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U.S. DEPARTMENT OF ENERGY

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YUCCA MOUNTAIN

YUCCA MOUNTAIN SITE CHARACTERIZATION PROJECT

FLUID FLOW IN UNSATURATED, FRACTURED ROCK

8.3.1.2.2.8

REVISION 0

PREPARED BY

U. S. GEOLOGICAL SURVEY

DEPARTMENT OF ENERGY · UNITED STATES OF AMERICA

NOVEMBER 26, 1991

YUCCA MOUNTAIN PROJECT

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Revision Number 0

Prepared by: U. S. Geological Survey

Date: 11/26/91

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RECORD OF REVISIONS

REVISION NUMBER	REVISION	DATE
RO	Study rationale and plans for two activities: Development of conceptual and numerical models of fluid flow in unsaturated, fractured rock (Section 3.1) Validation of conceptual and numerical models of fluid flow in unsaturated, fractured rock (Section 3.2)	11-25-91

ABSTRACT

This study plan describes the plans for two site-characterization activities whose objectives are to develop, refine, and validate conceptual and numerical models describing gas flow as well as liquid water and solute movement in unsaturated, fractured rock at the proposed Yucca Mountain high-level radioactive waste repository site. The primary function of these models will be to help design and interpret hydrologic and pneumatic tests, and to provide information about model parameters that can be incorporated into site-scale models which are being studied under Study 8.3.1.2.2.9 (Site unsaturated-zone modeling and synthesis). The activities include:

- o Development of conceptual and numerical models of fluid flow in unsaturated, fractured rock, and

- o Validation of conceptual and numerical models of fluid flow through unsaturated, fractured rock.

The rationale for the fluid flow in unsaturated, fractured rock study is described in Sections 1.3 (regulatory rationale) and 2 (technical rationale). Section 3 describes the specific plans for the two activities, including proposed methods for design, refinement, and application of models.. Section 4 summarizes the application of study results to other site-characterization investigations. Section 5 consists of the study schedule and milestones, Section 6 is a list of study references, and Section 7.1 covers quality assurance requirements.

FLUID FLOW IN UNSATURATED, FRACTURED ROCK

YMP - USGS - SP 8.3.1.2.2.8, RO

STUDY PLAN

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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 hydrologic, geologic, and geochemical information to evaluate the suitability of Yucca Mountain for development as a high-level nuclear-waste repository, and the ability of the proposed mined geologic-disposal system (MGDS) to isolate the waste in compliance with regulatory requirements. In particular, the project is designed for the Department of Energy (DOE) to evaluate whether the MGDS will meet the requirements of Federal Regulations 10 CFR Part 60, 10 CFR Part 960, and 40 CFR Part 191, and, if so, to demonstrate this finding in its environmental-impact statement and license application.

This study plan describes the USGS plans for development and validation of numerical and conceptual models for fluid flow in unsaturated, fractured rock. The study is organized into two activities:

- 8.3.1.2.2.8.1 - Development of conceptual and numerical models of fluid flow in unsaturated, fractured rock; and
- 8.3.1.2.2.8.2 - Validation of conceptual and numerical models of fluid flow through unsaturated, fractured rock.

Note that the numbers (e.g., 8.3.1.2.2.8.1) used throughout this plan serve as references to specific sections of the YMP Site Characterization Plan (SCP). The SCP (U.S. Department of Energy, 1988) 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 this study within the SCP Geohydrology Program. The fluid flow in unsaturated, fractured rock study (Study 8.3.1.2.2.8) is one of nine studies planned to characterize the unsaturated zone at Yucca Mountain. Five of these studies, including unsaturated zone infiltration (Study 8.3.1.2.2.1), water-movement tracer tests (Study 8.3.1.2.2.2), unsaturated-zone percolation surface-based study (Study 8.3.1.2.2.3), unsaturated-zone gaseous-phase movement (Study 8.3.1.2.2.6), and unsaturated-zone hydrochemical characterization (Study 8.3.1.2.2.7), are surface-based evaluations. Two studies, the unsaturated-zone percolation ESF (exploratory studies facility) study (Study 8.3.1.2.2.4) and diffusion tests in the ESF (Study 8.3.1.2.2.5), will evaluate *in situ* hydrologic characteristics of

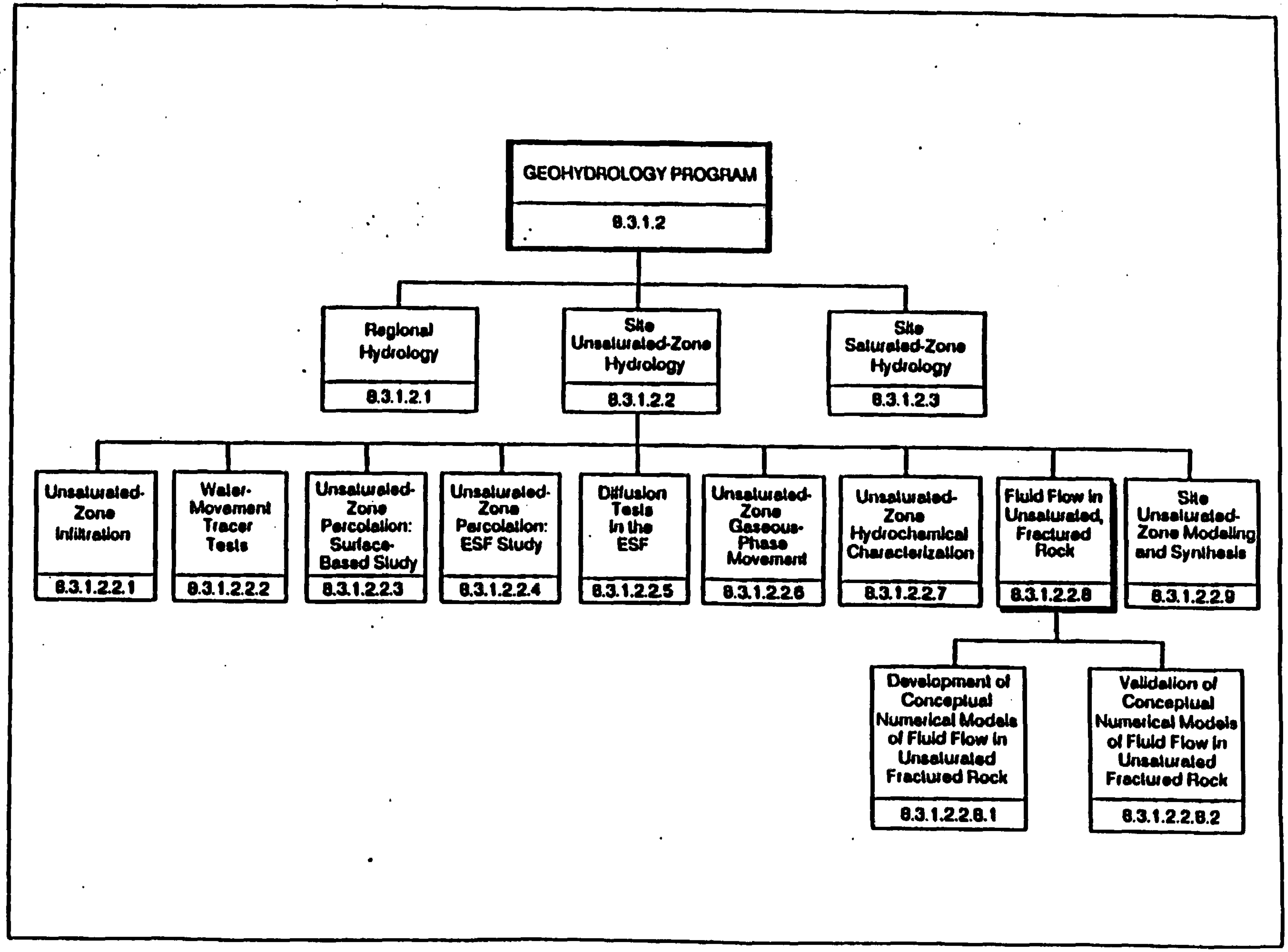

Figure 1.1-1. Diagram showing the location of study within the unsaturated-zone investigation and organization of the Geohydrology Program.

Yucca Mountain from shafts and underground drifts associated with the exploratory studies facility (ESF). The final study planned under the unsaturated-zone hydrology program is site unsaturated-zone modeling and synthesis (Study 8.3.1.2.2.9).

The two activities within this study, development of conceptual and numerical models of fluid flow in unsaturated, fractured rock (Activity 8.3.1.2.2.8.1), and validation of conceptual and numerical models of fluid flow in unsaturated, fractured rock (Activity 8.3.1.2.2.8.2), will be used to test hydrologic hypotheses against the results of experimentation at the laboratory and field scales.

Time requirements to conduct tests and overall schedule constraints are also considered in development of the activities.

The plans for development and validation of conceptual and numerical models for unsaturated, fractured rock are presented in Sections 3.1 and 3.2, respectively. The descriptions include (a) objectives, (b) technical rationale, and (c) tests and analyses.

Application of the study results is discussed in Sections 1.3 and 4. Study and activity schedules and milestones are presented in Section 5. A study plan reference list is presented in Section 6. Quality assurance requirements are documented in Section 7.1.

1.2 Objectives of study

The modeling of fluid flow in unsaturated, fractured rock will help to design and interpret hydrologic and pneumatic tests and provide information about hydrologic properties and processes that can be incorporated into site-scale models (see SCP Study 8.3.1.2.2.9, Site unsaturated-zone modeling and synthesis).

The objectives of the study are to develop and to refine conceptual and numerical models describing fluid flow and transport in variably saturated, fractured rock. The primary application of these models will be on laboratory and field-testing scales.

The objectives of individual activities in the fluid flow in unsaturated, fractured rock study are:

8.3.1.2.2.8.1 - Develop detailed conceptual and numerical models of fluid flow and transport within unsaturated, fractured rock at Yucca Mountain; and

8.3.1.2.2.8.2 - Evaluate the reasonableness of the concepts on which the models developed under Activity 8.3.1.2.2.8.1 are based, by using the results of laboratory tests and tests performed in the exploratory studies facility (ESF) to assess the adequacy of model performance.

1.3 Regulatory rationale and justification

The results of the fluid flow through unsaturated, fractured rock modeling study will be used to characterize fluid flow processes and thereby support studies concerned with flow-path characterization and determination of ground-water fluxes and travel times within the unsaturated zone. Information derived from the study principally will support, by contributing to Study 8.3.1.2.2.9 (Unsaturated-zone modeling and synthesis), the performance determinations of pre-waste-emplacement, ground-water travel time (Performance Issue 1.6) and the predictions of radionuclide releases to the accessible environment (Performance Issue 1.1). Other issues which benefit indirectly from this study are waste-package containment (Performance Issue 1.4), waste-package and repository engineered barrier performance (Performance Issue 1.5), characterizing the near-field environment of the waste package (Design Issue 1.10), design of repository seals (Design Issue 1.12), and Nuclear Regulatory Commission (NRC) siting criteria (Performance Issue 1.8).

The overall regulatory-technical relations between the SCP performance-assessment needs and the results of this study are described in the geohydrology testing strategy presented in SCP Section 8.3.1.2 and the issue-resolution strategies for performance assessment presented in SCP Sections 8.3.2 through 8.3.5.

The present study indirectly contributes to the resolution of performance and design issues by developing and validating conceptual and numerical descriptions (models) of fluid- and solute-transport processes, descriptions that will serve as a basis for the site-scale unsaturated-zone modeling and synthesis efforts of Study 8.3.1.2.2.9 (described in YMP-USGS SP 8.3.1.2.2.9, Site unsaturated-zone modeling and synthesis).

The model development and validation of the present study plan are designed to support Study 8.3.1.2.2.9 by focusing on seven technical issues, which are explained later in this study plan in Sections 3.1.2, 3.1.4, and 3.1.7. Briefly stated, the technical issues are: 1) the conditions for fluid flow in unsaturated, fractured rock; 2) the nature and role of channeling processes with respect to water and radionuclide transport; 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; 6) spatial heterogeneity in fractured-rock permeability; and 7) the role of hydrologic discontinuities in diverting water laterally.

To address these technical issues, the investigators in the present study will examine existing hypotheses and generate alternative hypotheses to explain the behavior of fluids in unsaturated, fractured rock. Concurrently they will develop and apply both analytical methods and numerical approaches that will be used to plan and interpret hydrologic experiments with the objective of testing the hypotheses. The formulation and testing of hypotheses will proceed iteratively. Hydrologic and geologic data upon which hypotheses will be based, as well as the hydrologic experiments for hypothesis-testing, will originate from other site-characterization studies (identified in Section 3.1).

Project-organization interfaces between the fluid flow through unsaturated, fractured rock study (8.3.1.2.2.8) and YMP performance and design issues are illustrated in Figure 1.3-1. The figure also indicates project interfaces with other site-characterization programs. 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.

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 Section 8.3.5.

Performance Issue 1.6
(Pre-waste-emplacement ground-water travel time)

Requirements for resolution of this issue include refinement and validation of conceptual and numerical models of fluid flow through the unsaturated zone at Yucca Mountain. The activities outlined in this study will provide a conceptual and numerical model basis for the site unsaturated-zone modeling and synthesis study (Study 8.3.1.2.2.9), whose objectives include integration of data and analyses to synthesize a comprehensive qualitative and quantitative description of the site unsaturated-zone hydrologic system.

One of the NRC performance objectives for a high-level waste repository is that the location of the geologic repository should be such that the pre-waste-emplacement ground-water travel time to the accessible environment should be at least 1,000 years at a high level of confidence. SCP Table 8.3.5.12-2 lists required performance parameters, along with performance-parameter goals and the desired confidence level for each goal. The identified parameters of concern are effective porosity (n_e), flux (q), the ratio of percolation flux to saturated hydraulic conductivity (q/K_s), and the distance along the flow path (d). These parameters need to be ascertained for all hydrogeologic units identified in the table.

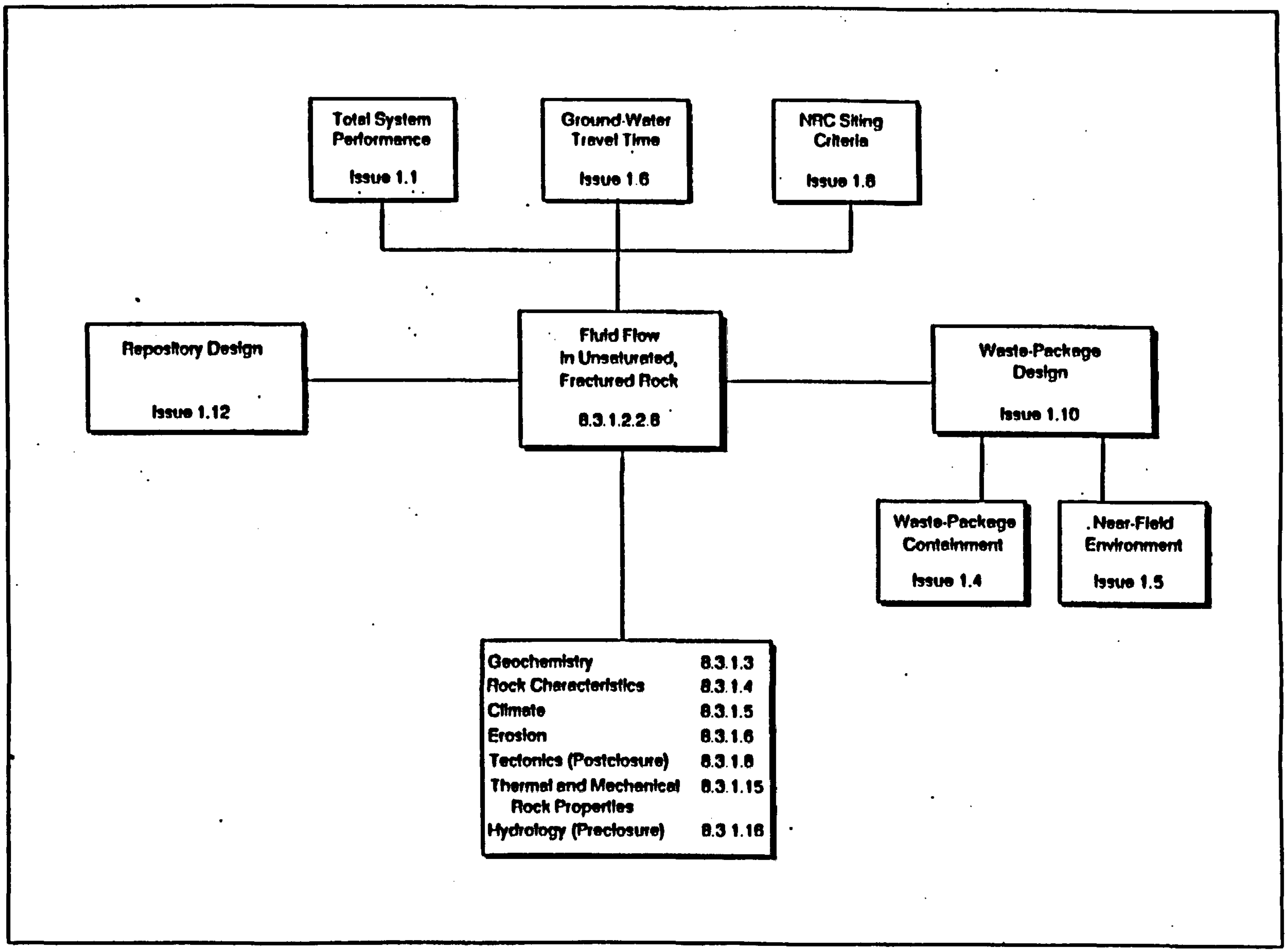

Figure 1.3-1. Interfaces of the study with YMP performance and design issues and other site-characterization programs

Although the scope of this study is constrained to model development and validation at a laboratory or field-testing scale, site-scale characterization must address the supporting performance parameters identified in SCP Table 8.3.5.12-3 to obtain an accurate representation of the cumulative distribution of ground-water travel time in the unsaturated zone, to account for heterogeneities that exist at the site.

