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Topical Report No. 1

# CATEGORIZING UNCERTAINTY IN ORDER TO DEMONSTRATE COMPLIANCE WITH 10 CFR 60.113(a)(2): PRE-WASTE-EMPLACEMENT GROUNDWATER TRAVEL TIME

**DRAFT**

## 1. INTRODUCTION

The Code of Federal Regulations stipulates in 10 CFR 60.113(a)(2) that

> "The geologic repository shall be located so that pre-waste-emplacement groundwater travel time along the fastest path of likely radionuclide travel from the disturbed zone to the accessible environment shall be at least 1,000 years or such other travel time as may be approved or specified by the Commission."

This regulation and 60.122(b)(7) outline the requirements for a minimum pre-emplacement radionuclide groundwater travel time to the accessible environment. It is not practical to measure groundwater travel time directly and in situ along the path of likely radionuclide transport. The travel times that are anticipated in these environments are too long to facilitate direct measurements within the time frame outlined in the Nuclear Waste Policy Act. The Act calls for creating a repository in a much shorter time frame than that which would be required if the minimum groundwater travel time requirement of 1,000 years was measured directly. Consequently it becomes necessary to predict groundwater travel time within the constraints of the hydrogeologic system being considered for a high level radioactive waste repository. The prediction of groundwater travel time at the time frames of interest (1,000 to 10,000 years) requires that the groundwater travel time be predicted based upon measured hydrogeologic coefficients. The primary coefficients in the saturated zone are hydraulic conductivity, effective porosity, storativity, and hydraulic gradient.

Unsaturated flow characteristics are dependent upon a more complex relationship with respect to hydraulic conductivity, moisture content, porosity, moisture tension, and flux.

These hydrogeologic coefficients must be measured and quantified. Uncertainties arise in the quantification of these coefficients because of several factors, including testing methodologies and procedures, multiple defensible interpretations of data, spatial relationship of the data, and scale. This topical report outlines the categories of uncertainty that are relevant to the prediction of pre-waste-emplacement groundwater travel time.

This report is generic in nature. It must be recognized that there is a significant difference between the conceptual models of saturated groundwater flow and unsaturated flow. Concepts of saturated groundwater flow usually deal with conceptual hydrogeologic models that incorporate areas of groundwater recharge and areas of groundwater discharge. Groundwater flow between the areas of recharge and discharge is controlled by the distribution of transmissivity (hydraulic conductivity). Boundary conditions play a significant role in this hydrogeologic model because groundwater flow usually has a very significant horizontal component of flow. Conversely, flow in the unsaturated zone is primarily vertical. Flow in the unsaturated zone is controlled by conditions and processes of flow within the vertical realm of the accessible environment above the repository. This particular topical report is written with respect to saturated groundwater flow; points of divergence from saturated flow concepts are pointed out for those considerations that are characteristic of unsaturated flow phenomena.

## 1.1 Ranking System

A ranking system has been developed in this topical report which incorporates issues into one of three main categories. This ranking system is based on the degree of necessity that a particular hydrogeologic coefficient or characteristic is required for the prediction of groundwater travel time. The ranking system categories are:

A. Essential for quantifying groundwater travel time.

B. May be essential for quantifying groundwater travel time.

C. Is not essential for quantifying groundwater travel time.

The identification of major subject areas inherent in the delineation of uncertainties associated with the prediction of groundwater travel time is difficult. However, three major areas have been delineated in this topical report. The first subject area is the conceptual hydrogeologic model. The delineation of conceptual hydrogeologic models requires considerable knowledge about the geology of the site in question. Subsequently this knowledge is converted to assumptions about the distribution of hydraulic conductivity, effective porosity, and hydraulic gradient for purposes of further testing. The true distribution (as opposed to the initially assumed distribution) of these coefficients and the consequent conceptual hydrogeologic model(s) define the projected groundwater flow path(s) along which radionuclides could migrate from the repository to the accessible environment. As the initial conceptual model is tested the distribution of hydrogeologic coefficients is altered as necessary. Presumably the assumed conceptual model approaches the true conceptual model as experiments are conducted.

