COMPLIANCE DETERMINATION STRATEGY
RRT 3.2.2.1 FAVORABLE CONDITION: NATURE AND RATE OF HYDROGEOLOGIC PROCESSES

APPLICABLE REGULATORY REQUIREMENTS:

10 CFR 60.122(b)(1)
10 CFR 60.21(c)(1)(ii)(B)
10 CFR 60.21(c)(1)(ii)(F)

TYPES OF REVIEW:

Acceptance Review (Type 1)
Safety Review (Type 3)
Detailed Safety Review Supported by Analyses (Type 4)
Detailed Safety Review Supported by Independent Tests, Analyses, or Other Investigations (Type 5)

RATIONALE FOR TYPES OF REVIEW:

Acceptance Review (Type 1) Rationale:

This regulatory requirement topic is license application-related because, as specified in the license application content requirements of 10 CFR 60.21(c) and the regulatory guide "Format and Content for the License Application for the High-Level Waste Repository (FCRG)", it must be addressed by the U.S. Department of Energy (DOE) in its license application. Therefore, the staff will conduct an Acceptance Review of the license application for this regulatory requirement topic.

Specifically, the staff will conduct a review for completeness of the information as it relates to favorable conditions associated with the nature and rates of hydrogeologic processes at the Yucca Mountain site that have occurred during the Quaternary and are expected to have no effect, or to have a favorable effect, on waste isolation.

Safety Review (Type 3) Rationale:

This regulatory requirement is related to containment and waste isolation. It involves the presence of natural hydrogeologic processes taking place during the Quaternary within the geologic setting at Yucca Mountain that, when projected into the future, are considered to either have a positive effect on, or are not expected to adversely impact, the capability of the site to isolate waste. These processes present favorable conditions that can support, with reasonable assurance, the demonstration of compliance with the performance objectives contained in 10 CFR 60.112 and 10 CFR 60.113. Furthermore, these favorable conditions, either individually or in combination, could have a positive counter effect on the potentially adverse conditions (PACs) that could influence groundwater flow and enhance the release of radionuclides to the accessible environment.

Although the presence of a given favorable condition is not a specific requirement (see NUREG-0804, 1983c, p. 151), a consideration and identification of the aggregate of favorable conditions (as identified in 10 CFR 60.122(b)) at the site is a regulatory requirement found in 10 CFR 60.21(c)(ii)(b) for which a determination of compliance is necessary in order to make a safety determination for construction authorization as defined in 10 CFR 60.31(a) (i.e., regulatory requirements in Subparts E, G, H, and I). Therefore, the staff will conduct a Safety Review of the license application to determine compliance with this regulatory requirement topic.

The language of 10 CFR 60.122(b)(1) makes no explicit reference to repository perturbations (e.g., heating and introduction of exotic materials) affecting projected Quaternary processes. Projections are to be based on the record of geologic history and are not to include the modifying effects of an emplaced geologic repository for high-level radioactive waste. This interpretation is confirmed by statements of consideration in NUREG-0804: "[The Commission's] interest in specifying that the geologic setting shall have an exhibited 'stability' since the start of the Quaternary Period was to assure only that the processes be such as to enable the recent history to be interpreted and to permit near-term geologic changes to be projected over the relevant time period with relatively high confidence. This concept is best applied by identifying as potentially adverse conditions, those factors which stand in the way of such interpretation and projection...." (NRC, 1983c, p. 22). Also from NUREG-0804 is: "the new definition of 'anticipated processes and events' includes the assumption that processes operating in the Quaternary Period continue to operate but with perturbations caused by the presence of emplaced radioactive waste superimposed thereon....What the Commission has intended was the structural, tectonic, hydrogeologic, and geomorphic processes be such as to enable the recent history to be interpreted and to permit near-term geologic changes to be projected with relatively high confidence," (NRC, 1983c, p. 53). Here the distinction between Quaternary processes and repository induced perturbations is explicit. The latter are superimposed on the projection of the former in identifying anticipated processes and events. Projection of Quaternary processes is not intended to include repository perturbations.

The review for favorable conditions shall focus on determining whether the DOE has been able, in the license application to: (1) determine whether these conditions exist at the Yucca Mountain site; and (2) establish either no effect or a positive effect on waste isolation. More specifically, the review shall determine whether or not the nature and rates of the hydrogeologic processes that occurred during the Quaternary, and deemed by DOE to constitute favorable conditions, can indeed be considered as such. This review shall not address potentially adverse conditions, for these are the subject of other license application review plans, namely: 3.2.2.5 (PAC: Flooding), 3.2.2.7 (PAC: Natural Phenomena and Groundwater), 3.2.2.8 (PAC: Structural Deformation and Groundwater), 3.2.2.9 (PAC: Changes in Hydrogeologic Conditions), 3.2.2.11 (PAC: Potential for the Water Table to Rise and Inundate a Repository, 3.2.2.12 (PAC: Perched Water Bodies), 3.2.3.7 (PAC: Gaseous Radionuclide Movement), and 3.2.4.2 (PAC: Changes to Hydrologic Conditions from Climate).

A number of phenomena could affect the hydrogeologic processes governing groundwater flow and, therefore, the performance of a deep geologic repository for the disposal of high-level radioactive waste in unsaturated, fractured media. The key processes are (Parsons et al., 1991):

- Precipitation,
- Infiltration,
- Percolation, and
- Recharge.

The proposed repository horizon at Yucca Mountain will be in the unsaturated zone, approximately 300 m above the present level of the water table. Furthermore, the location of Yucca Mountain is in a high desert climate that is characterized by low precipitation, low humidity, high evapotranspiration rates, low infiltration rates, and low recharge (DOE, 1998). There is desert vegetation resulting from short, mild winters and long, hot summers (Parsons et al., 1991). As a result, data available to date seem to suggest extremely low percolation rates from the surface through the unsaturated zone past the repository to the saturated zone.

Yucca Mountain is located on the central western side of a large regional groundwater flow basin. This region is one of the most arid ones in the United States and, thus, receives very low rainfall, which is the primary source of recharge to the basin (DOE, 1988, p. 3-69). The recharge in the basin is relatively small except for large precipitation areas (e.g., regions of higher elevation with precipitation rates of 200 mm/yr or greater) and below major washes, such as Fortymile Wash (DOE, 1988, p. 3-70). Discharge is mainly due to evapotranspiration, except for discharge areas associated with structural barriers to flow that cause the groundwater to discharge (e.g., near Beatty and in the eastern parts of Death Valley) (DOE, 1988, p.3-70). Therefore, infiltration and percolation rates are low; ^{36}CL infiltration studies in valley fill alluvium formations northeast of Yucca Mountain indicate that infiltration does not occur below a depth of ~2 m (Norris et al., 1985). In summary, the groundwater flow system at Yucca Mountain during the Quaternary seems to be primarily characterized by steady drying conditions. Should this drying persist into the future, it is not perceived to have an adverse effect on the ability of the site to isolate the waste; however, if any future information suggests that drying causes adverse consequences, the review of this favorable condition will be re-evaluated.

Several investigators (e.g., Winograd and Doty, 1980; Pexton, 1984; Winograd et al., 1985; and Winograd and Szabo, 1986) have studied the groundwater levels in the basin where Yucca Mountain is located. The data collected and analyzed by these and other investigators provide very strong evidence that there has been a steady lowering of the water table during the Quaternary. Depending on the investigator(s), the modern water-table level is anywhere from 50-70 m to 130 m lower than since the middle of the Pleistocene. There are several hypotheses that have been offered to explain the lowering of the water table. Some believe that it is the result of lower moisture and more arid climates, while others speculate that it is due to a combination of tectonism, increase aridity, and deposition due to erosion. The strongest evidence (e.g., see Winograd and Szabo, 1986) points to a tectonic uplift, by as much as 1,000 m in the last 3,000,000 yr, of the Sierra Nevada that has prevented moisture and storms approaching from the Pacific Ocean to reach the region where Yucca Mountain is located. This had a direct lowering effect on the amount of precipitation, which eventually caused the lowering of the water table.

Winograd and Doty (1980) state that future water levels will fluctuate a few tens of meters around the current levels, while Winograd and Szabo (1986) conclude that the progressive lowering of the water table in the Great Basin during the Quaternary will continue and that "a combined decline of the regional water table in the next 100,000 yrs (and beyond)" is possible. A lower water table has two possible positive effects on the groundwater flow system insofar as waste isolation is concerned. First, a lower water table means, if the flow through the unsaturated zone is primarily vertically downward, a longer travel path within the unsaturated zone to the interface with the saturated zone. This will, in turn, result in longer groundwater travel times and, consequently, slower migration of radionuclides from the repository to the accessible environment. Second, a lower water table reduces the likelihood of the repository becoming inundated. Some preliminary modeling exercises suggest that the climate regime over the next 10,000 yr is not expected to produce water table rises sufficiently high to inundate the repository (DOE, 1988, p. 3-229). An even lower water table would require an even greater climate change than currently expected.

In summary, two potentially favorable conditions resulting from Quaternary hydrogeologic processes have been identified:

1. Low infiltration, percolation, and recharge due to the low precipitation and high evapotranspiration characteristics of arid climates; and

2. Lowering of the water table.

While it can be argued that these two conditions are not truly independent, for the first one may contribute to the second, it may be advantageous, for the sake of simplicity, to examine them separately.

Detailed Safety Review Supported by Analyses (Type 4) Rationale:

The staff considers that there may be high potential risk of noncompliance with applicable regulatory requirements because, for the Yucca Mountain site, there exist a number of Key Technical Uncertainties. Therefore, the staff will conduct a Detailed Safety Review Supported by Analyses of the license application to determine compliance with this regulatory requirement topic.

These Key Technical Uncertainties are considered to require a Type 4 review because there is a high risk of noncompliance with the post-closure performance objectives related to controlled release rate and overall system performance. This concern of high risk of noncompliance will require analyses above and beyond that required for a Safety Review in order to assure that uncertainties and potential adverse effects on performance have been adequately evaluated and minimized to the extent practical.

This regulatory requirement topic includes one Key Technical Uncertainty identified in Section 3.3 (Assessment of Compliance with the Groundwater Travel Time Performance Objective). It also incorporates Key Technical Uncertainties contained in Sections 3.2.2.8 (PAC: Structural Deformation and Groundwater), 3.2.2.12 (PAC: Perched Water Bodies), and 3.2.4.2 (PAC: Changes to Hydrologic System from Climate). Although these uncertainties also apply to this section, the evaluation of these Key Technical Uncertainties will be performed under their respective sections of the License Application Review Plan:

(1) The nature of the large hydraulic gradient located north of Yucca Mountain.

(2) Uncertainty in modeling groundwater flow through unsaturated fractured rock caused by the lack of codes tested against field and laboratory data.

(3) Uncertainty in identifying which conceptual models adequately represent isothermal and nonisothermal liquid and vapor phase movement of water through unsaturated fractured rock at Yucca Mountain.

(4) Uncertainties associated with determining characterization parameters.

(5) The uncertainty associated with predicting precipitation and temperature (climate) at the Yucca Mountain site for 10,000 years into the future.

(6) Developing a conceptual groundwater flow model that is representative of the Yucca Mountain site groundwater flow system.

Key Technical Uncertainty Topic: The nature of the large hydraulic gradient located north of Yucca Mountain.

Description of Uncertainty: The cause of the large hydraulic gradient located north of Yucca Mountain is unknown. Whatever geologic feature causes the high gradient appears to function as a groundwater barrier. This causes hydraulic heads in the saturated zone north of Yucca Mountain to be much higher than those underlying the site. At Yucca Mountain, the water table occurs at depths of about 150-360 m below the proposed underground facility (DOE, 1988, p. 3-41).

Performance Objective at Risk: 10 CFR 60.112

Explanation of Risk: The geologic feature that causes the high hydraulic gradient may be susceptible to seismic disruption. If site characterization demonstrates this, then a performance assessment scenario will have to be developed in which the feature would be removed, permitting the southward flow of groundwater previously stored behind the barrier. In such a scenario, released groundwater would flow southward in sufficient amounts to significantly raise the potentiometric surface. Although a rise of the water table under such a scenario would probably not be great enough to inundate the repository, it would reduce the thickness of the unsaturated zone. Since the unsaturated zone at Yucca Mountain is considered the principal component of the natural barrier, a thinner zone would reduce the ability of the natural barrier system to isolate wastes. It is also possible that geologic structures similar to that which causes the high gradient could form elsewhere, such as south of the site. Such a scenario could also cause a rise of the potentiometric surface beneath Yucca Mountain.

Description of Resolution Difficulty: It is not expected that there will be any difficulty in determining the cause of the high hydraulic gradient. DOE has plans to drill new exploratory holes to identify the geologic source of the high gradient, and additional geophysical work is also planned. However, if the source is found to be fault-related, then modeling scenarios involving disruption of the fault will need to be analyzed to evaluate whether the potentiometric surface beneath Yucca Mountain is susceptible to dramatic changes. This kind of groundwater modeling can help estimate the magnitude of hydrologic changes that may occur, but it is subject to all of the uncertainties that exist within the hydrologic testing and groundwater modeling programs, including the uncertainties of model calibration. Also, the potential for new flow "barriers" to evolve south of Yucca Mountain will be difficult to estimate. Such estimates will probably be based mostly on expert opinions.

The isolation of high-level nuclear wastes is considered to be favored by building the disposal facility in an unsaturated zone. It is thought that waste canisters may last longer if not immersed in water, and that any wastes that may escape will travel more slowly under unsaturated conditions. However, these perceived advantages could vanish if the repository were to become saturated in the future, or if the thickness of the unsaturated barrier were significantly reduced in thickness.

Key Technical Uncertainty Topic:

Uncertainty in modeling groundwater flow through unsaturated fractured rock caused by the lack of codes tested against field and laboratory data.

Description of Uncertainty:

Compliance demonstration of this regulatory requirement topic will require quantitative prediction of the potential for future perched water bodies to form or to provide a faster flow path from an underground facility to the accessible environment. Computational models will be the primary methods used to estimate the likelihood of perched water bodies forming in the unsaturated zone. This is because the conditions that trigger fracture flow and the rate of flow when it does occur have a big effect on the potential for perched water bodies to form.

There are currently three approaches to modeling unsaturated fractured rock flow. These approaches are the equivalent continuum model of Klavetter and Peters (1986), the dual continuum approach, and models which directly incorporate discrete fractures. However, these approaches were theoretically developed and need to be tested against laboratory or field experiments to build confidence. There are not yet any experimental methods currently available which would allow the composite continuum model to be verified.

Performance Objectives at Risk :

10 CFR 60.112, 60.113(a)(1)(ii)(B), or 60.113(a)(2).

Explanation of Nature of Risk:

Modeling of groundwater flow through unsaturated fractured rock will play an important role in demonstrating compliance with this potentially adverse condition. Failure to demonstrate compliance with this potentially adverse condition would make it harder to demonstrate compliance with the overall system performance objective. This is because the formation of perched water could result in increased waste canister failure rates and faster radionuclide transport to the accessible environment. However, a determination of compliance or noncompliance may not be possible if it cannot be established that the unsaturated groundwater flow models are adequate representations.

