understood for one-dimensional compression than centrifugation; therefore, more information about the actual pore-volume reduction process that occurs within the core will be gained from one-dimensional compression.

(2) The one-dimensional compression method recovers gas from the sample pore space, which is not possible using centrifugation. The chemical and isotopic composition of the gas in the sample may also be useful in pore-fluid characterization.

Centrifugation and one-dimensional compression can be used on crushed or broken cores which are unsuitable for triaxial compression. One-dimensional compression, triaxial compression,

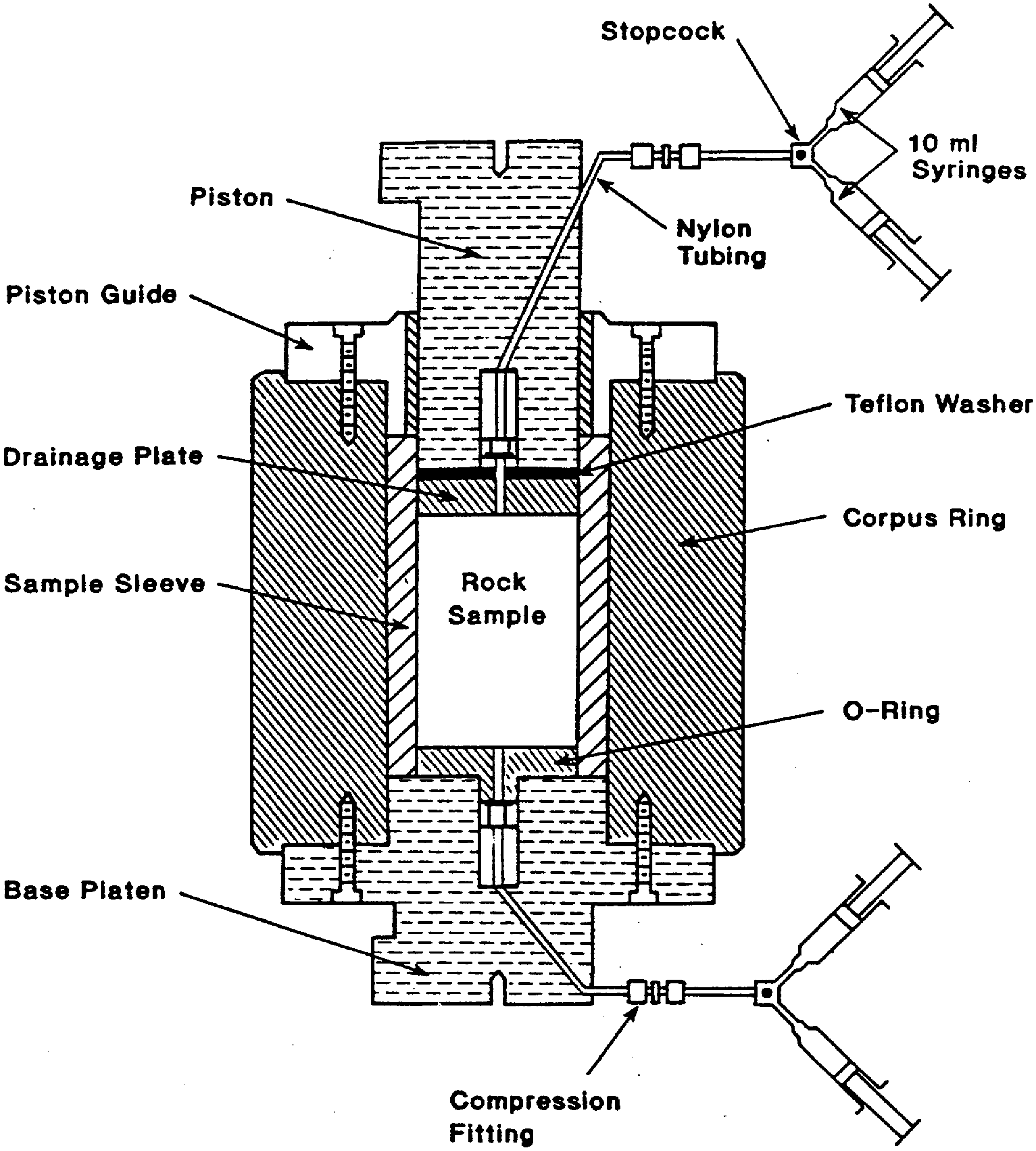
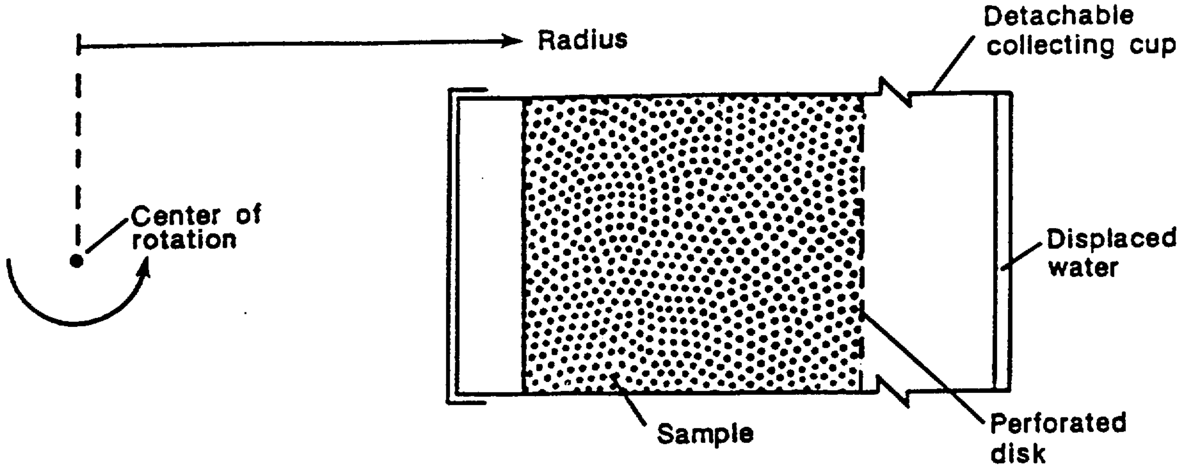


Figure 3.8-10. Diagram showing apparatus for pore-water extraction by one-dimensional compression.

Drainage method



Immiscible displacement

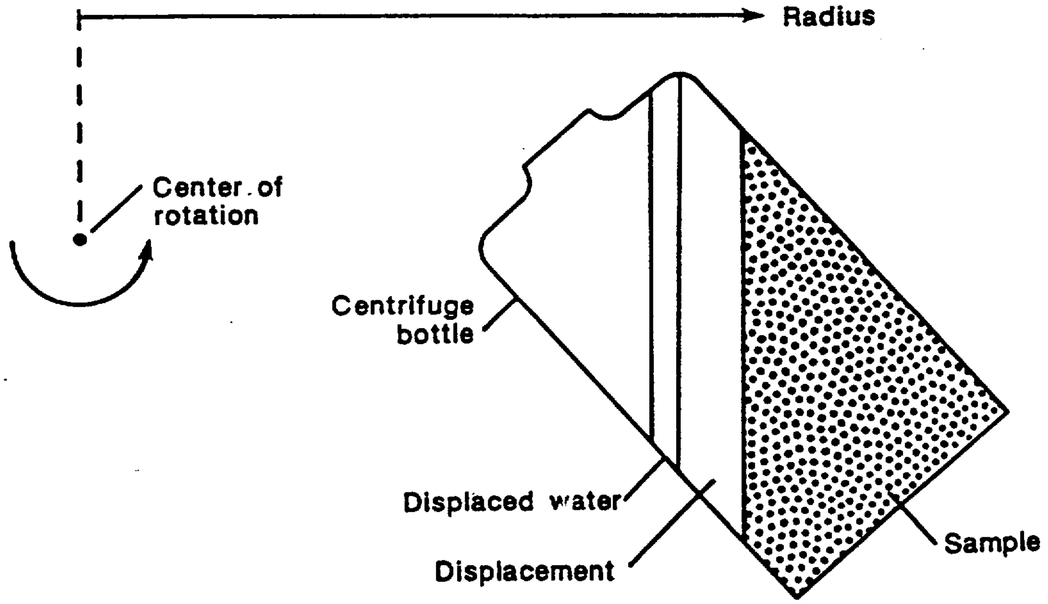


Figure 3.8-11. Diagram showing methods of centrifugation for hydrochemistry tests.

and centrifugation are preferred over vacuum distillation because cation and anion concentrations are not preserved through the distillation process. Immiscible displacement is the least-favored method, because by forcing a new fluid through the sample, it introduces additional potential for error - either by adding trace water present in the immiscible fluid or by chemical reactions between the immiscible fluid and the core. (Centrifugation would be performed only using simple drainage and not incorporating an immiscible fluid for this same reason.)

Whether a representative water sample is extracted from a core sample can be verified in two ways. First, by taking water samples at each pressure level during the compression procedure, corresponding chemical-concentration data relating cation and anion concentrations to each axial pressure will be obtained. If the ion concentrations do not change with increasing pressure, then the compression process is not affecting the original pore-water composition. (Also, if a sharp change in concentration is noted at a higher pressure level, future testing can secure representative samples by holding pressures below that level.) Preliminary results from the pore-water extraction prototype testing indicate that the mean concentration of dissolved ions generally decreases slightly (≈ 15 percent) during compression. The relative abundance of major cations does not vary with increasing pressure, and the relative abundance of major anions varies moderately with increasing pressure. However, these changes are minor relative to differences in pore-, fracture-, and saturated-zone-water chemistry from natural waters from different geologic units (Peters and others, 1992). Second, water-sample analyses from cores which were extracted by centrifugation were compared to analyses from nearby cores extracted by triaxial compression. Although not an unequivocal demonstration, similar chemical concentrations obtained by both methods support the validity of compression for producing representative pore water samples (Yang and others, 1990).

The pore-water extraction by triaxial- and one-dimensional compression prototype testing has determined proper extraction procedures to produce representative water samples and has determined that no particular rock-core orientation is more favorable than another for water extraction (Yang and others, 1988). The methods developed during the prototype test will be implemented during ESF hydrochemistry testing.

Core samples containing fractures will be used to determine the chemical and isotopic composition of near-fracture pore-water. The section of core near the fracture will be chipped off of the core sample and the water extracted by one-dimensional compression. These chemical results will be compared to chemical results from the remaining intact core sample.

An absorbent rope segmented into one foot sections will be inserted into the boreholes and pressed against the borehole wall using a borehole liner system. Upon retrieval any water will be removed from each section of the absorbent rope for chemical analysis. Borehole televiewer logs and core logs will be used to correlate water collected in the absorbent rope segments tc occurrent fractures.

If a perched-water zone is encountered, it will be sampled according to technical procedure HP-231T or by using a specially designed borehole liner system. The perched water study is further described in Section 3.7.

3.8.3.6 Analyses of water samples

Cation concentrations will be determined by using inductively coupled plasma (ICP) by subcontractor laboratories, and anion concentrations will be determined using ion chromatography at the USGS Central Laboratory, Denver, Colorado or at the UZ Hydrochemistry Lab, Denver, Colorado according to technical procedure HP-202. Stable-isotope ratios will be analyzed using mass spectrometry performed by the USGS Research Laboratory, Reston, Virginia. Low-level-concentration gas counters or liquid scintillation counters will be used to determine ^3H activity at the University of Miami, Miami, Florida, or in Reston, Virginia, or at the UZ Hydrochemistry Lab, Denver, Colorado according to technical procedure HP-204. Large ^{14}C samples will be analyzed using conventional gas-counting methods by Geochron, Inc. in Boston, Massachusetts. Small ^{14}C samples will be analyzed by tandem-accelerator mass spectrometry (TAMS) at the University of Arizona, Tucson, Arizona. ^{36}Cl will be analyzed using TAMS at the Lawrence Livermore National Laboratory, Livermore, California. All water samples will be analyzed for the presence of tracers (bromide, nitrate, iodide, borate, lithium, etc.), using ion chromatography (IC) and high-pressure liquid chromatography (HPLC) either in-house according to technical procedure HP-202 or by a subcontractor laboratory.

^{36}Cl for age dating is dependent on the extent of *in-situ* production in the subsurface. If this interference is minimal, ^{36}Cl will be used for water-age dating. $^{18}O/^{16}O$, $^{13}C/^{12}C$, and D/H stable-isotope ratios are preferred over other stable-isotope ratios because more background data are available, and standard analysis techniques already exist for these isotopes. Use of ICP, IC, GCMS, HPLC, and TAMS is preferred over atomic adsorption because these techniques can analyze more than one element at a time, whereas atomic adsorption must determine each element individually and so would require much more time to complete an analysis.