The second subject area is the data base that is required for deriving coefficients that are required for calculating groundwater travel time. The conceptual hydrogeologic model cannot be separated from the process of predicting groundwater travel time. Scenarios that may be used to predict groundwater travel time must be consistent with the conceptual hydrogeologic models as they are modified to fit the available data base. A valid conceptual hydrogeologic model will delineate the "fastest path of likely radionuclide travel from the disturbed zone to the accessible environment."

The third subject area is the prediction of groundwater travel time which can follow two fundamental courses. The first fundamental course predicts the likely radionuclide travel path and groundwater travel time(s) using a deterministic approach. The deterministic approach predicts groundwater travel time using appropriate values for the hydrogeologic coefficients that are required for predicting groundwater travel time along the likely flow path. The deterministic approach requires that the values of the coefficients be determined along the fastest path of likely radionuclide travel from the disturbed zone to the accessible environment. Determining the absolute values may not be realistic; a practical approach allows the interpretation of appropriate ranges of values for the coefficients. The ranges of values can be used to predict groundwater travel times. The scale of the values represented by different test techniques is of particular concern. The scale of the tests must be considered in the prediction of groundwater travel time. The different scales that result from the use of different testing techniques create uncertainty in the correlation of these values and in the development of valid ranges of values of hydrogeologic coefficients.

The second fundamental course for predicting groundwater travel time is referred to as a stochastic/deterministic or probabilistic prediction. This second fundamental course requires the use of a deterministic equation for calculating groundwater travel time; the difference between the deterministic and the stochastic approaches lies in the values of the coefficients that are used to predict groundwater travel time. The stochastic approach uses some distribution of values for a given coefficient such as hydraulic conductivity; the values used to calculate groundwater travel time may be selected from such a distribution by some randomized selection process. The generated values are assumed to be representative of the values found in the hydrostratigraphic unit of interest. A sufficient number of hydrogeologic tests are required to define the probability distribution of values from which the required coefficients can be extracted. The scale of the values represented by different test techniques is of particular concern. The scale of tests must be considered in the prediction of groundwater travel time. The different scales that result from the use of different testing techniques create uncertainty in the correlation of these values and in the development of a valid probability distribution of values of hydrogeologic coefficients.

The Federal Regulations pertain specifically to the prediction of pre-emplacement groundwater travel time from the edge of the disturbed zone to the accessible environment. It should be noted that the hydrodynamics of transport of dissolved solids are not relevant to the discussion of pre-emplacement groundwater travel time. Dispersion is not relevant to this discussion except possibly in the interpretation of tracer tests for measuring effective porosity.

The examples cited in this topical report are not necessarily comprehensive. An attempt has been made to present a broad range of examples to explain further the headings under consideration. An outline of the categories of uncertainty with their assigned ranking is appended to this topical report. As noted, the assigned ranking predicts the necessity for obtaining information about that particular coefficient or condition or process under consideration. The assignment of rankings is influenced heavily by professional judgment. In our opinion this condition is unavoidable.

# 2. CONCEPTUAL HYDROGEOLOGIC MODEL(S)

A conceptual hydrogeologic model(s) is essential to the regulatory process because such models characterize the framework of the groundwater flow systems which will transport radionuclides away from the repository to the accessible environment. The conceptual hydrogeologic model deserves ranking in category "A" because of its importance to predicting groundwater travel time. The conceptual model outlines the hydrostratigraphy or the hydrogeologic zonation for a given site. The definition of the hydrostratigraphic units is based on a number of inputs including the geologic framework, the initially assumed distribution of values for the hydrogeologic coefficients within the framework, and the associated boundary conditions which establish the limits on the hydraulic gradient. The conceptual model is important because initially several conceptual models may fit the early data. Fewer models may be defensible as additional data are collected. It is important to the regulatory process that this process be recognized. The testing plans developed for any site should reflect the fact that multiple conceptual models may fit the early data base; the testing plan should not be developed to validate a single early time conceptual model.