Unsaturated, fractured fluid-flow modeling in the present study will provide to Study 8.3.1.2.2.9 the conceptual and numerical tools for the estimation of supporting performance parameters needed to assess ground-water travel time in individual unsaturated-zone units. These supporting parameters (e.g. unsaturated-zone fracture permeability in the repository area), are used to define various aspects of the unsaturated-zone models and fracture hydrologic characteristics models. These aspects include initial and boundary conditions, material properties, system geometry, and validation of model concepts. The results of these investigations will yield input into the understanding of performance parameters for the unsaturated-zone units (see SCP Table 8.3.5.12-2). Examples of these performance parameters are flux, unsaturated hydraulic conductivity, effective porosity, distance along flow paths, and percolation rates. The site-scale models (Study 8.3.1.2.2.9) will incorporate all of the above parameters.

The purpose of the present study will be to aid in the design and interpretation of hydrologic and pneumatic tests, particularly those which are slated to be conducted in the exploratory studies facility (ESF). These models will be conducted in an iterative fashion, as data are developed by the supporting tests. The insights gained will be incorporated into the site-scale (Study 8.3.1.2.2.9) models. All tests conducted in conjunction with this study will be conducted at the laboratory and field-testing scales. Numerical models may be required to extrapolate the data to scales relevant to the site-scale modeling study.

Performance Issue 1.1
(Total system radionuclide release to the accessible environment)

This issue is concerned with the total system performance and radionuclide release rates to the accessible environment. It requires that the geologic setting, engineered barrier system, shafts, boreholes, and seals be selected and designed so as to limit the cumulative releases of radionuclides for 10,000 years following permanent closure of the repository. The results of the present study will have applications to this issue by supplying descriptive and numerical models of fluid flow in unsaturated, fractured rock that can be incorporated into site-scale models, which can then be used to satisfy numerous performance parameters. These will be used to address expected partial performance measures (EPPMs) for the unsaturated-zone liquid pathway and for the gas pathway for the nominal (Class E) scenario, in which matrix flow predominates at undisturbed unsaturated-zone barriers.

Performance Issue 1.4
(Waste-package containment)

This issue is restricted to assessing waste package performance under anticipated processes and events, and only for the period of 1,000 years following closure of the repository. This study indirectly supports this issue by providing descriptive and numerical models of fluid flow in unsaturated, fractured rock, which will be incorporated into site unsaturated-zone models (Study 8.3.1.2.2.9). These models will provide information on the quantity of water that can contact either the container or the waste. The quantity of water can have a significant effect on the performance of materials used in waste packages. Both the amount and the method by which water is delivered to a waste package can affect the corrosion rate and mechanism. The performance measure is the quantity of liquid water that can contact the container.

Performance Issue 1.5
(Waste-package and repository engineered-barrier performance)

Issue 1.4, as stated, is restricted to assessing waste-package performance under anticipated processes and events for a period of 1,000 years following closure of the repository. The performance of the waste packages during this 1,000-year containment period is intimately linked to the performance required thereafter by the engineered-barrier system in controlling radionuclide releases as addressed in Issue 1.5. The present study indirectly supports this issue by providing descriptive and numerical models of fluid flow through unsaturated, fractured rock, which will be incorporated in the site unsaturated-zone models. These models will be used in calculating the flow and transport in the near-field host rock. The applicable performance measures are quantity of gas phase and liquid water within the near-field host rock.

Design Issue 1.10
(Characteristics and configuration of the waste package)

The present study supports this issue by providing descriptive and numerical models for fluid flow in unsaturated, fractured rock, which will be incorporated into site unsaturated-zone models. This information may be useful in characterizing the near-field (pre-waste emplacement) environment of the waste package by indicating the quantity and quality of water that can contact either the container or the waste.

The results of this study will also support (indirectly through Design Issue 1.10) resolution of the performance issues concerned with releases from the engineered-barrier system (Performance Issues 1.4 and 1.5) where the applicable performance measure is the concentration of radionuclide species in the gas phase, liquid water, and adsorbed phases within the near-field host rock. Quantity and quality of water in the near-field environment will apply to the hydrologic performance parameters of these issues.

Design Issue 1.12
(Characteristics and configurations of shaft and borehole seals)

Unsaturated-zone models developed in the present study will indirectly (through their contribution to Study 8.3.1.2.2.9) support the design of repository seals. Fluid flow in fractures and the influence of fracture flow on the quantity of water which may enter the shaft and contact borehole seals is poorly understood. Models developed in this study may indirectly help resolve Issue 1.12 by providing an understanding of fluid flow in fractures. The applicable performance measure that may be supported by this study is quantity of water in the near-field environment. Design Issue 4.4 (Repository design and technical feasibility) also requires information on water quantity, and may be supported by this study through Design Issues 1.10 and 1.12.

Performance Issue 1.8
(NRC siting criteria)

This performance issue addresses the NRC siting criteria of two sets of conditions that describe human activities and natural conditions, processes, and events. The first set consists of favorable conditions (FCs) that, if present, enhance the ability of the site to isolate waste. The second set consists of potentially adverse conditions (PACs) that, if present, could adversely affect the ability of the site to isolate waste. Siting criteria require that demonstrations be made regarding each of these conditions.

Through support of Performance Issue 1.6, the present study indirectly (through Study 8.3.1.2.2.9) addresses the following favorable conditions:

- FC 1: The nature and rates of tectonic, hydrogeologic, geochemical, and geomorphic processes (or any of such processes) operating within the geologic setting during the Quaternary Period, when projected, would not affect or would favorably affect the ability of the geologic repository to isolate the waste.

- FC 7: Pre-waste-emplacement, ground-water travel time along the fastest path of likely radionuclide travel from the disturbed zone to the accessible environment that substantially exceeds 1,000 yr.

- FC 8: For disposal in the unsaturated zone, hydrogeologic conditions that provide -

  (i) Low moisture flux in the host rock and in the overlying and underlying hydrogeologic units;

  (ii) A water table sufficiently below the underground facility such that fully saturated voids contiguous with the water table do not encounter the underground facility;

  (iii) A laterally extensive low-permeability hydrogeologic unit above the host rock that would inhibit the downward movement of water or divert downward-moving water to a location beyond the limits of the underground facility;

  (iv) A host rock that provides for free drainage; or

  (v) A climatic regime in which the average annual historic precipitation is a small percentage of the average annual potential evapotranspiration.

The present study will indirectly support the issue-resolution strategy for ground-water travel time in Performance Issue 1.6.

The present study, by providing conceptual and numerical models describing fluid flow through the unsaturated zone to Study 8.3.1.2.2.9, is an associated study in evaluations of the following PACs and their potential consequences. The associations of the study with various PACs are tabulated in SCP Section 8.3.5.17.

- PAC 2: Potential for human activity to adversely affect the ground-water flow system, such as ground-water withdrawal, extensive irrigation, subsurface injection of fluids, underground pumped storage, military activity, or construction of large-scale, surface-water impoundments.

- PAC 5: Potential for changes in hydrologic conditions that would affect the migration of radionuclides to the accessible environment, such as changes in hydraulic gradient, average interstitial velocity, storage coefficient, hydraulic conductivity, natural recharge, potentiometric levels, and discharge points.

- PAC 6: Potential for changes in hydrologic conditions resulting from reasonably foreseeable climatic changes.
- PAC 8: Geochemical processes that would reduce sorption of radionuclides, result in degradation of the rock strength, or adversely affect the performance of the engineered barrier system.
- PAC 11: Structural deformation, such as uplift, subsidence, folding, and faulting, during the Quaternary period.
- PAC 15: Evidence of igneous activity since the end of the Quaternary period.
- PAC 16: Evidence of extreme erosion during the Quaternary period.
- PAC 20: Rock or ground-water conditions that would require complex engineering measures in the design and construction of the underground facility or in the sealing of boreholes and shafts.
- PAC 22: Potential for the water table to rise sufficiently so as to cause saturation of an underground facility located in the unsaturated zone.
- PAC 23: Potential for existing or future perched-water bodies that may saturate portions of the underground facility or provide a faster flow path from an underground facility located in the unsaturated zone to the accessible environment.
- PAC 24: Potential for the movement of radionuclides in a gaseous state through air-filled pore spaces of an unsaturated geologic medium to the accessible environment.

2 RATIONALE FOR STUDY

2.1 Technical rationale and justification

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

2.1.1 Statement of problem and study justification

Quantitative evaluation of the geohydrologic system encompassing the unsaturated zone at Yucca Mountain is essential to the site-characterization program because the repository construction is proposed to be sited within the variably saturated Topopah Spring welded unit of the Paintbrush Tuff. Additionally, the quantification of liquid flux through the overlying Paintbrush nonwelded unit and the Tiva Canyon welded unit are of concern in understanding the isolation of the repository from infiltration. Characterization of the Calico Hills nonwelded unit underlying the proposed repository site is of equal importance because it is presumed to act as a barrier to the saturated zone, lying approximately 150 to 200 meters below the level of the repository.

The study and quantification of moisture storage and movement within thick, layered sequences of variably saturated, variably fractured tuffs is largely unprecedented. It remains to be demonstrated to what extent such a geohydrologic system can be represented by the conventional theory of fluid storage and movement in variably saturated dual-porosity media. The moisture flow and storage within the unsaturated zone of the repository block are controlled by the structural, stratigraphic, lithologic, and climatologic settings. Moisture is presumed to be present both as liquid water and as water vapor within interstitial, fracture, and lithophysal openings. Moisture movement within the unsaturated zone is envisioned to be complexly three-dimensional. Specifically, liquid-water flow within interconnected pores and fractures is expected to occur as well as advective and diffusive vapor-phase movement, primarily within the interconnected air-filled fracture openings and secondarily within the rock-matrix pore space. Because liquid-water fluxes are expected to be small under conditions presently existing within the unsaturated zone at the site, the movement of water vapor may contribute significantly to net moisture flow, especially within the highly fractured welded tuff units. Furthermore, because liquid water and water vapor are expected to be in local thermodynamic phase equilibrium under all but highly transient conditions, liquid-water saturation and water-vapor concentration are coupled through the prevailing geothermal regime. A further complication arises from the need to consider and account for the occurrence of dissolved constituents in both the liquid and gas phases. The concentrations and transport of these solutes within the unsaturated zone are coupled to the occurrence and movement of liquid water and pore gas and, additionally, may be affected by chemical interactions with the surrounding rock matrix. Consequently, hydrologic evaluation of the site, in its most general aspect, constitutes a problem of two-phase, multi-component, coupled heat and moisture flow within a layered sequence of tilted, faulted, and fractured, variably saturated tuffaceous geohydrologic units of highly dissimilar and variable hydrologic, mechanical, and thermal properties.

Therefore, conceptual and numerical models describing fluid flow through unsaturated, fractured rock play an important role in describing a portion of the unsaturated geohydrologic system.

2.1.2 Hydrologic model development

A numerical hydrologic model is a mathematical representation for a physical geohydrologic system. The model is constructed from geohydrologic data obtained for the system and from conceptual models developed specifically for the system. A conceptual model is a representation of the system that idealizes the underlying geologic framework and identifies the hydrologic processes and boundary conditions acting within and on the system. The geologic framework includes the stratigraphic, lithologic, and structural setting. The hydrologic processes include the movement and storage of moisture (occurring as either or both liquid water and water vapor), of pore gas, and, possibly, of liquid- or gas-phase solutes.

The fundamental geohydrologic data that are required to define the hydrologic system and to validate the numerical and conceptual hydrologic models are to become available only as site characterization proceeds. Consequently, hydrologic model development will be accomplished in an iterative sequence of steps. These steps consist of collecting basic geohydrologic data and performing tests and experiments to explain and quantify particular concepts and hypotheses. Numerical hydrologic modeling will be used at many stages to perform preliminary analyses, to design and analyze tests and experiments, and to analyze and interpret field data. The principal hydrologic modeling effort, however, and the objective of this study, is to construct mathematical representations to simulate the physical processes which govern fluid flow through partially-saturated fractured rock. The primary function of these models will be to help design and interpret hydrologic and pneumatic tests and to provide information about model parameters that can be incorporated into site-scale models (Study 8.3.1.2.2.9). As such, the models to be developed in this study are intended for application primarily at both the laboratory and field-testing scales. This, too, will be a complex multi-step process that divides into two activities as follows: (1) development of conceptual and numerical models and (2) validation of conceptual and numerical models.

2.1.3 Analytical strategies

As stated in Section 1.2, the overall objectives of the present study are to develop and refine conceptual and numerical models for the description of fluid flow and transport in variably saturated, fractured rock. Thus its role in the Site Characterization Program is not the measurement of geohydrologic properties or processes. Rather, the investigators will employ observed and measured hydrologic and geologic data from other SCP studies, as well as the body of existing knowledge in their discipline, to formulate possible scientific explanations, or hypotheses, that address the technical issues considered by the investigators as critical in their efforts to represent unsaturated flow in fractured rock. For each of the technical issues, it is probable that several hypotheses will emerge, having sufficient credibility to merit testing by means of hydrologic experimentation. The investigators will generate numerical models that will represent the physical properties and processes, and their interactions, that are embodied in the proposed hypotheses.

The investigators will collaborate with investigators in other SCP unsaturated-zone studies to design hydrologic experiments to test these hypotheses by means of observation and measurement in the field and laboratory. An experiment to test a given hypothesis would be designed to measure one or more hydrologic properties or processes (for example, liquid flux within a block of variably saturated fractured tuff) considered to be reliable indicators of whether the experimental system performs as described by the hypothesis. The representation of the same given hypothesis in a numerical model will allow the calculation of model-estimated values for the same hydrologic properties or processes that are the subjects of the experiment.

The investigators responsible for the given hypothesis and its corresponding numerical model will, together with the investigators responsible for the parallel experiment, interpret the results. Simply stated, this interpretation will be the comparison of measured experimental hydrologic data against corresponding model-estimated data, for selected hydrologic parameters that best indicate whether the behavior of the experimental system is adequately described (or, in a sense, predicted) by the hypothesis/model.

There can be various outcomes of such an interpretation. If experimental and modeled results should be in sufficient agreement, the hypothesis/model would be supported by experimental evidence, and the investigators would repeat and vary the experiment to further test the validity of the hypothesis. The hypothesis/model would be refined as necessary to incorporate aspects of the behavior of hydrologic processes that may be learned from changing the conditions of the experiment. If experimental and modeled results should not satisfactorily agree, the hypothesis/model may be judged not to be a valid description of the properties and processes under experiment, and may be significantly revised or else considered disproved. The investigators may also reexamine and possibly revise the design of the experiment if they believe that it has not isolated and measured the selected hydrologic parameters with sufficient sensitivity.

The investigators of this study and those of associated experimental studies will test hydrologic hypotheses and models against experiments in an iterative process, with the goal of arriving at the most scientifically plausible and defensible explanations in each of the technical issues.

2.2 Constraints on the study

2.2.1 Accuracy of models

In order to treat problems that are mathematically tractable, a numerical model rarely can allow for the full range of complexity of the specific physical system that the model is intended to represent. Rather, the numerical model generally is based on a set of simplified and idealized hypotheses abstracted from the conceptual model. In the case of a geohydrologic system, these hypotheses must include the essential hydrologic processes and conditions that control the system. As a result of this simplification, the model yields an approximation of the physical system, the accuracy of which must be assessed before the model can be applied with confidence. Often, models may fail to accurately represent a physical system because of parameter uncertainty due to spatial variability and measurement error, or inconsistency in the scales at which parameters are measured and applied. However, models may also not accurately represent a hydrologic system because the physical processes controlling the system behavior have not been correctly identified or described by the model at the temporal and spatial scales of interest. In general, as the scale of model application increases, less detail in the treatment of the physical processes and system geometry can be considered by the model and, unfortunately, it becomes increasingly difficult to perturb the physical system in a manner that isolates and tests specific model components. Because site-scale models are applied at temporal and spatial scales that are not compatible with scales at which controlled experiments can be conducted, direct comparison with experimental data is not possible for these models. Direct comparison with data measured under unperturbed conditions is complicated by the fact that state variables may be measured at scales vastly different than those considered by the model. However, various components of these site-scale models can be isolated with laboratory and field experiments. Models appropriate to the testing scale, such as those developed and tested under this study, can be directly compared to measured data and used to evaluate models designed for application at larger scales.

A more detailed discussion of validation and validation criteria for models developed in this study is included in Section 3.2 of this study plan. Requirements for accuracy and precision of test instrumentation in associated investigations contributing to the present study will be addressed within the appropriate study plans for those investigations.

2.2.2 Potential impacts of activities on the site

This study will have no physical impact on the site. The information generated from this study, however, might influence the performance of studies which would impact the site (i.e., the various data-gathering studies). Activities directly associated with development and validation of conceptual and numerical models are the intact-fracture test (Activity 8.3.1.2.2.4.1), the percolation test (Activity 8.3.1.2.2.4.2), and the bulk permeability test (Activity 8.3.1.2.2.4.3). These will be prototyped in the laboratory and at analog sites. Portions of the actual tests will be conducted in the exploratory studies facility and the data incorporated into this study. The impact on the site due to contributing individual studies is addressed within those studies and will not be addressed here.