^{14}C dating will determine the age of the water in the unsaturated zone, and ^3H will be analyzed for use as an indicator of recent meteoric water. Stable-isotope ratios will provide information on the flow path of the water through the unsaturated zone and any high-temperature rock/water interactions. Age and flow-path length together will be used to estimate travel times of water in the unsaturated zone. Ion concentrations will provide information about chemical processes involving the rock matrix and pore water. Tracer concentrations will help determine the effects of ESF construction and drilling on water in the unsaturated zone. Refer also to the beginning of Section 3.8.2 for more detail concerning the uses of the chemical and isotopic analyses of pore water.

3.8.3.7 Methods summary

The activity parameters to be determined by the tests and analyses described in the above sections are summarized in Table 3.8-3. Also listed are the selected and alternate methods for determining the parameters. The alternate methods will be utilized only if the primary (selected) method is impractical to measure the parameter(s) of interest. In some cases, there are many approaches to conducting the test. In those cases, only the most common methods are included in the tables. The selected methods in Table 3.8-3 were chosen wholly or in part on the basis of accuracy, precision, duration of methods, expected range, and interference with other tests and analyses.

The USGS investigators have selected methods that they believe are suitable to provide accurate data within the expected range of the activity parameter. Models and analytical techniques have been or will be developed to be consistent with test results.

3.8.4 Quality assurance requirements

The USGS Quality Assurance Program Plan for the YMP (USGS, 1989) requires technical procedures for all technical activities that require quality assurance.

Table 3.8-4 provides a tabulation of technical procedures applicable to this activity. Approved procedures are identified with a hydrologic procedure number. Procedures identified as "TBD" will be approved prior to being needed for use in site characterization.

Equipment requirements and instrument calibration are described in the technical procedures. Lists of equipment and stepwise procedures for the use and calibration of equipment, limits, accuracy, handling, calibration needs, quantitative or qualitative acceptance criteria of results, description of data documentation, identification, treatment and control of samples, and record requirements are included in these documents.

Table 3.8-3. Summary of tests and methods for the hydrochemistry activity (SCP 8.3.1.2.2.4.8)

Methods (selected and alternate)	Activity parameter
Analysis of gas samples	
Age dating of carbon dioxide gas samples using conventional gas counter (selected)	Radioactive-isotope activity
Age dating by scintillation counting of tritium in water vapor (selected)	"
Stable-isotopes analyses ($^{18}O/^{16}O$ and D/H in water vapor, $^{13}C/^{12}C$ in carbon dioxide gas) (selected)	Stable isotope ratios
Gas composition (including tracers) by gas chromatography (selected)	Pore-gas composition
Argon-39 dating of gas (alternate)	Radioactive-isotope activity
Hydrochemical determination by sample analysis and modeling (selected)	Flow paths, hydrochemical determination
Hydrological determination, other activities (alternate)	"
Mass spectrometry (alternate)	Stable isotope ratios
Hydrochemical determination by sample analysis and modeling (selected)	Travel times, hydrochemical determination
Hydrologic determination, other activities (alternate)	"
Analysis of water samples	
Carbon-14 dating on ground water (selected)	Radioactive-isotope activity
Age-dating of carbon dioxide in water samples using tandem-accelerator mass spectrometry (selected)	"
Tritium dating of ground water (selected)	"

Table 3.8-3. Summary of tests and methods for the hydrochemistry activity (SCP 8.3.1.2.2.4.8) (continued)

Methods (selected and alternate)	Activity parameter
Analysis of water samples (continued)	
Stable-isotope analyses ($^{18}O/^{16}O$, D/H, and $^{13}C/^{12}C$ ratios) (selected)	Stable-isotope ratios
ICP and ion chromatography (selected)	Water quality, cations and anions
Chlorine-36 dating of ground water (alternate)	Radioactive-isotope activity
Argon-39 dating of ground water (alternate)	"
Mass spectrometry for other stable isotopes (alternate)	Stable isotope ratios
Atomic absorption (alternate)	Water quality, cations and anions

Table 3.8-4. Technical procedures for the hydrochemistry activity (SCP 8.3.1.2.2.4.8)

Technical Procedure Number (YMP-USGS-)	Technical Procedure
Collection and transport of gas samples from boreholes	
HP-56	Gas and water-vapor sampling from unsaturated-zone test holes
HP-160	Methods for collection and analysis of samples for gas composition by gas chromatography
HP-176	Procedure to collect gas composition at selected depth intervals
HP-239T	Method for removing traced drilling air from unsaturated zone boreholes
TBD	Method for installing a full borehole liner system for collection of gas, water vapor and fracture water
TBD	Method for collecting carbon dioxide in KOH solution using a fritted glass plate bubbler
Preparation of gas samples for analysis	
HP-86	Method for degassing carbon dioxide and water (vapor) samples from unsaturated-zone test holes
HP-190T	Silica gel dewatering
HP-194	Calculation of relative humidity at depth within unsaturated zone test holes using a silica get tower
Analyses of gas samples	
HP-160	Methods for collection and analysis of samples for gas composition by gas chromatography
HP-240	Method for analysis of CO_2 and CH_4 gas sample concentrations using Summit Interest SIP 1000
HP-242	Method for analyzing the concentration of halocarbon gases with an ITI Leakmeter 120
Collection and transport of core samples	
HP-07	Use of a trace gas for determining atmospheric contamination in a dry-drilled borehole
HP-12	Method for collection, processing, and handling of drill cuttings and core from unsaturated-zone boreholes at the well site, NTS

Table 3.8-4. Technical procedures for the hydrochemistry activity (SCP 8.3.1.2.2.4.8) (continued)

Technical Procedure Number (YMP-USGS-)	Technical Procedure
	<u>Collection and transport of core samples (continued)</u>
HP-131	Methods for handling and transporting unsaturated-zone core and rubble samples for hydrochemical analysis
HP-237T	Methods for sealing unsaturated-zone borehole core samples to preserve moisture content
HP-238T	Injection of a trace gas for determining atmospheric contamination in a dry-drilled borehole
TBD	Method for boring short (1-2 meter) small diameter (2.5-5 cm) boreholes
TBD	Gas sampling from short boreholes
TBD	Method for injecting a trace gas into drilling air using an automated injection system
	<u>Extraction of water from core samples</u>
HP-110	Extraction of pore waters by centrifuge methods
HP-125	Method for extraction of pore water from tuff cores by triaxial compression
HP-126	Extraction of residual water from tuff samples by vacuum distillation
HP-223	Method for pore water extraction using one-dimensional compression
HP-231T	Identification, monitoring, and sampling of perched or ground water encountered while drilling surface-based boreholes
HP-249	Method for pore water extraction using high pressure one-dimensional compression
TBD	Method for extraction of pore water using immiscible displacement
TBD	Method for preparing core for pore water extraction
TBD	Method for collection of near-fracture pore water

Table 3.8-4. Technical procedures for the hydrochemistry activity (SCP 8.3.1.2.2.4.8) (continued)

Technical Procedure Number (YMP-USGS-)	Technical Procedure
	<u>Analyses of water samples</u>
HP-202	Analysis of water samples for anion and cation concentrations by Ion Chromatography
HP-204	Liquid Scintillation spectrometry method for tritium measurement of H_2O samples
HP-209	Method for preparing tracers for addition to a water supply system
HP-229	Determination of water content and physical properties for laboratory rock samples

3.9 Multipurpose-boreholes testing near the exploratory shafts

The multipurpose-boreholes testing has been deleted because the original concept of the construction of exploratory shafts has been changed to an exploratory-studies facility with ramps and drifts. The orignal purpose for the multipurpose-boreholes was to provide hydrologic and engineering properties data in the immediate areas of the shafts prior to their construction and to provide for the monitoring of changes in ambient conditions that may have resulted from shaft construction. These needs are no longer valid.

3.10 Hydrologic properties of major faults encountered in the ESF

3.10.1 Objectives of activity

The objectives of this activity are to:

1. measure the pneumatic and hydraulic permeability, porosity, and anisotropy of the major faults and their associated fault zones. In this study plan, fault refers to a planar feature along which movement has occurred. Fault zone refers to the fault and any rock whose fractures and/or other alterations are directly attributed to the fault;
2. conduct long-term monitoring for vertical flow of gas, water vapor, and water in the major faults of the unsaturated zone;
3. conduct tracer tests to estimate the tortuosity and effective porosity of the faults and their associated fault zones.
4. conduct geothermal logging in selected boreholes to determine the nature, if any, of recharge occurring along high-angle faults and fault zones.

3.10.2 Rationale for activity selection

While quantifying the hydrologic properties of the major faults is absolutely necessary for understanding and modeling of the proposed repository site, attempts to quantify the hydrologic properties of large features, such as faults, by testing on a much smaller scale at one, or at the most a few, selected test sites will be far from conclusive. A fault may vary from a simple planar structure with little associated fracturing, to an extensive broken zone (tens of meters wide) where the actual fault plane is no longer identifiable. The faults hydrologic properties are dependent on both random spatial factors and non-random factors such as rock type and depth below land surface. Attempts to extrapolate the fault characteristics measured at one point in one rock type to a larger area should be done only with great care and a large amount of supporting information explaining how and why the extrapolation is justified.

Selection of the fault and fault zone test sites will attempt to address two key issues: (1) identify and test sites that are considered to represent the potentially fastest pathways that could allow rapid transmission of water from the surface to depth and/or rapid transmission of gas and water vapor from depths to the surface, and (2) identify and test sites that are representative of the existing moisture conditions and average permeability of the rock mass. The major fault test sites will be selected at locations where the following conditions exist (listed in descending order of priority):

1. identification of water flow in the fault or fault zone,
2. large open main fault trace,
3. high density of fractures,
4. large aperture fractures,
5. proximity to the proposed repository,
6. fracture mineral coatings,
7. observed changes in rock moisture content over relatively short distances, and
8. temperature gradients.

Yucca Mountain contains and is bounded by west-dipping high-angle normal faults that, depending on location and ambient hydrologic conditions, may serve as pathways for or barriers to gas, vapor, or water flow. As currently conceived, the repository would be excavated mainly in the relatively unfaulted western part of one structural block in the mountain. The repository would be bounded on the west by the Solitario Canyon fault, on the northeast by Drill Hole Wash structure, and on the east and southeast by the western edge of an imbricate normal fault zone. The Ghost Dance fault is expected to approximately bisect the repository area. In the case of dual-ramp access to the underground testing facility (see Reference Configuration Option 30, Figure 3.10-1), the Bow Ridge fault may be intercepted by the north ramp at an approximate distance of 1.5 km from the repository area. These faults are major structural features found typically at intervals of 1 to 2 km and generally have offsets of more than 100 m.

Additional faults of a second type will be encountered at the eastern and southeastern boundary of the repository. Within the structural blocks at Yucca Mountain are numerous steep, west-dipping normal faults. They generally strike north to north-northwest; they are closely spaced and typically have less than 3 m of offset, forming an imbricate pattern.

It is possible that structural flow paths may sometimes be truncated at the contact between the geohydrologic units. It has also been observed that some fault zones contain clay gouge. More ductile rock, like the nonwelded tuffs, typically produces sealing gouge material along fault zones and thus has greater "healing properties." Thus, it is expected that hydraulic conductivity probably varies significantly along fault zones and is perhaps greater in the welded units (e.g., TCw and TSw) than in the nonwelded units (e.g., PTn).

Generalized conceptual models for moisture flow within the unsaturated zone beneath Yucca Mountain have accounted for the presence of these structural features (Montazer and Wilson, 1984; Sinnock et al., 1986). It is generally believed that major faults affect flow significantly in the unsaturated zone. The precise nature of that impact, however, will depend on a number of interrelated hydrologic and geologic parameters. It is conceivable, for example, that under relatively low ambient moisture conditions, faults may impede any lateral moisture flow in the repository block (caused by anisotropy in matrix hydraulic properties or contrasts in such properties at contacts between geohydrologic units). Under such conditions, perched-water bodies may form where the faults transect zones or horizons of significant lateral flow.

Conversely, under conditions of relatively high moisture, faults may serve as highly conductive pathways for vertical water flow. This phenomenon may be especially important in the more competent units TCw and TSw. The conceptual models at Yucca Mountain presently suggest that fractures and faults (especially the high-angle normal faults) are the principal conduits of downwardly transmitted infiltration (see Section 3.4.2).

Under present climatic conditions, the general understanding of the major faults at Yucca Mountain is that they are dry above the water table and therefore dry above and immediately below the repository. This means that if the major faults are highly permeable they may provide a potentially fast pathway to the surface for vapor and other gases from the repository horizon.