## 2.1 Geologic Framework

Uncertainties about the conceptual hydrogeologic model begin with the geology that constitute the framework for the conceptual model. The geologic framework deserves ranking in category "A" because of its importance in defining the framework for the conceptual model. Delineation of the geologic framework requires information obtained by test drilling and observation of formation exposures. Other sources of information, including borehole geophysics and surface geophysics, can help define the geologic framework. Hydrostratigraphic unit boundaries are aligned frequently with geologic boundaries. A change in facies within a sedimentary formation frequently coincides with a change in measured hydraulic conductivity. Significant changes in the values of hydrogeologic coefficients can be encountered in crossing bedding plane boundaries between different sedimentary formations. The typical confining units (aquitards) considered in most sedimentary basins consist of shales, mudstones, and other fine-grained deposits. The basalt sequence at the Hanford site consists of alternating layers of basalts which are characterized by their internal geologic structures. These geologic structures generally are referred to as the flow top, the flow interior, and the flow bottom. A distinction is not made between the flow top and the flow bottom in most cases. The flow interior can be subdivided into structural features which include the colonnade and entablature. The basalt flow interiors are believed to possess low hydraulic conductivity and act as confining units (aquitards) similar to the shales and other fine-grained deposits common to sedimentary basins. The sequence of formations at the Nevada Test Site is characterized more by the matrix porosity and the interconnectedness of the fractures and pores within the welded tuffs. The Nevada Test Site repository horizon is located in welded tuffs.

Folds and faults can be very important influences on groundwater flow. Fold axes often coincide with zones of preferential groundwater flow due to the axial fracturing associated with the stresses which caused the folding. Significant fracturing aligned with anticlinal axes may exist within the basalts. The synclinal axes are believed to be less fractured than the anticlinal axes. Faults may or may not be associated with zones of higher hydraulic conductivity due to the fracturing of the rocks. Fault gouge can weather into a clay in which case the fault acts as an impediment to flow. Faults also may act as conduits that allow the vertical migration of radionuclides from the repository horizon to overlying or underlying formations. In this regard faults may act as preferential pathways that must be considered in the conceptual model. The conceptual model must accommodate these potentially fast migration paths which could allow radionuclides to move across a number of formations at a relatively rapid velocity.

## 2.2 Hydrogeologic Coefficients

Uncertainty exists regarding the distribution of values of hydrogeologic coefficients within the geologic framework. Knowledge about this distribution ranks in category "A". It is very important to determine the spatial distribution of values for the hydrogeologic coefficients such that the conceptual hydrogeologic model can be defined adequately. It is not possible to calculate or predict meaningful values for groundwater travel time without knowledge of the distribution of hydrogeologic coefficients. The distribution of values will determine the boundaries for the hydrostratigraphic units and will reflect zones of potential preferential flow (fastest path). The distribution of values will indicate the degree and nature of anisotropy and heterogeneity within the hydrostratigraphic unit. It is important to measure anisotropy and heterogeneity because of their potential effects on the groundwater flow path. The discontinuities created by geological processes must be tested for their effect upon the hydrogeologic coefficients. As explained above, discontinuities such as faults may act as an impediment to flow or they may constitute preferential flow paths. The only available procedure for determining whether such discontinuities constitute flow impediments or fast pathways is to test them in order to measure their hydrogeologic coefficients and to evaluate their characteristics.

## 2.3 Boundary Conditions

The boundary conditions of the hydrogeologic framework must be defined; however, uncertainties exist with respect to boundary conditions. The importance of defining the boundary conditions ranks this item in category "A".

Geologic boundaries frequently define hydrogeologic boundaries. Faults, facies changes, and fold axes frequently delineate hydrogeologic boundaries. As explained above such boundaries may be either barrier boundaries or recharge boundaries based on the nature of the hydrogeologic coefficients at the boundary. Unfortunately, uncertainty exists about the delineation of these geologic boundaries. The potential importance of identifying geologic boundaries places this item in category "B". Other examples of geologic boundaries include collapse breccia, and sedimentary features such as buried stream channels.