Description of Resolution Difficulty:

This difficulty should be resolved by testing unsaturated fractured rock flow codes against physical experiments. Should it be determined that existing codes are inadequate, new codes may have to be developed and tested.

Key Technical Uncertainty Topic:

Uncertainty in identifying which conceptual models adequately represent isothermal and nonisothermal liquid and vapor phase movement of water through unsaturated fractured rock at Yucca Mountain.

Description of Uncertainty:

To address this regulatory requirement topic, predictions will be made through the use of computational models which are based on conceptual and mathematical models of the dominant physical-chemical mechanisms. These conceptual models will also be used to decide what site characterization parameters should be obtained, to design the characterization program, to interpret data from the tests, to interpret the distribution of site characterization parameters, to assign model inputs, and to interpret model results.

Any uncertainty in the appropriateness of the conceptual models will, therefore, reduce the reliability of model predictions as well as the adequacy of that portion of the site characterization program designed to address this regulatory requirement.

Performance Objectives at Risk:

10 CFR 60.112, 60.113(a)(1)(ii)(B), or 60.113(a)(2).

Explanation of Nature of Risk:

Failure to demonstrate compliance with this regulatory requirement would make it more difficult to demonstrate compliance with the overall system performance objective. The formation of perched water could result in increased waste canister failure rates and faster radionuclide transport to the accessible environment, a result that may affect the overall performance of the repository. Conceptual models will be used in all phases of demonstrating compliance with this regulatory requirement topic. Not knowing which conceptual models are appropriate representations of the site will increase the uncertainty associated with demonstrating compliance with this regulatory requirement topic.

Description of Resolution Difficulty:

Uncertainty in the conceptual models of isothermal and non-isothermal liquid and vapor phase transport of water in unsaturated rock may be reduced by performing appropriate laboratory and field experiments for model validation. In addition, resolution of this difficulty will probably require the collection of model specific characterization data, and the elicitation of the opinions of experts.

Key Technical Uncertainty Topic:

Uncertainties associated with determining characterization parameters.

Description of Uncertainty:

To address this regulatory requirement topic, predictions will be made which are based on the values of numerous characterization parameters. These parameters will contain uncertainties due to experimental and measurement error, errors in test interpretation, conceptual model errors, and errors from incorrectly defined parameter ranges and distributions.

Performance Objectives at Risk:

10 CFR 60.112, 60.113(a)(1)(ii)(B), or 60.113(a)(2).

Explanation of Nature of Risk:

Characterization parameters will be used in all phases of demonstrating compliance with this regulatory requirement topic. The inability to determine appropriate site parameters will increase the uncertainty of being able to demonstrate compliance with this regulatory requirement topic. Failure to demonstrate compliance with this regulatory requirement topic would make it more difficult to demonstrate compliance with the overall system performance objective. This is because the formation of perched water could result in increased waste canister failure rates and faster radionuclide transport to the accessible environment.

Description of Resolution Difficulty:

Resolution of this difficulty will probably require prototype testing, the collection of site characterization data, and appropriate use of expert opinion.

Key Technical Uncertainty Topic: The uncertainty associated with predicting precipitation and temperature (climate) at the Yucca Mountain site for 10,000 years into the future.

Description of Uncertainty: The analysts consider that it is very difficult to predict climatic variations (precipitation, temperature, etc.) over the next 10,000 years.

Performance Objective at Risk:10 CFR 60.112

Explanation of Nature of Risk: Precipitation and temperature change will affect the flux of water in the unsaturated zone which, in turn, may contribute to adverse effects on canister degradation, radionuclide release, and radionuclide transport to the accessible environment. Until subsurface hydrologic conditions and processes are better understood, it will be difficult to evaluate the consequences of significantly increasing the precipitation. The nature and timing of climatic changes may, when considered in the context of all other adverse effects on the performance of the repository, prove to have an adverse effect on performance.

Description of Resolution Difficulty: There are numerous factors that prevent scientists from accurately projecting future climates. Even day-to-day weather predictions are very limited, primarily because atmospheric phenomena are chaotic in nature and behavior. The factors that cause climate change are poorly understood because such changes occur very slowly over time scales that exceed the historical record.

One climatic factor, concerning Earth's orbital and rotational characteristics (Milankovitch cycles), can readily be predicted. Most other factors are not easily evaluated. For example, long-term variations in energy output from the sun are poorly understood, and generally unknown. Short-term periodicity in the form of sunspot cycles is well known, but hypothesized longer-term trends have not yet been confirmed due to the short period of historic astronomical records. Another independent variable in climate change is the effect of volcanism. The stratospheric injection of volcanic ash has a short-term cooling effect on Earth's climate. But it is reasonable to conclude that periods of anomalously high volcanic activity could temporarily offset greenhouse warming effects, or could accelerate cooling trends caused by other phenomena. It is not possible to predict future periods of more intense volcanic activity.

Certain anomalous climatic trends defy prediction. For example, when it occurs, the El Niño Southern Oscillation (ENSO) can significantly influence climate in the western U.S. This phenomenon results from a complex atmospheric-oceanic interaction, and may be more a result of other factors than an independent variable in itself.

Present and future human activities will probably have a strong influence on climate changes. The current trend of increasing atmospheric CO_2 is thought to have produced a very gradual world-wide warming trend in the relatively short time since the start of the Industrial Revolution. Although this trend is reasonably established, it is not possible to predict the range and impacts of future human activities.

The analysts conclude that a safety determination could be made by independently evaluating paleoclimatic information submitted by DOE in the License Application and by acquiring and using codes and models developed by DOE. The analysts do not at this time consider that a higher level of review will be necessary. Although results of climate modeling will always be controversial, there are no known major improvements that could be incorporated within global climate models by an NRC-sponsored research program. Other government agencies are actively pursuing research in climate modeling, mainly in connection with the theorized global "greenhouse" warming. Given the scope of those efforts, the NRC staff consider that their results and conclusions should be adequate to support the high-level waste program. Nonetheless, the staff will continue to independently evaluate the progress and acceptability of climate studies and modeling by all parties, given the significance of this subject with respect to groundwater conditions at Yucca Mountain.

Key Technical Uncertainty Topic: Developing a conceptual groundwater flow model that is representative of the Yucca Mountain site groundwater flow system.

Description of Uncertainty: The focus of this Key Technical Uncertainty is the site groundwater flow system. A conceptual model of the Yucca Mountain site groundwater flow system will be based on descriptive information, much of which will be input to a mathematical model (i.e., governing equation embodied in a computer code) used to predict GWTT. There are limitations in the type and amount of descriptive information that can be obtained because only a portion of the total system can be characterized and because of limitations inherent in the current state of the art in testing technology.

General Information Needs: Section 3.1.2 of the FCRG specifies the descriptive parameters and generic processes that are necessary to develop a conceptual model of both the regional and site hydrogeologic systems. As summarized from Section 3.1.2 of the FCRG, general information needs include:

- Hydrogeologic framework:
    - hydrogeologic units
    - geologic features that could serve as potential pathways of high fluid flux
    - physical boundaries of regional (or sub-regional) systems
- Potentiometric levels, matric potentials, and gradients
- Characteristics of individual hydrogeologic units
- Recharge and discharge
- Hydrochemical and isotopic characteristics
- Pathway Analysis

The descriptive information needs to be integrated into a general understanding of how groundwater flows at the Yucca Mountain site. This is an iterative process. Specifically, this integrated view of groundwater flow defines priorities with respect to processes that need to be considered (and those that could be safely ignored, if any), the interactions among processes and their dimensionality. At Yucca Mountain, for example, flow through three-dimensional networks of discrete fractures and other macropores embedded within the porous rock is an important consideration. Variability of flow channels within individual fractures, as well as flow interactions between fracture networks and the host rock need to be understood. The constitutive relationships, parameters and material properties needed to describe these processes require definition as part of the conceptual modeling building process. The staff believes that priorities should be based on laboratory, field and numerical experiments rather than on expert judgment. Some parameter needs, such as hydraulic coefficients of individual hydrogeologic units, may be defined, to a certain extent, by the particular mathematical model(s) (governing equations) selected to best represent the important flow processes in numerical simulations. In turn, conclusions over the most appropriate mathematical models may be revised because of either new information that redefines important processes or limitations in testing methods available to obtain needed parameters.

The conceptual groundwater flow model of the Yucca Mountain site also needs to provide sufficient information to describe the hydrogeologic variability of the site. For each descriptive parameter of the conceptual model, spatial variability throughout the site is uncertain. Describing hydrogeologic variability requires a database that is representative of the site. To date, parameter variability is the one uncertainty for which propagation methods are well accepted (e.g., Monte Carlo simulations using probability distribution functions, Turning Band methods); therefore, a direct mapping of uncertainty in parameter spatial variability to uncertainty in the estimates of GWTT is, in principle, possible (Davis, et al., 1990). Poor representation and quantification of statistical properties of parameter data could undermine confidence in conclusions in predicted performance of the geologic setting.

Primary Sources of Uncertainty: Primary sources of uncertainty in describing parameter variability include:

- Measurement error:
  - operator error
  - instrument calibration or malfunction
  - correction factors
  - test interference
- Sampling bias:
  - number, location or orientation of tests
  - statistical methods used to express spatial variability
- Limitations of testing methods and procedures:
  - instrumentation

- validity of analytical assumptions used to derive data from indirect measurements

- scale at which test methods are applied

These sources of uncertainty were considered by the staff in the site characterization analysis (SCA; NRC, 1989) of DOE's site characterization plan (SCP) for the Yucca Mountain site (DOE, 1988). These sources of uncertainty continue to be an important consideration in NRC's pre-licensing reviews of DOE study plans, technical procedures and quality assurance audits and will remain so during the NRC safety review of DOE's compliance demonstration with this performance objective contained in the license application. A brief discussion of these three primary sources of uncertainty is provided in the following sections. A summary of both unresolved site specific technical concerns identified by the staff in previous reviews of DOE documents and any generic technical issues (i.e., those related primarily to testing and analysis methods) identified by the staff related to these sources of uncertainties is also provided. Comments provided to DOE previously by staff and subsequently resolved will not be discussed. Specific technical concerns and generic technical issues are discussed in more detail in later sections. It should be noted that additional site specific concerns or generic technical issues could be identified in the future based on staff review of specific DOE study plans or published test results.

(1) Measurement Error: Measurement error can affect the representativeness of the database and its subsequent utility in describing the hydrogeologic variability. Measurement error can result from operator error, failure to calibrate instruments, instrument failure or the misapplication of data correction factors. For convenience, interference between tests is also considered a source of measurement error.

A methodology for quantifying the magnitude of measurement errors relative to natural geologic variability was presented by Rasmussen et al., (1990). The demonstrated methodology employs replicate sampling and measurement, duplication of procedures, and redundancy using independent test methodologies. Redundant sampling and analysis provides improved reliability of parameter estimates (Rasmussen, 1985). Sample replication employs repeated measurement of individual samples to provide an estimate of procedure uncertainty. Sample duplication employs parallel laboratories or equipment to estimate the error introduced by individual equipment or laboratories. Redundant procedures use different procedures use different procedures to estimate a common parameter. When used in conjunction, these approaches provide a higher level of confidence in the estimated parameters. The approaches also provide measures of parameter uncertainties.

The staff has not identified any generic technical issues related to measurement error. Further, the staff has not identified any site specific technical concerns related to operator error, instrument calibration/malfunction or application of data correction factors in any hydrology related, DOE study plan reviewed to date. However, the staff has expressed to DOE some site specific concerns related to test interference. The staff has expressed a concern about the effects of ventilation of the exploratory studies facility (ESF) on planned testing and the potential for irreversible changes to baseline site conditions (refer to comment no. 123 of the SCA; NRC, 1989). During review of DOE's study plan for saturated zone testing of the C-hole sites with reactive tracers (DOE, 1989), the staff noted the considerable potential for interferences among the tests proposed, especially given the large number of hydrologic and tracer tests planned and brought this matter to DOE's attention (NRC, 1991). During review of DOE's site characterization progress report (No. 7; DOE, 1992a), the staff raised a question (related to comment no. 123 in the SCA; NRC, 1989) about DOE's evaluation of the potential for air movement from the ESF to adversely impact the collection of geochemical data necessary for site characterization (NRC, 1993a). These concerns remain under discussion.

(2) Sampling Bias: Sampling bias can also affect the representativeness of the data base and its subsequent utility in describing hydrogeologic variability. The potential for sampling bias depends in part on the selection process used to locate boreholes or other monitoring points, both areally and vertically. For example, borehole locations could be selected for either geologic investigative reasons or convenience, rather than hydrogeologic investigative reasons. Borehole locations frequently are selected based on an interest in investigating a particular geologic feature that may or may not coincide with suspected geologic features that can affect the flow of groundwater.

Sampling bias may substantially affect estimated hydrogeologic parameters if boreholes are installed parallel to the orientation of the geologic structure. Rasmussen et al., (1990) demonstrate that vertical boreholes may not intersect vertical fractures and that inclined fractures provide improved estimates of formation hydraulic and pneumatic properties. Rasmussen et al., (1993) also demonstrate that parameters estimated from oriented core segments can be used to estimate mean field behavior, but poorly estimate locations of enhanced permeabilities. In general, for regularly spaced planar features, the sampling frequency decreases as the sine of the angle of incidence between the borehole and the feature decreases.

In a certain sense, all databases of hydraulic characteristics of unsaturated, fractured rock will be biased due to limitations in the ability to monitor the discrete nature of fluid flow. Chuang et al., (1990) and Haldeman et al., (1991) note that solutes migrate through discrete channels within fractured rock, and that a dense sampling network would be required to detect individual channels. Selection of relevant test locations will be problematic due to the isolated nature of flow channels in fractured rock. Also, due to the isolated nature of saturation in rock fractures, Rasmussen (1991) showed that the possibility exists for water to be absent, present under positive, and present under negative pressures within a single fracture. Thus, for an unsaturated fracture, discrete saturated flow channels will likely be present and solutes may be present in only a small fraction of these. In addition, perched water may be found in unsaturated, fractured rock resulting from the effect of channel interconnections between fractures.

Therefore, the staff believes that the criteria (or absence thereof) used to select test locations (and orientations) can unnecessarily bias data collection, introducing uncertainty into the data collected from those boreholes. Some bias is, by nature, unavoidable. For convenience, discussions of sampling bias will also include consideration of statistical methods used in describing the spatial variability of hydraulic coefficients and other parameters.