Fluid flow in fractures and faults is a complicated phenomenon that is highly sensitive to hysteresis, air entrapment, the presence of fracture coatings, fracture roughness, and a host of other hydraulic and geological parameters. For example, fluid flow is strongly influenced by matric potential. Small increases in bulk saturation may lead to sudden increases in fluid flux through

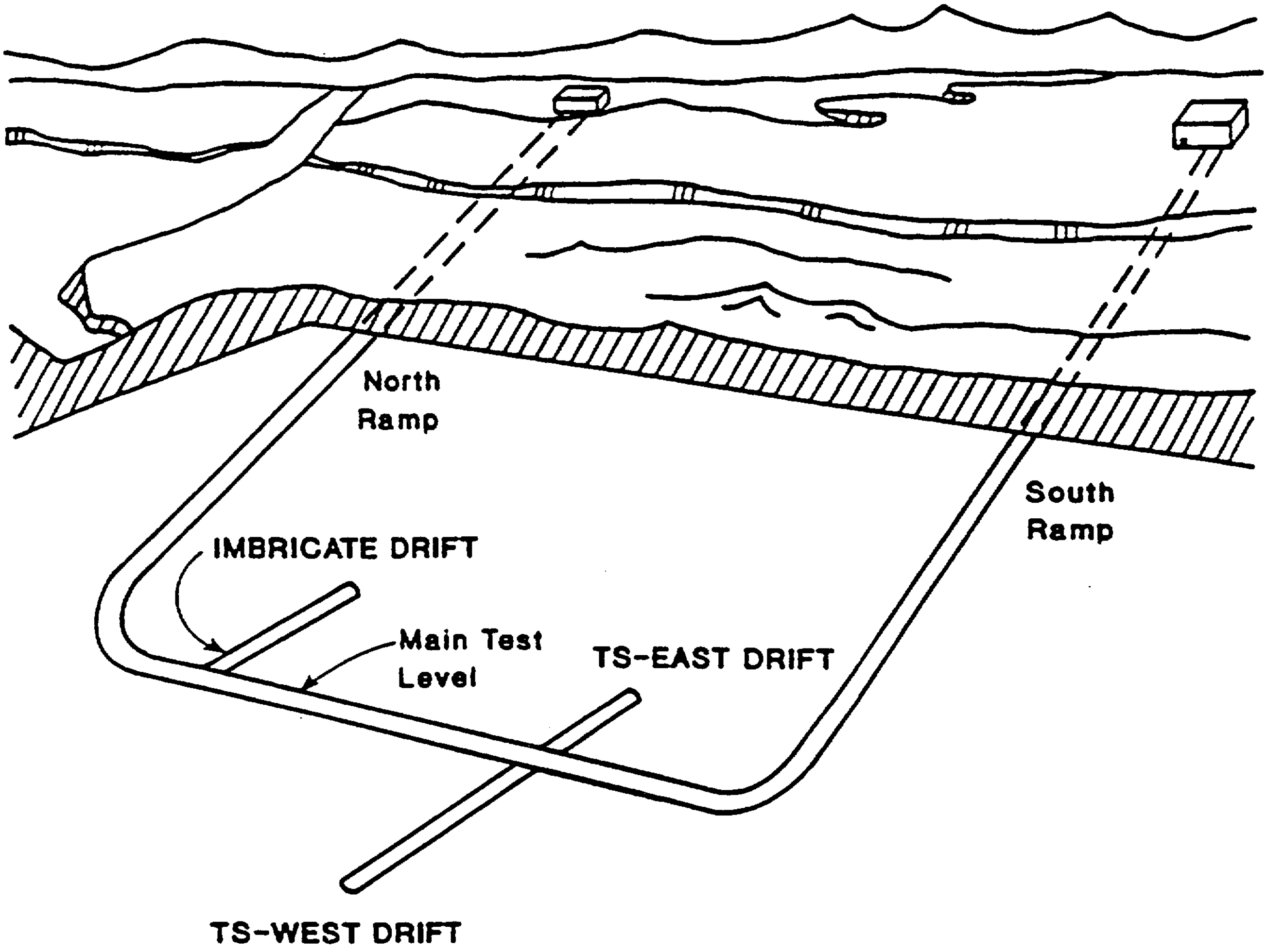


Figure 3.10-1. ESF option 30 configuration.

fractures and faults. Faults may be bounded by zones of extensive disturbance, such as imbricate zones, which may further enhance the conductivity of the overall structure. In more ductile units (e.g., the Paintbrush Tuff nonwelded unit), clay gouge may actually reduce the conductivity of the fault and form an impermeable barrier to flow across the zone of disturbance. Although the amount of fluid flow in major faults is considered to be small under present moisture conditions, additional understanding of the factors controlling that flow must be obtained in order to meet site-characterization requirements. The information gathered from the tests described herein will be used to improve this understanding and refine conceptual models which account for the presence of faults or fault zones.

Prototype testing was conducted to develop equipment and methodology for determining pneumatic and hydraulic properties of structural features such as fractures and faults. One of the specific purposes of prototype testing was to design and evaluate a cross-hole pneumatic and hydraulic test system that could be used in a number of ESF hydrologic tests, including the test described in this study plan. Developing, testing, and refining each of these components during prototype testing increased the likelihood that ESF tests which utilize cross-hole pneumatic and hydraulic tests will be successful in meeting their objectives.

3.10.3 General approach and summary of tests and analyses

Hydraulic and pneumatic properties of the major faults intercepted by the ESF will be quantified by this activity. The proposed dual-ramp access to the ESF (Reference Configuration Option 30) will provide a greater opportunity to inspect and characterize both the geology and hydrology of the major faults than was provided in earlier test plans. It is anticipated that all major faults will be intercepted by either the ramps, main test-level drift, by the east and west access drifts excavated off the main test level, or in any excavations in the Calico Hills nonwelded unit (Calico Hills drifts). Some major faults will be intercepted at more than one location. Such access will provide a higher degree of confidence in the characterization of major faults in and near the repository by allowing tests to be performed at multiple locations along the plane of a fault or fault zone. It may also be possible to visually inspect faults and fault zones at the contacts of geohydrologic units.

The major faults and/or fault zones expected to be tested are:

1. North Ramp
    a) Bow Ridge fault
    b) imbricate fault zone
    c) Drill Hole Wash structure

2. South Ramp
    a) Dune Wash fault
    b) imbricate fault zone
    c) Abandon Wash fault zone
    d) Yucca Ridge fault

3. Main Test Level
    a) Ghost Dance fault

4. TSw East
    a) Ghost Dance fault

5. Calico Hills drifts
    a) Solitario Canyon fault
    b) Ghost Dance fault
    c) Imbricate fault zone

6. Imbricate drift
    a) imbricate fault zone

Other major faults encountered, particularly those where moisture flow is detected, will also be considered for testing.

If ESF design and construction schedules permit, boreholes drilled specifically for geothermal testing should be drilled to intercept selected major faults and fault zones. This can be accomplished by constructing a small alcove off the ramps or main test level drift and conducting the drilling and testing operations from the alcove. The proposal is to dry drill a near-horizontal (inclined slightly downward) borehole to intersect the fault. The geothermal logging will consist of logging the borehole at an interval of one to two days initially, and weekly thereafter, until the drilling disturbances have subsided and the ventilation in the fault and/or fault zone can be measured. The geothermal logging will involve pushing the temperature probe into the geothermal borehole. The borehole may be either cased or uncased, depending upon borehole conditions. If the borehole is cased, the PI may elect to fill the casing with water to facilitate thermal contact with the surrounding rock. The principal investigator for the geothermal investigations at Yucca Mountain, or his designated representative, will determine the exact location and orientation of any geothermal boreholes drilled in the ESF.

The identification of faults and the characterization of their physical properties comprise a portion of the geologic mapping activity in the ESF (SCP Activity 8.3.1.4.2.2.4 in YMP-USGS SP 8.3.1.4.2.2, Structural features in the site area). Upon identification of major faults by the geologic mapping activity, the PI will determine if the major fault will be tested according to the criteria outlined in Section 3.10.2. If the major faults is selected for testing, one or two test alcoves containing HQ3 boreholes will be installed (see Figure 3.10-2). The borehole drilling will use tracer-tagged air to remove the cuttings. In addition, all fluids used in drilling and/or testing will be tracer-tagged to insure future identification.

In order to quantify the fault and associated fault disturbed zone permeability and porosity, it will be necessary also to quantify the undisturbed tuff. Permeabilities and porosities of the faults, fault disturbed zones, and undisturbed tuff will cover several orders of magnitude. Because the testing requires that all three of these be quantified, the equipment and test configuration was designed to maximize the testing range and allow for modification as more information is obtained. Maximizing the range of the mass flow controllers and sensitivity of the pressure transducers the equipment, will allow single hole testing in rock with permeability ranging from $10^{-18}m^2$ up to $10^{-9}m^2$. Using three boreholes (#1, #2, and #3) in a triangular configuration with approximately 5 meter sides (see Figure 3.10-2), scoping calculations show that, for the gas injection ranges and pressure transducers available, cross-hole testing can be conducted in rock with permeability ranging from approximately $10^{-15}m^2$ to $10^{-11}m^2$ and porosity ranging from .001 to .1. Permeabilities less than $10^{-15}m^2$ would generally require long test times for cross-hole testing and would be limited to single hole testing. Single-hole testing at the high end range of $10^{-9}m^2$ corresponds to the permeability of a permeable gravel, however it is possible that the faults may be more permeable than this. If this is the case and it is determined that accurate measurements of permeabilities greater than $10^{-9}m^2$ are required, then the system will have to be modified to handle higher flow rates and the boreholes located closer together if cross-hole testing is to succeed. Permeability of the undisturbed tuff will be characterized in boreholes #1, #2, and #3, if possible. If it is not possible to characterize the undisturbed tuff in these boreholes, a fourth borehole (#4) will be drilled into undisturbed (minimally fractured and faulted) tuff. This borehole will be drilled away from the fault trace, as shown in Figure 3.10-2.

Following cross-hole testing in the three perpendicular boreholes, two additional 30 meter boreholes (#5 and #6) will be installed. These boreholes will be located from 1 to 3 meters from the main trace of the fault and will be parallel to the fault plane (see Figure 3.10-2). These boreholes will be used to expand testing on the main trace of the fault plane and the rock in the first few meters perpendicular to the main trace. In faults where it is more a fault zone and there is no identifiable main trace, the boreholes will be located at the zone of greatest fracturing with the purpose of testing in the highest permeability zone of the fault. Testing in these boreholes will utilize the same equipment as used in the first three boreholes. Assuming a main trace of the fault is identified boreholes #5 and #6 will be used to conduct tests across the fault or define whether the fault is a constant head or impermeable boundary. Using boreholes parallel to the main trace will allow testing over a larger area of the fault than was possible with the perpendicular boreholes. Preliminary modeling shows that for permeabilities ranging from $10^{-15}m^2$ to $10^{-10}m^2$ the distance from the main trace to the borehole should range from 1 to 3 meters. Assuming that a main trace is identifiable a final 30 meter borehole (#7) will be drilled parallel to and in the main trace. This borehole will allow single hole testing in the main trace and will provide some statistical evaluation of the range of the fault permeability. The equipment for single hole testing has a maximum range of $10^{-9}m^2$. In faults zones where a main trace is not identifiable borehole #7 will not be required.

Figure 3.10-3 summarizes the organization of the testing strategy for major faults. A descriptive heading for each test and analysis appears in the boxes of the second and fourth rows. Below each test/analysis are the individual methods that will be utilized during testing. Figure 3.10-4 summarizes the objectives of the activity, and the activity and site-characterization parameters measured during testing. Cross-references to other studies that provide input to the major-faults testing also appear in both figures.

The two figures summarize the overall structure of the planned activity in terms of methods to be employed and measurements to be made. The descriptions in the following sections are organized on the basis of these charts. Methodology and parameter information are tabulated as a means of summarizing the pertinent relations among (1) the site-characterization parameters to be determined, (2) the information needs of the performance and design issues, (3) the technical objectives of the activity, and (4) the methods to be used.