2.2.3 Time required versus time available

A tentative schedule of work activities and reports is given for each of the two activities of this study in Section 5. This study and the activities within rely heavily on the data-gathering activities of other studies, and therefore the time required to perform the present study is dependent on the time schedules of supporting studies. The model development itself will closely follow the schedules specified in Section 5.

2.2.4 Representativeness of repository scale and correlation to repository conditions

The models to be developed in this study are intended for application primarily at both the laboratory and field-testing scales. Among the concepts to be explored is that of the Representative Elementary Volume (REV). The REV for a given parameter is that volume of rock at which the model parameter becomes relatively invariant with further increases in scale. At the scale of the REV, the true medium can be replaced conceptually with an equivalent porous medium whose behavior is described by that parameter. By definition, the real and fictitious media exhibit sufficiently similar behavior at that scale with regard to the process in question. The presence of an REV in a highly heterogeneous medium, such as that expected at Yucca Mountain, is questionable. However, the concept will be explored, with results being incorporated into the site-scale model (SCP 8.3.1.2.2.9).

2.2.5 Interrelationships of tests involving significant interference with other tests

This study is concerned with modeling and analysis and will not interfere with other tests. However, it is designed to interface with

Activities 8.3.1.2.2.4.1, 8.3.1.2.2.4.2, and 8.3.1.2.2.4.3, which are all associated with the exploratory studies facility. Both conceptual and numerical modeling techniques will be conducted in conjunction with those activities throughout the development and implementation of the associated studies. The completion of this study is contingent upon the scheduling for construction of the exploratory studies facility. This study will have an ongoing role in the design and interpretation of those activities from the prototype phase through the final tests conducted in the exploratory studies facility.

Similarly, the level of input from the results of this study into Study 8.3.1.2.2.9 (Site unsaturated-zone modeling and synthesis) will be constrained by the schedule for completion of the exploratory studies facility.

3 DESCRIPTION OF ACTIVITIES

This study is organized into two activities:

- 8.3.1.2.2.8.1 - Development of conceptual and numerical models of fluid flow in unsaturated, fractured rock; and
- 8.3.1.2.2.8.2 - Validation of conceptual and numerical models of fluid flow in unsaturated, fractured rock.

The plans for these activities are described in Sections 3.1 and 3.2.

3.1 Development of conceptual and numerical models of fluid flow in unsaturated, fractured rock

3.1.1 Objective of activity

The objective of this activity is to develop detailed conceptual and numerical models of fluid flow and nonreactive tracer transport through unsaturated fractured rock at Yucca Mountain. Because an important function of these models will be to assist in the design and interpretation of hydrologic and pneumatic tests, models will be developed to cover a variety of test scales, ranging from the laboratory to the field-testing scale. A second important function of these models will be to integrate data collected from a variety of scales and estimate model parameters at those scales that are not amenable to direct testing. A final function of the models developed under this activity will be to investigate flow processes that influence fluid fluxes and travel times so that these processes can be more accurately accounted for by site-scale models.

3.1.2 Key technical issues to be addressed

This activity is not directly associated with the measurement of any parameters. Rather, it involves the development of the numerical and analytical tools necessary to plan and interpret hydrologic experiments, integrate data collected at a variety of scales, and provide a description of the fluid and solute transport and storage processes that can serve as a basis for the site-scale unsaturated-zone modeling (Study 8.3.1.2.2.9, Site unsaturated-zone modeling and synthesis).

3.1.3 Rationale for activity selection

The testing methodology necessary to physically characterize the nature of flow and transport in unsaturated, fractured rock is not yet as fully developed as for other hydrologic environments. Numerical modeling can play an important role in site characterization by helping investigators evaluate various experimental designs. By simulating physical experiments with numerical models prior to their actual execution, the investigator may gain insight into the relative importance of different processes that may affect test results, evaluate the manner in which artificially imposed boundary conditions may cause the system to deviate from its natural behavior, estimate test duration and the density of sampling points in time and space necessary to unambiguously interpret the test results, and consider experiments with alternative designs. The conceptual and numerical tools developed as part of this activity provide a basis for evaluating the benefits and limitations of various experimental designs, and also for interpreting the results from these experiments.

Direct measurement of unsaturated-zone hydrologic parameters at scales relevant to the site-scale modeling study (Study 8.3.1.2.2.9) may not be feasible because of the difficulty in changing the saturation state of large volumes of fractured, low-permeability rock in a controlled manner. Therefore, many of these parameters will need to be estimated on the basis of laboratory-scale measurements, observations of the fracture geometry, and numerical modeling. Physical testing will be conducted on a wide range of scales. The numerical models developed as part of this activity permit integration of data collected over a range of scales as well as facilitate the extrapolation of data from the measurement scale to the modeling scale.

Important technical issues to be addressed by site characterization include estimation of the liquid flux through the proposed repository block, and description of the prevalent flow mechanisms and flow paths. An estimate of the liquid flux though the repository block provides an upper bound on the volume of water that can potentially contact the waste canisters. The liquid flux, in combination with a knowledge of the dissolution kinetics of the matrix in which the waste is embedded and the solubility limits of the constituent radionuclides, provides a means of estimating the maximum potential mass release rates from the proposed repository. The liquid flux is expected to be both spatially and temporally variable. Although the areal-averaged value of downward flux at the proposed repository horizon may be small or negative (thereby indicating the predominantly upward movement of water in the form of vapor), locally there may be water moving rapidly downward along specific fractures or other structural features. A knowledge of the spatial distribution of flux, flow mechanisms, and potential flow paths is therefore needed in order to calculate ground-water travel-time distribution.

Identification of the prevalent flow mechanism is important because if the flux is predominantly through the fractures, the effective flow and transport porosity may be much less than the total porosity, and so for a given flux, the average particle velocity is greater and travel times correspondingly shorter when the flux is controlled by the fractures. Furthermore, the surface area available for radionuclide adsorption is orders of magnitude greater within a matrix block than the surface area represented by the adjacent fracture walls. The combination of slower water velocity and greater surface area and residence times means that adsorption is a much more effective retardation mechanism if flow is predominantly through the matrix.

Field evidence for fracture-dominated flow under highly transient conditions in the near surface includes (1) the presence of water at the bottom of neutron holes UZN2, UZN7, UZN26, and UZ44 shortly after rainstorms (E.P. Weeks, written communication); and (2) the occurrence in boreholes UE25 UZ#4 and UE25 UZ#5 of large water contents and tritium values as great as 65 tritium units in nonwelded units lying beneath highly-fractured welded units (A. Flint, written communication, 1989). However, discontinuities in the fracture system may attenuate the movement of moisture, particularly if fractures terminate at contacts with the highly porous nonwelded and partially welded units. Above the proposed repository horizon, the partially welded base of the Tiva Canyon Member, the Yucca Mountain Member, the Pah Canyon Member, and the partially welded top of the Topopah Spring Member of the Paintbrush Tuff, collectively referred to as the Paintbrush (PTn) hydrogeologic unit (Peters and Klavetter, 1988), may significantly buffer periodic, highly transient infiltration events, releasing water to the underlying densely welded, fractured portions of the Topopah Spring Member of the Paintbrush Tuff at a more or less steady rate. Water may also be diverted laterally downdip within the non- to partially welded units, in part because of an overall anisotropy in permeability that results when considering these units collectively, and possibly by capillary barriers formed either between these units or between the non- to partially welded units and the fractures of the densely welded portions of the underlying Topopah Spring Member. Within the densely welded portions of the Topopah Spring Member, fracture flow may also occur under quasi-equilibrium conditions if the numerical value of flux is greater than the matrix saturated hydraulic conductivity (assuming the potential gradient is approximately unity). Quasi-equilibrium is defined as a condition in which fracture-matrix potential equilibrium exists locally, but the value of potential changes slowly in time or space. Because of the contrast in size between the pores of the welded tuff matrix and fracture apertures, and the affinity of water for openings with a smaller radius of curvature, water will reside preferentially in the matrix pores when a condition of fracture-matrix water potential equilibrium exists.

Even under those conditions in which a significant proportion of the flux is occurring within the fractures, physical retardation mechanisms such as matrix diffusion of solute, with or without capillary imbibition, may effectively remove solute from the fractures. It is important to examine processes that may inhibit the exchange of solute and liquid between fractures and matrix. These processes may involve the entrapment of air both within isolated pores or as a continuous phase pushed ahead of an advancing wetting front within a fracture-bound matrix block, flow impedance due to fracture coatings, or flow channeling within a specific fracture or along specific pathways through the fracture network.

Fracture permeability has been found to be a sensitive function of the average fracture aperture (Pyrak-Nolte and others, 1987; Gale and others, 1985), which is in turn dependent on the compressive stress normal to the fracture plane. Therefore, fracture permeability is expected to change both with depth and with fracture orientation relative to the principal stress directions. Characterization of these effects, as for those processes described above, requires not only physical experimentation but also well-developed theory as embodied in analytical or numerical models.

3.1.4 Summary of technical issues addressed

To support studies more directly involved with ground-water flux and the issue of ground-water travel time, this activity will develop or adapt models to:

(1) determine the conditions under which flow within fractures located within the unsaturated zone is likely to occur;

(2) study the nature of channeling processes and the implications of channeling for the transport of water and radionuclides;

(3) examine factors influencing the extent to which the fractures and matrix interact, including the effects of fracture coatings and the potential for the interference of different phases in double-porosity media;

(4) develop methods for estimating the relative permeability of unsaturated fractured rock in order to provide a basis for indirectly estimating the flux through Yucca Mountain on the basis of *in-situ* measurements of water potential;

(5) describe the effect of stress changes on the permeability and relative permeability of rough-walled natural fractures;

(6) develop or adapt models to characterize the spatial heterogeneity in the permeability of fractured rock; and

(7) examine the conditions under which hydrologic discontinuities are effective mechanisms for diverting water laterally.

These technical issues are listed in Table 3.1-1, along with the modeling strategy proposed to resolve them, the data required, and the tests that have been planned to acquire that data. As shown in Table 3.1-1, a single technical issue may be examined with more than one modeling strategy, and several modeling strategies will be used to explore more than one technical issue. The various modeling approaches are described in the following sections.

Table 3-1.1 Association of technical issues with modeling strategy used for issue resolution, required data, and data source.

Technical Issue	Modeling Strategy	Required Data	Data Source [a,b]
(1)	Variable-aperture model	aperture variation	Intact-fracture test
		relative permeability of fractures to water as a function of water potential	
		in-situ water potentials	Site vertical borehole studies
	Double-porosity model	relative permeability of fractures as a function of water potential	Intact-fracture test
		relative permeability of tuff matrix as a function of water potential	Matrix properties test
		in-situ water potentials	Site vertical borehole studies
(2)	Variable-aperture model	aperture variation	Intact-fracture test
	Fracture-network model	fracture lengths, interconnectedness	Fracture mapping
		hydraulic (pneumatic) aperture distribution	Pneumatic testing
	Channel models	number and volumetric flow rates of seeps in drifts and ramps of the ESF	Perched-water test
(3)	Variable-aperture model	aperture variation	Intact-fracture test

	Double-porosity models	block-size distribution	Fracture mapping Pneumatic testing
		fracture coatings	Fracture mapping Percolation testing
		fracture continuum permeability	Pneumatic testing
		matrix continuum permeability relative permeability to air and water as a function of water saturation	Matrix properties test
(4)	Fracture-network model	aperture variation, relative permeability of fractures to water as a function of water potential	Intact-fracture test
		fracture lengths, interconnectedness	Fracture mapping
		hydraulic (pneumatic) aperture distribution	Pneumatic testing
(5)	Variable-aperture model	aperture variation, fracture permeability and relative permeability to water as a function of normal stress	Intact-fracture test
		in-situ stresses before and after drift excavation	Excavation-effects test
(6)	Stochastic continuum model	spatial distribution of matrix permeability	Matrix properties test
		spatial distribution of fracture permeability	Pneumatic testing

(7)	Double-porosity models	matrix relative water permeability as a function of water potential	Matrix properties test
		fracture relative water permeability as a function of water potential	Intact-fracture test
		in-situ water potentials	Site vertical borehole studies
		fracture-network continuity	Fracture mapping

a. Data sources

Activity 8.3.1.2.2.3.1 Matrix hydrologic properties testing.

Activity 8.3.1.2.2.3.2 Site vertical borehole studies.

Activity 8.3.1.2.2.4.1 Intact-fracture test in the exploratory shaft facility.

Activity 8.3.1.2.2.4.2 Percolation tests in the exploratory shaft facility.

Activity 8.3.1.2.2.4.3 Bulk-permeability tests in the exploratory shaft facility.

Activity 8.3.1.2.2.4.5 Excavation effects test in the exploratory shaft facility.

Activity 8.3.1.2.2.4.7 Perched-water test in the exploratory shaft facility.

Activity 8.3.1.4.2.2.4 Geologic mapping of the exploratory shafts and drifts.

b. Pneumatic testing is to take place as part of the Bulk-permeability tests and the Site vertical borehole studies, as well as SCP Activity 8.3.1.2.2.4.4, Radial borehole tests in the exploratory shaft facility.

3.1.5 Numerical model development

Completion of evaluation of the specified modeling strategies will be contingent upon completion of laboratory or field activities with which these modeling efforts interface. The specific modeling strategies enumerated may rely on computer codes which already exist, for which modification of existing code may be required, or for which new code may need to be developed. Evaluation of these codes will be conducted in compliance with the YMP-USGS Software Quality Assurance Program according to QMP-3.03 for each of the computer programs developed or used in this study. Further quality assurance will be provided by USGS technical review as specified in YMP-USGS-QMP-3.04, "Technical Review of YMP-USGS Publications." Graded QA report packages will be developed to comply with AP-5.28Q, Quality Assurance Grading.

Because this study is expected to be ongoing for a period of years, the literature will be continually reviewed and newly applicable models will be incorporated into the study as knowledge in the area of unsaturated, fractured rock hydrology is expanded. Guidelines for conducting such analyses will be followed in accordance with AP-1.10Q.

3.1.6 Summary of equipment requirements

This activity does not directly incorporate scientific equipment for which standard procedures, e.g. ASTM or API standards, data acquisition, data reduction, and analysis are required. No instrumentation for specified tolerances, accuracies, or precision is required. Adjunctive studies (e.g. Study 8.3.1.2.2.4, Unsaturated-zone percolation - ESF studies) will address technical specifications required for instrumentation used within their appropriate study plans. Where numerical models are used, assumptions, limitations, and statistics, if appropriate, will be specified in conjunction with analyses of the methods.

3.1.7 General approach and summary of proposed modeling strategies

Because the scale of investigation and the processes involved may vary, a wide variety of models will be used to support the experimental program and investigate the technical issues broadly described in the preceding section. In general, models appropriate to the different scales of investigation will be developed. When possible, multiple models will be developed for application at a given scale in order to evaluate the uncertainty associated with any particular modeling approach. Different modeling strategies for describing the flow of fluids and solute in unsaturated, fractured rock are discussed in this section. The movement of nonreactive tracer transport is considered by some of these models because of the information tracers can provide about the mechanisms of fluid transport. In generic terms, these modeling strategies include single-fracture variable-aperture models, fracture-network models, channel models, double-porosity models, and stochastic continuum models. For some of these modeling categories, such as double-porosity models, more than one type of model may exist.

Although validation of these models against specific experiments is planned, as discussed in Section 3.2 of this study plan, these models will also be checked for consistency against observations made in Studies 8.3.1.2.2.3 (Unsaturated-zone percolation - surface-based studies), 8.3.1.2.2.7 (Unsaturated-zone hydrochemistry), 8.3.1.2.2.1 (Unsaturated-zone infiltration), and 8.3.1.2.2.6 (Unsaturated-zone gaseous-phase movement).

3.1.7.1 Variable-aperture models

The validity of past modeling studies employing discrete fractures is suspect for several reasons, among them being that, with the exception of Smith and others (1985), these models have simulated fractures as planar features with parallel walls within which the fluid flux is proportional to the aperture cubed. Evidence summarized in Gale and others (1985) indicates that significant deviations from the cubic law can occur at elevated normal stresses. As apertures close, roughness of the fracture walls exerts a relatively greater influence on fluid flow. In addition, increases in contact area at high normal stresses result in increasingly tortuous flow paths which are not accounted for by the cubic law, even when this law is modified to account for roughness.

There is further evidence that fluid and tracer movement may be highly channelized (Neretnieks and others, 1987), particularly along fracture intersections (Abelin and others, 1987). The implication of extensive flow channeling within fractures is that fluids move much faster and solute breakthrough occurs earlier than would be predicted by models based on parallel plate assumptions and the cubic law. Flow channeling within fractures also reduces the importance of matrix diffusion as a retardation mechanism because the surface area across which diffusion takes place is reduced, and because fluid velocity is increased and residence time decreased relative to an equivalent parallel-plate fracture having the same hydraulic aperture. More physically realistic models of fracture flow recognize that aperture varies within the plane of a fracture. Aperture variation within a fracture controls the extent to which flow is channelized and also the distribution and permeability of the fluid phases (air and water) at different fluid phase saturations.