Uncertainty usually exists about the location of recharge and discharge areas. The importance of defining the location of recharge and discharge areas ranks in category "C". Their precise location is not absolutely essential to defining a conceptual hydrogeologic model, especially on large scale models. The locations can be determined on a qualitative basis which is sufficient for developing a conceptual model.

Rates of recharge and discharge in a conceptual model for the saturated zone also rank in category "C". It should be noted, however, that rates of recharge and discharge rank in category "A" for the Nevada Test Site. The ranking is different at the Nevada Test Site because at this site the repository would be placed in the unsaturated zone. The rate of recharge and movement of water through the unsaturated zone determines the rate of flux through the unsaturated zone. Consequently the rate of recharge is important to the conceptual model for the Nevada Test Site.

Uncertainty exists regarding the nature of the upgradient and downgradient boundary conditions within the conceptual hydrogeologic model. Knowledge about these boundaries ranks in category "C". The precise location and the nature of the boundaries are critical to understanding groundwater flow for the purpose of calculating groundwater travel time. These boundaries usually can be determined adequately for purposes of modeling the groundwater flow system; boundary conditions frequently can be extended to a distance at which the boundaries have little influence on hydrogeologic conditions within the repository area and within the limits of the accessible environment (5 km). The upgradient and downgradient boundaries usually are assumed to be constant head or constant flow boundaries. The effect of these boundary conditions will vary depending upon how they are used for predicting groundwater travel time and for defining the conceptual model.

Uncertainty usually exists about whether steady or unsteady flow conditions exist at a given site. The nature of flow ranks in category "B" in the saturated zone but in category "A" for the unsaturated zone. The nature of the flow conditions is very important to the unsaturated zone because, as pointed out previously, the rate of flux through the repository horizon and overlying and underlying unsaturated units is dependent upon the nature and rate of recharge. The nature of the flow conditions in the unsaturated zone may depend upon depth. It is possible that the periodic nature of recharge (pulses) may be diminished, or damped, with depth. The flow rate may be steady state at depth. The uncertainty about whether steady flow conditions or unsteady flow conditions exist at depth is critical to the conceptual model and to the prediction of groundwater travel times.

Knowledge about initial conditions also produce uncertainty. Initial conditions rank in category "B" for the saturated zone and in category "A" for the unsaturated zone. Initial conditions are difficult to define in many cases because of the practical problems encountered in determining whether steady state flow conditions exist at depth. Man's influence on the hydrogeologic system may be significant but not determinable based on the available data. Man may have influenced hydrogeologic conditions significantly within the Palo Duro Basin because of petroleum exploration and production activities in surrounding oil reservoirs. The scarcity and large spatial distribution of data preclude a definitive argument regarding the nature of man's influence on the hydrogeologic environment.

The matter is complicated further by the fact that nature and geologic processes are not steady state. The geologic history of the western United States is particularly relevant regarding the nature of changes in both topography and geologic structure. It is important to recognize the effects of changes in geology and topography because such changes can impact boundary conditions such as the location of recharge and discharge areas. In addition, erosional processes can change the stress distribution within low hydraulic conductivity units. This stress rate distribution can create anomalous fluid pressures within these low hydraulic conductivity units which are not easily deciphered based on historical hydrogeologic perspectives. In summary, it is important to recognize that nature is not static and hydrogeologic conditions have been evolving over geologic time. Nevertheless, the rate of natural change of the hydrogeologic properties may be insignificant in the time frame of 1,000 to 10,000 years required for groundwater travel time calculations.