3.10.3.1 Borehole drilling and coring

Geothermal boreholes, if drilled, should begin at preselected site(s) where the major fault can be intersected. The locations(s) will be selected by the principal investigator or a designated representative. The selection of the site(s) will be determined by the results of the geologic mapping in the ESF. A small drilling alcove will probably be required. The geothermal borehole will be dry drilled to intersect the fault. Core need not be collected if this will shorten the drilling time for the borehole, because time is such a critical element in the geothermal logging. The length of the geothermal borehole will be determined by the geometry of the ESF in relation to the major faults(s) to be tested. The borehole will be inclined slightly downward, approximately 3 to 5 degrees. The geothermal logging will require a borehole that can handle standard

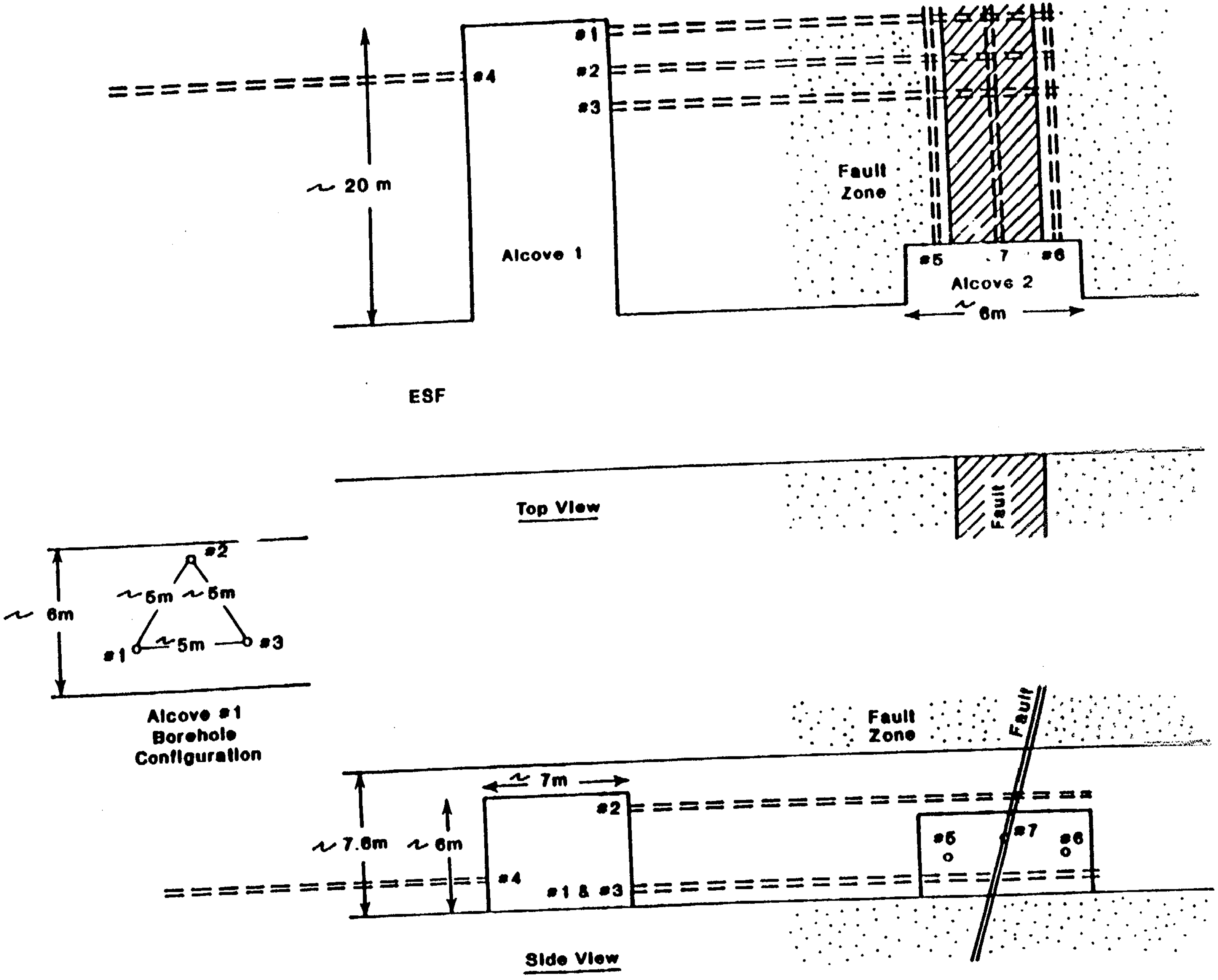


Figure 3.10-2. Schematic of major faults alcoves and borehole configuration.

weight pipe with a minimum 2.5 inch inside diameter: the probe is approximately 2.0 inches in diameter. The pipe may be filled with water to facilitate the thermal contact with the surrounding rock. Keeping the air space between the pipe and the borehole wall to a minimum is also highly desirable in order to minimize any air flow in the borehole.

One or two alcoves will be required at each fault test location in order to provide adequate access to the fault and a suitable area for staging drilling and testing operations off the main drift. The boreholes will be HQ3 size and will provide core. If possible, the core should be oriented. A schematic diagram (Figure 3.10-2) illustrates the desirable configuration for fault testing. The precise configuration of the boreholes, angle, and spacing, will probably vary according to the following local conditions: (1) geometrical relationship between the drifts, alcoves, and the plane of the fault or fault zone; and (2) estimates of the permeability of the fault(s) based on either the geological mapping data or on a preliminary pneumatic injection test performed in a single borehole intercepting the fault. The first alcove will be parallel to the fault. Alcove dimensions will be determined by logistics and the test requirements. Three boreholes, approximately 30 meters long, will be drilled perpendicular to the fault, parallel to each other and in the configuration of an equilateral triangle with approximately 5-m sides. The exact dimensions are still open to discussion and will probably be changed as we obtain more information. The location of the alcove in relation to the fault will depend on the width of the fault zone. It is preferable to locate the alcove outside the fault zone so that the boreholes can be drilled from undisturbed tuff through the fault zone and into the fault. This will allow testing of the fault and the fault zone. However, air-permeability testing equipment limitations will probably restrict the alcove location to within 30 m of the fault. If the width of the fault zone is such that the first alcove is constructed in the fault zone, the fourth borehole will be drilled.

During ESF construction, geologic and fracture mapping will be conducted continuously with ESF construction. This information on lithology, fracture density, and fracture orientation as it relates to the major faults and the associated fault zone will be available to the PI to aid in locating the alcoves and in selecting the final configuration of the boreholes. Information on the fault fillings, fracture density, and fracture fillings will be used to evaluate the applicability of the approximately 5 meter triangular borehole configuration, data on fault orientation will determine the orientation of the boreholes and mapping of the horizontal extent of the fault zone will determine the location of the alcoves. The rock properties where the ramps cross the major faults are expected to have a wide range of welding and therefore the associated fracture zone will be variable. In addition, the amount of fracture and fault filling will vary with rock type. Judging from the large fault displacement seen in the Yucca Mountain area, it is also possible that testing at a major fault site may be conducted in two different stratigraphic units. Such a condition will require a great deal of input in determining the borehole configurations. This input will include results from matrix hydrologic properties testing such as discussed in Section 3.4 of this study plan.

Following completion of the testing in the first alcove, drilling of the boreholes in the second alcove will begin, if, in fact, the second alcove is constructed. The second alcove, if constructed, will be located at the fault. The alcove, if constructed, will extend from a minimum of 2 to 4 meters on both sides of the fault and will be large enough to accommodate testing and instrumentation

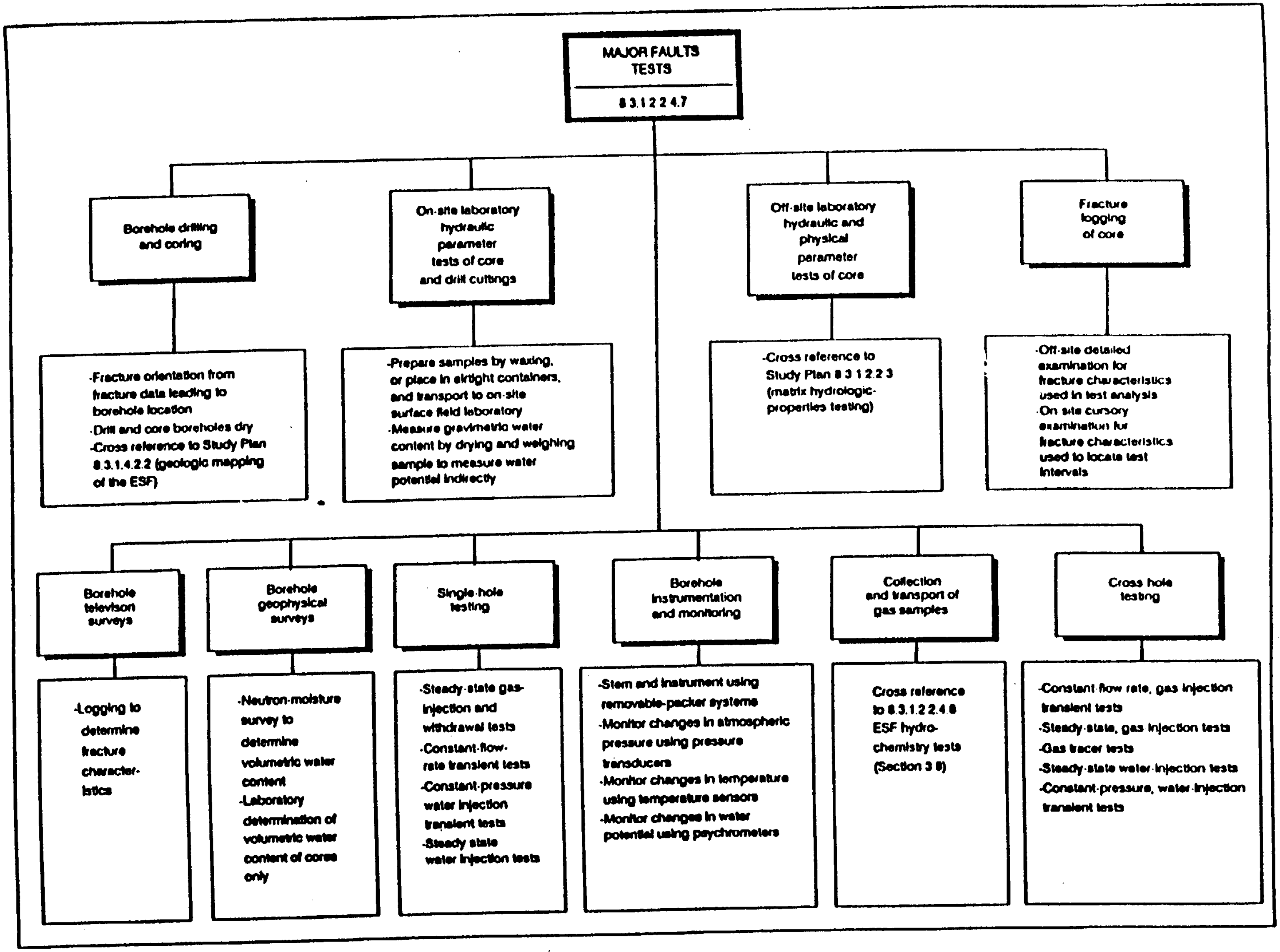
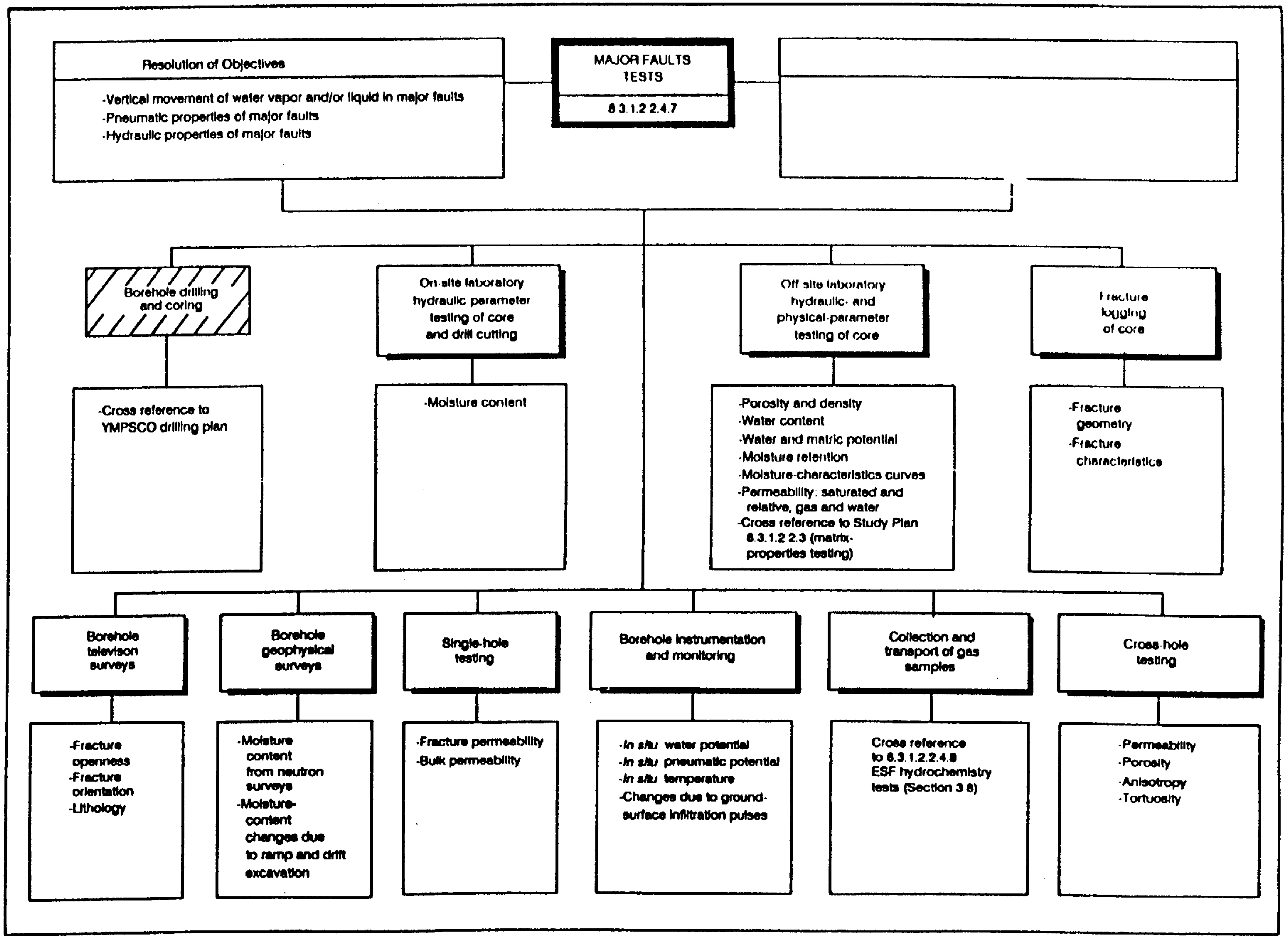


Figure 3.10-3. Organization of the major-fault testing strategy showing tests, analyses, and methods.