A variable-aperture model similar to that described by Pruess and Tsang (1990) has been developed to calculate the relations between the permeabilities of water and air to their respective saturations within the plane of a variable-aperture fracture. A fracture of specified average aperture is first discretized into spatially correlated cells of constant aperture using the turning-bands method (Journel and Huijbregts, 1978) and a distribution function that characterizes aperture variability. Within each constant-aperture cell the cubic-law relationship between fluid flux and aperture is assumed to hold. The initial matric potential of the fracture and the capillary-rise law for parallel plates are used to calculate an initial cutoff aperture. A cell is completely filled with either gas or liquid, and therefore contributes only to the permeability of the phase it contains. In general, the algorithm considers all constant-aperture cells within the fracture plane with apertures larger than the cutoff aperture to be air-filled, thus contributing only to air permeability. All cells less than this value are considered to be water-filled and contribute solely to the water permeability. Intrinsic (single-phase) permeability within a cell of constant aperture is taken as aperture-squared, divided by twelve. The liquid saturation at this level is simply the summation of the volume of all cells with aperture less than the cutoff aperture, divided by the total volume of the simulated fracture. Matric potential at a given cutoff-aperture is determined from the cutoff aperture and the capillary-rise law for parallel plates. Equivalent permeability of the fracture to a given phase at the calculated phase saturation is derived by computing the flux of that phase through the fracture for a prescribed gradient.

The procedure described above determines one point in the relationship between phase permeabilities, phase saturations, and matric potential. The procedure is repeated by incrementing the latest value of matric potential and determining a new cutoff aperture until the fracture is completely filled. At this point, the intrinsic (single-phase) permeability of the fracture is defined, which can then be used to calculate the relative permeability at other matric potentials. To examine effects of hysteresis, the model provides the option of either starting at full saturation and dewatering the fracture, or starting at residual saturation and imbibing water. The model determines if a continuous water-filled pathway exists between a cell and the upstream or downstream boundaries before allowing a cell with aperture smaller than the cutoff aperture to fill. Similar provision is made for the drainage of large-aperture cells when desaturation of the fracture is simulated.

The variable-aperture model is a useful conceptual tool that may allow inferences to be drawn concerning the behavior of unsaturated fractured tuff based on field and laboratory measurements of physical and pneumatic apertures. For instance, preliminary modeling using the model described above has indicated that the ratio of hydraulic to average aperture is a function of the variance in the assumed aperture distribution. Field measurement of hydraulic and average aperture might then form the basis for assuming a particular aperture variance for that fracture when estimating the unsaturated properties of that fracture. Alternatively, the relative permeability curves calculated with the variable-aperture model can be compared to a step-function approximation in which relative permeability to water is equal to unity when the matric potential is greater than the air-entry potential calculated from its equivalent parallel-plate hydraulic (or pneumatic) aperture and the capillary-rise law for parallel plates, and zero at potentials lower than this air-entry potential.

Previous modeling (Moreno and others, 1988) and experimental studies (Schrauf and Evans, 1986) have indicated that the average physical aperture is generally 1.5 to 2.0 times the equivalent parallel-plate hydraulic or pneumatic aperture. The experimental evidence presented in Abelin and others (1987) suggests this ratio may be close to 10. Therefore, the assumption that the relative permeability curve can be approximated by such a step function may be inherently conservative in terms of estimating fracture flux under partially saturated conditions, because at a given measured matric potential such an approximation would suggest that for certain fractures the aperture is filled and conductive to water when it is in fact drained and non-conductive. Experience to date, based upon limited test cases, has shown that the equivalent hydraulic (or pneumatic) aperture overpredicts the absolute magnitude of the matric potential at which the average physical apertures drain, thereby providing an upper estimate of the liquid flux through a fracture.

The variable-aperture flow model can also be used to examine the fractional area of the fracture that contains water at different matric potentials. Observations on the latter subject are important in simulations of water flows from matrix block to matrix block across partially saturated fractures. Wang and Narasimhan (1985) proposed that cross-fracture flow is a function of the effective permeability of the matrix adjacent to the fracture and the fractional area of the intervening fracture that is water-filled. These fractional areas calculated with the variable-aperture model may also provide insight to the manner in which the wetted surface area of matrix blocks in a double-porosity medium varies as a function of the saturation or matric potential of the fracture continuum.

The variable-aperture flow model can also be used in conjunction with a particle-tracking method to explore the relations between hydraulic and tracer aperture (see, for example, Moreno and others,

1988) and examine the effects of channeling on tracer transport within a fracture.

Numerical modeling by Tsang and Tsang (1989) has shown that under saturated conditions, the location of channels within a fracture plane (that is, the principal flow paths within the fracture plane) depend on flow direction. Preliminary modeling using the variable-aperture model described above has shown that under partially saturated conditions the location of the principal channels for flow, as determined from particle tracking, also depends on the matric potential or saturation state of the fracture. Smaller-aperture pathways carry most of the water at small matric potentials and larger-aperture pathways carry most of the water at large matric potentials. Although these and other modeling studies (Moreno and others, 1988) have demonstrated the importance of channeling within a single fracture plane, its importance in a network of fractures is less clear, since the large- and small-aperture pathways in a given fracture need not necessarily be aligned with pathways of similar aperture in intersecting or abutting fractures, unless these pathways are themselves the result of the flow of water (for example, mineral dissolution or precipitation). The variable-aperture model described above will therefore be used to investigate the channeling behavior of randomly joined fractures with different aperture characteristics.

3.1.7.2 Fracture-network models

Fracture-network models provide a useful means of conceptualizing the mechanisms by which fluids and solutes move through fractured rock. However, applications of these models on a site-specific basis are generally limited by the large amounts of detailed data these models require. Further limitations arise from complications involving the measurement of hydraulic and transport apertures. Estimates of hydraulic aperture based on pumping or injection tests conducted from boreholes are biased toward the apertures in the immediate vicinity of the borehole (Smith and others, 1987). Estimates of aperture based on tracer tests are sensitive to departures of the flow field from a radial flow pattern, as well as to the location of intersecting fractures which provide fluid to the pumped fracture. A review of the literature on fracture-network modeling also reveals that, in general, numerically generated fracture networks have borne little resemblance to fracture networks that have been mapped in the field.

Nonetheless, fracture-network models are useful conceptual tools. For instance, through use of these models it has become clearer why, in densely fractured rock with apparently well-connected fractures, flow into drifts can be limited to just a relatively few areas (see, for example, Neretnieks and others, 1987), thereby suggesting that the rock does not behave as a continuum with regard to its flow characteristics. The reason is that if the variance in the statistical distribution of hydraulic apertures is large, and the fracture length relative to the length of the flow field is small, there are very few paths along which flow can take place in an uninterrupted series of large-aperture fractures. Since the capacity of any individual path through the network to transmit water is limited by the least transmissive fracture along that path, and the probability of having only highly transmissive fractures along a path is small, it can be concluded that the rock will generally be of lower permeability than the intensity of fracturing might suggest, except for those few rare paths along which all the fractures are highly permeable. Note that the reason that flow has become concentrated at a few locations is quite distinct from that discussed in the previous section, where flow is concentrated at a few locations within a single fracture plane because of aperture variation within that fracture. In any field setting, both mechanisms probably cause flow to be concentrated along a few specific pathways.

The conclusion that for saturated conditions fractured rock is least likely to behave as an equivalent continuum when the variance in fracture hydraulic apertures is large and more likely to behave as a continuum when hydraulic apertures are more uniform in size is supported by the work of Long and others (1982). For unsaturated conditions, the tendency for flow to become concentrated along specific pathways in a network of fractures with varying hydraulic apertures has not yet been investigated either through modeling or experimentation. Capillary theory suggests that the specific pathways for water flow through fractured rock will depend on the water potential of the rock, with larger-aperture fractures being the principal conduits at large water potentials and smaller-aperture fractures forming the main water-transmitting pathways at smaller water potentials. Thus one possible response to desaturation is that flow through the fracture system remains highly localized, but that the areas in which flow is concentrated change with the saturation state of the rock. An additional complication is the effect that gravity may have on the manner in which water is distributed between various pathways. An alternative hypothesis is that the fractures become more uniform in their hydraulic behavior when the largest-aperture fractures and large-aperture channels are drained. Thus, the variance in hydraulic aperture effectively becomes smaller as the medium desaturates, at least over some range of water potentials, with the consequence that channeling which results from a high variance in hydraulic aperture may become less important under conditions of partial saturation and flow becomes more uniformly distributed in space. This study will examine these hypotheses by performing numerical fracture-network flow studies that incorporate the relations between relative permeability, saturation, and matric potential generated by the variable-aperture model (described in Section 3.1.7.1) for fractures with different average apertures. The FMMG code (Okusu and others, 1989), which was developed to create an integrated finite-difference mesh from a user-specified fracture network, can be used with TOUGH (Pruess, 1987) for these investigations.

Because of the difficulty in obtaining measurements of hydraulic apertures from field testing or estimating hydraulic apertures from measurements of the physical aperture, Cacas and others (1990a) left the aperture distribution as an unknown in their fracture-network model and adjusted this distribution until they were able to recreate the variance in the flow rates observed in single-hole packer tests. A similar approach for determining the pneumatic and hydraulic aperture distribution will be employed by this study.

The manner in which fractures terminate affects the conductivity of the network. Networks in which fractures terminate only when abutting other fractures are inherently more interconnected than networks (of the same fracture density) in which fractures terminate blindly in the matrix, since the former condition assures that every fracture intersects at least two other fractures. Barton and Hsieh (1989) presented an analysis of fracture terminations from the fracture-trace map of pavement 1000 in the densely welded orange brick unit of the Topopah Spring Member of the Paintbrush Tuff. Their analysis indicated that approximately 60 percent of the fracture terminations occur with one fracture abutting against another fracture, roughly 39 percent occur after the fracture has intersected another fracture, and only 1 percent of the fracture terminations end blindly in the matrix. If these observations in the surface pavements are indicative of the geometry of the fracture network at depth, it can be concluded that the fracture network of the Topopah Spring unit is well connected. However, based on the above analysis, flow within the unit may still be spatially erratic if the variance in hydraulic aperture is large. Similar analyses made by Barton and Hsieh (1989) of three surface pavements of the Tiva Canyon Member of the Paintbrush Tuff indicate a different character to the fracture-network, with the percentage of blind fracture terminations considerably higher and the fracture-network connectivity correspondingly lower.

Barton and Hsieh (1989) also reported fractal dimensions of 1.6 to 1.7 for the three pavements in the Tiva Canyon unit and a fractal dimension of 1.8 for the fracture network depicted by the fracture-trace map of the pavement in the Topopah Spring unit. The fact that a fractal dimension can be calculated for these surface pavements indicates that the basic fracture patterns repeat over a wide range in scales, suggesting that from mapping within limited exposed areas inferences can be made concerning the character of the fracture network at larger scales.

Fracture maps produced by Study 8.3.1.4.2.2 (Structural features in the site area), and particularly by Activity 8.3.1.4.2.2.4 (Geologic mapping of the exploratory shafts and drifts), will be used to constrain the analyses within the present study to numerically generated fracture networks that have gross characteristics similar to those depicted by the maps, which provide a concise visual record of the abutting and cross-cutting relationships, the manner in which fractures cluster, and an indication of the length distribution and the connectivity of the network. The fractal dimension of the network also provides an additional constraint, and analyses will be restricted to those numerically generated fracture networks that have fractal dimensions similar to those determined from the maps.

3.1.7.3 Channel models

As discussed in Sections 3.1.7.1 and 3.1.7.2, flow within fractured rock may be highly localized under water-saturated conditions because of aperture variations within single fractures or variability in equivalent hydraulic apertures of the fractures comprising the network. Observations of highly localized flow through water-saturated rock were recorded in both the Stripa experimental mine and at the Forsmark repository site in Sweden (Neretnieks and others, 1987). Inflow monitoring of the Stripa site found that 95.2 percent of observed flow occurred in less than 16 percent of the monitored area. Similar observations were made at the Forsmark site, where 50 percent of the flow was carried in 10 percent of the channels, of which highest flow rates were from channels of very narrow width or essentially were from point discharges occurring at fracture intersections.

Similar phenomena have been observed at Rainier Mesa, approximately 25 miles northeast of the proposed Yucca Mountain site. Henne (1982) measured seeps yielding from 0.5 l/min to 8 l/min in G-tunnel, whereas Classen and White (1979) found that major water-transmitting regions constituted about 3 percent of the total area studied.

If localization of flow through the unsaturated zone at Yucca Mountain occurs as discussed above, even the most extensive drilling program may not adequately characterize the areal distribution of flux through the unsaturated zone because the likelihood of penetrating active flow channels would be small. However, the drifts associated with the exploratory studies facility (ESF) provide large horizontal surface areas upon which the spatial and temporal distribution of flow may be observed. Current plans call for characterizing the flow rates and quality of all water entering the drifts (Activity 8.3.1.2.2.4.7, Perched-water test in the exploratory shaft facility). The exact method by which flow measurements are to be made depends on the volume of flow. Additionally, Activity 8.3.1.4.2.2.4 (Geologic mapping of the exploratory shafts and drifts) would provide in-depth characterization of the fracture network, thereby also providing possible insight as to the mechanisms by which flow is concentrated. Monitoring the flux into the drifts will provide valuable additional data which could be used to support estimates of flux calculated as part of Study 8.3.1.2.2.3 (Unsaturated-zone percolation - surface-based studies). It is recognized that due to stress redistribution around the drift, observations made on the drift walls may not represent exactly the channeling characteristics of undisturbed rock beneath the drift, through which radionuclide migration may take place. Additional problems involved with monitoring include the possible absence of any measurable flux. The absence of any measurable flux would be a valuable observation in itself, but would preclude the application of the type of channel model described below.

Characterizing the degree to which flow is localized or channelized under present-day recharge rates provides important input for the issue of ground-water travel time from the repository horizon. The wetted surface area per unit volume of rock must be known to predict the efficiency of the system in retarding the migration of radionuclides. The retardation of radionuclides by sorption is proportional to both sorption capacity per surface area and the available exposed wetted surface area. Small wetted surface areas would imply that diffusion of solute from the relatively mobile water of the fractures to the relatively immobile water within the rock matrix will be of limited importance as a retardation mechanism. Matrix diffusion is an especially effective retardation mechanism for sorbing solutes because the surfaces of the matrix grains provide a surface area per unit rock volume that is orders of magnitude larger than the surface area provided by the surfaces of the matrix blocks themselves.

This study proposes to develop a channel model similar to that described by Neretnieks and others (1987), which utilizes observations on the number, width, and flow rate of channels providing inflow to the ESF. Implicit in that particular model is the assumption of steady-state flow, a condition that may or may not exist at the proposed repository horizon at Yucca Mountain. Also, since the model is largely empirical, it does not attempt to describe the nature of channeling under any but the current recharge regime, or the mechanism by which flow becomes localized. As described in Section 3.1.7.2, the specific pathways for transport may depend on the saturation state of the rock.

The model requires channel characteristics such as the width and frequency of channels providing a certain volumetric flow rate. This information is used to define discrete classes of channels. The transport characteristics of the rock can be analyzed by calculating the contributions from each class of channels, and then summing the flux-weighted contributions from each class to compute the total mass or flux-weighted concentration arriving at a surface some arbitrary distance from the source. The channels can be treated as being completely independent of each other, or complete mixing among channels can be assumed. The effluent concentration for a single channel is calculated with a model which considers diffusion into the matrix. Although the goal of this study is the characterization of flow and flow mechanisms, the model does consider sorption on the inner surfaces of the intact rock and so may also be useful to those studies concerned with characterizing radionuclide migration. The analytical equation used to compute the effluent breakthrough curve for a single channel was described by Neretnieks (1987) as relatively insensitive to the flow porosity or residence time, quantities which are generally not as readily characterized as the other terms in the equation.

3.1.7.4 Double-porosity models

In the broadest sense, a double-porosity model is a model that considers the transmissive and storage properties of media having both primary and secondary porosity. Primary porosity is that associated with the deposition or creation of the rock unit, and secondary porosity is the additional pore space created by fracturing or mineral dissolution. The processes by which fluids and solute are transmitted and stored in such media may be examined by representing the spatial distribution of each porosity type explicitly with a so-called discrete fracture model, or by considering the primary and secondary porosity to be two separate continua that may or may not be in equilibrium with respect to the process of interest. An example of the latter type of model is the composite porosity model for unsaturated liquid flow described by Peters and Klavetter (1988), which assumes water-potential equilibrium between fractures and intact matrix.

Preliminary numerical simulations incorporating both a single discrete fracture and adjacent matrix half-blocks have indicated that for small-aperture fractures, matrix imbibition can significantly lessen the depths to which water can penetrate the fracture when water is ponded above the fracture. However, matrix imbibition is relatively less significant for attenuating water movement when fracture apertures are large. This is because matrix imbibition rates depend only on the pressure-head boundary conditions established at the fracture-matrix interface (assuming identical matrix properties and initial conditions) and these may be similar for both large- and small-aperture fractures subjected to ponding, whereas the volumetric flux of water through a fracture increases as a function of aperture raised to some power n, where n is greater than 3 (Pyrak-Nolte and others, 1987). In general, regardless of fracture aperture, water movement down the fracture slows with time as the wetting front moves further from the infiltration boundary. This observation may be attributed to several causes, namely: (1) the head gradient across the wetting front within the fracture becomes smaller with time due to head dissipation within the already saturated portion of the fracture; (2) as the head gradient at the upper surface approaches unity the flux density of water (i.e., the infiltration rate) is reduced to a value equal to the saturated hydraulic conductivity of the materials adjacent to the infiltration boundary; and (3) the length of the saturated portion of the fracture-matrix interface increases with time, thus tending to increase the total flux of water crossing the interface into the matrix. This third effect is counterbalanced to some extent by a decrease with time in the matric potential gradient across the wetted portion of the fracture-matrix interface. The matric potential gradient normal to the fracture plane eventually approaches zero (for a vertically oriented fracture), thus causing matrix imbibition rates to also approach zero.