To address the potential for sample bias, DOE has planned to apply two approaches to select test locations for the surface based testing program (DOE, 1988; p. 8.3.1.4-88). These approaches are the "feature sampling" program and the "systematic" program. The feature sampling program is to test specific hypotheses about behavior of the site where boreholes are located where anomalous behavior is expected or proximal to important structures controlling variability. The systematic program is to provide representative sampling (conditionally unbiased) that is presumed is to either yield smaller predictive uncertainty if known anomalies are avoided or greater uncertainty if extreme behavior is not restricted to known anomalies (DOE, 1988; p. 8.3.1.4-88). For the systematic program, DOE plans to use graphical, statistical, and geostatistical techniques, in addition to geologic interpretations, to provide a first-pass estimate of the adequacy of drill hole density and down-hole sampling patterns in characterizing the repository block (DOE, 1993; Study Plan 8.3.1.4.3.1; p. ii). This evaluation is to be performed on an on-going basis so that sampling patterns and drill hole spacings can be adjusted if required. DOE's specific study plan concerning the systematic program has only recently been submitted to the NRC and has not yet undergone detailed review by the staff. DOE's specific plans and procedures related to statistical methods to describe the spatial variability of hydraulic coefficients and other parameters are only discussed in a general way in the SCP. The staff expects that more detailed discussion of DOE's plans and procedures on parameter estimation techniques will be provided in individual study plans, such as those on unsaturated and saturated zone synthesis and modeling (DOE study plans 8.3.1.2.2.9 and 8.3.1.2.3.3). To date, these study plans have not been reviewed in detail by NRC staff.

Although the staff has not yet reviewed and commented on DOE's overall systematic data collection program or methods for determining the spatial variability of individual parameters, during review of the SCP the staff identified nine site specific technical concerns which were related to the number and location of testing activities associated with DOE's site characterization program (for background, refer to comment nos. 13, 14, 16, 19, 20, 35, 39, 40 and 41 contained in the NRC's SCA; NRC, 1989). Seven of the nine comments have been resolved. The two comments that remain unresolved relate to concerns about: (1) the adequacy of the number and location of proposed boreholes to define the potentiometric surface (comment no. 19); and (2) the adequacy of the number and location of proposed saturated zone stress (pumping) tests in the vicinity of the Yucca Mountain Site (comment no. 20). Additional concerns with respect to availability of sufficient data to define regional and sub-regional hydraulic head, gradient and hydrogeologic boundaries to support multi-dimensional modeling of the regional hydrogeologic system were identified during the staff review (NRC, 1993b) of DOE's study plan on regional hydrologic system synthesis and modeling (DOE, 1992b).

In general, determining the spatial variability of some parameters will be more difficult than others. Data characterizing unsaturated rock constitutive relations are generally scant. The spatial structure of the material properties most difficult to obtain, such as moisture characteristic curves over a broad range of pressure, may have to be analyzed indirectly through correlations with more easily measured parameters such as porosity or saturated hydraulic conductivity. This may necessitate developing and testing models to correlate these parameters (Ababou, 1991; p. 7-1).

By necessity, the testing scale will vary from laboratory to field scale at Yucca Mountain. Additional uncertainty is introduced by combining the results of different types and scales of hydrogeologic tests. Various tests will stress different volumes of rock; the difference in volume of rock tested may be several orders of magnitude. No definitive method has been presented by the technical community that adequately addresses the problems associated with combining the results of tests obtained at different scales. Scale effects are an important factor both in determining whether the number and location of particular tests are adequate to collect a database representative of the site and in assessing the applicability of statistical methods used to express the spatial variability of hydraulic coefficients. Therefore, the staff considers this topic to be an important, generic technical issue.

(3) Limitations of Testing Methods and Procedures: Limitations of testing methods and procedures is a source of uncertainty that is much more difficult to address, particularly considering the large number of methods involved in obtaining all the information necessary to describe the hydrogeologic system. Some methods for obtaining information related to individual components of a conceptual groundwater flow model are discussed in detail in the following sections.

In its review of the SCP, the staff did not identify any site specific technical concerns or generic technical issues about methods used to derive hydraulic coefficients and constitutive relationships of the rock matrix or individual fractures at the laboratory scale. DOE is generally aware of limitations of available instrumentation and methods as evidenced by the large amount of prototype work discussed throughout the SCP.

Although DOE is considering a number of methods to interpret field scale stress tests, it remains unclear as to what analytical models are the most appropriate to use at Yucca Mountain. At this time, few field scale tests have been initiated and very few results of the hydrologic testing program have been published and available for review by the staff. However, the staff has identified a site specific technical concern about DOE's possible plans to initiate single-well tests as an alternative to a second multiple-well test site in the saturated zone (NRC, 1989; comment no. 19). The staff is of the opinion that multiple-well tests are more representative of the bulk behavior of the flow system. Comment no. 19 remains unresolved.

Determining effective hydraulic coefficients (from field scale tests that represent the bulk behavior of a large volume of rock) in the unsaturated zone will be difficult. It may be possible to conduct and interpret field scale pneumatic (gas phase) tests to determine pneumatic permeability. At this time, it is not clear whether pneumatic permeability tests can yield estimates of unsaturated hydraulic properties. The staff believes that establishing the relationship between parameters obtained from pneumatic and hydraulic tests is an important generic technical issue.

Specific Uncertainties in Descriptive Parameters and Processes: In the following sections, various descriptive parameters and processes forming a conceptual groundwater flow model are considered individually in order to discuss in more detail unresolved site specific technical concerns about measurement error or sample bias briefly mentioned above. In addition, information needs that are particularly difficult to provide through standard and accepted methods are discussed in order to identify any generic technical issues warranting additional NRC efforts such as independent analyses or confirmatory research.

(1) Hydrogeologic framework: Uncertainties about the conceptual groundwater flow model begin with the geology that constitutes the framework for the conceptual model. Important components of the hydrogeologic framework are: (1) hydrogeologic units; (2) geologic features that could serve as potential pathways of high fluid flux (e.g., persistent discontinuities such as faults or other zones of high permeability); and (3) the physical boundaries of the regional or subregional hydrogeologic systems. Delineation of the hydrogeologic framework requires information obtained by test drilling and observation of formation exposures. Other sources of information, including borehole geophysics, surface geophysics or geochemical facies data can help define the hydrogeologic framework.

Hydrogeologic units are aligned frequently with geologic (or stratigraphic) boundaries. For example, a change in facies within a sedimentary formation frequently coincides with a change in measured hydraulic conductivity. The Yucca Mountain site is composed primarily of layered, welded and non-welded tuff. The repository horizon will be located within welded tuff. DOE will need to define the basis for establishing hydrogeologic units such as stratigraphic relationships, thickness, lateral extent, lithology or hydrogeologic characteristics. At the regional scale, DOE has defined a number of hydrogeologic units that include the valley fill aquifer, volcanic rock aquifers and aquitards, upper carbonate aquifer, upper clastic aquitard, lower carbonate aquifer and the lower clastic aquitard (DOE, 1988; p. 3-60). DOE has also defined hydrogeologic units in the site unsaturated zone based on three broadly based rock types that include densely to moderately welded tuffs that are highly fractured, nonwelded vitric tuffs containing few fractures and nonwelded zeolitized tuffs containing few fractures (DOE, 1988; p. 3-144). These general relationships, particularly at the site scale, will be refined through site characterization.

Geologic features, such as faults, are an important component of a conceptual groundwater flow model. Discontinuities such as faults may act as an impediment to flow or they may constitute preferential flow paths. Types of faults in the area of Yucca Mountain include both strike-slip faults (like the Las Vegas Valley shear zone and the Death Valley Furnace Creek zone) and Basin and Range normal faults and other extensional structures (DOE, 1988; p. 1-84). Methods to detect faults include mapping of visible stratigraphic offset or scarps, coincident intersection by boreholes and, indirectly, by applying geophysical techniques or observing hydrogeologic anomalies. DOE will also have the ESF available to observe the distribution and characteristics of faults (DOE, 1988; p. 8.3.1.4-65).

Geologic boundaries, such as faults, facies changes or fold axes, frequently define regional or subregional hydrogeologic boundaries. The occurrence and movement of groundwater at the Yucca Mountain site is controlled, in part, by the regional hydrogeologic system (DOE, 1988; p. 3-50). DOE has defined three groundwater subbasins that make up the regional hydrogeologic system. These include: (1) Oasis Valley; (2) Alkali Flat-Furnace Creek Ranch; and (3) Ash Meadows (DOE, 1988; p. 3-50). The Yucca Mountain site lies within the Alkali-Flat Furnace Creek subbasin. The relative importance of identifying physical boundaries of the hydrogeologic flow system depends on the spatial and time scales of interest. For example, if an interest lies in predicting future changes to the hydrogeologic system due to climate change (necessitating consideration of large spatial and time scales), then describing the limits of the hydrogeologic system based on defensible physical boundaries, coupled with information on the distribution of hydraulic head, is very important (e.g., the internal response of the regional scale system will be sensitive to the initial and changing conditions encountered at the lateral limits of the flow system). If the interest is in computing the pre-waste-emplacement GWTT from the disturbed zone to the accessible environment (smaller spatial and time scales), then the physical boundaries of the flow system are less important. This is because (1) it is often more defensible to estimate the flux entering or leaving the site scale hydrogeologic system (initial boundary conditions of the mathematical model used to do the calculations) due to the availability of more information on characteristics of the hydrogeologic units and the three-dimensional distribution of hydraulic head available at the site scale than generally is available at the regional or subregional scales; or (2) the lateral boundaries can often be assumed, defensibly, to be very distant (in effect, approaching infinity) in the mathematical model; and (3) changes in boundary conditions over future time are not a factor in determining <u>pre-waste-emplacement</u> GWTT; therefore, sensitivity of the site scale flow system to changing boundary conditions encountered at the lateral limits of the regional or subregional flow systems is not germane to demonstrating compliance with the performance objective for the geologic setting.

(a) Measurement error: The staff has not identified any site specific technical concerns or generic technical issues about measurement error related to defining hydrogeologic units, detecting geologic features that could serve as potential pathways of high fluid flux or identifying physical boundaries of the regional or sub-regional hydrogeologic systems.

(b) Sampling bias: The staff has expressed to DOE a concern about the availability of sufficient data to define regional and sub-regional hydraulic head, gradient and hydrogeologic boundaries to defend the boundary conditions assumed in multi-dimensional modeling of the regional hydrogeologic system (NRC, 1993b). As discussed previously, changes in regional scale flow fields predicted by multi-dimensional mathematical models will greatly depend on the representativeness of the regional boundary conditions. These boundary conditions are generally inferred from observed physical or hydraulic boundaries. However, because regional scale information is of less importance than site-scale information in predicting pre-waste-emplacement GWTT, this concern will not be discussed further in this review plan. Currently, there are no other unresolved site specific technical concerns about sampling bias related to defining hydrogeologic units, detecting geologic features that could serve as potential pathways of high fluid flux or identifying physical boundaries of the regional or sub-regional hydrogeologic systems. In addition, the staff has not identified any generic technical issues about sampling bias related to defining hydrogeologic units, detecting geologic features that could serve as potential pathways of high fluid flux or identifying physical boundaries of the regional or sub-regional hydrogeologic systems.

After addressing potential measurement error and sampling bias, it will still be necessary for DOE to interpolate and extrapolate information obtained from a finite number of observation points distributed in three-dimensional space; hence, some uncertainty in the hydrogeologic framework will remain. For example, a fault without surface expression will remain undiscovered unless it is coincidentally intersected by a borehole (an unlikely occurrence given many high-angle faults at Yucca Mountain and the use of vertical boreholes), has a significant geophysical signature, produces a hydrogeologic anomaly, or is encountered in the ESF. However, the staff believes describing the general hydrogeologic framework of the Yucca Mountain site will be a generally straightforward task that can be accomplished and defended using available geostatistical techniques.

(c) Limitations of testing methods and procedures: To date, the staff has not identified any site specific technical concerns or generic technical issues about methods for defining hydrogeologic units, detecting geologic features that could serve as potential pathways of high fluid flux or identifying physical boundaries of the regional or subregional hydrogeologic systems.

(2) Potentiometric levels, matric potentials, and gradients: Fluid flow requires a potential gradient. The three-dimensional distribution of hydraulic head defines the hydraulic gradient and thus, the direction of groundwater flow both vertically and horizontally. The discussion in this section will focus primarily on site-scale concerns and issues because this scale is most relevant to determining pre-waste-emplacement GWTT.

Monitoring plans, including methods and procedures used by DOE to measure hydraulic head in the saturated zone, are generally discussed in the SCP under the study on the characterization of the site saturated zone groundwater flow system (DOE, 1988; Activity 8.3.1.2.3.1.2 - Site potentiometric evaluation; pp. 8.3.1.2-375 to 8.3.1.2-382). Methods and procedures considered by DOE to measure the matric potential of unsaturated rock are generally discussed in the SCP under the study on characterization of percolation in the unsaturated zone (surface-based study) (DOE, 1988; Activity 8.3.1.2.2.3.1 - Matrix hydrologic properties testing; pp. 8.3.1.2-183 to 8.3.1.2-200). Additional data on matric potential will be acquired under the study on characterization of percolation in the unsaturated zone (ESF study). To date, the staff has not performed detailed reviews of these study plans.

(a) Measurement error: Currently, there are no unresolved site specific technical concerns or generic technical issues about errors in measuring potentiometric levels, gradients or matric potentials at the Yucca Mountain site that resulted from staff review of the SCP. Some years ago, as the focus shifted from waste disposal in the saturated zone to the unsaturated zone at Yucca Mountain, there was a general concern expressed within the technical community about the alteration of core samples from in situ conditions due to fluids introduced during well drilling (a factor to be considered when measuring water content in core from which in situ matric potentials can be inferred). To address this concern, DOE has planned and conducted prototype tests; air rotary coring as only one example, to develop methods and procedures to minimize sample disturbance during collection, handling and storage (DOE, 1988; p. 8.3.1.2-184).

(b) Sampling bias: Based on a review of DOE's plans for site potentiometric level evaluation presented in the SCP (DOE, 1988; Section 8.3.1.2.3.1.2), the staff commented that the potentiometric surface in the controlled area is not adequately defined by existing well locations, and will not be adequately defined by proposed additional well sites (NRC, 1989; comment no. 20). In comment no. 20, it was noted that few wells are located to monitor the saturated zone in an area south and south-southeast from the site. Only one well (WT-17) occurs in an area of over 12 square kilometers (km), located south of wells WT-1 and G-3 and east of well WT-10. Included in the western part of this area (near well WT-10) is a zone of steep horizontal hydraulic gradient that is poorly defined. This area of few wells is entirely within the controlled area and more detail is needed on the potentiometric surface to support performance assessments of the site. The staff also noted in comment no. 20 that potentiometric contours in the vicinity of well USW G-1 are questionable based on data from borehole USW UZ-1 that suggests that the potentiometric surface is significantly different from that shown in the SCP (DOE, 1988; Figures 3.28 and 8.3.1.2-21). The staff recommended that this possibility be investigated through additional saturated zone activities in the vicinity of the Solitario Canyon borehole study and that additional wells should be constructed, and other data collected, in the controlled area south of the perimeter drift in the area south of wells G-3 and WT-1 and east of WT-10 to adequately characterize the potentiometric surface in that area. Comment no. 20 remains unresolved. There are no other unresolved site specific technical concerns related to sample bias either in delineating the potentiometric surface or collecting data on matric potentials within the controlled area at the Yucca Mountain site that resulted from the staff review of the SCP.