F ə 3.10-4. Organization of the major-fault test strategy showing tests, analyses, and site para ers. cross-hatched box indicates that no si ə para will be generated.

needs. The alcove, if constructed, will be large enough to allow drilling of two HQ3 approximately 30-meter boreholes (#5 and #6, see Figure 3.10-2), one on each side of the fault at distances of from 1 to 3 meters perpendicular to the fault. The boreholes will be drilled parallel to the fault. Following testing in boreholes #5 and #6, one additional borehole (#7) will be drilled. Borehole #7, HQ3 approximately 30 meters in length, will be drilled parallel to boreholes #5 and #6 and directly along the fault plane (see Figure 3.10-2). If the major fault is more of a fault zone and no real fault plane is identified, the second alcove, if constructed, will be located in the most intensely fractured part of the fault zone and only boreholes #5 and #6 will be required. If there is more than one major fault associated with the fault zone, the principal investigator may request additional alcoves and boreholes similar to the second alcove.

3.10.3.2 On-site laboratory hydraulic-parameter testing of core and drill cuttings

Selected core and drill-cuttings samples obtained during the drilling process will immediately be sealed in wax, or placed in air-tight canisters and transported to a field laboratory, where gravimetric-water content of selected core and cuttings will be determined. Information obtained will be used in the interpretation of gas-injection tests and will serve as baseline data for the newly drilled boreholes. This activity is described in the matrix hydrologic-properties testing activity (Activity 8.3.1.2.2.3.1.) in YMP-USGS SP 8.3.1.2.2.3 (Unsaturated-zone percolation - surface-based studies).

3.10.3.3 Off-site laboratory hydraulic- and physical-parameter testing of core

Core and cuttings samples not utilized during on-site hydrologic testing will be sent off site to laboratories for testing the following properties: volumetric water content, grain density, porosity, bulk density, water potential, matric potential, water retention, saturated water and gas permeability, and relative permeability. The information obtained from these tests will be used in the interpretation of gas injection tests and will serve as baseline data for the newly drilled boreholes. Methods used to measure these important hydrologic parameters are described in the matrix hydrologic-properties testing activity (Activity 8.3.1.2.2.3.1) in YMP-USGS SP 8.3.1.2.2.3 along with possible alternatives.

3.10.3.4 Fracture logs of core

If continuous coring is possible, a cursory examination of the core for fracture characteristics (e.g., type of fracture, depth to fracture, etc.) will be made on site during drilling. In the laboratory, a more detailed examination of the core will be made to develop detailed fracture-characteristic logs. These logs will include fracture frequency, width, coatings and fillings. Fracture data from boreholes will be used in selecting test intervals for single and cross-hole testing along with selection of the long-term monitoring zones. No alternative methods for this activity were identified, although borehole-television cameras will also be used to view fractures in situ.

3.10.3.5 Borehole television surveys

Following completion of drilling all boreholes will be logged with an oriented television camera for fracture characteristics and lithology. The survey will be used for fracture orientation and to determine whether the fractures intersecting the borehole are open or closed. The fracture data will be used to supplement ramp- and drift-wall mapping and to determine the location of test intervals and long-term monitoring zones. An alternative to borehole-television surveys is to maintain orientation of the core during drilling. This would require a special oriented-core barrel. The oriented core could be used to determine fracture orientation; however, it is often difficult to determine from core whether fractures are open or closed, and if they are drilling-induced or natural, especially at greater depths where weathering is not as prominent.

3.10.3.6 Borehole geophysical surveys

Following television logging, all boreholes will be caliper-, natural gamma-, gamma-gamma-, and neutron-logged. Neutron surveys will be conducted on a periodic basis. These data will be used to look at long-term drying or wetting trends. The neutron tool will be calibrated as described in the USGS technical procedure.

3.10.3.7 Single-hole pneumatic testing

The first borehole of Figure 3.10-2 will be used for preliminary single-hole air-injection testing. The hole will be oriented near perpendicular to the plane of the fault and will be counted as one of the three perpendicular boreholes. Constant-rate, steady-state and transient tests will be used to estimate the fault-zone permeability and fault permeability. Single hole pneumatic testing will use a borehole packer-instrumentation system or a SEAMIST borehole liner with a movable injection interval, flow meters, and pressure transducers to conduct pneumatic testing in the fault zone and in the fault. The test zones will be selected based on fracture mapping, core examination, and borehole television and geophysical testing.

The SEAMIST single-hole testing system, if utilized, consists of a borehole membrane and screened injection interval that make up an injection unit (see Figure 3.10-5). The membrane is a balloon type unit that unfolds down the borehole in an inversion installation technique. The inversion installation allows the liner to be essentially blown down the borehole thereby eliminating any need to drag or push packers into the borehole. To conduct single-hole injection tests, first the injection screen is installed at the desired test interval and then the membrane is averted down the borehole. The screened interval is on rollers and can be installed at any location. The membrane forms a seal covering the entire borehole except where the screened interval prevents the membrane from contacting the borehole. Gas injection to the injection interval is through a special injection line that connects the injection interval to the alcove yet will not interfere with the membrane. The system will allow the entire length of the borehole to be tested and is superior to packers because the membrane eliminates the potential of the injected air to short-circuit and flow back cut the borehole. Because the SEAMIST system is new technology and has had limited field testing, there is the possibility that the system might not operate as hoped. If this happens, the SEAMIST system will be replaced with a standard borehole-packer instrumentation system.

Prototype testing has determined that several gas-injection and -withdrawal methods will be utilized during the single hole testing. They include: (1) single-hole, constant-flow-rate, transient tests, and (2) single-hole, steady-state, gas-injection and -withdrawal tests.

Because the pneumatic permeability of the rock is dependent on the moisture content, it is important to evaluate the influences the air injection may have on the moisture content. Present theory on

Yucca Mountain holds that the matric potential is generally dry suchthat the fractures and/or large pores that are responsible for most permeability are dry and therefore the testing will provide good estimates of the rock permeability. As a general rule, the injection pressures will be limited to 1.0 bars and therefore will not change the permeability of any rock with a matric potential less than -1.0 bars. If the laboratory matric potentials of the core samples show matric potentials greater than 1.0 bars, testing pressures will be lowered to less than the matric potentials.

Single-hole fluid injection or withdrawal (production) field tests are commonly used to evaluate reservoir or aquifer permeability. These tests utilize only one active well and no observation wells. Rock parameters are evaluated from data (flow rates and pressure collected from a single borehole (Earlougher, 1977; Govier, 1977). The two single-hole methods listed above are briefly described below. A thorough treatise on each method can be found in the references accompanying each description.

Steady-state gas-injection and -withdrawal tests will be used to determine the permeability of individual fractures and faults (Govier, 1977). Steady-state tests consist of injecting gas into or withdrawing gas from the rock until the downhole pressure and uphole measured injection (withdrawal) flow rates remain constant. Trautz (1984) used this method to characterize fractures in unsaturated fractured tuffs. Schrauf and Evans (1984) also used this method to evaluate the relation between the gas conductivity and geometry of natural fractures in the laboratory.

The single-hole constant-rate transient test consists of injecting gas into the rock at a constant rate and at the same time monitoring the transient pressure response (i.e., change in pressure with time). Constant-production-rate transient tests are commonly used in the oil industry to evaluate gas-reservoir parameters (Earlougher, 1977). An alternative to this method, which is listed in Table 3.10-1, is a constant-pressure transient test. As the name implies, gas is injected or produced from the rock at a constant pressure while the change in gas-flow rate is monitored with time. Such a test is seldom made because it is much easier to measure pressure accurately than it is to accurately measure flow rate (Earlougher, 1977). Constant-rate tests, however, may inadvertently become constant-pressure tests, and so it is desirable to be able to analyze both types of tests.

The results of the initial single-hole tests will be compiled with the information obtained from core, video logs, borehole geophysics, and geological mapping. Estimates of fracture permeability will then be used to plan the optimal borehole configuration for subsequent borehole drilling and cross-hole tests. Although ramp excavation effects are believed to be minimized by the 20-m depth of the alcove, the effects of excavation in the vicinity of the ramp and alcove will be considered in the preliminary analyses. Methods and data that are required to compensate for these effects will be provided in the excavation effects test, as described in Section 3.5. The results of a single-hole test, as just described, can be heavily influenced by wellbore conditions, making it difficult or impossible to calculate effective porosity. In addition, it is impossible to characterize the anisotropic nature of a rock using a single-hole test. For these reasons, the data obtained from the exploratory hole will have limited usefulness in site characterization. Its purpose will be realized chiefly in providing input for scoping calculations that can be used to optimize subsequent test strategies at each testing location in the ESF.

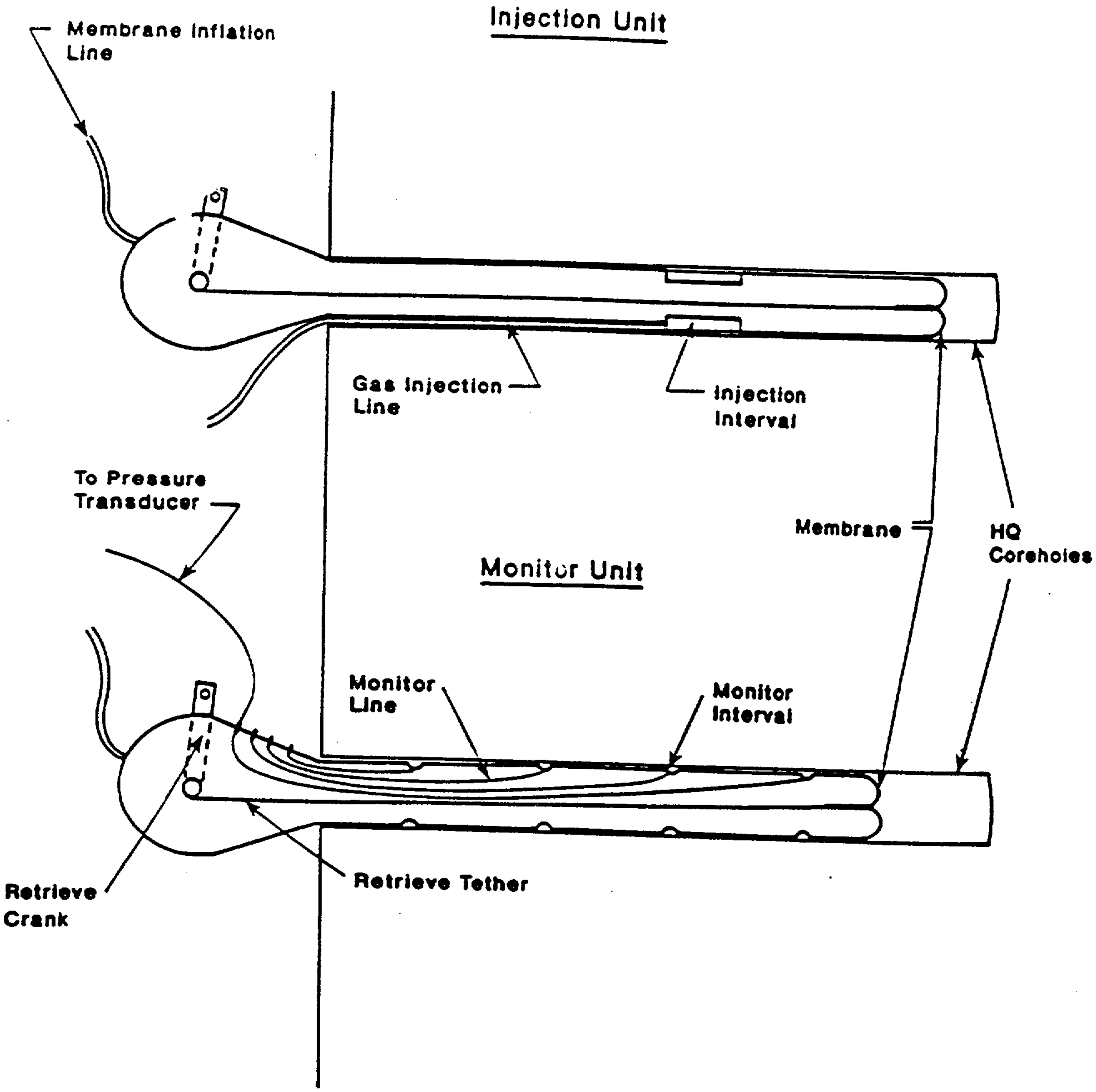


Figure 3.10-5. Schematic of SEAMIST system showing injection and monitor units.