These same numerical simulations also indicated that the propagation of the moisture front in the fractures nearly ceases after the imposed head is removed, because of the small storage capacity of the fractures and water imbibition by the matrix. Drainage from the matrix block to the fracture did not occur during moisture redistribution and would probably not occur unless the matrix block had become nearly completely saturated.

The simulations also suggested that if water tends to pond in the same location following precipitation events, each subsequent infiltration event results in water traveling farther down the fracture than in the previous event, because matric-potential gradients and air-filled porosity are less and matrix imbibition rates correspondingly smaller in subsequent events. Pathways gradually develop in which water moves freely through the fractures with relatively little attenuation by matrix absorption.

Air initially present within partially saturated, fracture-bound matrix blocks may reduce the ability of intact matrix blocks to imbibe water moving through the fracture system. Air entrapment, which occurs when a highly continuous air phase ahead of a wetting front becomes compressed by the advancing water, decreases imbibition rates primarily because the pneumatic component of the water potential gradient partially or completely offsets the capillary pressure component. Air encapsulation, which can be regarded as incomplete saturation behind a wetting front, with residual air existing in relatively isolated pores, results in decreased imbibition rates because the relative permeability to water along the imbibition surface is limited to that which exists when the relative permeability to air goes to zero. The fraction of the pore space filled with air when the relative permeability to air goes to zero is the residual air saturation, and the corresponding water saturation is the "satiated" water saturation (Luckner and others, 1989). If the satiated water saturation is much less than 1.0 and the ambient saturation of the matrix is high, the matrix may possess a limited capacity to store water moving through the fractures. The satiated water saturation (or residual air saturation) must therefore be considered an important data item. These and other characteristics of the matrix will be provided by Activity 8.3.1.2.2.3.1 (Matrix-properties testing) in Study 8.3.1.2.2.3 (Unsaturated-zone percolation - surface-based studies).

Because the assumption of water-potential equilibrium may not be justifiable in some circumstances (Nitao, 1991), and because the application of discrete-fracture models is limited to highly idealized fracture systems, the development of more flexible models for treating fracture-matrix exchange processes of both fluids and solute is necessary. Further discussion will therefore be limited to double-porosity models that treat a fractured rock mass as two interacting, overlapping continua. The first continuum consists of relatively low-permeability, primary-porosity matrix blocks, and the second of high-permeability, secondary-porosity fissures. Each point in space is thus associated with two values of the state variables, one for the fracture domain and one for the matrix domain. Most of the storage potentially available to water and solute is associated with the primary porosity of the matrix blocks, whereas most of the mobility of fluids and solutes is associated with the potentially highly transmissive fractures. Although discontinuous at the microscopic level, both the fracture and matrix domains are treated mathematically as continua in order that meaningful spatial averages and gradients of pressure head and concentration can be defined. Implicit in this approach is the assumption that the scale of the problem is such that equivalent porous media properties can be defined for the fracture as well as the matrix domains, and that only the large-scale behavior and not the local details of the flow system are of interest.

Double-porosity models describe the time-dependent fluid-and-solute exchange process between fractures and matrix and require only estimates of fracture porosity and matrix porosity, rather than estimates of effective flow or transport porosity. The latter may have values which range between the values for total porosity (fracture plus matrix) and fracture porosity, with the actual value depending on residence time and hence on flow rate. It is anticipated that the results of double-porosity models will be less sensitive to errors in estimates of fracture porosity than single-porosity or composite-porosity models, which allow no fracture-matrix interactions, especially when fracture porosity is very small and subject to large uncertainty. This is because for very small values of fracture porosity these errors may be insignificant relative to the additional matrix storage made available to the fracture continuum through the matrix-fracture transfer term of the double-porosity model.

The fracture and matrix continua interact through a "leakage" term which depends, in part, on the matrix-block geometry, and is greatly influenced by the surface-to-volume ratio of the blocks (e.g., Huyakorn, Lester, and Faust, 1983; Huyakorn and others, 1983; and Barker, 1985). While this ratio is easily determined for well-defined block geometries such as slabs and spheres, the appropriate ratio may be difficult to determine for volumes of rock containing blocks of irregular shapes and varying sizes. For the purpose of deriving exact analytical expressions for the leakage term, it is convenient to assume that the irregular-shaped blocks can be replaced conceptually in the model either by slabs, spheres, or cubes whose sizes are either constant or whose size distribution can be estimated (see, for example, Neretnieks and Rasmusson, 1984). The basis for this approximation is the observation that for certain problems when the penetration depths of solute or water within the rock matrix are small relative to the size of the block, the curvature of the surfaces has not yet influenced the diffusion process and hence at early times the diffusion rates are insensitive to the actual block geometry (Neretnieks and Rasmusson, 1984; Zimmerman and others, 1990).

Estimation of the effective surface area per unit volume of rock is difficult. An upper limit on the surface area between matrix and actively conducting fractures may be obtained from shaft- and drift-wall mapping. However, because all of the fractures probably are not actively participating in the flow process, [illegible] because channeling within fracture planes may further reduce the total surface area across which water or solutes may diffuse into the matrix, estimates of the ratio of surface area to block volume based on fracture mapping may overestimate the effective value. If water movement through the unsaturated zone at Yucca Mountain is highly channelized, either along specific fracture pathways, or along a fracture plane, the surface area of the rock in contact with the moving fluid may be small, and matrix diffusion of either water or solute may be limited. Therefore, characterization of the degree to which flow is channelized must be considered a high priority.

In the saturated zone, estimates of the effective surface area per unit volume of rock may be possible from tracer tests, conducted in the field, that employ both a diffusing and a nondiffusing tracer to differentiate between the effects of dispersion and matrix diffusion. The nondiffusing tracer might be a colloidal material larger than the average pore size of the intact matrix. Using the dispersive term determined from the breakthrough curve of the nondiffusing tracer, and laboratory measurements of diffusivity for the diffusing tracer, the surface-to-volume ratio in the leakage term may be calibrated so that the simulated breakthrough curve of the double-porosity model matches the observed breakthrough curves of the diffusing tracer. In the unsaturated zone, large-scale tracer testing will be conducted with air as the test fluid. Since all gases diffuse, a completely nondiffusing tracer does not exist and effective block size will need to be determined by other means. One approach may be to use tracers with significantly different masses, for example helium and sulfur hexaflouride, which should theoretically possess different diffusion rates. Another approach might be to use the same tracer at several different flow rates in order to isolate the effects of matrix diffusion and dispersion. Because dispersion is linearly related to flow velocity and matrix diffusion becomes a less effective physical retardation mechanism as residence time becomes shorter, tracer tests run at different rates should be able to allow calculation of the dispersivity, which is an intrinsic parameter independent of flow rate, as well as calculation of an effective diffusion coefficient. Cross-hole gas-tracer tests will be performed in the exploratory studies facility (see, for example, Activity 8.3.1.2.2.4.3, Bulk-permeability tests in the exploratory shaft, in YMP-USGS SP 8.3.1.2.2.4, Unsaturated-zone percolation -- ESF studies) and from surface-based boreholes (see YMP-USGS SP 8.3.1.2.2.3, Unsaturated-zone percolation - surface-based studies) at the UZ-9 borehole complex. Moench (1984) presented type curves for pumping or injection tests in double-porosity media that allow the effective block size to be determined from the pressure response in observation wells. These type curves are easily adapted for use with highly compressible fluids such as air and will be applied to the results of the cross-hole air-injection tests to provide independent estimates of effective block size.

For fluid-flow problems, interblock flow is typically assumed to be negligible at the field scale, and only the transfer of fluid between fractures and matrix is considered by many models (e.g., Huyakorn, Lester, and Mercer, 1983; Moench, 1984; and Zimmerman and others, 1990). Permeability and porosity of the fracture continuum are determined from hydraulic tests (for example, Moench, 1984), or in the case of drained fractures in the unsaturated zone, pneumatic tests. In the unsaturated zone, calculation of the leakage term for fluid transfer is more complicated because, unlike the governing equation for either saturated flow or chemical diffusion, the governing equation for unsaturated flow is nonlinear and not amenable to exact analytical solution. However, Zimmerman and others (1990) were able to derive approximate solutions for the absorption of water into porous spherical, cylindrical, and slab-like blocks and also derived a scaling relation, based on the ratio of surface area to volume, for predicting the rate of absorption into irregular-shaped blocks. While the approximate analytical solutions for the spheres and cylinders had only fair accuracy when compared to the results of numerical simulations, the analysis also showed that when the values of fractional uptake of water predicted by the numerical model for various geometries were plotted against normalized time, the rates of water uptake by the matrix blocks were quite insensitive to the actual geometries of the blocks. Normalized time as defined by Zimmerman and others (1990) is a function of the unsaturated flow properties of the medium and the initial saturation, and is proportional to the square of the ratio of surface area to volume.

The scaling relation can be used to calculate an appropriate leakage term in double-porosity models when block sizes and shapes are variable. Such models would be used to examine the depths to which infiltrating pulses of water may penetrate the unsaturated zone at Yucca Mountain. Because a single curve can adequately describe the relationship between fractional uptake and normalized time for all block sizes and shapes, the flow rate into any block can be determined from the product of the initially air-filled pore volume of the block, the slope of the fractional uptake versus normalized time curve at the normalized time determined for that block, a constant which accounts for the effects of the unsaturated material properties and initial saturation of the block, and the square of the ratio of surface area to volume of that block. If the histogram or frequency distribution of the ratios of surface area to volume for the blocks within the rock volume is known from mapping or other sources, the total leakage from the fracture continuum to the matrix continuum at any time can be estimated by summing the contributions from the individual blocks.

An additional approach for modeling the exchange of fluids or solute between fractures and matrix is based on the Multiple Interacting Continuum (MINC) model described by Pruess and Narasimhan (1985). The methodology is implemented in conjunction with numerical simulators such as TOUGH (Pruess, 1987) that are based on the integrated finite-difference method and which utilize a local rather than global coordinate system. The MINC conceptual model assumes that thermodynamic conditions in the matrix blocks depend primarily on the distance from the nearest fracture, an assumption that implies that thermodynamic equilibrium exists locally within that portion of the fracture domain conceptually associated with the matrix blocks. The basis for this approximation is that permeability within the fracture continuum is assumed to be much higher than that of the matrix blocks, and so local equilibrium in the fracture continuum is re-established instantaneously relative to the response time of the matrix to some perturbation of the system. For each computational cell in the fracture continuum, a preprocessor calculates the geometric parameters for a single fictitious matrix block whose computational cells are conceptually nested within each other. Each computational cell of this fictitious matrix block has a volume and intercell surface area which is the sum of the volumes and intercell surface areas of all matrix computational cells centered a certain distance from a fracture surface. The sum is taken over all matrix blocks located within that particular computational cell of the fracture continuum. In this manner, transient processes involving an unlimited number of matrix blocks can be treated with relatively few matrix computational cells. It may also be possible to assume that the block-size distribution within a fracture computational cell is known only in a statistical sense or to randomly generate block-size distributions using stochastic fracture-network models.

In solute-transport studies in double-porosity media (Huyakorn, Lester, and Faust, 1983; Neretnieks and Rasmusson, 1984), it is generally assumed that advection and dispersion are the dominant transport processes in the fracture system, and that diffusion is the dominant transport process in the matrix. Neretnieks and Rasmusson (1984) described an integrated finite-difference model for the advective-dispersive transport of solute in fractured porous media which utilized the multiple interacting continuum concepts described above to account for the effects of matrix diffusion. That study incorporated information on matrix block sizes derived from drift-wall mapping to generate a histogram of equivalent cubical matrix-blocks of different sizes. This histogram was then used to generate a "pseudobody", or fictitious matrix block, for each cell in the fracture continuum computational mesh. Loss of solute from the fracture continuum took place by diffusion into this pseudobody. This approach will be used to examine solute transport in fractured porous rock.

3.1.7.5 Stochastic fracture continuum models

Fractured rock is extremely heterogeneous with respect to its flow and transport properties. Even dense sampling networks and intensive testing might not define the exact spatial distribution of these properties in highly fractured geologic settings. However, hydrologic models require that flow and transport variables be defined at discrete locations within the flow domain, including those that have not been sampled. Uncertainty in input variables due to natural variability and limited sampling results in uncertainty in the output variables (pressure head, seepage velocity, Darcy flux, etc.) produced by these models. The stochastic method assumes that the input variables to such models are random values drawn from an associated probability distribution and that these variables are spatially structured. The randomly generated input variables are often constrained to reproduce the known values at where these have been measured. The spatial structure can be described using conventional geostatistical measures such as the spatial covariance or semivariance. However, it has recently also been noted that property distributions in natural environments exhibit correlations over many scales with no effective bound on the range of correlations (Hewett, 1986). In these cases, the methods of fractal geometry may provide a better description of nested or self-similar structures than conventional geostatistical techniques. The observation that natural media are often structured or spatially correlated with respect to their flow or transport properties implies that a measurement made at one location provides information about the value of that variable at a second unmeasured location, information which exceeds that provided by a knowledge of the statistical distribution alone. Previous modeling studies have indicated that the large-scale flow and transport properties of a medium are generally sensitive to the spatial distribution of hydraulic conductivity, as determined by measurements made at some smaller scale.

Typically, a stochastic approach involves the repetitive numerical solution of the flow or transport equations in the discretized domain using randomly drawn but spatially structured input variables to produce statistical distributions of the output variables. These distributions are then analyzed to determine the probability that any particular outcome will occur, given that the form and parameters of the input variables, as well as correlations between them, have been correctly identified, that the spatial structure is correctly described, and the model adequately describes the physical processes at the temporal and spatial scales of interest.

The stochastic methodology has been used to characterize flow at the scale of both a single fracture (Moreno and others, 1988; Tsang and others, 1988) and at the field scale. At the field scale, fractured rock has been treated both as a network of discrete fractures whose characteristics are known only in a statistical sense (Cacas and others, 1990a; Cacas and others, 1990b; and Schwarz and Smith, 1988), and also as a heterogenous, porous continuum whose spatial variability with respect to hydraulic conductivity is characterized by a variance and a semivariogram (Neuman, 1987). The goal of these and other similar analyses has been both to estimate the global behavior of the rock with regard to fluid flow or solute transport, and to examine the variability in behavior at smaller scales.

Following Neuman (1987), who suggested treating fractured rock as heterogeneous continuum that is the product of a random, partially structured process, the principal stochastic model for flow in fractured rock to be developed by this study is a stochastic continuum model constructed on the basis of hydraulic conductivities as determined from single-hole, air-injection packer tests (see Activity 8.3.1.2.2.4.3, Bulk permeability tests in the ESF, in YMP-USGS SP 8.3.1.2.2.4, Unsaturated-zone percolation - ESF studies). Although the test fluid is air, the single-hole packer tests should provide good estimates of the hydraulic conductivity in fractured, welded tuff formations where the fractures are believed to be drained in most locations and dominate the overall permeability of the rock. The spatial correlation structure of the logarithms of the measured hydraulic conductivity values will be examined using semivariograms, which express the variance or average squared difference between pairs of values of log hydraulic conductivity measured a given distance from each other. Analyses will also be performed to determine if the structure displays a fractal character. As described by Hewett (1986), the fractal character can be related to geostatistical measures such as the autocovariance or semivariance. The fractal dimension can be determined from the slope of a log-log plot of spectral density versus frequency, or the slope of a log-log plot of semivariance versus lag spacing. In geostatistics, the strength of the correlation at a given separation distance is a function of the volume or "support" over which the measurements are made, with the variability generally increasing (and the degree of spatial continuity decreasing) as the size of the support becomes smaller. When treating fractured rock as a stochastic continuum, the size of the support is determined by choosing an injection interval at which measurable conductivities are readily obtained. For instance, in the ESF Bulk permeability test (Activity 8.3.1.2.2.4.3), the injection intervals must straddle a sufficient number of fractures so that there are very few tests in which the flow rate is so small that it cannot be measured.

By performing the packer tests in several boreholes having different orientations, a semivariogram for several different directions can be defined. The dependence of the degree of spatial continuity on direction is referred to as "structural" anisotropy. As described by Neuman (1987), the conductivity measurements themselves can be treated as scalar quantities, and the directional influences, which are a consequence of the manner in which the boreholes and fractures intersect, are treated as random noise in the data. The effect of fracture orientation on the hydraulic conductivity of the rock is assumed to be taken into account through the large-scale structural anisotropy.

After a semivariogram has been fitted to the data from single-hole packer tests, the hydraulic conductivity between the boreholes at the site will be estimated using conditional simulation, so-called because the simulated hydraulic conductivity fields ("realizations" of the stochastic process) are constrained to reproduce the data at the measurement locations. Simulation, whether conditioned on measured data or not, is preferable to kriging in certain instances because simulation more faithfully reproduces the correlation structure of the measured hydraulic conductivity field, whereas kriging provides the best estimates at unmeasured locations but tends not to preserve the structure, generally interpolating more smoothly than the measured data would suggest reasonable. Preservation of the correlation structure of the hydraulic conductivity field is considered essential to reproducing the dispersive characteristics of the medium with solute-transport models. Conditional simulation is typically accomplished by generating a spatially structured random field, determining the residuals between the measured and simulated values at the measurement locations, and adding the residuals to the simulated values at the measurement locations to reproduce the measured values. To preserve the spatial structure, the residuals at the measurement locations are then kriged to estimate the residuals to be added to the simulated values at locations for which parameter estimates are to be generated. For hydraulic-conductivity fields which display a fractal structure, it is also possible to use simulation methods which preserve this structure (Voss, 1985).