Finally, the staff did not specifically identify any generic technical issues about sampling bias in collecting information on potentiometric levels, gradients or matric potentials at the Yucca Mountain site in its review of the SCP. However, the ability to characterize the spatial distribution of matric potential at appropriate scales in unsaturated, fractured rock is limited. This limitation relates to the coupling of fluid potential with osmotic gradients, thermal gradients and atmospheric water activity (Rasmussen and Evans, 1987).

(c) Limitations of testing methods and procedures: Measuring hydraulic head in the saturated zone is a relatively straightforward task and the experience base in applying typical downhole methods is large. Methods include manually lowering steel measuring tapes downhole, using downhole flotation devices wired to chart recorders or use of downhole pressure transducers linked to computerized monitoring systems. DOE collects continuous (in up to two wells at any one time), hourly, monthly or quarterly measurements of water levels where the hourly and continuous water-level data are collected in real time using computerized data collection systems (DOE, 1992a; p. 2-49). The staff did not identify any site specific concerns or generic technical issues related to methods and procedures for measuring hydraulic head in the saturated zone in its review of the SCP.

Measuring matric potential (or matric suction) in the unsaturated zone is difficult, particularly in consolidated rock. This difficulty results from standard equipment being designed primarily for unconsolidated soils, the potential for disturbance of ambient conditions from drilling and coring and the general lack of any experience base in collecting such data from consolidated rock. The staff did not identify any site specific technical concerns about limitations of testing methods and procedures related to measuring matric potential in its review of the SCP. However, early on staff recognized this topic as an important generic technical issue for the Yucca Mountain site. Techniques useful for estimating field matric potentials were evaluated by Rasmussen and Evans (1987). This research indicated that the osmotic tensiometer is unsuitable for most fractured rock applications due to the biodegradability of the semipermeable membrane used to isolate the formation fluid from the osmotic solution used to monitor matric potentials. DOE has considered a number of methods including the adaptation of tensiometer-transducer and heat-dissipation probe techniques to permit more direct measurement of matric potentials in rock core (DOE, 1988; p. 8.3.1.2-190) and has obtained thermocouple psychrometer measurements of matric potential on approximately 100 samples from one borehole (DOE, 1992a; p. 2-36). DOE is currently using a chilled-mirror psychrometer to provide water activity data (from which matric potential can be calculated) by employing a Peltier-cooled mirror to detect the dewpoint and an infrared sensor to measure temperature (DOE, 1992a; p. 2-36). At the Apache Leap Tuff site, an NRC supported research site, the matric potential is inferred from the field measured water content and the laboratory derived characteristic curves (Rasmussen, et al., 1990; p. 27).

It should be noted that discrete discontinuities (such as fractures) may affect ambient matric potentials. A matric potential continuum may not exist across discrete discontinuities. Rapid matric potential changes may occur across inclined fractures and funneling of fluid flow (and solute transport) along inclined fractures may occur due to the capillary barrier provided by such discontinuities. This results in uncertainty in the spatial distribution (variation) of the hydraulic gradient in the unsaturated zone regardless of the number of measurements of matric potential available. This fundamental uncertainty precludes confirmation of flow (and transport) models in the unsaturated zone.

(3) Characteristics of hydrogeologic units: Determining the characteristics of individual hydrogeologic units is an iterative process. Deciding which characteristics (specific coefficients for a specific governing equation) need to be determined depends on which governing equation adequately describes how groundwater flows at the site; in turn, conclusions over the most appropriate governing equation may change as new information is obtained. Not all of the coefficients in the governing equations that could potentially be used for Yucca Mountain will necessarily be either physically measurable or physically based (i.e., non-empirical).

Considerable information about the hydrogeology of the site will be derived from both laboratory and field scale hydrogeologic tests. This information is converted into assumptions about the spatial variability of the values of hydraulic coefficients, such as hydraulic conductivity or effective porosity. The spatial variability of these coefficients, in large part, defines the projected groundwater flow fields and transport paths along which GWTT is determined and radionuclides could migrate from the repository to the accessible environment. In addition, probabilistic predictions of the performance of the geologic repository requires uncertainty and sensitivity analyses that involves determination of statistical parameters for various hydraulic coefficients.

The characteristics of hydrogeologic units within both the saturated and unsaturated zones may be represented by numerous coefficients and constitutive relationships (refer to section 3.1.2 of the FCRG). Because the subject regulatory requirement is related to GWTT, this section will focus on characteristics of hydrogeologic units that are generally relevant to groundwater flow (isothermal and nonisothermal). In addition, the discussion in this section will focus primarily on site-scale concerns and issues because this scale is most relevant to determining pre-waste-emplacement GWTT. Relevant characteristics of hydrogeologic units are summarized below.

For saturated media, relevant characteristics include:

- General physical characteristics:

    - porosity

- matrix porosity
- fracture porosity
- effective porosity

- o fracture characteristics
  - density
  - spacing
  - orientation
  - fracture/matrix sealing along surfaces
  - areal extent and interconnectivity
  - distribution of aperture sizes

- General hydraulic characteristics (determined in the field):

  - o intrinsic permeability/compressibility
  - o effective hydraulic conductivity/specific storage
  - o transmissivity/storage coefficient
  - o saturated thickness
  - o leakage coefficients for aquitards

- Thermal properties:

  - o thermal conductivity (from core and/or field tests)

  - o heat capacity or specific heat

For unsaturated media, relevant properties include:

- General physical characteristics:

  - o matrix properties (determined in laboratory)
    - bulk density
    - skeletal density
    - effective porosity
    - pore surface area
    - pore size distribution

  - o fracture properties
    - density
    - spacing
    - orientation
    - porosity
    - aperture sizes

  - o fracture surface characteristics (determined in laboratory)
    - fracture/matrix sealing along surfaces
    - surface profiles/roughness
    - capillary aperture

- conductance

- General hydraulic characteristics:

  - matrix/fracture (determined in laboratory)
    - intrinsic permeability
    - saturated hydraulic conductivity
    - wetting and drying moisture characteristic curves (relationship of water content to matric potential)
    - unsaturated hydraulic conductivity as a function of water content and matric potential
    - pneumatic permeability
    - water content

  - matrix/fracture (determined in the field)
    - effective hydraulic conductivity
    - pneumatic permeability
    - water content

- Thermal properties

  - thermal conductivity (from core and/or field tests)

  - heat capacity or specific heat

Specific methods and procedures to be used by DOE to obtain matrix and fracture material properties, for both the unsaturated and saturated zones, are discussed in the following study plans, as referenced in the SCP (DOE, 1988):

- Study Plan 8.3.1.2.2.3 Characterization of percolation in the unsaturated zone--surfaced based study

- Study Plan 8.3.1.2.2.4 Characterization of percolation in the unsaturated zone--exploratory study facility

- Study Plan 8.3.1.2.2.6 Characterization of gaseous-phase movement in the unsaturated zone

- Study Plan 8.3.1.2.3.1 Characterization of the site saturated zone groundwater flow system

These study plans have not undergone a detailed review by the staff.

The following sections will consider the sources of uncertainty in characteristics of hydrogeologic units.

(a) Measurement error: The staff, in its review of the SCP, did not identify any site specific technical concerns or generic technical issues about operator error, instrument calibration, malfunction or application of data correction factors, related to determining the characteristics of hydrogeologic units.

However, the staff has expressed to DOE some site specific concerns related to test interference. The staff has expressed a concern about the effects of ventilation of the exploratory studies facility (ESF) on planned testing and the potential for irreversible changes to baseline site conditions (refer to comment no. 123 of the SCA; NRC, 1989). During review of DOE's study plan for saturated zone testing of the C-hole sites with reactive tracers (DOE, 1989; Study Plan 8.3.1.2.3.1.7), the staff noted the considerable potential for interferences among the tests proposed, especially given the large number of hydrologic and tracer tests planned, and brought this matter to DOE's attention (NRC, 1991).

(b) Sampling bias: As previously stated, describing hydrogeologic variability (heterogeneity and anisotropy) requires a database of hydraulic coefficients that are representative of the site. The distribution of tests across a site is an important factor in determining the representativeness of the database. Also discussed under this topic are concerns related to the application of statistical methods used to express the spatial variability of hydraulic coefficients (parameter estimation techniques).

Based on the staff review of DOE's plans for characterization of the site saturated zone groundwater flow system discussed in its SCP (DOE, 1988; Section 8.3.1.2.3.1), the staff recommended that plans should include the construction and testing of one or more additional multiple-well complexes similar to the C-hole complex (NRC, 1989; comment no. 19). The proposed multi-well tests at the C-hole complex will be used to evaluate hydrogeologic conditions along flow paths east-southeast of the repository block. However, there is an area of 12 square km to the south and south-southeast in which there is only one well, WT-17. Included in the western part of this area is a zone of high horizontal gradient that is poorly defined. This area, entirely within the controlled area, includes potential groundwater flow paths from the repository to the accessible environment. Numerous faults occur in this area, including the Solitario Canyon, Abandoned Wash, Bow Ridge, Midway Valley, Paintbrush canyon and other faults. Multi-well testing in this area would provide information necessary for evaluating hydrogeologic properties (field scale values for certain coefficients). The staff believes that testing at only one multiple-well complex will not be adequate to develop the hydraulic coefficients for the saturated zone flow system between the repository and the accessible environment. Comment no. 19 remains unresolved. There are no other unresolved site specific technical concerns that resulted from the staff review of the SCP about sampling bias related to collecting data on the characteristics of hydrogeologic units at Yucca Mountain.

DOE's overall strategy for obtaining a database sufficient to describe the spatial variability of hydraulic coefficients is described in the study plan on the systematic acquisition of site-specific subsurface information (DOE, 1993; Study Plan 8.3.1.4.3.1). Specific DOE methods and procedures for geostatistical analyses and parameter estimation related to determining the spatial variability of hydraulic coefficients will be provided in study plans on unsaturated and saturated zone testing, referenced previously in this discussion, as well as study plans on the synthesis and modeling of the site unsaturated and saturated flow systems (DOE study plans 8.3.1.2.2.9 and 8.3.1.2.3.3). With one exception, none of these study plans have undergone a detailed review by NRC staff. DOE's study plan related to the saturated zone hydrologic system synthesis and modeling is currently undergoing detailed review by the staff (DOE, 1992c; Study Plan 8.3.1.2.3.3).

Uncertainty in the spatial variability of hydrogeologic parameters can be propagated to the estimate of GWTT. Some propagation methods are well-accepted, such as Monte Carlo simulation. Typically, numerical values of the parameters used in Monte Carlo simulation are selected using statistical sampling methods (e.g., Latin Hypercube Sampling, Random Sampling, and Importance Sampling), and this sampling depends on the range of possible values that each parameter could assume and the shape of the distribution function, usually a probability distribution function (pdf), that assigns a likelihood to each of the values in that range. A poor representation and quantification of the range of possible values and the pdf will translate to a poor representation of the uncertainty in GWTT. Ababou (1991) provides a review of methods to assess variability (three-dimensional heterogeneity and anisotropy) over a broad range of scales for both purely saturated and purely unsaturated flow. In that review, two types of heterogeneity were considered; the continuous heterogeneity of porous media and the discontinuous heterogeneity represented by fractures. In addition, much of the review focused on statistical continuum interpretations (the application of stationary random field models) of available aquifer data and unsaturated soil properties. Stochastic models, based on geometric probability and random functions, can be used to represent the spatial variability in geologic media.

Determining the spatial variability of hydraulic coefficients is not without problems. The use of stationary random field models of heterogeneity assumes statistical homogeneity of the data. Certain hydraulic coefficients such as hydraulic conductivity appear to be scale dependent. Therefore, the implied length scale of the values of hydraulic coefficients derived from different test techniques is of concern because the resulting data could violate the assumption of statistical homogeneity. Hydrogeologic tests will be performed on a variety of scales at Yucca Mountain. Hydraulic coefficients will be derived from tests from a scale of centimeters (i.e., laboratory testing of core samples or cuttings), meters (downhole logging and geophysical testing) to hundreds of meters (i.e., saturated zone pumping/tracer field tests). There are both physical and theoretical limitations on the radius of testing influence in the unsaturated zone. There are also practical reasons for limiting the number of large scale field tests in the saturated zone. Regardless of these limitations, data derived from different testing techniques need to be integrated into a conceptualization of the hydrogeologic system. Additional demands for a data base sufficiently large to allow defensible use of statistical analyses tends to focus efforts towards a large number of smaller scale tests (e.g., emphasis on laboratory derived data). It is necessary to understand the effect of local-scale trends in values of hydraulic coefficients on global-scale trends in order to develop effective values of hydraulic coefficients from values derived from different test techniques. The staff believes that lack of universally accepted methods to transfer information from one scale of analysis to another (upscaling) is one root cause of uncertainty in the description of the site hydrogeologic conditions and subsequent performance assessments. Therefore, the effects of the scale dependency of hydraulic coefficients on statistical expression of coefficient variability in space is an important generic technical issue.

Determining the spatial variability of hydraulic coefficients increases in complexity in the unsaturated zone because hydraulic coefficients are pressure dependent (i.e., vary with saturation as described by moisture characteristic curves that relate water content to matric potential). There have been few attempts to describe the spatial variability of the nonlinear constitutive relations of unsaturated porous media. Ababou (1991) considers two approaches to characterize the spatial structure of relative unsaturated conductivity curves (Cross correlations and Similar Media Hypothesis) for porous media. Additional models may have to be developed for fractured rock.

(c) Limitations of testing methods and procedures: The number of testing methods available to quantify all of the hydraulic coefficients and constitutive relationships listed previously is too large for those methods to be considered individually here. Therefore, the discussion in this section will highlight those areas where unresolved site specific technical concerns or generic technical issues exist.

A factor to be considered in characterizing the unsaturated zone is that most instrumentation was developed for use in porous soils. Further, most of the experience base is in unconsolidated soil. Therefore, testing of unsaturated, consolidated rock, both in the laboratory and in the field, requires adaptation or development of new equipment. DOE is generally aware of limitations of available instrumentation as evidenced by the large amount of prototype work discussed throughout the SCP (DOE, 1988). In general, the staff believes that sufficient methods exist for determining hydraulic coefficients and constitutive relationships at the laboratory scale; even with a comparatively limited experience base applying these methods to consolidated rock.