In addition to fracture data, rock-matrix lithology and hydrologic properties will be determined for the core obtained from the initial exploratory hole. The physical properties that will be determined from core samples include matrix pore geometry, welding, grain density, bulk density, and porosity. Fracture or fault geometry data will include orientation, roughness, and, in the event of multiple faults, spacing. Mineralization along fracture or fault walls will also characterized if present. The hydrologic properties that will be determined from the core samples include moisture content (gravimetric and volumetric), water potential, matrix potential, and moisture retention.

All core will be examined on site immediately before it is sealed in wax or placed in air-tight canisters (for shipment to the surface field laboratories). Some samples will also be sent to laboratories off the site for more complicated analyses (e.g., water potential, matric potential, moisture retention, saturated water and gas permeability, and relative permeability). This work is included in the matrix hydrologic properties testing activity (Activity 8.3.1.2.2.3.1) of Study 8.3.1.2.2.3.

An additional source of information will be the planned natural gamma, gamma-gamma, neutron-moisture, and caliper geophysical logs. In all boreholes, this suite of geophysical logs will be used to aid in the location of fault zones and the determination of moisture-content distributions. Periodic temperature logs will also be made in some boreholes to help determine the thermal gradient across the fault zone.

Although a one-point sample taken from a single borehole is an inadequate representation of a large planar structure, some information obtained from the matrix-properties and geophysical-log testing will be immediately useful in assessing the hydrologic significance of a fault or fault disturbed zone under consideration. Such an assessment would be used only in guiding decisions pertaining to the scheduling and implementation of subsequent testing activities and not for actual site characterization. For example, a moisture-content profile obtained from the core may provide information on the recent history, if any, of moisture flow through the specified fault. Structures, such as fracture coatings, which provide immediate evidence of significant moisture flow (especially if it is determined to be recent) will be given a relatively higher priority in the ESF test scheduling. Water flow, if present, will be measured using the techniques described in the perched water test (Section 3.7).

3.10.3.8 Cross-hole pneumatic, hydraulic and tracer testing

Following the single-hole testing and preliminary data evaluation, the location and drilling of the second and third boreholes will be completed. Following completion of the drilling, the second and third boreholes will be single-hole tested. All previously given drilling and single-hole testing requirements apply to the second and third boreholes.

Once the boreholes have been cored, fracture mapped (with video camera), and logged with the suite of geophysical probes, preparations will begin for cross-hole pneumatic (air or nitrogen) testing. Cross-hole testing will be conducted between each of the boreholes. The cross-hole testing will use the single-hole equipment plus an additional two SEAMIST borehole monitor units. The SEAMIST monitor units consist of a borehole membrane with up to 15 monitor intervals (see Figure 3.10-5). The membrane operates the same as the injection interval membrane but differs in that the membrane has up to 15 monitor screens that are permanently installed in the membrane. The monitor screens are connected to the alcove by small diameter tubing. These monitor screens allow the pressure response at the monitor interval to be monitored in the alcove by connecting a pressure transducer to the tube. The tube can also be used to withdraw gas samples from the monitor intervals. Once the monitor unit is installed in a borehole, the borehole changes from a single line source to 15 point sources. As with the injection unit, if the SEAMIST monitor unit does not operate as needed, the system will be replaced with an inflatable packers system. The single-hole-testing SEAMIST injection unit will then be used to conduct cross-hole testing between injection and monitoring intervals on the same side of the fault, in the fault, and on opposite sides of the fault. (See Sections 3.4 and 3.10.3.1 through 3.10.3.7 of this study plan.)

The exact spacing and orientation of the holes will be determined from analysis of data obtained from fracture mapping, borehole television and geophysical logging, and the results of pneumatic tests from the single-hole testing. The boreholes will be oriented to maximize the number of fracture intersections. The boreholes will be spaced in order to maximize the distance between the boreholes while still allowing a pressure transient response between boreholes in a reasonable period of time. It is anticipated, however, that an expected minimum spacing of 5 m between the holes will be required.

Cross-hole pneumatic and hydraulic field tests, commonly referred to as "interference tests" in the petroleum industry, are used to evaluate reservoir permeability and storativity, determine the location of structural features such as faults, no-flow and recharge boundaries, and evaluate homogeneous versus anisotropic conditions in reservoirs (Earlougher, 1977) and fractured aquifers (Hsieh and Neuman, 1985; and Hsieh and others, 1985). Cross-hole testing is a descriptive phrase used to describe a multiple-well test. Multiple-well tests require at least one active (producing or injecting) well and at least one observation well; however, only one active well will be utilized at any given location and time during this study. Gas will be injected or produced from an isolated test interval in one of the boreholes, and the response of the formation to the change in fluid pressure will be monitored in numerous nearby observation intervals located in other boreholes. The test results, namely active- and observation-well fluid pressures, and injection or production-flow rates, will be used to calculate reservoir or aquifer parameters. Analysis of the test results is dependent upon flow-domain boundary conditions, the type of fluid injected into the formation, the saturation state of the formation, and the type of test conducted (e.g., steady-state or transient).

The methods described with regard to single-hole tests apply equally to cross-hole testing. The greatest difference between the two test configurations is the quality of results that can be determined from the test data. Single-hole test results can be heavily influenced by wellbore conditions (i.e., skin effects caused by wellbore damage or improvement), making it difficult or impossible to calculate reservoir parameters. In addition, it is impossible to characterize the anisotropic nature of a reservoir using a single-hole test. The cross-hole tests provide a convenient test configuration for estimating the permeability anisotropy of the fault and fault zone. Types of cross-hole tests to be conducted include (1) constant-rate transient gas-injection and recovery tests, and (2) steady-state gas injection and withdrawal. A possible alternative to these methods could be constant-pressure gas-injection tests.

Following pneumatic testing, cross-hole tracer testing will be conducted. Tracer travel times between selected intervals can be compared to velocities calculated from conductivities and porosities and used to estimate tortuosity. Tracer testing will be conducted in cooperation and under guidelines of the geochemistry staff, using methods described in Section 3.8.

Following pneumatic and tracer testing, several test sites will be selected for hydraulic testing. Faults that were tested at more than one location should have one test site selected for hydraulic testing. Pneumatic and hydraulic test results will differ due to gravity, air entrapment, Klinkenberg effect, and other possible influences. However, an opportunity to compare pneumatic and hydraulic test results is important in the site characterization program. If reliable techniques can be derived for estimating permeability (and hydraulic conductivity) from air- and water-injection test data at the field scale (that scale which corresponds to the zone which is evaluated in the air- or water-phase testing), then pneumatic testing results may be more efficient and provide a more comprehensive assessment of the permeability of the formations containing faults or fault zones than an estimate provided by laboratory experiments. It will be necessary to perform cross-hole pneumatic tests followed by hydraulic tests at select locations in order to determine the usefulness of effective air permeability in calculating hydraulic conductivity. A full discussion of the use of multiple testing approaches for estimating hydraulic conductivity is included in Section 2.1.2 of this study plan.

Obviously, sites chosen for a comparative analysis of hydraulic and pneumatic testing should be representative of other fault-testing locations in both welded and nonwelded units. However, they should also be situated away from areas where water might interfere with other test activities. The selected hydraulic test sites should provide the confidence needed for correlating pneumatic and hydraulic parameters.

Hydraulic testing will also allow for long-term monitoring following water injection. Because some of the hydraulic test sites have alternate sites where no water will be injected, this will allow long-term monitoring of the same fault following air versus water injection.

3.10.4 Long-term instrumentation and monitoring of boreholes

A final phase of testing major faults or fault zones consists of instrumenting and monitoring for long-term observation of *in-situ* hydrologic properties. The long-term monitoring will last from 5 to 7 years. Packers will be used to isolate selected monitoring intervals in the fault and fault zone. Monitoring will be done in at least one borehole at all major-fault test sites and one borehole will be left for future logging and possible testing. Monitoring will include pressure transducers for pneumatic pressure, thermistors for temperature, and thermocouple psychrometers for relative humidity. Prototype testing by the USGS has shown that thermocouple psychrometers can be calibrated with salt solutions to a sensitivity of 0.05 bars and accuracy of 0.7 bars over a range of -1 to -75 bars. Prototype thermistor testing has developed thermistors with sensitivity of 0.001 C°, and accuracies of 0.005 C° over a range of 10 to 50 C°. Prototype pressure transducer testing and development has resulted in units with sensitivities of 10.0 Pascals, and accuracies of 20.0 Pascals over a range of 0.5 to 1.5 atms.

Long-term monitoring in selected boreholes will monitor changes in pressure, temperature and relative humidity in the faults and may allow detection of any water pulses that might percolate through the unsaturated zone. This type of information will be especially valuable if one or more of the major-fault test sites is also a geohydrologic unit-contact site. This will provide an opportunity to investigate the hydraulic continuity of the major vertical structures passing through the geohydrologic unit contacts.

The long-term monitoring just described is based on the premise that during infiltration events, percolation of water will disturb the *in situ* matrix potential and temperature.

3.10.5 Methods summary

The parameters to be determined by the tests and analyses described in the above sections are summarized in Table 3.10-1. Also listed are the selected and alternate methods for determining the parameters and the current estimate of the parameter-value range. The alternate methods will be utilized only if the primary (selected) method is impractical to measure the parameter(s) of interest. In some cases, there are many approaches to conducting the test. In those cases, only the most common methods are included in the tables. The selected methods were chosen wholly or in part on the basis of accuracy, precision, duration of methods, expected range, and interference with other tests and analyses.

The USGS investigators have selected methods which they believe are suitable to provide accurate data within the expected range of the site parameter. The test results will be used to develop models and analytical techniques that describe the site flow system. The expected ranges of the site parameter have been bracketed by previous data collection and computer modeling and are shown in Table 3.10-1.

3.10.6 Quality assurance

The USGS quality-assurance program plan for the YMP (USGS, 1989) requires documentation of technical procedures for all technical activities that require quality assurance.

Equipment requirements and instrument calibration are described in the technical procedures. Lists of equipment and procedures for the use and calibration of equipment, limits, accuracy, handling, and calibration needs, quantitative or qualitative acceptance criteria of results, description of data documentation, identification, treatment and control of samples, and records requirements are included in these documents.

Table 3.10-1. Summary of tests and methods for the major-fault activities (SCP 8.3.1.2.2.4.10) in the Exploratory Studies Facility.

Methods (selected and alternate)	Site-characterization parameter
On-site laboratory hydraulic parameter testing of core and drill cuttings	
Measure gravimetric water content by drying and weighing sample **(selected)**	Water content, gravimetric, rock matrix
Off-site laboratory hydraulic- and physical-parameter testing of core	
Matrix hydrologic properties testing **(selected)**	Bulk density, rock matrix
•	Grain density, rock matrix
•	Moisture retention, rock matrix
•	Permeability, relative, gas, rock matrix
•	Permeability, relative, water, rock matrix
Matrix hydrologic properties testing **(selected)**	Permeability, saturated, gas, rock matrix
•	Pneumatic permeability, bulk, fractured rock
•	Porosity pore-size distribution, matrix
•	Porosity, bulk, fractured rock
•	Water potential, rock matrix, and total fractured rock
Fracture logging of core	
Off-site detailed examination for fracture characteristics used in test analysis **(selected)**	Fracture characteristics: distribution, aperture, alteration
On-site cursory examination for fracture characteristics used to locate test intervals **(selected)**	Fault characteristics: width, coatings
Borehole television surveys	
Television logging to determine fracture characteristics	Fracture characteristics: distribution, aperture, alteration
•	Fault characteristics: width, orientation, coatings

Table 3.10-1. Summary of tests and methods for the major-fault activities (SCP 8.3.1.2.2.4.10) in the Exploratory Studies Facility. (continued)

Methods (selected and alternate)	Site-characterization parameter
On-site laboratory hydraulic parameter testing of core and drill cuttings	
Borehole geophysical surveys	
Neutron-moisture survey to determine volumetric water content (selected)	Water content, volumetric, rock matrix
Laboratory determination of volumetric water component of cores only (selected)	•
In-site pneumatic testing	
Single-hole and multihole, steady-state, gas-injection and -withdrawal tests (selected)	Permeability, pneumatic
•	Anisotropy
•	Fault aperture
Single-hole and multihole, gas-injection, constant-flow-rate, transient tests (selected)	Permeability, pneumatic
•	Anisotropy
•	Porosity
•	Fault permeability
Single-hole and multihole, gas injection, constant-pressure, transient tests (alternate)	Permeability, pneumatic
•	Anisotropy
•	Porosity
•	Fault permeability
Gas tracer testing	Tortuosity