## 2.4 Flow Processes

The flow processes that are inherent in a conceptual model rank in category "A" because of the importance of the nature of fluid movement within the media considered for a repository. It is probable, for example, that saturated groundwater flow will dominate the transport processes at the BWIP site and the Palo Duro Basin site. Conversely, unsaturated liquid water flow and/or water vapor flow will dominate the transport process at the Nevada Test Site. It is important to understand the interaction of the unsaturated liquid water flow and water vapor flow processes at the Nevada Test Site in particular. Which of these processes is dominant must be determined for each site. Variable fluid density also influences flow processes. Uncertainties exist regarding the influence of variable fluid density on the nature of both lateral and vertical groundwater flow at both the Hanford site and the Palo Duro Basin site. The Hanford site is characterized by water with low total dissolved solids content but with a significant thermal gradient. The Palo Duro Basin site is characterized by waters that exhibit a high total dissolved solids content below the repository horizon. However, the shallow saturated sediments above the repository horizon have a low total dissolved solids content. Differences in total dissolved solids content in a vertical sense and areal sense make it difficult to determine the distribution of head that defines the direction of groundwater flow and the magnitude of the hydraulic gradients. The potential for vertical flow at the Palo Duro Basin site also is compounded by geothermal temperatures that increase with depth. The combined influence of differences in total dissolved solids concentrations and geothermal temperature gradients influence the perspective with which lateral and vertical hydraulic head gradients must be evaluated.

## 2.5 Hydrochemical and Isotopic Variables

Uncertainty exists about the hydrochemical and isotopic characteristics of groundwater at the sites under consideration. These variables rank in category "B". Hydrochemical and isotopic characteristics may be more or less important, dependent upon the site. Such characteristics at the BWIP site at present are not believed to be significant with respect to the definition of conceptual models for the site. Conversely, such information may be important and beneficial in evaluating the Palo Duro Basin site.

Uncertainty usually exists regarding the distinctness of the hydrochemical and isotopic characteristics of the groundwater from different portions of the groundwater flow system. The uncertainty can exist because of the lack of dynamics in the concentrations of the constituents within the groundwater flow system. The small variations in concentrations within and between hydrostratigraphic units makes it difficult to interpret the hydrochemical system (i.e., 15% of 5 ppm may not be greater than detection limits as opposed to 15% of 10,000 ppm). The Hanford site is noted for its low total dissolved solids content and its low dynamics regarding various chemical constituents. Uncertainty exists regarding isotopic characteristics in part because of difficulties in measuring isotopic characteristics.

Uncertainty also exists because of questions of equilibration of the hydrochemical and isotopic characteristics within the geologic framework.

It is not always evident whether the hydrogeologic environment is in equilibrium with the geologic environment. Isotopes in groundwater may still be evolving and their characteristics changing along groundwater flow paths.

The evolution of groundwater requires consideration; groundwater hydrochemistry evolves along its flow paths as it encounters different mineralogies and hydrogeologic conditions at depth. The evolution of the groundwater is not always easy to define because of questions regarding the direction and the rate of movement of groundwater from suspected recharge areas toward suspected discharge areas.

Uncertainty also exists regarding the correlation of groundwater flow paths and travel times with the hydrochemistry and the isotopic characteristics of that groundwater. Groundwater flow paths are not always self-evident; the direction of groundwater flow can be difficult to define in areas of low hydraulic gradient such as at the Hanford site.

# 3. UNCERTAINTY IN KNOWLEDGE ABOUT THE THREE-DIMENSIONAL DISTRIBUTION OF HYDRAULIC HEAD

The three-dimensional distribution of hydraulic head is a primary input required for the prediction of groundwater travel time. The three dimensional distribution defines the direction of groundwater flow both vertically and horizontally. Uncertainty exists regarding the three-dimensional distribution which is critical to the groundwater travel time prediction process. The three dimensional distribution of head ranks in the "A" category because the direction of groundwater flow is important to the delineation of fastest path. The three-dimensional distribution of hydraulic head defines the hydraulic gradients along the pathways (directions) of groundwater flow.

## 3.1 Groundwater Flow Direction

The direction of groundwater flow defines the conceptual flow path which must be considered for predicting groundwater travel time. Upward vertical movement is not conducive to preventing radionuclides from entering the accessible environment. The Code of Federal Regulations (10 CFR Part 60.122(e)(ii)) stated preferable conditions include "Downward or dominantly horizontal hydraulic gradient in the host rock and immediately surrounding hydrogeologic units; and (iii) Low vertical permeability and low hydraulic gradient between the host rock and the surrounding hydrogeologic units." The direction of horizontal and vertical gradients is so fundamental to waste containment; it ranks in the "A" category.