Mathematical modeling strategies to simulate groundwater flow will likely involve indirect approaches (see discussion under the Key Technical Uncertainty topic on mathematical models). These indirect approaches represent the groundwater flow system as a continuum. Characteristics of hydrogeologic units are represented by unique "effective" hydraulic coefficients and constitutive relations that are assumed to express the field scale, bulk behavior of continua. Typical methods and procedures used to determine hydraulic coefficients at field scale, such as saturated hydraulic conductivity, require the creation of a hydraulic stress on the hydrogeologic system. The response to this controlled stress is monitored and recorded. Generally, the measured data are evaluated based on established assumptions and concepts (a model of the assumed configuration and interaction of the flow system) that can be expressed in the form of partial differential equations. The application of the solutions of these partial differential equations, in analytical form and which are generally quite robust, is used to quantify the hydraulic coefficients such as transmissivity (and hydraulic conductivity), storativity and effective porosity. Uncertainty in the derived data arises because either field conditions may not match the assumptions implicit in these models or, from a different perspective, more than one analytical model may successfully predict the observed responses from the stress test.

The general experience base in field scale stress testing of saturated media is quite large. The staff believes that field scale tests for determining hydraulic coefficients of saturated rock can be interpreted by using appropriate adaptations of available analytical models (type-curves) or inverse methods.

The experience base in field scale testing of unsaturated, fractured rock is extremely limited. In addition, determining field scale effective hydraulic conductivity in the unsaturated zone is more difficult due to the lack of liquid water, limitations in the scale of tests that can be accomplished and the time required for re-equilibration. One possible method is to inject water into a single borehole wherein the injection rate is converted into an effective hydraulic conductivity (for the wetting phase; water) using a number of available analytical solutions described and referenced in Rasmussen et al., (1990; pp. 26-27). It may be possible to conduct and interpret field scale pneumatic (gas phase pressure and/or tracer) tests to determine hydraulic permeability. Rasmussen et al., (1993) and Kilbury et al., (1986) present a methodology using field-estimated pneumatic permeabilities as a surrogate for field hydraulic permeabilities. Good agreements between central tendencies and values estimated at 105 locations in fractured rock at the Apache Leap Tuff site appears to demonstrate that air permeability tests can be used to provide estimates of the mean and the spatial variation of saturated hydraulic permeability at field scales (Rasmussen, et al., 1993). It remains to be demonstrated, however, that air permeability tests can be used to estimate unsaturated hydraulic properties on field scales. A promising technique may be the use of cross-borehole air-phase tracer tests to estimate moisture-dependent, macropore and micropore porosities and permeabilities. Additional procedures will be required to characterize flow channels within fractures. Field-scale experiments will also be needed to estimate the degree of fracture-matrix interactions.

Based on review of the SCP, the staff has identified a site specific technical concern about DOE's consideration of plans to initiate single-well hydraulic tests as an alternative to a second multiple-well test site in the saturated zone (NRC, 1989; comment no. 19). DOE's stated purpose of additional saturated zone testing after completion of testing at the only available multiple-well complex (C-hole complex) is *to refine and confirm the understanding of geologic structure and saturated flow parameters determined during tests at the C-hole complex* (DOE, 1988; p. 8.3.1.2-370). It is the opinion of the staff that this proposed alternative will not provide the information necessary to describe physical features and determine hydraulic coefficients representative of the bulk behavior of the saturated zone (i.e., an effective hydraulic conductivity that accounts for both matrix and fracture pathways). DOE acknowledges the limitations of single-well testing by stating that *multiple-well tests will be needed to evaluate complex heterogeneous flow models. While useful for investigating many aspects of saturated-zone hydrology beneath Yucca Mountain, results of single-well tests have limited use in understanding the nature and areal distribution of bulk aquifer properties* (DOE, 1988; p. 8.3.1.2-369). The importance of multiple-well testing for characterizing saturated flow has been expressed previously by staff (NRC, 1983a). The staff's position has been that such tests would facilitate objective verification of any conceptual model, provide bulk values of hydraulic coefficients including vertical hydraulic conductivity, improve hydraulic head data, provide information on hydrogeologic boundaries, and permit calibration of mathematical models so that GWTT can be defensibly estimated (NRC, 1983a; p. 3-11). The staff recognizes that there are conditions where single-well testing is necessary. For example, if no response to pumping is observed in wells a short distance away from the pumped well, then the only viable testing method available may be single-hole tests. Further, it is important to insure that the integrity of the repository is not compromised by an excessive number of boreholes. However, compared with multiple-well tests, results from single-hole tests will not be representative of large-scale hydrogeologic conditions across the site; the scale of importance to performance assessment (NRC, 1983b).

(4) Recharge and discharge: The amount and location of recharge and discharge are controlling factors in the movement of water and thus, are important components of a conceptual groundwater flow model. The terms recharge and discharge are often used with respect to regional groundwater flow and refer to the net gain or loss of water from the regional saturated zone. For the purposes of determining pre-waste-emplacement GWTT, the rate and distribution of infiltration at the Yucca Mountain site, not recharge and discharge throughout the regional system, is the information of primary importance and thus, the focus of this discussion. Direct recharge (deep percolation to the water table) at the site is from precipitation. There is no direct discharge of groundwater through springs or other such features at the site. Specific methods and uncertainties related to obtaining supporting information considered in determining recharge, such as precipitation, runoff and evapotranspiration, will not be discussed under this Key Technical Uncertainty.

The amount and distribution of infiltration is an important boundary condition incorporated into numerical models used to calculate GWTT. Typically, this type of boundary incorporates an average infiltration rate. However, in fractured, unsaturated rock such as at the Yucca Mountain site, the occurrence of high intensity rainfall events, arriving erratically in time, may drastically modify the subsurface flow regime from what would be inferred from an average infiltration rate model (Patrick, 1993; p. 6-7). DOE has concluded that the spatial and temporal distribution and magnitude of infiltration into the system may be the most important independent parameter influencing flow path development (DOE, 1992d; p. 2-9). DOE has also indicated that rapid infiltration associated with transient pulses of water appears to occur in the near-surface fracture systems at Yucca Mountain. Infiltrated water may be attenuated or redistributed due to variability in hydraulic characteristics of hydrogeologic units (e.g., variations in matrix hydraulic conductivity, fracture frequency/conductivity, etc.). In addition, the mass transfer of water in the vapor phase may also affect the amount of infiltrated water that deeply percolates through the unsaturated zone to the water table (in effect, a form of discharge). These factors, when combined, influence the relative proportion of matrix and fracture flow of liquid water.

Specific methods and procedures to be used by DOE to determine the rate and distribution of infiltration at the Yucca Mountain site are discussed in the study plan of characterization of unsaturated zone infiltration (Study Plan 8.3.1.2.2.1). To date, the staff has not undertaken a detailed review of this study plan.

(a) Measurement error: The staff did not identify any site specific technical concerns or generic technical issues about measurement error, related to determining the rates or distribution of infiltration at the Yucca Mountain site, during review of the SCP (DOE, 1988).

(b) Sampling bias: The staff did not identify any site specific technical concerns or generic technical issues about sampling bias related to determining the rates or distribution of infiltration at the Yucca Mountain site, during review of the SCP (DOE, 1988). In general, sampling biases can be introduced by excluding locations that may have relatively higher infiltration and recharge rates, such as near ephemeral stream courses or where fractured bedrock is exposed.

(c) Limitations of testing methods and procedures: The simplest method to estimate net infiltration is the water balance approach where recharge equals precipitation less the sum of surficial runoff and evapotranspiration. Other methods include approaches such as coupling field measurements of capillary pressure with hydraulic properties to estimate recharge, measuring water table fluctuations from which recharge can be estimated, the use of artificial or natural tracers and numerical experiments (Sniff, et al., 1988).

Methods to estimate infiltration rates to the subsurface have been evaluated at two unsaturated, fractured tuff sites in Arizona. The Gringo Gulch Tuff was studied by Kilbury, et al., (1986) who demonstrated the effectiveness of surface-based estimates of infiltration at the earth-atmosphere interface. Additional studies by Rasmussen and Evans (1993) at the Apache Leap Tuff site used watershed rainfall and runoff data in conjunction with field and laboratory estimates of rock matrix properties to identify the net rate of infiltration at the earth-atmosphere interface. Sniff et al., (1988) summarized a number of hydrogeologic studies of precipitation and recharge that were conducted in various parts of the world (particularly in arid and semi-arid regions) to show what kinds of correlations exist between precipitation and the amount of precipitation that ultimately becomes recharge. They found that for any given annual precipitation rate, a large range can exist in the amount of the precipitation that becomes recharge and that this appears to be true even in arid and semi-arid regions, where potential evapotranspiration can be many times larger that the precipitation. In comparing the various methods used to determine recharge, they caution that each has its proper place in hydrologic studies. Direct methods of measurement will usually give a good estimate of the recharge rates for a discrete location during a specific time period. A mass balance method is usually used to yield a recharge rate for larger hydrologic systems. The use of tracer studies, especially natural environmental tracers, can give information as to the degree of recharge variation, not only spatially, but also in time. They found that estimation of a recharge rate based upon a general precipitation versus recharge correlation for a large area is a gross first order approximation. The percentage of the precipitation that actually becomes recharge does not necessarily approach zero at some given precipitation level, as has been shown in many studies worldwide. They also concluded that the use of any general correlation for the prediction of groundwater recharge at the Yucca Mountain site should be viewed with caution.

DOE's general plan to characterize the present (and future) spatial distribution of infiltration rates over the repository block is described in the SCP (DOE, 1988; Study 8.3.1.2.2.1; pp. 8.3.1.2-157 to 8.3.1.2-179). DOE will conduct water budget studies in order to evaluate their potential as a tool in estimating infiltration rates in different surficial materials covering Yucca Mountain under different climatic conditions. If useful, DOE plans to apply water budget methods to monitor infiltration from both natural and artificial precipitation events. DOE acknowledges the limitations of water budget methods in determining either net infiltration or specific infiltration rates noting that the combined error from precipitation, runoff, and evapotranspiration measurements may be equal to or larger than infiltration values in desert climates (DOE, 1988; page 8.3.1.2-169). Because of this limitation, DOE plans to obtain direct measurements of infiltration rates and water budget methods will be used only for confirmatory purposes. Specifically, DOE will use a combination of methods to directly measure infiltration rates. Neutron access hole studies will monitor natural infiltration in approximately 100 holes located in areas of varying surficial hydrologic properties. Additional studies will monitor natural infiltration beneath as many as 25 small and 12 large rainfall-simulation control plots located in major hydrogeologic surficial units. Artificial infiltration tests will be conducted in various surficial materials to assess upper flux boundary conditions under simulated wetter conditions (not directly germane to pre-waste-emplacement GWTT). Artificial infiltration studies include double-ring infiltrometer studies, ponding studies, small-plot rainfall simulation studies and large-plot rainfall simulation studies. These studies cover a range of spatial scales.

The staff believes that information on net infiltration from water balance methods applied at various scales coupled with direct measurement of infiltration rates from test sites distributed throughout the site will likely be adequate to set upper bounds on the amount of infiltrated water that percolates deeply to the water table. However, this upper bound could be overly conservative. As noted previously, infiltrated water may be attenuated or redistributed due to variability in hydraulic characteristics of hydrogeologic units (e.g., variations in matrix hydraulic conductivity, fracture frequency/conductivity, etc., that are also uncertain) and the mass transfer of water in the vapor phase. Therefore, estimating the amount and distribution of liquid water that percolates through the unsaturated zone to the water table requires estimates of vapor phase water movement. One objective of DOE's planned gaseous-phase circulation study is to provide information needed for numerical experiments to quantify vapor fluxes and gas transport (DOE, 1988; Study 8.3.1.2.2.6; pp. 8.3.1.2-322 to 8.3.1.2-334).

Finally, the staff did not identify any site specific technical concerns or generic technical issues about limitations of testing methods and procedures, directly related to measuring the rates or distribution of infiltration at the Yucca Mountain site, during review of the SCP (DOE, 1988). As stated previously, the staff has not undertaken a detailed review of DOE's study plan on characterization of unsaturated zone infiltration (DOE Study Plan 8.3.1.2.2.1).

As discussed in the following section, the geochemical characteristics of water and gas in the unsaturated zone may serve as an independent indicators of the amount and distribution of deep percolation and flow paths identification for deeper waters.

(5) Geochemical and isotopic characteristics: The in situ geochemical characteristics of water and gas have significant potential as an independent indicators of both how deeply and quickly infiltrated water (of various ages) has percolated through the unsaturated zone and the potential mass transfer of water between fractures and matrix. The geochemical characteristics of groundwater within the saturated zone also have potential as independent indicators of groundwater flow paths and velocities.

Specific DOE activities to evaluate the geochemical characteristics of water and/or gas in order to assess how quickly and deeply infiltrated water has percolated through the unsaturated zone and to evaluate groundwater flow paths and velocities in the saturated zone are discussed in the following study plans.

- Study Plan 8.3.1.2.2.3 Water movement test (Activity 8.3.1.2.2.1 Chloride and chlorine-36 measurements of percolation at Yucca Mountain)

- Study Plan 8.3.1.2.2.4 Characterization of Yucca Mountain percolation in the unsaturated zone-ESF study (Activity 8.3.1.2.2.4.8 Hydrochemistry tests in the ESF and Activity 8.3.1.2.4.10 Hydrologic properties of major faults encountered in main test level of the ESF)

- Study Plan 8.3.1.2.2.6 Characterization of gaseous-phase movement in the unsaturated zone

- Study Plan 8.3.1.2.2.7 Hydrochemical characterization of the unsaturated zone

- Study Plan 8.3.1.2.3.2 Characterization of saturated-zone hydrochemistry

These study plans have not undergone a detailed review by the staff.

An analysis of the geochemical characteristics of groundwater will typically include the major cations and anions, total dissolved solids, Eh/ph and trace metals. In addition, both radioactive and stable isotopes provide the potential to directly determine the nature of two-phase flow of through a dual porosity medium representative of the fractured, unsaturated tuff at the Yucca Mountain site. An evaluation of geochemical methods that have potential use in estimating the travel time of groundwater are provided in Davis and Murphy (1987). Water, Waste and Land, Inc. (1988), working under an NRC technical assistance contract, summarized the potential use of environmental tracers for the estimation of net infiltration (deep percolation) at Yucca Mountain. Both radioactive (Tritium, Chlorine-36, Carbon-14, Silicon-32, Argon-39, Iodine-129, Krypton-81 and Krypton-84) and stable isotopes (Carbon system, Deuterium and Oxygen-18 system) were evaluated. Estimating the travel time of groundwater from isotopic information requires knowledge of the coincident geochemistry as well as the application of assumed conceptual and mathematical models.

(a) Measurement error: During review of DOE's site characterization progress report (No. 7; DOE, 1992a), the staff raised a question (related to comment no. 123 in the SCA; NRC, 1989) about DOE's evaluation of the potential for air movement from the ESF to adversely impact the collection of geochemical data necessary for site characterization (NRC, 1993a). This question remains a point of discussion with DOE.

(b) Sampling bias: The staff did not identify any site specific technical concerns or generic technical issues about sampling bias related to characterizing the geochemical characteristics of the Yucca Mountain site groundwater flow system, during review of the SCP (DOE, 1988).

(c) Limitations of testing methods and procedures: Specific limitations in testing methods and procedures are generally unique to specific geochemical indicators and cannot be discussed individually here. However, some limitations, or problem areas, in using geochemical indicators can be considered generic. These include: (1) sample collection methods and limits in available sample size; (2) preservation and analysis; and (3) interpretations.