Table 3.10-1. Summary of tests and methods for the major-fault activities (SCP 8.3.1.2.2.4.10) in the Exploratory Studies Facility. (continued)

Methods (selected and alternate)	Site-characterization parameter
On-site laboratory hydraulic parameter testing of core and drill cuttings	
Borehole instrumentation and monitoring	
Monitor pressure changes within test intervals using pressure transducers (selected)	Pneumatic-potential distribution and fluctuation
Monitor changes in chemical composition of rock-unit gases (selected)	Diffusive tortuosity, fractured rock and rock mass
"	Gaseous diffusion coefficient, fractured rock units
Monitor changes in temperature within borehole using temperature sensors (selected)	Temperature, distribution and fluctuations
Monitor changes in water potential within boreholes using psychrometers (selected)	Water potential, distribution and fluctuation
Collection and transport of gas samples	
Cross reference to 8.3.1.2.2.4.8 ESF hydrochemistry tests (selected)	Pore gas composition
"	Radioactive isotopes
"	Stable isotopes
Cross-hole hydraulic testing	
Cross-hole, steady-state, water-injection tests across geohydrologic-unit contacts (selected)	Permeability, water
Cross-hole, constant-rate, water-injection, transient tests across geohydrologic-unit contacts (selected)	"
Cross-hole, constant-pressure, water-injection, transient tests across geohydrologic-unit contacts (alternate)	"

4 APPLICATION OF STUDY RESULTS

4.1 Application of results to resolution of design and performance issues

The results of this study will be used in the resolution of YMP performance and design issues concerned with fluid flow (both liquid and gas) within the unsaturated zone beneath Yucca Mountain. The principal applications will be in assessments of ground-water and gas travel times (Issues 1.1 and 1.6), and design analyses related to the underground-repository facilities (Issues 1.10, 1.11, and 4.4). Issues concerned with the waste-package containment and engineered-barrier system releases (Issue 1.4 and 1.5) and repository seals (Issue 1.12) will also use the hydrologic information resulting from this study.

The application of site information from this study to design- and performance-parameter needs required for the resolution of design and performance issues is addressed in Section 1.2. Logic diagram (Figure 2.1-1) and Table 2.1-1 are used to summarize specific relations between performance- and design-parameter needs and activity parameters determined from this study.

4.2 Application of results to support other site-characterization investigations and studies

Data collected in this study will be employed in other studies in Investigation 8.3.1.2.2 (Description of the unsaturated-zone hydrologic system at the site), as well as in studies concerning the following investigations:

8.3.1.3.1 - Studies to provide the information on water chemistry within the potential emplacement horizon and along potential flow paths;

8.3.1.3.8 - Studies to provide the required information on retardation of gaseous radionuclides along flow paths to the accessible environment;

8.3.1.4.2 - Geologic framework of the Yucca Mountain site;

8.3.1.15.2 - Studies to provide the required information for spatial distribution of ambient stress and thermal conditions; and

8.3.1.16.3 - Ground-water conditions within and above the potential host rock.

In Investigation 8.3.1.2.2, of which Study 8.3.1.2.2.4 is a component, several other studies will employ data generated in this study.

Study 8.3.1.2.2.6 (Characteristics of gaseous-phase movement in the unsaturated zone) will employ gaseous-phase movement data generated in Activity 8.3.1.2.2.4.4 (Radial-borehole tests) in the description of the pre-waste-emplacement gas-flow field at Yucca Mountain, identifying structural controls on fluid flow, determining the conductive properties of the unsaturated zone for gas flow, and modeling the transport of water and tracers in the gas phase. Among the data contributed would be unsaturated-zone fluid-transmissive properties, fluid potential, fluid flux, and fracture geometry and characteristics.

Study 8.3.1.2.2.7 (Hydrochemical characterization of the unsaturated zone) will employ gas- and water-analysis data for radioactive isotopes, stable-isotope ratios, pore-gas composition, and cation/anion concentrations generated in Activity 8.3.1.2.2.4.8 (Hydrochemistry tests in the ESF). The data will be used both in gas-phase chemical investigations (gas-transport mechanism, flow direction, flux, and travel time) and aqueous-phase chemical investigations (ground-water flow direction, flux, travel time, and water-rock interaction). Data on unsaturated-zone ground-water compositions resulting from the hydrochemistry tests (Activity 8.3.1.2.2.4.8) will also be used to support assumptions about ground-water compositions in the laboratory sorption tests (Investigation 8.3.1.3.4). The water composition used in sorption testing must be compared to that determined by the hydrochemistry activity to assure that the laboratory-sorption data are valid.

Study 8.3.1.2.2.8 (Fluid flow in unsaturated, fractured rock) will receive important information from Study 8.3.1.2.2.4 in order to select, develop, verify, and validate numerical codes for modeling fluid flow in the unsaturated zone. Virtually all data on unsaturated-zone hydrologic processes collected in the four activities described in this study plan will be used as input to the fracture-flow modeling in the unsaturated zone.

In Study 8.3.1.2.2.9 (Site unsaturated-zone modeling, and synthesis), the unsaturated-zone hydraulic properties listed above and derived in part from Study 8.3.1.2.2.4 will be employed in the development of an evolving conceptual model of their spatial distribution, the selection, development, and testing of hydrologic-modeling computer codes, simulation of the natural hydrogeologic system, and stochastic modeling and uncertainty analysis.

In Investigation 8.3.1.3.1, Study 8.3.1.3.1.1 (Ground-water chemistry model) will employ water-analysis data for radioactive isotopes, stable-isotope ratios, and cation/anion concentrations measured in Activity 8.3.1.2.2.4.8 (Hydrochemistry tests in the ESF) as data for the unsaturated-zone ground-water composition model.

In Investigation 8.3.1.3.8, Study 8.3.1.3.8.1 (Gaseous radionuclide transport calculations and measurements) will employ the same gaseous-flow analysis data from Activity 8.3.1.2.2.4.8 as data required for water chemistry. The study will also employ analyses of gas samples from this activity for radioactive isotopes, stable-isotope ratios, and pore-gas composition as data required for identification of gaseous radionuclide species and gas-phase composition. From Activity 8.3.1.2.2.4.4 (Radial-borehole tests), the above study will employ data on unsaturated-zone transmissive properties, fluid potential and temperature, and fluid flux, as well as fracture geometry and properties as required data for determining flow paths for gaseous transport.

In Investigation 8.3.1.4.2, both the component stratigraphic and structural studies will employ geologic information generated in the ESF percolation study. Study 8.3.1.4.2.1 (Characterization of the vertical and lateral distribution of stratigraphic units within the site area) will be the principal means of investigating the stratigraphy of the site and will receive some lithostratigraphic data from Study 8.3.1.2.2.4. Among these data will be rock-unit contact locations and configurations and rock-unit vertical and lateral variability from Activity 8.3.1.2.2.4.4, Radial-borehole tests. Study 8.3.1.4.2.2 (Characterization of structural features within the site area) will employ data on fracture geometry and characteristics collected in Activities 8.3.1.2.2.4.4 (Radial-borehole tests) and 8.3.1.2.2.4.5 (Excavation-effects test).

Investigation 8.3.1.15.2 (Spatial distribution of ambient stress and thermal conditions) will employ data generated in Activity 8.3.1.2.2.4.5 (Excavation-effects test) on *in-situ* stress magnitude and orientation and fracture deformation.

In Investigation 8.3.1.16.3, Study 8.3.1.16.3.1 (Determination of the preclosure hydrologic conditions of the unsaturated zone at Yucca Mountain, Nevada) will compile and synthesize data collected in Study 8.3.1.2.2.4 for use in addressing preclosure repository design requirements, design analyses, and underground-facilities technology.

5 SCHEDULES AND MILESTONES

5.1 Schedules

The proposed schedules presented in Figures 5.1-1, 5,1-2, 5.1-3, and 5.1-4 summarize the logic network and reports for the four activities of the ESF construction-phase hydrologic testing included in this study plan. These figures represent a summary of the schedule information which includes the sequencing, interrelations, and relative durations of these activities. Specific durations and start and finish dates for these activities are being developed as part of ongoing planning efforts. The development of the schedule for the present study has taken into account how the study will be affected by contributions of data or interferences from other studies, and also how the present study will contribute or may interfere with other studies.

Accurate characterization of unsaturated-zone percolation will require several years of hydrologic testing and monitoring.

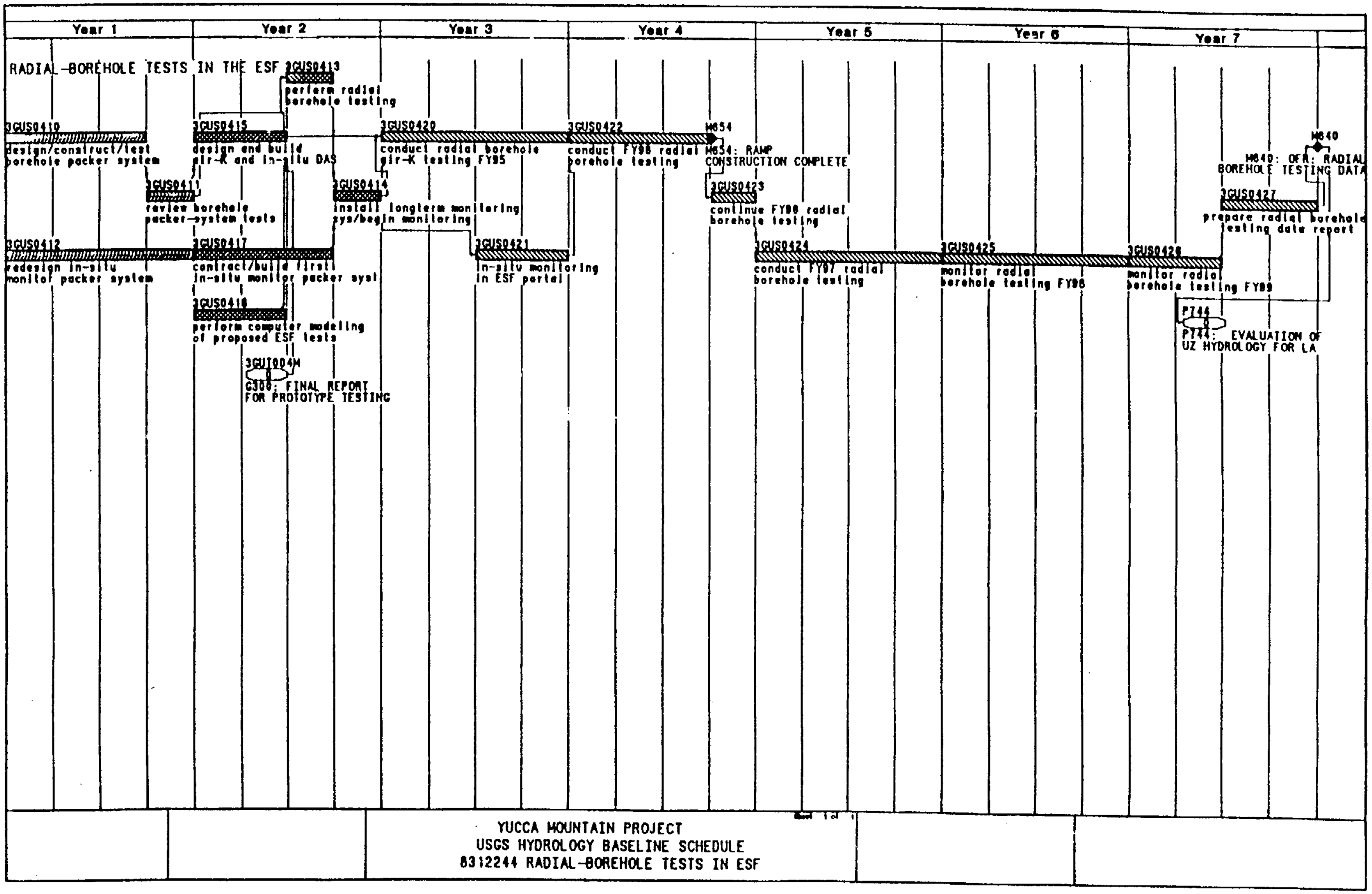


Figure 5.1-1. Summary network for the radial-borehole activity.