## 3.2 Measurement Technique

Uncertainty exists regarding the true magnitude of hydraulic heads and the resulting hydraulic gradients that determine direction of flow. In this regard measurement technique is a primary source of uncertainty that must be considered in both the saturated and unsaturated zones. A significant difference may be encountered in the conversion of fluid pressures to hydraulic heads based upon the position of the transducer in the borehole or piezometer tube. The transducer may have been placed opposite the zone of interest (hundreds or thousands of feet below ground) or the transducer may have been placed within a few tens of feet of the surface of the water in the borehole or piezometer tube. The use of steel surveying tapes raises questions regarding the accuracy of measurements because of slight differences in the quality control standards associated with production of the tapes and in the use of the tapes for measuring vertical distances below a given datum. The variable length of the tape suspended in the borehole may alter the accuracy of the measurement; the variable length will cause the suspended weight to vary which will fall outside the standards established for using the tape. Head measurements deserve ranking in the "A" category because of the importance in defining the three-dimensional distribution of head.

The head measurements in the unsaturated zone usually are accomplished with tensiometers or psychrometers which measure the moisture tension in the vicinity of the measuring device. Uncertainties exist regarding the validity of these measurements because of the disturbed nature of the material adjacent to the borehole. Considerable uncertainty can occur because of fluid injection into the borehole during drilling which may alter fluid tension. Uncertainty also exists regarding the accuracy of the tension measurements because of the measurement technique.

### 3.3 Energy Fields Other Than Fluid Potential

Other sources of uncertainty exist regarding the three-dimensional distribution of head. Other sources of energy deserve a ranking in the of "B" category. Other energy fields that may affect the distribution of head include temperature, chemical, and electrical fields. The potential for convection or coupled flow phenomena, thermal diffusion, or streaming potentials may be important to the evaluation of gradients.

# 4. UNCERTAINTY IN APPROPRIATENESS OF TESTING METHODS AND PROCEDURES

The testing methodologies and procedures used in the definition and quantification of hydrogeologic coefficients induces uncertainty. The importance of the methodologies and procedures ranks methodologies and procedures in the "A" category. The typical methodologies and procedures used in the science of hydrogeology require the creation of a hydraulic stress on the hydrogeologic system. The response to this controlled stress is monitored and recorded; the data are evaluated based on established assumptions and concepts. An analytical representation of these concepts is used to quantify the coefficients. The coefficients that must be quantified include transmissivity (and hydraulic conductivity), hydraulic gradient, storativity, and effective porosity.

## 4.1 Fundamental Flow Equations

Uncertainty occurs in the application of the partial differential equations that are used to evaluate the data obtained from stressing the hydrogeologic system. This uncertainty ranks in the "B" category. The application of these partial differential equations and their solutions in analytical form requires knowledge about the geologic conditions that form the framework for the conceptual hydrogeologic model. These analytical solutions require that certain assumptions be met before the analytical solutions are valid. The analytical solutions are quite robust and in some cases can be applied to conditions under which the assumptions are not fully met. It is for this basic reason that the question of whether the partial differential equations apply to conditions believed to exist at the test site ranks in the "B" category.

## 4.2 Scale

A major concern exists regarding the compatibility of the scale of the conceptual hydrogeologic model(s) with the scale of the mathematical model(s) that are used for evaluating test data. The scale of the conceptual model and the scale of the mathematical model are seldom equal. The importance of scale ranks it in the "A" category. It is important to specify the scale of the testing and the scale of the conceptual model so that the disparity in scales can be evaluated. Conceptual hydrogeologic model scales frequently are on the order of tens to hundreds of square miles. The scale of a typical hydrogeologic test is on the order of a few tens of feet of radius to a few kilometers or miles in radius. It is not uncommon for the difference in scales to be at least an order of magnitude. Some tests, such as tracer tests, are restricted severely in scale. The scale is restricted primarily because of the time required to move the tracer from point A to point B and not because of limitations in the theory.