Collecting liquid water samples in unsaturated rock is problematic. Although some efforts to extract aqueous solutions by triaxial compression (i.e., high pressure) from rock samples are underway (Yang et al., 1988; Peters et al., 1992), there are large uncertainties in the compositions of solutions derived using this technique. Aqueous samples have also been extracted from partially-saturated soils and sands by ultracentrifugation techniques (Edmunds et al., 1992; Puchelt and Bergfeldt, 1992). It is not clear whether compositions of water extracted from rock cores by ultracentrifugation or by high-pressure "squeezing" techniques accurately represent the compositions of in situ pore water. In addition, the difficulty in collecting liquid water samples in unsaturated rock necessarily limits the size of the sample. This could limit the analysis of geochemical indicators of interest. The above limitations do not apply to geochemical analysis of gases or of liquid water in the saturated zone.

Sample preservation and analysis are also generic factors in geochemical characterization. For example, preservation of dissolved gases is an immediate concern upon sample collection. Geochemical analyses also can be technically complex and costly. For example, there are not many laboratories equipped to analyze for the noble gases.

Translating geochemical information into conclusions about liquid and gas movement may become very complex. Carbon-14, as one example, is one of the most common environmental tracers used. Interpretation of Carbon-14, using very simple models, requires a number of assumptions including: (1) the atmospheric production of radiocarbon has been constant for the last 100,000 years; (2) the mixing and uptake of carbon dioxide have been uniform and rapid; (2) no "young" or "old" carbon has been added to the sample since it was isolated from the global equilibrium state; and (4) no isotopic fractionation has occurred to alter the standard Carbon-14, Carbon-13 and Carbon-12 ratios in the samples (Water, Waste, and Land, Inc., 1988). Recently, uranium-related radionuclides are being evaluated for use in verifying Carbon-14 interpretations. Interpretation of other geochemical indicators generally requires similar assumptions, unique to the specific indicator.

(6) Pathway Analysis: Ultimately, all the descriptive information on the site groundwater flow system needs to be interpreted and synthesized into a general description of the fluid pathways to the accessible environment. DOE's general plans to integrate descriptive information obtained from site characterization, for both the unsaturated and saturated zones, into conceptual and mathematical models are described in a number of individual studies identified in the SCP (DOE, 1988). Individual study plans will provide more detailed information about DOE methods to estimate the spatial variability of various descriptive parameters and modeling the site unsaturated and saturated zones. Study plans describing these activities include:

- Study Plan 8.3.1.2.2.8 Fluid flow in unsaturated, fractured rock
- Study Plan 8.3.1.2.2.9 Site unsaturated-zone modeling and synthesis
- Study Plan 8.3.1.2.3.3 Saturated zone hydrologic system synthesis and modeling

To date, the study plans noted above that relate to the unsaturated zone have not undergone a detailed review by NRC staff. The study plan related to saturated zone hydrologic system synthesis and modeling is currently undergoing a detailed review by the staff.

Finally, the staff believes that the important physical factors to be considered in calculating pre-waste-emplacement GWTT at Yucca Mountain, are:

- Unsaturated zone:
    - Variation in ambient matric potential and resulting hydraulic gradient across the Yucca Mountain site
    - Spatial variability of hydraulic characteristics of individual hydrogeologic units
    - Magnitude and distribution of infiltration rates across the Yucca Mountain site
    - Attenuation of infiltrated water (magnitude and distribution of deep percolation of liquid water through the unsaturated zone to the water table) resulting from water vapor movement, interaction between the matrix and fractures and spatial variability of hydraulic characteristics

- Saturated zone:
    - Variation in hydraulic head across the Yucca Mountain site
    - Spatial variability of hydraulic characteristics of individual hydrogeologic units
    - Structural control (large scale fracture network) of groundwater flow in the saturated zone.

Resolution of this Key Technical Uncertainty will depend in large part on addressing technical issues related to the above factors.

Performance Objective at Risk: 10 CFR 60.113(a)(2)

Explanation of Nature of Risk: The conceptual groundwater flow model of the Yucca Mountain site is inextricably related to the mathematical model that is implemented to quantitatively demonstrate compliance with the performance objective for the geologic setting. Failure to directly address sources of uncertainty in the descriptive information comprising the conceptual groundwater flow model undermines the technical defensibility of both the conceptual and mathematical model such that, in turn, the validity of predicted GWTT could be questioned.

Description of Resolution Difficulty: Resolution of this Key Technical Uncertainty requires the following:

- The DOE needs to demonstrate that their conceptualization of the Yucca Mountain site groundwater flow system is both representative of the site and technically defensible. This requires DOE to address all uncertainties in the conceptual model(s) in order to demonstrate:
    - The appropriateness of testing and test analysis methods used to characterize the Yucca Mountain site groundwater flow system

- The representativeness of the hydrogeologic database

- The appropriateness of geostatistical and stochastic methods used to describe the variability of hydrologic characteristics throughout the Yucca Mountain site

- The appropriateness of formal use of expert judgement, if any, in evaluating or synthesizing information about the Yucca Mountain site groundwater flow system

* The DOE needs to provide strategies or rationales for closing any open items (site specific technical concerns identified by the staff during review of DOE program documents) related to the conceptual model(s) of the Yucca Mountain site groundwater flow system.

* The DOE needs to demonstrate that alternative interpretations and contradicting information, if any, were considered in developing the conceptual model(s) of the Yucca Mountain site groundwater flow system.

* The staff needs to develop specific, technical review criteria for determining that DOE's conceptualization of the Yucca Mountain site groundwater flow is both representative of the site and technically defensible. Specifically, these criteria need to serve as bases for staff decisions in determining the acceptability of test, test analysis, statistical, and formalized expert judgement methods used by DOE in the site characterization program.

The staff has identified a number of generic technical issues that warrant independent research by the NRC. Issues, or lack thereof, are presented below in the context of the three primary sources of uncertainty in conceptual groundwater flow models:

* Measurement error: The staff has not identified any significant, generic technical issues related to measurement error. Rather, the staff believes that DOE can readily address the potential for measurement error in advance by developing and implementing study plans and technical procedures under a sound quality assurance program that includes field testing instruments, methods and procedures. This should allow test results to be reproduced or independently evaluated.

* Sampling bias: Important generic technical issues with respect to sampling bias include:

    - What are acceptable geostatistical and stochastic methods (parameter estimation techniques) for expressing the spatial variability of effective hydraulic coefficients?

    - What are acceptable methods for expressing the spatial variability of constitutive relations for unsaturated, fractured rock?

    - What methods can be used to address the effects of test scale on the statistical expression of spatial variability of hydraulic coefficients?

- Limitations of testing methods and procedures: Important generic technical issues include:

  - What are the acceptable methods for determining field scale, effective hydraulic coefficients for unsaturated, fractured rock?

  - What is an acceptable approach for characterizing the spatial distribution of infiltration.

  - What geochemical methods are acceptable to be used as independent checks of assumptions made about the relative proportion of matrix versus fracture flow?

  - How can geophysical information (e.g., geotomography and gamma logs) be used to determine persistent discontinuities and in development of spatial correlation structures in unsaturated rock?

Planned analytical work undertaken by the staff in support of compliance determination methodology development for this regulatory requirement will support development of technical review criteria to be used by staff in determining the representativeness and technical defensibility of DOE's conceptualization of the Yucca Mountain site groundwater flow system.

Aspect of several different NRC funded research projects, as well as tasks performed as technical assistance to the staff, at the Center for Nuclear Waste Regulatory Analyses (CNWRA) will support staff efforts to resolve this Key Technical Uncertainty. Laboratory and field studies performed in the Geochemical Analogs and Thermohydrologic research projects provide information that will help identify conceptual models appropriate for characterizing groundwater flow through Yucca Mountain (Patrick, 1993).

Studies conducted at the Peña Blanca field site as part of the Geochemical Analog Project provide information from which a conceptual model of flow and transport through saturated and unsaturated fractured volcanic rock can be formulated. Studies performed as part of this investigation that support the conceptualized models include laboratory and field calculations of the hydraulic properties of the medium and the conduct of field-scale experiments to estimate flow and transport through fractured porous media at field scales. The limited size of the Peña Blanca field site provides an opportunity to conduct experiments and observe processes in the field at a scale small enough and of limited duration to be meaningful. Observation of past geochemical processes and planned hydrological and geochemical experiments can provide information that would constrain the range and scope of feasible conceptual models.

Laboratory studies conducted as part of the Thermohydrologic Project are directed at the investigation of flow characteristics through fractured, porous media. These laboratory studies are designed to provide an understanding of the complex physical processes that control groundwater flow through unsaturated fractured, porous media. Non-isothermal laboratory-scale experiments and analyses conducted in the Thermohydrologic Project suggest that an appropriate conceptual model of the Yucca Mountain flow system will be a function of the heat load imposed at the repository. Physical processes important at a relatively low heat load level are not expected to be the same as those encountered at a relatively high heat load level (Green et al., 1992). An understanding of these inter-related processes is important in the appropriate formulation of a conceptual model to determine groundwater travel time through Yucca Mountain.

Additionally, a subtask in Technical Assistance, Reduction of Groundwater Travel Time Uncertainty, is designed to address the conceptualization of groundwater flow. Conceptual issues recognized during the conduct of this subtask include fracture-matrix interactions, volume-averaging techniques and the appropriate incorporation of heterogeneities in to the model (Green et al., 1992). Resolution of these issues during future computational analyses is necessary in order to formulate a representative conceptual model.

NRC funded research at the University of Arizona will support staff efforts to resolve this Key Technical Uncertainty. This integrated characterization project, consisting of field and laboratory hydraulic, pneumatic, geochemical and thermal experiments in unsaturated, fractured rock, was established to evaluate alternate characterization strategies. In addition, work under this project includes evaluating sampling methods and using geochemical indicators to independently assess infiltration and recharge rates. An important task of this project is to provide data sets related to the interstitial, hydraulic, pneumatic and thermal properties of unsaturated, fractured rock in order to evaluate the larger issue of parameter uncertainty resulting from hydrogeologic variability. Data from the Apache Leap Tuff site in Arizona have been used to provide laboratory and field scale characterization data in unsaturated, fractured tuff. Sampling at 105 locations has demonstrated methodologies for obtaining moisture characteristic curves, unsaturated hydraulic conductivity relationships, relative air permeability relationships and unsaturated thermal conductivity relationships. These data are available for the rock matrix for a wide range of matric potentials, and at field scales for a more limited range of matric potentials. Sully and Rasmussen (1989), Tidwell et al., (1988), Rasmussen et al., (1988), Rasmussen et al., (1989) and Rasmussen and Evans (1990) provide methodologies for obtaining characterization data of unsaturated, fractured rock at laboratory and field scales. Results from the Apache Leap Tuff site in central Arizona have been published (Rasmussen, et al., 1989b; Yeh et al., 1988; Evans and Rasmussen, 1991). The project has demonstrated the importance of collecting data using consistent methods for all processes considered relevant to flow (and transport), including hydraulic, pneumatic and thermal properties for a wide range of matric potentials. Recommendations made to date include the use of inclined boreholes to capture spatial variation of vertically-oriented, persistent discontinuities such as faults and fractures, and the collection of data over a regular grid to identify spatial variability in hydrogeologic properties. Research results indicate that: (1) auto- and cross-correlation between parameters can be used to reduce data requirements if the form of the relationships are known; (2) characterization at multiple scales provides continuity in models from local to regional perspectives; (3) interpreted hydraulic parameters will be unique for each measurement (correction for scale effects will require knowledge of hydrogeologic unit tortuosity and fractal properties, if any); (4) data from the Apache Leap Tuff site indicates no significant autocorrelation of hydraulic and pneumatic parameters. The variation in hydraulic properties (three to five orders of magnitude) may preclude the ability to identify significant differences between individual units.

Detailed Safety Review Supported by Independent Tests, Analyses, or Other Investigations (Type 5) Rationale:

Because the following Key Technical Uncertainties are the most difficult to resolve, there may be the highest risk of noncompliance with the total system and subsystem performance objectives. For these uncertainties, very little can be done to reduce the risk, or compensate for the risk using, for example, favorable site conditions or engineered features.

(1) Uncertainty caused by the lack of experimental confirmation of the basic physical concepts of groundwater flow through unsaturated fractured rock.

(2) Uncertainty caused by the lack of established new data collection and interpretation techniques required to model groundwater flow through unsaturated fractured rock.

(3) Uncertainty in modeling the formation of perched zones by thermally driven flow.

(4) Developing a mathematical groundwater flow model that is representative of the Yucca Mountain site groundwater flow system.

Each of the other Key Technical Uncertainties applies to Section 3.2.2.1. However, evaluation of these will be done under their respective sections (i.e., Section 3.3, Assessment of Compliance with the Groundwater Travel Time Performance Objective, and Section 3.2.2.12, PAC: Perched Water Bodies).

Key Technical Uncertainty Topic:

Experimental confirmation of the basic physical concepts of groundwater flow through unsaturated fractured rock is needed.

Description of Uncertainty:

To address this regulatory requirement topic, predictions will use models of groundwater flow through unsaturated fractured rock. The conditions that trigger fracture flow and the rate of flow when it occurs, has a significant effect on the potential for perched water bodies to form.

All models are simplifications of basic governing physical laws of the process being modeled. If the basic concepts are incorrect, computational models based on these concepts may be inaccurate. To date, few experiments have been identified that rigorously test the concepts of unsaturated flow in fractured rock. This is supported by the Site Characterization Plan for Yucca Mountain, which states that "Theoretical models for liquid-water flow in single fractures have been developed (Montazer and Harrold, 1985; Wang and Narasimhan, 1985) but have not been field and laboratory tested" (US DOE, 1988, p. 3-171). Therefore, models of groundwater flow through unsaturated rock may be inaccurate.

Performance Objectives at Risk:

10 CFR 60.112, 60.113 (a)(1)(ii)(B), or 60.113(a)(2).

Explanation of Nature of Risk:

Modeling of groundwater flow through unsaturated fractured rock will play an important role in demonstrating compliance with this regulatory requirement topic. However, a determination of compliance or noncompliance may not be possible if it cannot be established that the models are based on sound physical concepts. Failure to demonstrate compliance with this potentially adverse condition would make it harder to demonstrate compliance with the overall system performance objectives. This is because the formation of perched water could result in increased waste canister failure rates and faster radionuclide transport to the accessible environment.

Description of Resolution Difficulty:

Resolution of this Key Technical Uncertainty would require the use of physical experiments to confirm the basic physical concepts of groundwater flow through unsaturated fractured rock.

Key Technical Uncertainty Topic:

The development of new data collection and interpretation techniques are required for codes which model groundwater flow through unsaturated fractured rock.