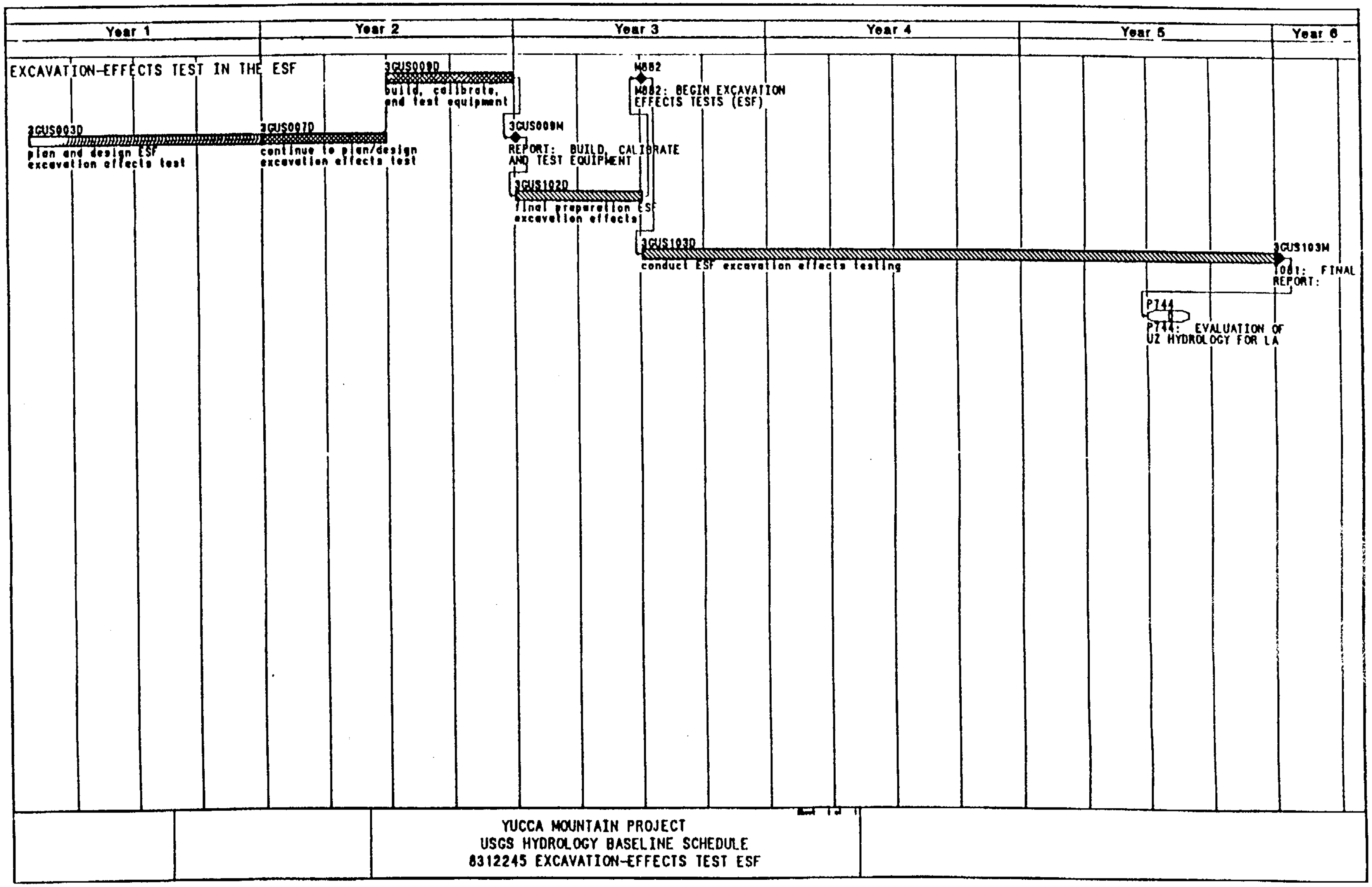


Figure 5.1-2. Summary network for the excavation-effects activity.

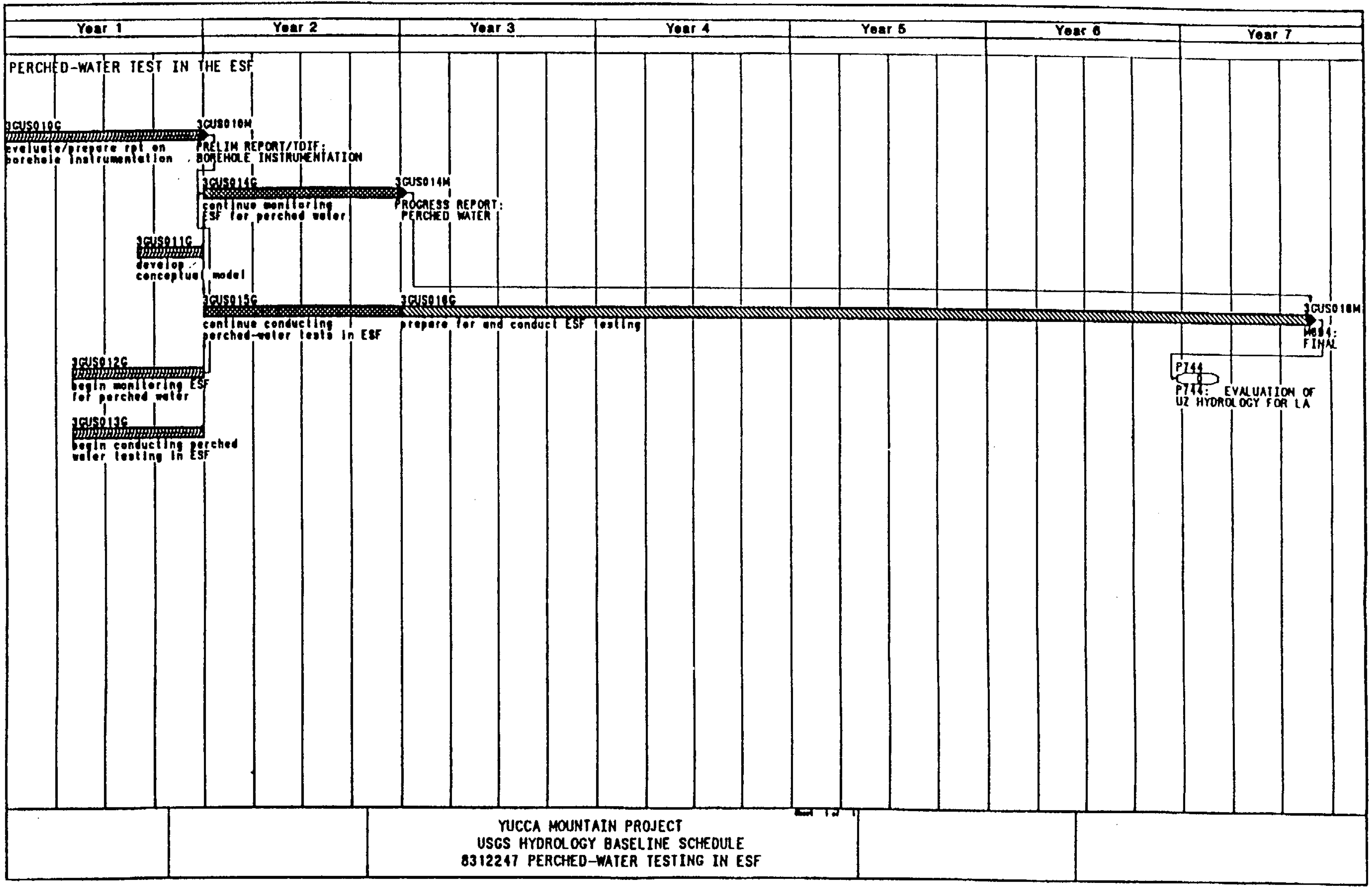


Figure 5.1.-3. Summary network for the perched-water activity.

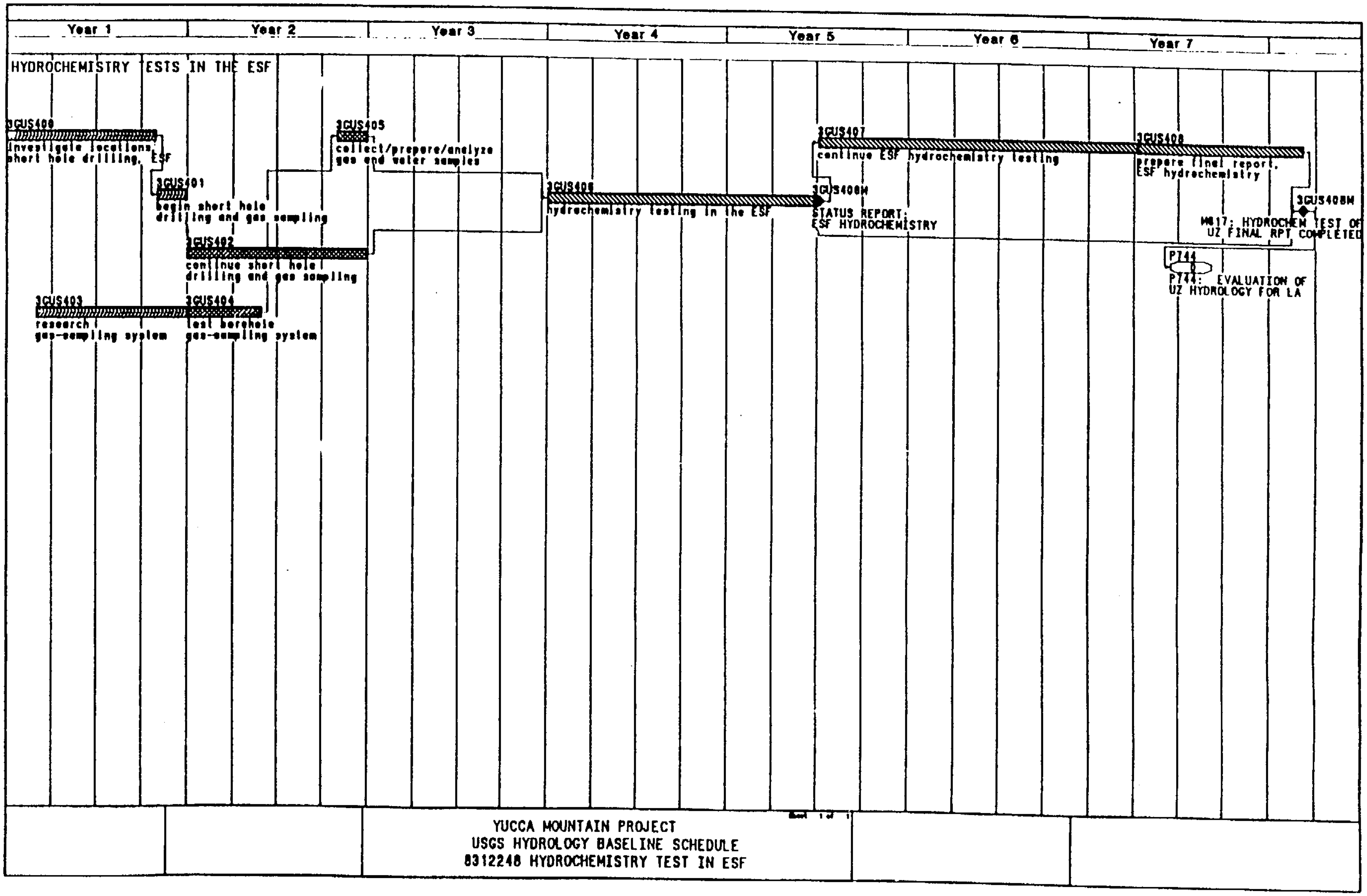


Figure 5.1-4. Summary network for the hydrochemistry activity.

5.2 Milestones

The milestone numbers, titles, levels, and corresponding work-breakdown- structure (WBS) number associated with the four activities of the ESF construction-phase hydrologic testing are summarized in Table 5.2-1.

The information presented in Table 5.2-1 represents major events or important summary milestones associated with the activities presented in this study plan as shown in Figures 5.1-1, 5.1-2, 5.1-3, and 5.1-4. Specific dates for the milestones are not included in the tables, as these dates are subject to change due to ongoing planning efforts.

Table 5.2-1. Milestone list for Study 8.3.1.2.2.4
(WBS number 1.2.3.3.1.2.4)

Milestone Number	Milestone	Milestone Level
	Radial-borehole tests in the ESF: 8.3.1.2.2.4.4	
M640	OFR: radial borehole testing data	3
M654	Ramp construction complete	3
	Excavation-effects testing: 8.3.1.2.2.4.5	
M882	Begin excavation effects tests (ESF)	3
3GUS009M	Report: build, calibrate and test equipment	3
3GUS103M	T081: Final report: excavation effects testing	3
	Perched-water testing: 8.3.1.2.2.4.7	
3GU5016M	M694: Final report: perched-water results	3
3GUS014M	Progress report: perched-water	3
3GUS01M	Preliminary report/TDIF: borehole instrumentation	3
	Hydrochemistry tests in the ESF: 8.3.1.2.2.4.8	
3GUS406M	Status report: ESF hydrochemistry	3
3GUS408M	M617: Hydrochemistry test of UZ final report completed	3

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