Statistical transport models have been able to theoretically define effective dispersivities for heterogeneous media when the statistical structure of the permeability distributions is known and the length of the flow path is large relative to the range of the spatial correlations (Neuman and others, 1987). However, at flow-path distances of the same order or smaller than the range of the semivariogram, the effective dispersion coefficient continues to grow, and models based on the concept of an effective dispersion coefficient provide poor estimates of the concentration distribution in any particular realization of the flow field. Under those circumstances, simulation is a more credible method of analysis.

Estimates of hydraulic conductivity generated for the three-dimensional space between the boreholes will form the basis for flow and transport calculations intended to investigate the scale-dependence of the flow and transport properties, and possible anisotropy of the rock with respect to hydraulic conductivity. As discussed earlier, to account for the uncertainty in the estimates of the hydraulic conductivity values between boreholes, it is necessary to analyze the flow and transport characteristics of the rock mass for many realizations and summarize the results statistically to characterize the possible behavior of the system with respect to flow and transport processes.

Neuman (1987) pointed out that for any given field environment, it may be possible to distinguish between possible alternative hydraulic conductivity realizations by using geophysical tools such as electromagnetic or seismic geotomography. He reported that the resolution of these geophysical techniques allowed the geotomographic images to be compared directly with the simulated conductivity values. Although no such geophysical investigations are currently planned as part of the bulk-permeability tests in the ESF (Activity 8.3.1.2.2.4.3), cross-hole pneumatic testing may provide a basis for distinguishing between the possible alternative hydraulic conductivity realizations. It may also permit verification of the ability of the stochastic continuum approach to recreate the global permeability tensor, if, in fact, one can be defined through cross-hole testing (Hsieh and others, 1985), or to predict in a statistical sense the existence of high-permeability pathways between boreholes.

Hydraulic conductivity and porosity values associated with the fracture and matrix domains do not necessarily share the same spatial correlation structure. This is, in part, because they are the results of different processes. In addition, the supports at which measurements are made are considerably different, and this in turn influences both the total variance and the spatial correlation structure. Matrix properties will be measured at the scale of hand specimens, while fracture continuum properties will be based on injection tests conducted in borehole intervals which span lengths of several meters or more. It is therefore necessary to determine a suitable scale at which to perform flow and transport computations which incorporate both fracture and matrix properties. As previously stated, for the fracture domain it is not possible to estimate the values of log hydraulic conductivity for volumes of rock smaller than that at which the measurements are made, since nothing is known about the variation in hydraulic conductivities or the spatial correlation structure except at the measurement scale. Therefore, the minimum size of computational cells in a stochastic continuum model incorporating both fracture and matrix properties is limited by the scale at which the fracture continuum properties have been measured. Estimation of matrix properties at the scale of the fracture domain computational cells will be done by generating a spatial distribution of matrix properties at grid sizes of the same dimensions at which the matrix property measurements were made, and then performing flow simulations through the heterogeneous matrix continuum bounded by the fracture domain computational cell to determine the equivalent homogeneous matrix hydraulic conductivity to be applied at that particular computational cell.

3.1.7.6 Summary of model functions

The technical issues to be addressed by this study plan require diverse modeling approaches covering a range of spatial scales. Some redundancy in the intended function of these models exists. However, the development of multiple modeling approaches is deemed prudent given that any particular approach has inherent limitations, as described in Sections 3.1.7.1 to 3.1.7.5. Figure 3.1-1 summarizes the technical functions of each modeling approach. The iterative nature of hypothesis formation, modeling, and experimentation must once again be emphasized. The modeling approaches described in the preceding sections are thought to be appropriate based on current understanding. This understanding is expected to continue to evolve with time.

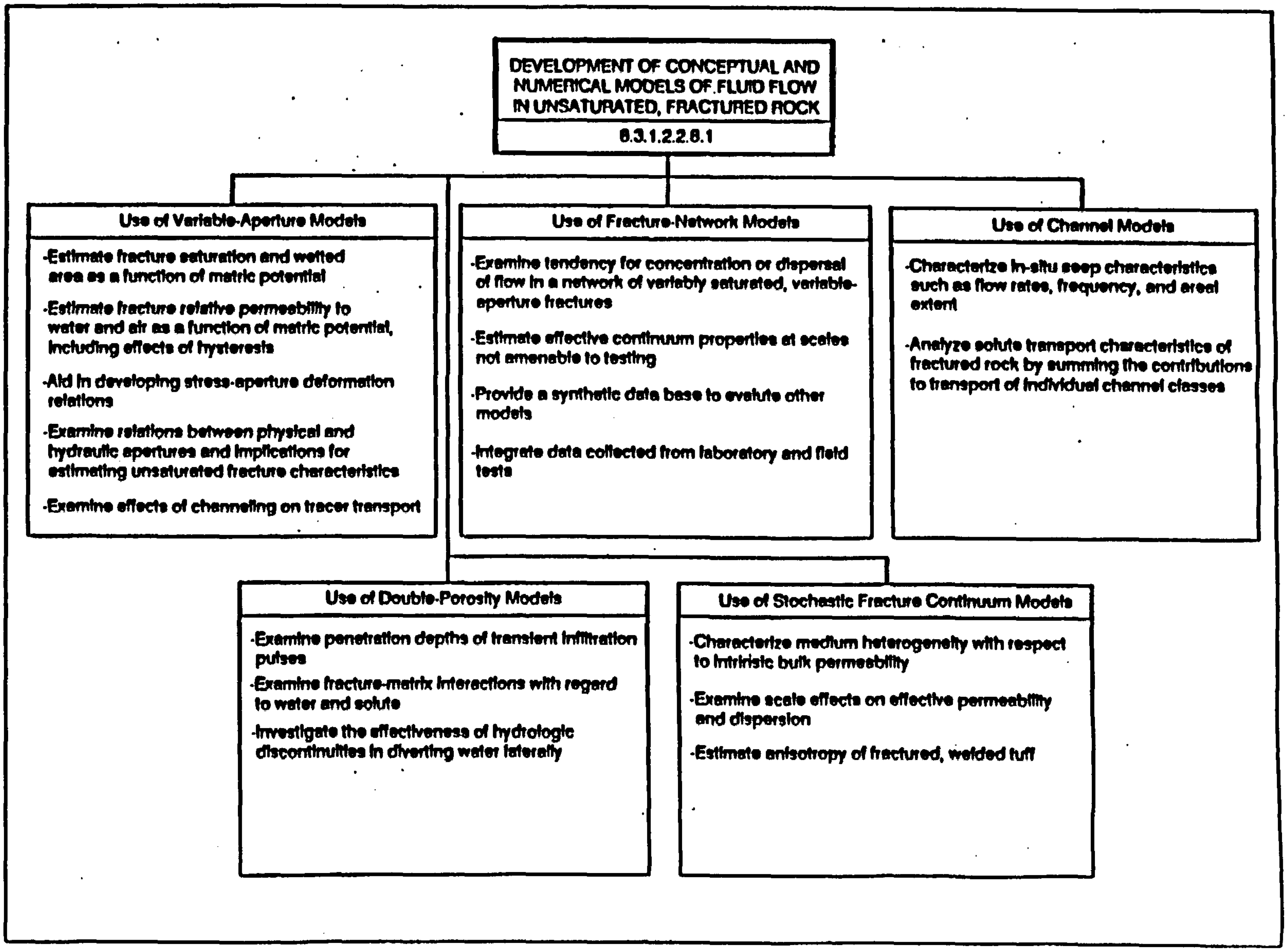

Figure 3.1-1. Diagram of the development of unsaturated-zone models activity, showing modeling approaches and associated technical functions.

3.2 Validation of conceptual and numerical models of fluid flow through unsaturated, fractured rock

3.2.1 Objective of activity

The objective of this activity is to evaluate the applicability of conceptual and numerical models developed under Activity 8.3.1.2.2.8.1 (Section 3.1) to the Yucca Mountain site, using the results of experiments currently planned for the ESF and associated laboratory experiments.

3.2.2 Technical issue to be addressed

The technical issue addressed by this activity is the applicability of conceptual and numerical models describing fluid flow and tracer transport in variably saturated, fractured rock to the Yucca Mountain site.

3.2.3 Rationale for activity selection

The purpose of the first part of this study was to examine and describe the mechanisms by which fluids move through and are stored in unsaturated fractured rock, in order to aid in the design of experiments, assess the limitations and implications of data collected from the site, and so that these mechanisms can be more properly accounted for in numerical models developed primarily to characterize the overall hydrologic system at Yucca Mountain. The second activity addresses the question of the validity of the numerical models developed in the first part of this study.

The iterative nature of hypothesis formation, modeling and experimentation has been emphasized in various sections of this study plan. Well-controlled experiments provide the basis for evaluating the conceptual understanding of the physical processes controlling fluid movement in unsaturated fractured rock and provide a basis for revising and updating this understanding. Experimentation also provides a basis for assessing the treatment of the identified controlling processes in numerical models.

3.2.4 General approach to model validation

A model is said to be a valid representation of a hydrologic system if it adequately describes the most important physical processes at the temporal and spatial scales at which the model is being applied. As described below, model validation is linked to both the calibration process and sensitivity analysis. In general, the process of model validation requires an independent estimate of the model parameters, and comparison of model output with measured data for some variable of interest. Traditionally, a model is calibrated by varying its parameters within their known range of uncertainty to minimize residuals between the predicted and observed values for a given set of boundary conditions, initial conditions, pumping stresses, etc. The calibrated model is then compared to data collected from the same system after it has been subjected to different hydrologic stresses, boundary conditions, or initial conditions, and residual errors are again calculated. Residual error should be uncorrelated in space or time and mean error should approach zero. Straight lines fit to scattergrams of simulated versus measured data should have a one-to-one slope, large correlation coefficients, and uncorrelated residuals. Residual error should also be uncorrelated with the measured values. If a second independent data set for the hydrologic system is not available, one possible approach is to calibrate the model on the basis of all observed values but one, and then predict the value of the variable of interest at the omitted calibration point. Each data point is systematically omitted from the calibration process and residuals are calculated at the omitted point. These residuals are then treated as if they were obtained from a second independent data set. No quantitative methodology has yet been universally accepted for validating stochastic models that generate distributions of values at a given point in space or time when only one measured value at that value of space or time is available for comparison. One possible approach would be to test if the measured data fell within the interval containing some arbitrarily large percentage, say 95 percent, of the generated values at that location.

The determination of what constitutes an acceptable residual error is case-dependent in that the acceptable error depends on both the goals of the modeling exercise and the influence that the errors may have on management decisions made on the basis of that modeling effort. For example, for models that calculate ground-water travel time, the model can be considered adequate if its known error is small enough that it does not alter the conclusion of whether the site does or does not meet the ground-water travel-time criteria. In this case, the goal is the determination of ground-water travel time and the management decision is whether or not to build a repository. For the subsystem models and model components described in this study plan, the determination of whether or not a model is a valid representation of a physical system would ultimately need to be related to the goals of the larger-scale models it supports. The cumulative error associated with the large-scale model would need to remain small enough that a management decision could be reliably made. The validation or acceptance criteria for models associated with this study must therefore be developed in the context of the large-scale modeling effort described in SCP Study 8.3.1.2.2.9 (Site unsaturated-zone modeling and synthesis).

As described earlier, direct measurement of unsaturated-zone hydrologic parameters at scales relevant to the site-scale modeling activity is not feasible because of the difficulty in changing the saturation state of large volumes of fractured rock in a controlled manner. For the same reason, experimental evidence to evaluate model behavior at these spatial scales may be lacking. An important step toward the validation of large-scale models, is the development of models of flow and transport in single fractures or simple fracture networks. Validation of these models against well-controlled laboratory experiments enables their use in generating a synthetic data base which can then be treated as a well-characterized natural system. This synthetic data base can then be used to expose the limitations of models developed for application at larger scales, at which the models cannot accommodate as much detail in the treatment of either process or system geometry. Such models might include double-porosity models, stochastic continuum models, or continuum models based on an REV approach.

In comparisons of numerical models with field experiments, there typically exists some uncertainty about the system geometry, making it unclear if disagreement between simulated and experimental results should be attributed to inadequate treatment of the physical processes at the temporal and spatial scales of interest, or to limited data concerning the geometry of the system. The use of a synthetic data base eliminates the uncertainty concerning the system geometry and allows the investigation to focus on the treatment of the physical processes. A synthetic data base may also permit an investigation into the consequences of knowing the geometry of the system imperfectly, or permit an assessment of the amount of data that needs to be collected. Clearly, however, the models used to generate this synthetic data base must have a firmly established physical basis. That is, at some point, these models must be tested against well-controlled laboratory or field experiments. The following section includes a description of the use of some experiments described in YMP-USGS SP 8.3.1.2.2.4 (Unsaturated-zone percolation - ESF studies) to validate certain aspects of single-fracture and simple fracture-network models. Certain moisture-transfer processes may be occurring at the site-scale that will not be examined with experiments associated with that study, but may be characterized by field measurements of water potential, pneumatic pressure and temperature (see YMP-USGS SP 8.3.1.2.2.3, Unsaturated-zone percolation - surface-based studies). These include vapor diffusion from higher-temperature regions at depth to cooler, shallower zones, or the removal of moisture from Yucca Mountain by barometric pumping. Characterization of these processes is beyond the scope of the present study.

3.2.5 Summary of validation studies

This study is concerned with the development of numerical and analytical models appropriate for application to unsaturated, fractured rock. While there are no experimental activities directly associated with this study, experiments have been planned, as parts of other studies, that can be used to evaluate the models developed in the present study. These experiments are described in detail in their respective study plans and therefore only the briefest overview of these experiments will be given here.

The ESF intact-fracture test (Activity 8.3.1.2.2.4.1, in Study 8.3.1.2.2.4, Unsaturated-zone percolation - ESF studies) will retrieve and test large-diameter cores containing fractures oriented either perpendicular or parallel to the core axis. Current plans require that a total of approximately 96 cores be obtained with minimal disturbance to the fractures at various horizons within the Tiva Canyon welded, Paintbrush nonwelded, Topopah Spring welded, and Calico Hills nonwelded hydrogeologic units. The cores will be taken to the laboratory and fitted with porous plates through which hanging water columns will be used to control the average water potential and hydraulic gradients within the core. Because the aperture distribution within a fracture, and hence the fracture permeability, is a strong function of the compressive stress normal to the fracture plane, curves describing the permeability of the core as a function of matric potential will be constructed at several different normal stresses for each fracture tested. Tracer tests will also be done at selected matric potentials and compressive stresses. After hydraulic testing has been completed, Wood's metal will be injected into the fractures of selected cores at a certain normal stress and the topography of both surfaces of the resulting cast digitized using a projection moire technique. From the topography of the surfaces of the cast, the aperture distribution of the fracture at that compressive stress can be computed. This aperture distribution can then be input into the variable-aperture model described earlier, and predictions of the liquid permeability of the fracture and tracer breakthrough curves at different matric potentials can be compared to the actual measurements. Similarly, aperture distribution for a given fracture as determined from the Wood's metal casts can be compared to aperture distributions computed from the topography of the fracture surfaces, using the stress-deformation fracture models described earlier.

The ESF percolation test (Activity 8.3.1.2.2.4.2, in Study 8.3.1.2.2.4) will utilize fractured cores and excavated blocks of fractured rock to evaluate various processes influencing fluid flow and tracer movement in unsaturated, fractured rock. Imbibition experiments utilizing fractured cores will permit an evaluation of fracture-matrix interactions, including such complicating effects as the presence of fracture coatings, matrix anisotropy, and interference between the liquid and gas phases. The block experiments will permit a comparison of flux predictions made on the basis of measured water potentials, air-permeability testing, and fracture characterization with known applied fluxes. Water-potential measurements, air-permeability testing, and fracture mapping are the basic test methods being used to characterize flux through the unsaturated zone at Yucca Mountain as a whole. Excavation of a block of fractured tuff approximately 2 meters on a side from the proposed repository horizon will permit control of the boundary conditions, access for the installation of small-diameter boreholes from all sides, and ample surface exposure for fracture-network characterization. The boreholes will be instrumented with thermocouple psychrometers and tensiometer-transducer systems to monitor water and matric potentials, respectively, and electrical conductance probes to monitor the arrival of tracers. Boreholes will be drilled to terminate at intersections with specific fractures so that moisture and tracer movement within those fractures can be detected, and within the adjacent matrix so that fracture-matrix interactions can be observed. The moisture state of the fractures within the block will be altered by sequentially decreasing the applied flux. The experiment will provide data on the behavior of a simple fracture network at various saturations, data that can be used to evaluate the performance of fracture-network models. Similar block experiments performed at the contact between the upper welded portion and the non- to partially welded basal portion of the Tiva Canyon Member (included within the Paintbrush (PTn) hydrogeologic unit), and at the contact between the non- to partially upper portion and the underlying densely welded part of the Topopah Spring Member are expected to provide detailed data on the mechanisms of water movement as water becomes laterally redistributed at fracture terminations in nonwelded tuff, or as diffuse moisture fronts in the nonwelded and bedded tuffs are channeled towards discrete fractures in the underlying welded tuff matrix.