Description of Uncertainty:

Modeling groundwater flow through unsaturated fractured rock will be an important part of addressing this regulatory requirement topic. However, if appropriate methods to collect data for unsaturated fractured rock flow codes do not exist, it will not be possible to adequately characterize the site or to calibrate the models used to predict groundwater flow through the unsaturated zone.

Currently, unsaturated fractured rock flow models designed for use at Yucca Mountain require either individual or bulk fracture properties. Furthermore, these codes require data on how the hydraulic properties of the fractures change as a function of changing moisture contents. However, appropriate measurement techniques for collecting unsaturated fracture hydraulic property data have neither been developed nor identified. Particular computer codes may use unique parameters which require different data collection or parameter estimation techniques. For example, dual continuum approaches to modeling unsaturated groundwater flow consist of one continuum for the porous matrix and one continuum for the fractures. The continua are connected by a fracture matrix transfer term that simulates flow between the fracture and the matrix. However, the fracture-matrix transfer term is a parameter that cannot be measured in the field or laboratory at this time.

Performance Objectives at Risk:

10 CFR 60.112, 60.113 (a)(1)(ii)(B), or 60.113(a)(2).

Explanation of Nature of Risk:

The modeling of groundwater movement through unsaturated fractured rock will be an important aspect of demonstrating compliance with this regulatory requirement topic. If appropriate methods are not available to collect data for unsaturated fractured rock flow codes, it will be difficult to adequately characterize the site or to model groundwater flow through the unsaturated zone. Failure to demonstrate compliance with this regulatory requirement topic would thus make it more difficult to demonstrate compliance with the overall system performance objective. This is because the formation of perched water could result in increased waste canister failure rates and faster radionuclide transport to the accessible environment.

Description of Resolution Difficulty:

Resolution of this Key Technical Uncertainty would require research to develop the appropriate testing techniques to collect the data and/or derive the code input parameters to model groundwater flow through unsaturated fractured rock.

Key Technical Uncertainty Topic:

Uncertainty in modeling the formation of perched zones by thermally driven flow.

Description of Uncertainty:

It has been hypothesized that rock drying by heat generated by radioactive decay of the spent fuel may cause the formation of perched water zones. In this process water near waste canisters is vaporized and driven away from the repository (any direction, laterally or vertically), until it reaches an area where the rock temperature is cool enough to cause condensation. If the condensed water encounters a low permeability material, rock water saturations may increase and form a perched zone. Modeling nonisothermal liquid and vapor phase movement of water through unsaturated fractured rock is still an area of active research and therefore standard approaches have not been established.

Performance Objectives at Risk:

This key technical uncertainty may lead to unwarranted conclusions concerning compliance with performance objectives 10 CFR 60.112, 60.113 (a)(1)(ii)(B).

Explanation of Nature of Risk:

Modeling of nonisothermal water movement as liquid or vapor through unsaturated fractured rock flow may play an important role in demonstrating compliance with this regulatory requirement topic. However, if it cannot be established that the models are adequate or inadequate representations, a determination of compliance or noncompliance would be very difficult. Failure to demonstrate compliance with this regulatory requirement topic would make it more difficult to demonstrate compliance with the overall system performance objective. This is because the formation of perched water could result in increased waste canister failure rates and faster radionuclide transport to the accessible environment.

Description of Resolution Difficulty:

Resolution of this difficulty could require research into the concepts and physics of modeling the flow of water as vapor and liquid under nonisothermal conditions in fractured rock. Resolution may also require (1) the development of field data collection techniques and (2) the design and testing of codes to do this type of modeling.

Key Technical Uncertainty Topic: Developing a mathematical groundwater flow model that is representative of the Yucca Mountain site groundwater flow system.

Description of Uncertainty: A mathematical model, in terms of one or more equations that represent an abstraction of the Yucca Mountain site groundwater flow system, is needed to predict the motion of groundwater and hence, to predict the effectiveness of the geologic setting as a barrier to the release of radionuclides in terms of calculated GWTT. This Key Technical Uncertainty covers three subtopics. These include: (1) the mathematical model(s) used to represent the conceptual model of the groundwater flow system; (2) the implementation of the mathematical model(s) as embodied in a computer code(s); and (3) the application of the computer code(s) for compliance calculations. Considered together, they define the integrated modeling strategy. Mathematical models, computer codes and their subsequent application for compliance calculations all contain elements of uncertainty.

Mathematical models: At Yucca Mountain, the groundwater flow system is comprised of stratified, heterogeneous, fractured, saturated and unsaturated hydrogeologic units. In general, developing a defensible mathematical representation of the Yucca Mountain site groundwater flow system will be more difficult for the unsaturated zone than the saturated zone. This is primarily due to variation of hydraulic properties with moisture content (i.e., the nonlinear nature of the governing equations resulting from the nonlinear pressure dependence of moisture content and hydraulic conductivity). Ababou (1991) considered alternative approaches to mathematically representing the unsaturated zone at Yucca Mountain. These approaches were broadly classified into two types, direct and indirect. After Ababou (1991, pp. 6-2 to 6-4), these are:

(1) Direct approach: The direct approach, in principle, requires only basic phenomenological equations to model the flow system, such as the classical Darcy-Richards type equations (and additional constitutive relations for fractures). However, while fine-scale spatial variations of groundwater velocity are known to play a significant role in radionuclide transport and dispersion, there are limits to how extensively and explicitly the broad spectrum of geologic heterogeneities causing spatial variations in velocity can be represented. Site-specific data may not be available with the required degree of detail so that much effort must be put in auxiliary analyses (e.g., statistical interpolation and conditioning, use of soft information, statistical continuum models of heterogeneous porous media, random fracture network models, and so on. Computational demands are likely to be high, particularly for fractured porous media with both continuum and discontinuum-type heterogeneity and the extreme disparity of active fluctuation scales; from fracture aperture scale up to the largest identifiable geologic features. This necessitates an informed evaluation of computational feasibility and a careful selection of advanced solution methods and computer resources.

(2) Indirect approaches: Alternatives to the direct approach utilize auxiliary hydrodynamic models in order to alleviate some of the demands of the direct approach. The objective of indirect approaches is to simplify the overall flow model by subsuming certain spatial features and processes in simplified black-box models. For example, heterogeneities and fractures would be subsumed in various submodels. Typically, these submodels express effective constitutive relations, matrix/fracture transfer relations, and other conceptual relations in a quasi-analytical fashion. Examples of indirect approaches include (after Ababou, 1991):

(a) Single equivalent continuum: The heterogeneous and/or fractured medium is treated as a single homogeneous continuum with unique effective coefficients (e.g., with specific moisture capacity and hydraulic conductivity tensor depending nonlinearly on pressure through known spatial-statistical properties of the medium). This type of approach captures the pressure-dependent anisotropy due to stratification, but not that due to fractures.

(b) Dual equivalent continuum (double porosity): In this approach the fractured medium is treated as a mixture of two distinct continua of unspecified geometry; a homogeneous matrix (relatively low porosity) continuum and a homogeneous fracture (relatively high porosity) continuum. Each continuum is represented by distinct pressure, flux and hydraulic coefficients. An effective transfer term is added to keep track of water transfer between the two continua. Currently, there are no testing methods to measure an effective transfer term for a specific site and conditions. The approach also requires refinements in modeling the transfer terms and defining the anisotropic conductivity of the fracture continuum.

(c) Combination of dual and single equivalent continua: Traditionally, the dual equivalent continuum model has been implemented assuming spatially uniform properties for each continuum (homogeneity). If effective flow models are made available for each type of equivalent continuum it may be possible to improve the overall model by combining the single and dual continuum approaches.

(3) Combination of direct and indirect approaches: The indirect approach to heterogeneous flow modeling can be used in combination with explicit modeling of certain types of heterogeneities that are either not accounted for by the auxiliary models, or too important to be treated implicitly (e.g., major geologic features such as faults, extensive fractures, bedding sequence of geologic units or large scale trends in hydraulic coefficients). In addition to explicit modeling of site-specific large scale geologic discontinuities and trends, auxiliary models would be used to deal with smaller scale heterogeneity in a more simplified manner.

Irrespective of the selected approach, the mathematical model(s) will represent an abstraction of the conceptual model such as, for example, approximating flow in a fractured rock using a dual porosity model or using Darcy's law. These abstractions introduce uncertainty due to the loss of information, the value of which cannot be determined a priori.

Computer Codes: Mathematical models will be implemented by computer codes. In principal, the governing equations can be solved using analytical, semi-analytical or numerical methods. The complexity of the Yucca Mountain site groundwater flow system is such that numerical methods will likely be required. This will require an approximation of the governing equations that will introduce uncertainty into the results. Additional potential sources of uncertainty in computer codes include coding errors and limits in the stability, precision and accuracy of available numerical techniques. Stable numerical techniques will be required to solve the complex equations needed to simulate the Yucca Mountain site groundwater flow system. In addition, the computer codes will likely need to allow propagation of parameter uncertainty into the results (e.g., hydrogeologic unit properties). The resulting computer codes will be difficult to develop, qualify and use (Updegraff, 1989; Runchal and Sagar, 1993). These sources of uncertainty cannot be quantified. Therefore, their impact on the demonstration of compliance with the performance objective for the geologic setting (or other performance measures) cannot be readily discerned (Davis, et al., 1990). However, it is possible to minimize the potential impact of the uncertainties. It is possible to directly address and compare the accuracy of numerical solution techniques (Ababou, 1991). In addition, the potential for coding errors can be minimized by applying a sound software quality assurance program (e.g., benchmarking and verification).

Compliance Calculations: The application of the computer code, or set of computer codes, will provide the calculated GWTT that will be used to quantitatively demonstrate compliance with the performance objective for the geologic setting. Sources of uncertainty in compliance calculations include: (1) the discretization scheme used in the application; (2) initial hydrologic conditions assumed, including boundary conditions; (3) system state assumed considering the temporal scale of time dependent processes; and (4) user errors. The potential for user errors can be minimized through the application of technical procedures developed under a sound quality assurance program. The affect of discretization schemes and initial conditions on predicted GWTT can be assessed by evaluating alternative schemes and assumptions. Given the complexity of the models involved, it is not yet clear how the significance of time dependent processes will be evaluated (e.g., significance of episodic, focused-recharge and transient flow through the unsaturated zone).

Ababou (1991) suggests a method to assess the advantages and disadvantages of various modeling strategies based on four criteria. After Ababou (1991; pp. 6-1 to 6-2), these criteria include:

- Equations: The governing equations and auxiliary models should be physically-based and generic, rather than empirical. In other words, the models and submodels should be based on as much physics as possible, with minimal use of empirical coefficients and adjustment parameters.

- Simplifying assumptions: The necessary simplifications introduced at various stages should: (1) form a self-consistent set of assumptions; (2) be consistent with the objectives of modeling; and (3) capture the known characteristics of the field site.

- Model Inputs: The model should be as parsimonious as possible in terms of input parameters, particularly in the absence of high-quality data. However, the selected model should not be so parsimonious as to ignore significant and singular features of the subject site.

- Computational feasibility: The numerical solution of model equations needs to be computationally feasible with current computing hardware, such as workstations and supercomputers. Computational feasibility depends on the efficiency of specific solution algorithms selected for numerical implementation of the model. Mathematical expressions of new conceptual models may require new algorithms for their solution. Owing to the complexity of unsaturated flow processes in highly heterogeneous and fractured media, it is expected that the numerical implementation of any realistic model of these processes will be non-trivial. Judicious selection or development of efficient algorithms may be key to the whole modeling approach.

The staff believes that a primary basis for determining the adequacy of mathematical model(s) used in demonstrating compliance with the performance objective for the geologic setting will be validation exercises. Numerous definitions have been proposed for the term "validation" (Nicholson, et al., 1992; Davis, et al., 1991; Silling, 1983); however, some consider the term to often be misinterpreted (McCombie and McKinley, 1993) while others consider its use misleading (Bredehoft and Konikow, 1992). The fundamental problem with the term is that it may be interpreted as sanctioning a model as either "valid" or "invalid." Rather, the basic purpose of the validation process is to provide a framework in which confidence in the model and its specific application can be established. The validation process, therefore, should provide the scientific basis for assessing the uncertainty in the predictive capability of models and codes used for performance assessment of a particular site in a regulatory context.

An approach to model validation consists of a critical assessment obtained through a comparison of model predictions against experimental results, where the experimental results were not used in defining model inputs. A variety of comparison methods (e.g., goodness of fit measures) would be used. The evaluation of the model's capability to capture the system behavior for a range of conditions and complexities is then used to establish confidence in the model. Thus, the validation process must be viewed from the perspective of building confidence in models and not to produce "validated" models, in the generic sense.

The difficulty in using this approach is associated with such factors as (after CNWRA, in preparation):

- Complexity of the processes and conditions being modeled

- Inherent variability of the physical and chemical properties of geologic media

- Difficulty in transferring the validation of a model from a set of idealized experiments to the actual field site

- Constraints posed by large space and time scales

There is much debate within the waste management community, both nationally and internationally, regarding the procedure for model validation. Several model validation approaches have been proposed (Davis, et al., 1991; Voss, 1990; Nicholson, et al., 1992), but none are considered definitive.

Neither the NRC regulation nor the Environmental Protection Agency (EPA) standard explicitly requires the DOE to "validate" its performance assessment models: However, an implied requirement is stated in 10 CFR 60.21(c)(1)(ii)(F), specifically:

Analyses and models that will be used to predict future conditions and changes in the geologic setting shall be supported by using an appropriate combination of such methods as field tests, in-situ tests, laboratory tests which are representative of field conditions, monitoring data and natural analogue studies.

At present, DOE views the validation process as a pivotal step to develop confidence in the predictive capability of performance assessment models (Glass and Tidwell, 1991; Tidwell, et al., 1992). DOE's testing program will not only provide information about specific parameters but will also provide phenomenological information about water flow through unsaturated, fractured tuff (DOE; 1988; p. 8.3.1.2.232). In particular, some of the planned ESF tests are intended to serve this purpose. Tests in the ESF that are particularly pertinent include: (1) intact fracture test; (2) percolation test; (3) bulk permeability test; and (4) radial boreholes test. DOE's overall strategy for demonstrating compliance with the performance objective for the geologic setting was presented in the SCP (DOE, 1988; pp. 8.3.5.12-1 to 8.3.5.12-69). Progress in conceptual, mathematical and calculational model development, as well as model validation, is reported in DOE (1992a). In general, progress is constrained by the availability of site data.

Performance Objective at Risk: 10 CFR 60.113(a)(2)

Explanation of Nature of Risk: The specific mathematical modeling strategy, defined in terms of the mathematical model(s), related computer code(s), and application of the computer code(s) for compliance calculations will represent an abstraction of the actual conditions and active processes of the Yucca Mountain site groundwater flow system. This is a result of explicit assumptions and approximations generally required to derive the governing flow equations of the mathematical model and limitations of current state-of-the-art numerical methods, computer hardware and field testing methods. It is not possible to quantify the effect of the assumptions and approximations used to derive the governing equations and their related application on predictions of GWTT. If these assumptions and approximations cannot reasonably be defended, then the defensibility of compliance demonstrations with the performance objective for the geologic setting may be at risk.