## 4.3 Limitations in Data Collection

Uncertainties also exist because of limitations in the techniques available to collect accurate hydrogeologic data. These limitations rate a ranking in the "B" category. As discussed previously, errors can occur in the measurement of head with basic methods such as a steel tape or the M-scope;

measurement error also can occur because of the position of a transducer in the borehole or piezometer tube. Uncertainties can occur during hydrogeologic coefficients tests. Achieving a constant rate of discharge during a test can be difficult. The measurement of head during a test can be difficult because of the characteristics of the fluids being tested at the repository site. These questions arise because the temperature and the salinity may change during the test. Changes in salinity or total dissolved solids content create a change in the density of the fluid; the measured head or pressure must be evaluated with this consideration in mind when determining the direction of vertical flow and gradient and the direction of horizontal flow and gradient.

Uncertainties develop during tracer tests. The typical recirculating tracer test utilizes two wells. Tracer is pumped down one well at a given rate while fluid is pumped from the second of the paired wells at the same rate. The difference between the head build-up in the injection well when compared to the head drawdown in the discharge well can indicate whether the assumptions required for analysis of the tracer test data are valid. Significant differences may occur between the head build-up and the head drawdown. At the BWIP site an approximate order of magnitude difference occurred between the mirror image of a cone of impression and the cone of depression. The assumption of porous media flow under homogeneous conditions probably was not met in this tracer test. Uncertainties arise because of the necessity for long tubing strings to reach the test horizons. In addition, the tubing string in the second of the paired wells must be equally long. The combined lengths of the tubing strings may add significantly to the distance the tracer must travel from the ground surface at the injection well to the ground surface at the discharge well where it is sampled and measured. The bulk of the travel time in fact may be within the tubing strings and not in the media being tested.

The collection of core and the selection of "representative" core samples for laboratory analysis is a significant issue at any site. The "representativeness" of the core samples creates a degree of uncertainty with a rank in the "B" category. The core sample may not be representative of the overall hydrogeologic properties that control fluid transport in a fractured medium. It is not uncommon for core from a fractured medium to be difficult to recover during coring operations. Typically, the best core recovery occurs in unfractured rock, which may not be representative of the transport capabilities on a scale larger than the scale of the core. This difference between representativeness of the core and the medium cannot be easily solved; this question is primarily one of scale. As noted previously, the question of scale is dependent upon the scale of the representative sample or test volume. The core is restricted because of its dimensions when removed from the borehole. In situ tests will stress a larger volume of rock than that which can represented in a core. The correlation of a value for hydraulic conductivity or effective porosity obtained from analysis of core and in situ analysis is not clear cut.

Uncertainty exists because of the selection process used to locate boreholes and monitoring points, both areally and vertically. The importance of the uncertainty introduced by the selection process ranks this category as an

"A". Uncertainty exists because boreholes may not be located appropriately with respect to lithologic, structural, and stratigraphic features. The borehole locations may have been selected for purely geologic investigative reasons rather than hydrogeologic investigative reasons. Borehole locations (areal and vertical) frequently are selected based on an interest in investigating a particular geologic feature. This process results in the borehole locations being selected by nonrandom procedures. These locations usually coincide with suspected geologic features which can affect the flow of groundwater. The resultant nonrandom procedure used for selecting borehole locations can bias data collection, thereby introducing uncertainty into the data collected from those boreholes. Most analytical and numerical methods used for quantifying hydrogeologic coefficients are dependent upon the geometry of the borehole configuration and the borehole completion within or among the specified zones of interest. For example, the "Neuman-Witherspoon ratio method" requires that observation wells or piezometers be completed in the confining units (aquitards) above and below the pumping unit (aquifer) at specified distances from the pumping well. In conjunction with these monitoring points in the aquitards, borehole completions also are required in the pumped zone (aquifer) at distances that correspond to the aquitard completions. Uncertainties exist because these completions may not be compatible at depth. Boreholes drilled at the surface generally do not have the required separation at the desired depth. Deviations from the vertical are common in the depth range of the boreholes and wells used at the high level waste repository sites.