The ESF Bulk-permeability test (Activity 8.3.1.2.2.4.3, in Study 8.3.1.2.2.4) is based on the pneumatic testing of packed-off intervals of boreholes. As currently planned, as many as four borehole clusters consisting of three boreholes each will be drilled at the main test level of the ESF. The holes within each cluster will be drilled from alcoves in a roughly conical pattern, with each hole diverging from its neighbor at an angle of approximately 120 degrees. Under the assumptions that the fracture system is drained of water under present-day moisture conditions and that the fracture system dominates the total permeability in welded tuff, single-hole and cross-hole tests using air can be used to approximate the water-saturated permeability of the rock. By redefining dimensionless variables used in type-curve matches, test results can be interpreted in a variety of different conceptual frameworks developed originally for water-saturated systems, including those developed for double-porosity systems by Moench (1984), and equivalent anisotropic continua (Hsieh and others, 1985). As described earlier, stochastic continuum models rely on the results of single-hole tests to establish the spatial structure of the permeability field in the directions parallel to the boreholes (Neuman, 1987). Conditional simulation can then be employed to numerically generate permeability fields having the same spatial structure. Conditional simulation permits a numerical investigation of scale effects and anisotropy for the rock volume between the boreholes. Scale effects and anisotropy in permeability can then be physically explored through cross-hole testing within the same borehole cluster from which the single-hole data were obtained, and comparisons made with the results of the simulations.

As currently planned, the ESF Excavation-effects test (Activity 8.3.1.2.2.4.5, in Study 8.3.1.2.2.4) will monitor the changes in stress, fracture deformation, and fracture permeability that accompany drift excavation. Three sets of holes oriented parallel to a planned drift extension will be drilled from an alcove located at the end of a drift. In the first set of holes, hydraulic pressure cells grouted into place will measure changes in load caused by drift extension, from which changes in stress can be calculated. In the second set of holes, extensometers will be emplaced to measure fracture deformation during drift excavation. In the third set of holes, air-injection packer tests conducted before and after drift extension will measure changes in rock permeability. The change in permeability can be attributed primarily to fracture deformation due to the larger compliance of the fractures relative to the intact matrix. The test provides a data base to field-test the stress-permeability relationships developed for fractures on the basis of laboratory measurements of fractured cores (see Activity 8.3.1.2.2.4.1, described above).

In addition to the tests described above, the drifts and ramps associated with the ESF will provide large surface areas on which to make observations on the spatial and temporal variations of flow quantities and flow mechanisms operating within the unsaturated zone at Yucca Mountain (see Activity 8.3.1.2.2.4.7, Perched-water test in the ESF, in YMP-USGS SP 8.3.1.2.2.4) that may not be evident from surface-based boreholes because of the limited area monitored by those boreholes. The relevance of process-oriented models described in this study plan, like the site-scale models described in YMP-USGS SP 8.3.1.2.2.9, (Site unsaturated-zone modeling and synthesis) will be evaluated at least qualitatively in light of those observations. The technical issues to be addressed by this activity and the modeling strategy to be used in resolving these issues are summarized below in Table 3.2-1, along with the data required to validate those models and the SCP activities that will supply that data. Figure 3.2-1 shows the data provided to the model validation efforts by associated activities.

3.2.6 Summary of equipment requirements

This activity does not directly incorporate scientific equipment for which standard procedures, e.g. ASTM or API standards, data acquisition, data reduction, and analysis are required. No instrumentation for

Table 3.2-1 Association of technical issues with modeling strategy used for issue resolution, required validation data, and validation data source.

Technical Issue [a]	Modeling Strategy	Required Data	Data Source [b]
(1)	Variable aperture model	aperture variation, volumetric flow as function of matric potential	Intact-fracture test
	Fracture-network model	volumetric flow as function of matric potential	Percolation tests
		fracture network geometry	
		pneumatic aperture distribution	
		water-potential distribution	
(2)	Variable aperture model	aperture variation	Intact-fracture test
		channel geometry	
		tracer breakthrough curves	
	Fracture-network model	fracture lengths, interconnectedness	Geologic mapping
		hydraulic (pneumatic) aperture distribution	Bulk-permeability tests
		spatial and temporal distribution of flow at Yucca Mountain	Perched-water test
(3)	Variable aperture model	aperture variation	Intact-fracture test

	Double-porosity model	cumulative imbibition into fracture cores	Percolation tests
		character of fracture coatings	
		matrix anisotropy	
		tracer breakthrough curves and water potential distributions from block studies	
(4)	Fracture-network model	volumetric flux as function of matric potential, fracture network geometry, pneumatic aperture distribution, and water potential distribution	Percolation tests
(5)	Stress-deformation model	topography of fracture surfaces, Wood's metal casts	Intact-fracture test
		in-situ stresses before and after drift excavation	Excavation-effects test
		rock deformation	
		permeability before and after drift excavation	
(6)	Stochastic-continuum model	spatial distribution of matrix permeability	Matrix-properties testing
		spatial distribution of fracture permeability	Bulk-permeability tests
		directional permeabilities	
		scale effects	

(7)	Double-porosity model	spatial distribution of water potential at hydrogeologic contact at various applied fluxes matrix relative water permeability as a function of water potential fracture relative permeability as a function of water potential	Percolation tests

a. Technical issues (see Section 3.1.4)

(1) Determine the conditions under which flow within fractures located within the unsaturated zone is likely to occur.

(2) Study the nature of channeling processes and the implications of channeling for the transport of water and radionuclides.

(3) Examine factors influencing the extent to which the fractures and matrix interact, including the effects of fracture coatings and the potential for the interference of different phases in double-porosity media.

(4) Develop methods for estimating the relative permeability of unsaturated, fractured rock in order to provide a basis for indirectly estimating the flux through Yucca Mountain on the basis of in-situ measurements of water potential.

(5) Develop models which describe the effect of stress changes on the permeability and relative permeability of rough-walled natural fractures.

(6) Develop or adapt models to characterize the spatial heterogeneity in the permeability of fractured rock.

(7) Examine the conditions under which hydrologic discontinuities provide effective mechanisms for diverting water laterally.

b. Data Sources

Activity 8.3.1.2.2.3.1 Matrix hydrologic properties testing.

Activity 8.3.1.2.2.4.1 Intact-fracture test in the exploratory shaft facility.

Activity 8.3.1.2.2.4.2 Percolation tests in the exploratory shaft facility.

Activity 8.3.1.2.2.4.3 Bulk-permeability tests in the exploratory shaft facility.

Activity 8.3.1.2.2.4.5 Excavation effects test in the exploratory shaft facility.

Activity 8.3.1.2.2.4.7 Perched-water test in the exploratory shaft facility.

Activity 8.3.1.4.2.2.4 Geologic Mapping of the exploratory shafts and drifts.

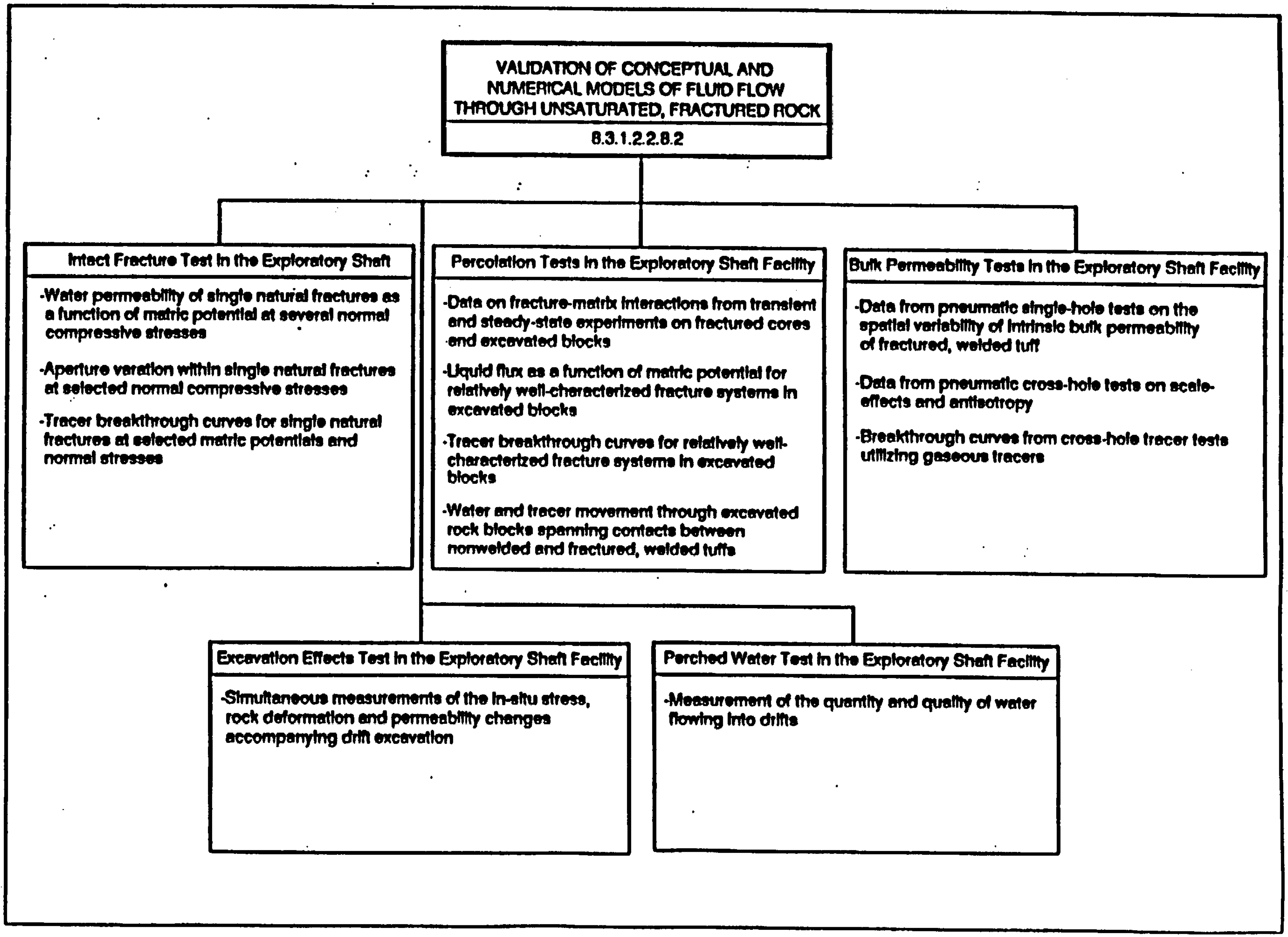

Figure 3.2-1. Diagram of the validation of unsaturated-zone models activity, showing data provided by associated activities.

specified tolerances, accuracies, or precision is required. Adjunctive studies, e.g. Study 8.3.1.2.2.4 (Unsaturated-zone percolation - ESF studies), will address technical specifications required for instrumentation used within their appropriate study plans. Where numerical models are used, assumptions, limitations, and statistics, if appropriate, will be specified in conjunction with analyses of the methods.

4 APPLICATION OF STUDY RESULTS

4.1 Application of results to resolution of performance and design issues

The results of this study will, through supporting Study 8.3.1.2.2.9 (Unsaturated-zone modeling and synthesis), be indirectly used in the resolution of YMP performance issues concerned with fluid flow (both liquid and gas) within unsaturated, fractured rock. The principal applications will be in limiting radionuclide releases (Issue 1.1), assessments of ground-water and gas travel times (Issue 1.6), NRC siting criteria (Issue 1.8), and design analyses related to the waste package (Issue 1.10). Issues concerned with waste package containment (Issue 1.4) and engineered barrier system release rates (Issue 1.5) will also use 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 1.3.

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

The models developed from this study will be utilized in other studies in Investigation 8.3.1.2.2 (Description of the unsaturated-zone hydrologic system at the site), as well as other studies in 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;
- 8.3.1.3.4 - Studies to provide information required on radionuclide retardation by sorption processes along flow paths to the accessible environment;
- 8.3.1.3.5 - Studies to provide the information required on radionuclide retardation by precipitation processes along flow paths to the accessible environment;
- 8.3.1.3.6 - Studies to provide the information required on radionuclide retardation by dispersive/diffusive/advective transport processes along flow paths to the accessible environment;
- 8.3.1.3.7 - Radionuclide retardation by all processes along flow paths to the accessible environment;
- 8.3.1.3.8 - Studies to provide the required information on retardation of gaseous radionuclides along flow paths to the accessible environment;
- 8.3.1.5.2 - Potential effects of future climatic conditions on hydrologic characteristics;
- 8.3.1.6.4 - Potential effects of erosion on hydrologic characteristics;
- 8.3.1.8.3 - Potential effects of igneous and tectonic activity on hydrologic characteristics;
- 8.3.1.16.3 - Ground-water conditions within and above the potential host rock.

The final product of Study 8.3.1.2.2.8 is a model or set of models to describe two-phase fluid flow in unsaturated, fractured rock. The final flow models will be incorporated into site unsaturated-zone models (Study 8.3.1.2.2.9) and used to perform a set of baseline simulations of the natural geohydrologic system. Study 8.3.1.2.2.9 will use the simulation of the presently existing natural system as initial conditions, and perform a sequence of simulations to extrapolate the system both forward and backward in time. The forward extrapolation will be based on expected most-probable changes in the site climatic regime derived from Study 8.3.1.5.1.6 (Future regional climate and environments); whereas the backward extrapolations will be based on past climatological conditions and variations inferred from Study 8.3.1.5.1.4, (Synthesis of the paleoenvironmental history of the Yucca Mountain region). The sequence of baseline simulations constitutes a standard set against which the effects of extreme or episodic changes in environmental conditions at the site may be assessed. This flow model (Study 8.3.1.2.2.9) will be used to define flow paths and calculate fluxes and velocities within the unsaturated zone, as described under Activity 8.3.1.2.2.9.3 (System integration). The use of the model(s) will have indirect application to the previously cited investigations as explained below.

Through its support of Study 8.3.1.2.2.9, the present study will contribute to Investigation 8.3.1.2.3 (Description of the saturated-zone hydrologic system at the site). In order to calculate flow paths, fluxes, and velocities within the saturated zone, input from unsaturated-zone flow models will be required. Study 8.3.1.2.3.3 (Site saturated-zone synthesis and modeling) defines model and computer code development for the saturated-zone system. In order to model this system the unsaturated-saturated zone interface boundary conditions must be defined. These boundary conditions will be defined from the unsaturated-zone models of Study 8.3.1.2.2.9, supported by the present study.

Investigations 8.3.1.3.1, 8.3.1.3.4, 8.3.1.3.5, 8.3.1.3.6, 8.3.1.3.7, and 8.3.1.3.8 deal with providing information on water chemistry; radionuclide retardation by sorption, precipitation, dispersive/diffusive/advective transport, and all processes; and gaseous radionuclide transport along possible flow paths to the accessible environment. The models in this study will support Study 8.3.1.2.2.9 in defining the possible flow paths in the unsaturated, fractured rock to be applied in these investigations.

Investigations 8.3.1.5.1, 8.3.1.5.2, 8.3.1.6.4, and 8.3.1.8.3 are concerned with the potential effect of climatic, erosional, and tectonic activities on the hydrologic system. The conceptual models and computer codes developed in this study, through their support of Study 8.3.1.2.2.9, will contribute to evaluating these effects for the unsaturated zone. The site unsaturated-zone models will serve as a baseline case that can be stressed to assess the effects.

The understanding of fluid flow in unsaturated, fractured rock developed during the present study will support Investigation 8.3.1.16.3 (SCP Section 8.3.1.16.3 outlines studies to be used in evaluating ground-water conditions within and above the potential host rock). Study 8.3.1.16.3.1 (Determination of the preclosure hydrologic conditions of the unsaturated zone at Yucca Mountain) will compile and synthesize pertinent results of this study and Study 8.3.1.2.2.9. These results will be used in addressing repository design requirements, design analyses, and underground facilities technology.

5 SCHEDULES AND MILESTONES

5.1 Schedules

Figure 5.1-1 presents an integrated schedule for development and validation of conceptual and numerical models of fluid flow in unsaturated, fractured rock.

The schedule summarizes the logic network and reports for the two activities of the study. It represents a summary of the schedule information including the sequencing, interrelations, and relative durations of the activities described in this study. Specific durations and start and finish dates for the 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.