Description of Resolution Difficulty: Resolution of the Key Technical Uncertainty requires the following:

- The DOE needs to demonstrate that the mathematical model(s) used to represent the Yucca Mountain site groundwater flow system are technically defensible. This requires DOE to address uncertainties in the mathematical model(s) by demonstrating the defensibility of:

    - The physical bases underlying the mathematical model(s)
    - Simplifying assumptions made in each stage of mathematical model(s) development
    - Validation experiments in terms of their representativeness of the Yucca Mountain site groundwater flow system as applied to the calculation of GWTT

- The DOE needs to demonstrate that the computer code(s) used to calculate GWTT are technically defensible. This requires DOE to address uncertainties in computer code(s) by demonstrating the defensibility of:

    - The process used to develop computer software (e.g., benchmarking and verification)
    - Precision and accuracy of applied numerical methods
    - Methods used to propagate parameter uncertainty into calculated GWTT

- The DOE needs to demonstrate that applications of computer code(s) to calculate GWTT for demonstrating compliance with the performance objective for the geologic setting are technically defensible. This requires DOE to address the uncertainty in the compliance calculations by demonstrating the defensibility of:

    - Procedural controls on the application of computer code(s)
    - Discretization schemes
    - Assumed initial and boundary conditions
    - Consideration of temporal or scale dependent processes

- The staff needs to develop specific, technical review criteria for determining that DOE's mathematical models, computer codes and compliance calculations are representative of the Yucca Mountain site and technically defensible.

- The staff needs to develop the basis for determining the acceptable methods for model validation. Pertinent questions to be considered include:

    - How does one gain confidence in the model's ability to extrapolate in time and space?

- How can confidence be gained for those components of the models that cannot be tested directly?

- Given the limitations in experimental capability, what is the relevance of possible differences between model predictions and experimental results and how are these differences to be resolved?

- The staff needs to develop the methods and tools for independent modeling of GWTT

Aspects of several different NRC funded research projects at the Center for Nuclear Waste Regulatory Analyses (CNWRA) will support staff efforts to resolve this Key Technical Uncertainty.

The CNWRA research project on Stochastic Analysis of Unsaturated Flow and Transport will evaluate the effects of small-scale variability on large-scale unsaturated flow (and transport) simulations as part of developing methods for realistic modeling of flow and transport processes at Yucca Mountain (Bagtzoglou, 1993; Sagar, in preparation). The technical objectives of the project include: (1) reviewing the literature on theoretical and experimental approaches, and assessing the status of available data in relation to simulation needs and approaches; (2) selecting a global approach for stochastic modeling of large-scale flow and transport in naturally heterogeneous variably saturated fracture rock; (3) developing submodels and incorporating these submodels and analyses into the global modeling approach; (4) developing technical interactions with the technical community towards the validation of flow and transport models for the proposed Yucca Mountain repository; (5) documenting, benchmarking and verifying the three-dimensional flow simulation code being used by the project (BIGFLOW 1.0); and (6) implementing large-scale simulations of three-dimensional variably saturated flow and transport under realistic hydrogeologic conditions and interpreting the results using geostatistical analysis, visualization and other tools.

The CNWRA research project on Performance Assessment includes specific activities related to conceptual model development, computational model development and model evaluation. While the focus of this project is on total system performance, aspects of the project related to developing and demonstrating a methodology for validating models is pertinent to this Key Technical Uncertainty.

Other research projects at both the CNWRA and University of Arizona will provide independent, site characterization data useful in developing conceptual models of groundwater flow in fractured, unsaturated rock (these projects are identified and discussed under the Key Technical Uncertainty topic related to developing a conceptual groundwater flow model). These data will support development of mathematical models and computational methods in the above referenced research projects. In addition, results of various laboratory and field scale tests will serve as useful validation experiments for groundwater flow in unsaturated, fractured rock.

REVIEW STRATEGY:

Acceptance Review:

In conducting the Acceptance Review for the favorable conditions concerning the nature and rate of hydrogeologic processes, the reviewer should determine if the content of the license application and its references for determining compliance with the applicable regulatory requirement is complete in technical breadth and depth as identified in the regulation guide Format and Content Regulatory Guide (FCRG).

The reviewer should determine that all appropriate information necessary for the staff to review the likelihood and possible favorable effects of these conditions is presented such that the assessments required by the regulatory requirements associated with total system and subsystem performance objectives or other technical criteria can be performed.

The information contained in the license application should be presented in such a way that the assumptions, data, and logic lead to a clear demonstration of compliance with the requirements. The reviewer should not be required to conduct extensive analyses or literature searches. The reviewer should also determine whether an appropriate range of alternative interpretations and models has been described.

Finally, the reviewer should determine if the U.S. Department of Energy (DOE) has either resolved all the NRC staff objections that apply to these requirements or provided all the information requested in Section 1.6.2 of the FCRG, for unresolved objections. The reviewer should evaluate the effects of any unresolved objections, both individually and in combinations with others, on: (1) the reviewer's ability to conduct a meaningful and timely review; and (2) the Commission's ability to make a decision regarding construction authorization within the three-year statutory period.

Safety Review:

This regulatory requirement topic is limited to consideration of the projection of Quaternary hydrogeological processes that have either no effect or would favorably effect the waste isolation capabilities of the site. It does not address projections of repository performance as required in 10 CFR 60.21 (c)(1)(ii)(c). These 'projection' type analyses will be covered in other sections of the license application (see Appendix A). The specific aspects of the license application on which the reviewer will focus are discussed below, and the Acceptance Criteria are identified in Section 3.0 of this review plan.

In conducting the safety review the reviewer should determine if the information presented in the license application and its references is an acceptable demonstration of compliance with the applicable regulatory requirements. At a minimum, the reviewer should determine the adequacy of the data and analyses presented in the license application to support DOE's demonstrations regarding 10 CFR 60.122(b)(1). This demonstration should be derived from the assessments presented and the conclusions reached by DOE in those other sections of the license application in Chapter 3.1 dealing with the favorable conditions and potentially adverse conditions. Specifically, DOE will need to: 1) provide information to determine whether and to what degree, these favorable conditions are present; 2) assure the sufficiency of the lateral and vertical extent of data collection to support assertions regarding the existence of these favorable conditions, and 3) evaluate the information presented under Items (1) and (2) as stated above, with assumptions and analysis methods that adequately describe the presence of the favorable conditions and ranges of relevant parameters. In general, the reviewer will assess the adequacy of DOE's investigations of these favorable conditions, both within and without the controlled area. In particular, the reviewer should evaluate the collection of data over the region encompassing the basin where Yucca Mountain is located.

For purposes of determining the presence or absence of these favorable conditions, data collection and other investigations should extend from the surface to a depth sufficient to demonstrate a suitable understanding of the favorable attributes of Quaternary hydrogeologic processes for inclusion in the assessment of compliance with the performance objectives in 10 CFR 60.112 and 60.113. DOE will also need to provide an explanation of the measures applied to assess the presence and absence of evidence for the nature and rates of Quaternary hydrogeologic processes. Analyses and models used to predict future conditions and changes in the geologic setting should be supported by field tests, in-situ tests, and laboratory tests which are representative of field conditions, monitoring data, and natural analog studies.

DOE will also need to provide an explanation of the measures applied to assess the presence or absence of evidence for the nature and rates of Quaternary geochemical processes. Analyses and models used to predict future conditions and changes in the geologic setting should be supported by an appropriate combination of field tests, in-situ tests, laboratory tests which are representative of field conditions, monitoring data, and natural analog studies.

For purposes of determining the presence or absence of this favorable condition, investigations should extend from the surface to a depth sufficient to determine critical pathways for radionuclide migration from the underground facility, and to a depth sufficient to demonstrate a suitable understanding of the favorable qualities of Quaternary geochemical processes such that reasonable bounds can be placed on the different conceptual models.

In conducting the aforementioned evaluations, the reviewer should determine that DOE uses: (1) analyses that are sensitive to evidence of the favorable condition; and (2) assumptions which are not likely to overestimate its effects. In general, the reviewer will assess the adequacy of DOE's investigations of the favorable condition, both within the controlled area and outside the controlled area (including the geologic setting) as necessary in the manner outlined in Section 60.21(c)(1)(ii)(B).

In order to conduct an effective review, the reviewer will rely on staff expertise and independently acquired knowledge, information, and data such as the results of research activities being conducted by the NRC's Office of Nuclear Regulatory Research, in addition to that provided by the DOE in its license application. The reviewer should focus on additional data which can refine knowledge of the favorable conditions associated with the nature and rate of hydrogeologic processes during the Quaternary and the likelihood of those processes persisting over the next 10,000 yr. It is incumbent upon the reviewer to have acquired a body of knowledge regarding these and other critical considerations in anticipation of conducting the review to assure that the DOE program on paleohydrogeology is sufficient in scope and depth to provide the information to resolve the concerns.

Detailed Safety Review Supported by Analyses:

A Detailed Safety Review and Analysis will be needed for evaluation of the Key Technical Uncertainties related to the large hydraulic gradient north of Yucca Mountain, hydrogeologic conceptual models, and understanding and predicting precipitation, infiltration, percolation, and recharge. The Key Technical Uncertainties associated with these topics are the same as those identified in other sections of the License Application Review Plan (see Table 3.2.2.1-1) and the evaluation of the Key Technical Uncertainties will be addresses in the appropriate Review Plan.

A Detailed Safety Review and Analyses will be needed to evaluate the Key Technical Uncertainties related to (1) the nature of the large hydraulic gradient located north of Yucca Mountain; (2) uncertainty in modeling groundwater flow through unsaturated fractured rock caused by the lack of codes tested against field and laboratory data; (3) identifying which conceptual models adequately represent isothermal and nonisothermal liquid and vapor phase movement of water through unsaturated fractured rock at Yucca Mountain; (4) uncertainties associated with determining characterization parameters; (5) prediction of precipitation and temperature (climate) at the Yucca Mountain site for 10,000 years into the future; and (6) developing a conceptual groundwater flow model that is representative of the Yucca Mountain site groundwater flow system. These Key Technical Uncertainties are the same as those identified in Review Plans 3.3 (Assessment of Compliance with the Groundwater Travel Time Performance Objective), 3.2.2.8 (PAC - Structural Deformation and Groundwater), 3.2.2.12 (PAC - Perched Water Bodies), and 3.2.4.2 (PAC - Changes to Hydrologic System from Climate). Evaluation of these Key Technical Uncertainties will be addressed in their respective Review Plans.

It should be noted that the information and analyses submitted in this section of the license application will be derived from the Compliance Reviews of information contained in other section of the license application (see Table 3.2.2.1-1). Therefore, during the Compliance Review those other license application sections, the reviewer should determine that the appropriate descriptive information necessary for the staff to conduct the Safety Reviews, described above has been provided, and that the information is both internally consistent, and consistent from section to section. Examples of specific review activities that will be required for each of the Key Technical Uncertainties listed above are described in their respective sections of the License Application Review Plan.

Detailed Safety Review Supported by Independent Tests, Analyses, or Investigations:

No Key Technical Uncertainty has been identified that is unique to this section of the license application. However, a Detailed Safety Review Supported by Independent Tests, Analyses, or Investigations will be needed for the Key Technical Uncertainties related to (1) uncertainty caused by the lack of experimental confirmation of the basic physical concepts of groundwater flow through unsaturated fractured rock; (2) uncertainty caused by the lack of established new data collection and interpretation techniques required to model groundwater flow through unsaturated fractured rock; (3) uncertainty in modeling the formation of perched zones by thermally driven flow; and (4) development of a mathematical groundwater flow model that is representative of the Yucca Mountain site groundwater flow system. This will ensure that the DOE has adequately demonstrated compliance with Items (1)-(3) described in Section 2.2.1 (see "Safety Review," paragraph 2). The review will help to assure that DOE has acceptably addressed this Key Technical Uncertainty so that it will not lead to noncompliance with the overall system and several of the subsystem performance objectives.

The Key Technical Uncertainties associated with these topics are the same as those identified in other sections of the License Application Review Plan (see Table 3.2.2.1-1). Evaluation of these Key Technical Uncertainties will be addressed in Review Plans 3.3 (Assessment of Compliance with the Groundwater Travel Time Performance Objective) and 3.2.2.12 (Perched Water Bodies). Examples of specific review activities that will be required for each of the Key Technical Uncertainties are described in their respective sections of the License Application Review Plan.

RATIONALE FOR REVIEW STRATEGY:

In view of the complexity of the key technical uncertainty addressed above, it is appropriate that the NRC conduct the independent activities described in order to (1) develop the licensing tools and technical basis necessary to judge the adequacy of DOE's license application, (2) assure sufficient independent understanding of the basic physical processes taking place at the geologic repository, and (3) maintain independent but limited confirmatory research capability under NRC auspices.

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Date of Analysis: August, 1993

APPLICABLE REGULATORY REQUIREMENTS FOR EACH TYPE OF REVIEW:

Type 1

10 CFR 60.122(b)(1)
10 CFR 60.21(c)(1)(ii)(B)
10 CFR 60.21(c)(1)(ii)(F)

Type 3

10 CFR 60.122(b)(1)

Type 4

10 CFR 60.122(b)(1)

Type 5

10 CFR 60.122(b)(1)

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Table 3.2.2.1-1 Key Technical Uncertainties contained in Section 3.2.2.1 of the License Application.

License Application	Title	Key Technical Uncertainty
3.2.2.8	PAC: Structural Deformation and Groundwater	The nature of the large hydraulic gradient north of Yucca Mountain
3.2.2.12	PAC: Perched Water Bodies	Uncertainty in modeling groundwater flow through unsaturated fractured rock caused by the lack of codes tested against field and laboratory data
3.2.2.12	PAC: Perched Water Bodies	Uncertainty in identifying which conceptual models adequately represent isothermal and nonisothermal liquid and vapor phase movement of water through unsaturated fractured rock at Yucca Mountain
3.2.2.12	PAC: Perched Water Bodies	Uncertainties associated with determining characterization parameters
3.2.2.12	PAC: Perched Water Bodies	Experimental confirmation of the basic physical concepts of groundwater flow through unsaturated fractured rock
3.2.2.12	PAC: Perched Water Bodies	The development of new data collection and interpretation techniques are required for codes which model groundwater flow through fractured rock
3.2.2.12	PAC: Perched Water bodies	Uncertainty in modeling the formation of perched zones by thermally driven flow
3.2.4.2	PAC: Changes to Hydrologic Conditions from Climate	The uncertainty associated with predicting precipitation and temperature (climate) at the Yucca Mountain site for 10,000 years into the future
3.3	Assessment of Compliance with Groundwater Travel Time Performance Objectives	Developing a conceptual groundwater flow model that is representative of the Yucca Mountain site groundwater flow system
3.3	Assessment of Compliance with Groundwater Travel Time Performance Objectives	Developing a mathematical groundwater flow model that is representative of the Yucca Mountain site groundwater flow system