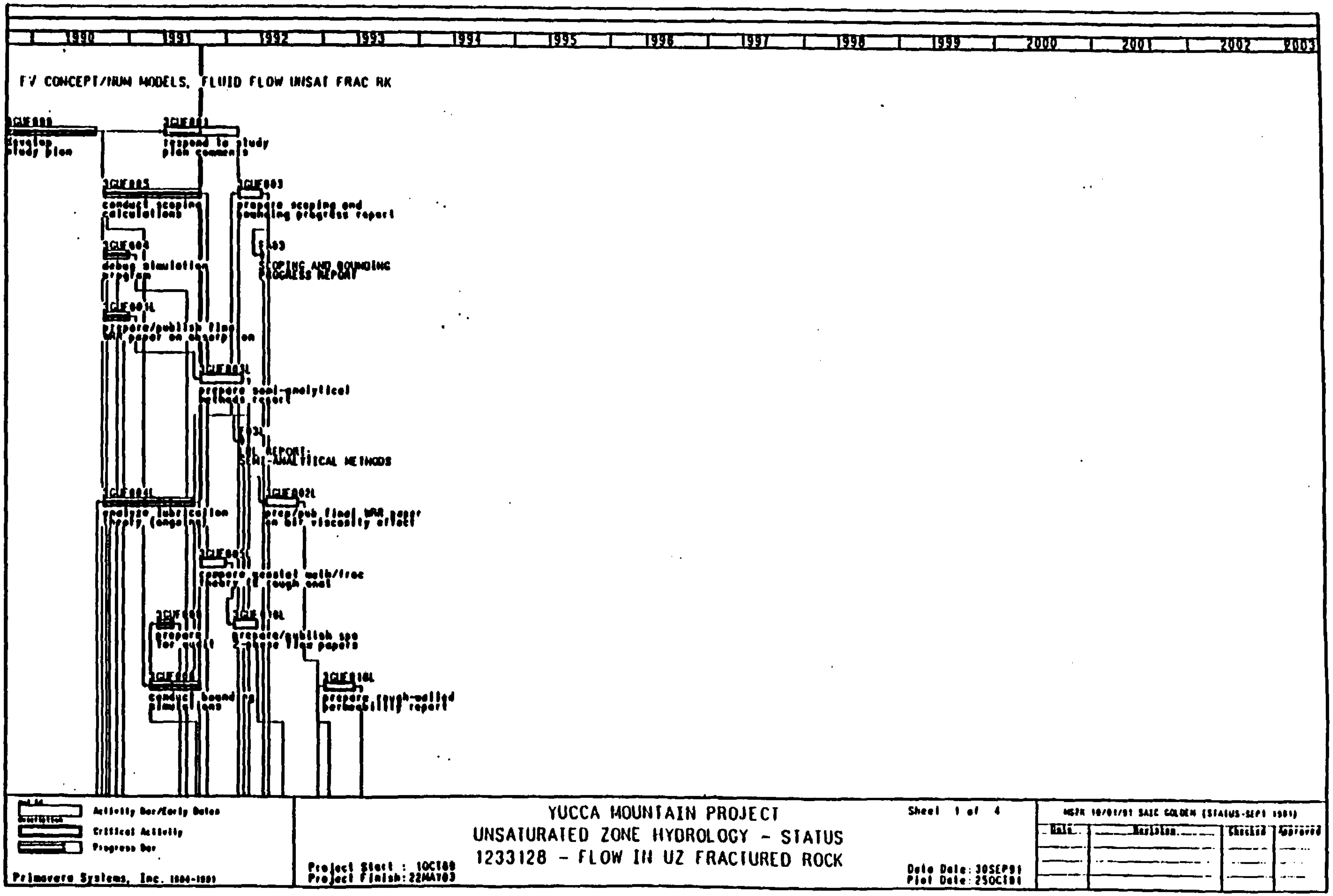

Figure 5.1-1a. Summary network for development and validation of unsaturated-zone models study.

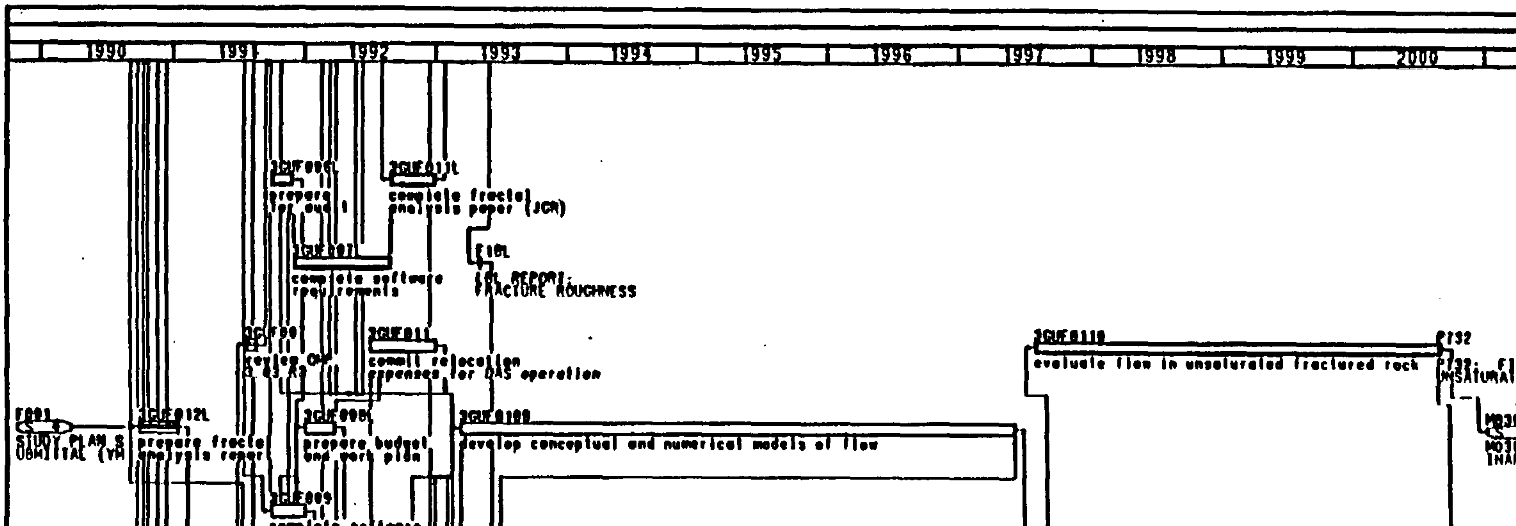

Figure 5.1-1b. Summary network for development and validation of unsaturated-zone models study.

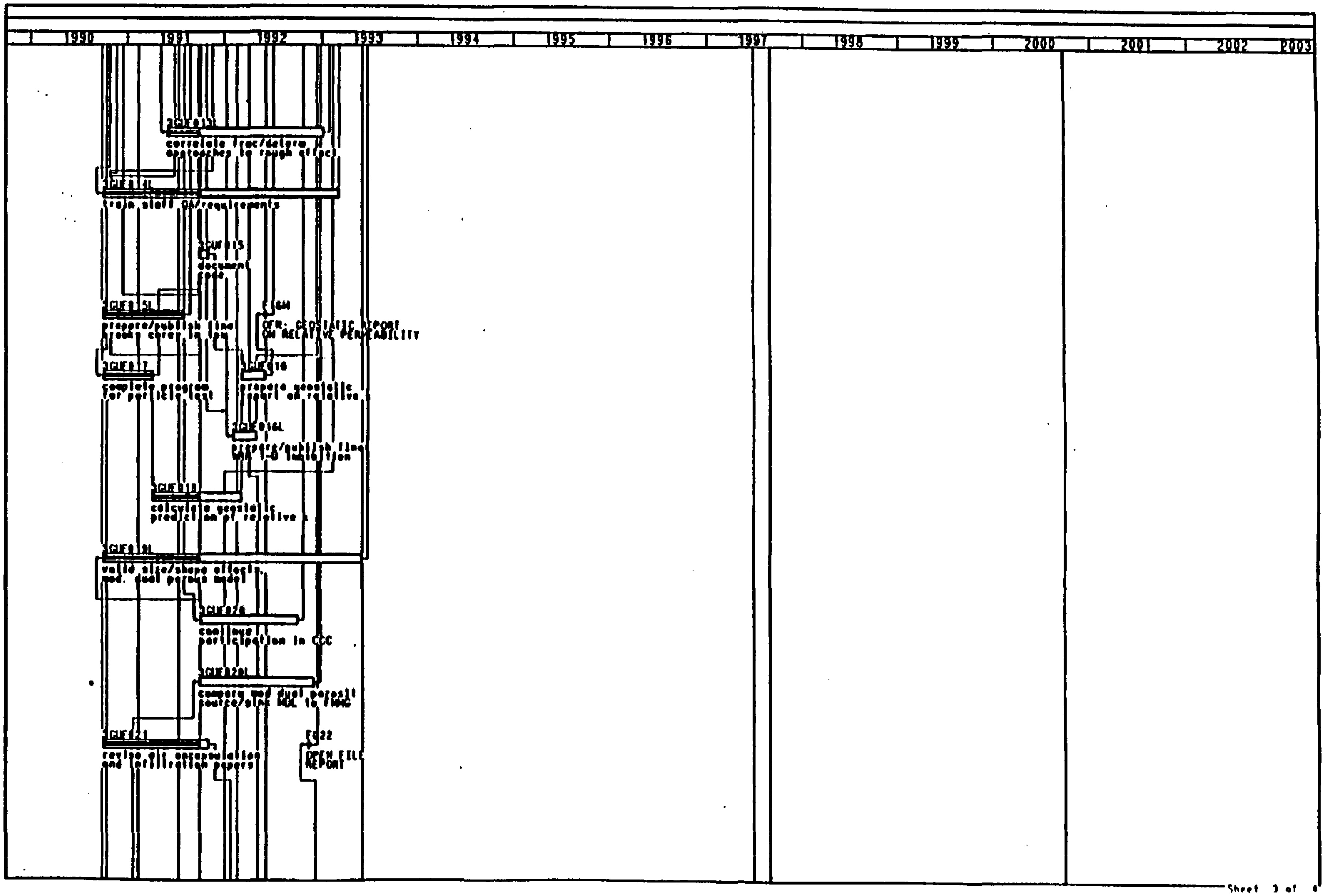

Figure 5.1-1c. Summary network for development and validation of unsaturated-zone models study.

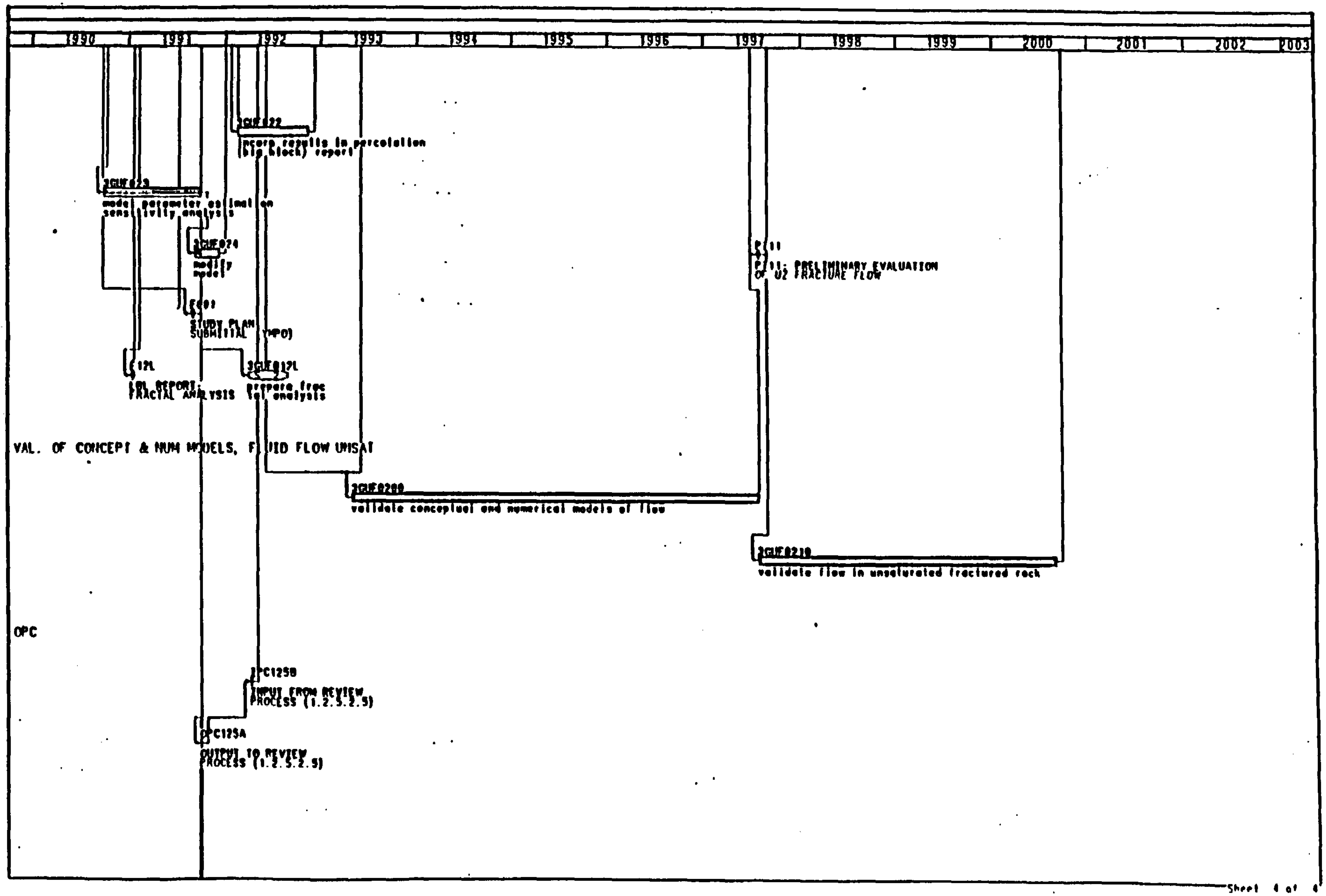

Figure 5.1-1d. Summary network for development and validation of unsaturated-zone models study.

5.2 Milestones

The milestone number, title, and corresponding work breakdown structure number associated with the fluid flow in unsaturated, fractured rock study 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 Figure 5.1-1. 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 8.3.1.2.2.8 (WBS 1.2.3.3.1.2.8)

[Note: No milestone dates available at this time.]

Milestone number	Milestone
Study: Fluid flow in unsaturated, fractured rock: 8.3.1.2.2.8	
F001	Study plan submittal (YMPO)
F03L	LBL report: semi-analytical methods
FA03	Scoping and bounding progress report
F16M	OFR: Geostatistical report on relative permeability
P711	Preliminary evaluation of UZ fracture flow
P732	Final evaluation of UZ fracture flow
F022	Open-file report
F005	Work authorization 1.2.3.3.1.2.8
F12L	LBL report: fractal analysis
F18L	LBL report: fracture roughness

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7 APPENDICES

7.1 Quality assurance requirements

7.1.1 Quality assurance requirements matrix

Determination of the quality status for the activities of this study will be made separately, according to AP-6.17Q, "Determination of the Importance of Items and Activities", which implements NUREG-1318, "Technical Position on Items and Activities in the High-Level Waste Geologic Repository Program Subject to Quality Assurance Requirements". The results of that determination will be contained in the Q-List, Quality Activities List, and Project Requirements List, which will be controlled documents.

The QA grading package for this study was transmitted to the Project Office on January 30, 1991.

Applicable NQA-1 criteria for Study 8.3.1.2.2.8 and how they will be satisfied

NQA-1 Criteria #	Documents addressing these requirements
1. Organization and interfaces	The organization of the OCRWM program is described in the Mission Plan (DOE/RW-005, June 1985) and further described in Section 8.6 of the SCP. Organization of the YMP-USGS is described in the following: QMP-1.01 (Organization Procedure)
2. Quality-assurance program	Requirements of the OCRWM Quality Assurance Program are specified in DOE/RW-214, "OCRWM Quality Assurance Requirements Document." The YMP-USGS QA Program is described in the following: QMP-2.01 (Management Assessment of the YMP-USGS Quality Assurance Program) QMP-2.02 (USGS Personnel Qualification) QMP-2.05 (Qualification of Audit and Surveillance Personnel)

QMP-2.07 (YMP-USGS Instruction)

Each of these QA programs contains Quality Implementing Procedures further defining the program requirements. An overall description of the QA Program for site characterization activities is described in Section 8.6 of the SCP.

3. Scientific investigation control and design

This study is a scientific investigation. The following QA implementing procedures apply:

QMP-3.02 (USGS QA Levels Assignment [QALA])

QMP-3.03 (Software Quality Assurance)

QMP-3.04 (Technical Review, Approval, and Distribution of YMP-USGS Publications)

QMP-3.05 (Work Request for NTS Contractor Services [Criteria Letter])

QMP-3.06 (Scientific Investigation Plan)

QMP-3.07 (YMP-USGS Review Procedure)

QMP-3.10 (Verification of Scientific Investigations)

QMP-3.11 (Peer Review)

QMP-3.13 (Design Input)

4. Administrative operations and procurement

QMP-4.01 (Procurement Document Control)

QMP-4.02 (Control of Intra-USGS Acquisitions)

5.	Instructions, procedures, plans, and drawings	The activities in this study are performed according to the technical procedures listed in Section 3 of this study plan, and the QA administrative procedures referenced in this table for criterion 3. QMP-5.01 (Preparation of Technical Procedures) QMP-5.02 (Preparation and Control of Drawings) QMP-5.03 (Development and Maintenance of Quality Management Procedures) QMP-5.04 (Preparation and Control of the YMP-USGS QA Program Plan) QMP-5.05 (Scientific Notebook)
6.	Document control	QMP-6.01 (Document Control);
7.	Control of purchased items and services	QMP-7.01 (Control of Purchased Items and Services)
8.	Identification and control of items, samples, and data	QMP-8.01 (Identification and Control of Samples) QMP-8.03 (Control and Transmittal of Technical Information to the Project Technical Data Base)
9.	Control of processes	Not applicable
10.	Inspection	Not applicable
11.	Test control	Not applicable
12.	Control of measuring and test equipment	QMP-12.01 (Instrument Calibration)
13.	Handling, shipping, and storage	QMP-13.01 (Handling, Storage, and Shipping of Instruments)

14.	Inspection, test, and operating status	Not applicable
15.	Control of nonconforming items	QMP-15.01 (Control of Nonconforming Items)
16.	Corrective action	QMP-16.01 (Control of Corrective Action Reports)
		QMP-16.02 (Control of Stop-Work Orders)
		QMP-16-03 (Trend Analysis)
17.	Records management	QMP-17.01 (YMP-USGS Records Management)
		QMP-17.03 (YMP-USGS Local Records Center)
18.	Audits	QMP-18.01 (Audits)
		QMP-18.02 (Surveillance)