The drilling and completion procedures used on the boreholes and piezometers can cause additional uncertainties. Drilling usually causes fracturing in the formations adjacent to the borehole as well as hydration of some formation minerals. The integrity of the packers or the cement seals used to isolate piezometers within zones of interest also produces uncertainty. The integrity of a packer or cement seal cannot be determined absolutely at the depths and under the geometry of the configurations used at the sites. The completions may leak fluid under stress. The amounts of leakage may be small but significant with respect to evaluating the data for quantification of the hydrogeologic coefficients.

Boreholes usually exist in the area of interest prior to the initiation of DOE exploration. The existing boreholes may not be plugged and sealed; in such cases the open intervals in the boreholes will allow interflow between units. The interflow creates uncertainty because the groundwater moving from one unit to another unit may alter the groundwater chemistry of the receiving unit. In addition, the flow of groundwater between units exists because there is a difference in fluid potential (head) between those units. The head within the borehole subsequent to leakage along the borehole is a composite or average of the heads in the interconnected units. The effect of the interconnection may be areally extensive depending upon the heads in the two units and their hydraulic conductivity. The influence of the interflow may be areally extensive depending upon the hydrogeologic characteristics of the units involved. The influence of the interflow may be significant enough to affect heads or fluid pressures measured in nearby boreholes or wells that are drilled for exploration and testing during the project.

## 4.4 Validity of Analytical Assumptions

Both analytical and numerical deterministic models are used for quantifying hydrogeologic coefficients. Uncertainties arise in the application of these deterministic models because field conditions may not match the assumptions implicit in these models. The uncertainty introduced by this problem ranks in the "B" category on the scale outlined in the introduction. The degree to which field conditions required by the selected analytical and numerical deterministic models are met creates uncertainty. The analytical approach or numerical model may provide defensible quantification of the coefficients even if the required conditions are not met. As has been noted above, the compatibility of the scale of the field test with the scale of the model selected for evaluating the test data also may introduce uncertainty. Scale is an essential issue that must be addressed in data interpretation and modeling. The majority of the numerical and analytical deterministic models that are used for calculating values for the hydrogeologic coefficients are based on the assumption that equivalent porous media flow can be applied to fractured rocks. The validity of this primary assumption is dependent upon the behavior of the fluids under both test conditions and in situ flow conditions. Uncertainty evolves from this assumption because of the nature of fractured media. Little information exists regarding fracture apertures, the number of fractures, and the interconnection of the fractures. It is difficult to assess the uncertainty associated with this assumption, especially considering the scales of the tests that may be used at a site. 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. Uncertainty is introduced by combining the results of these tests at different scales. No definitive approach has been presented by the technical community which addresses adequately the problems associated with combining tests at different scales.

## 4.5 Professional Judgment

Considerable uncertainty is caused by the necessity that so much professional judgment be used in the calculation of the distribution of values of the hydrogeologic coefficients. The importance of this uncertainty is reflected in its ranking in the "A" category. Numerous conditions inherent in the analysis and evaluation of test data require professional judgment. These conditions include the treatment of externally produced perturbations such as barometric effects, earth tides, and pumping extraneous to the test. These perturbations may occur in combination with or prior to the hydrogeologic testing. The identification and treatment of these perturbations requires a subjective analysis that relies heavily upon professional judgment. The analysis of hydrogeologic test data is complicated by these perturbations. Only occasionally can these perturbations be removed completely from the area of investigation. The perturbations must be treated so that the data from the test can be evaluated and analyzed with proper adjustments to the final result.

Professional judgment is required for selecting those portions of any hydrogeologic data base that will be evaluated. Significant differences can occur in the evaluation depending upon which portions of the hydrogeologic test data receive maximum emphasis. Early-time data from a pumping test may reflect fracture flow or casing storage effects if the data are obtained from the pumping well. Data obtained during late time will not reflect these near field influences at the pumping well. Late-time data usually will show the influence of boundary conditions that have been intercepted by the cone of depression created by the pumping test. Occasionally boundary conditions are encountered early in the test; difficulties can arise in trying to evaluate the test data for quantification of the basic hydrogeologic coefficients. Uncertainty exists because judgment is required to decide whether the early-time data and/or the late-time data should be weighted more heavily during analysis.

Additional uncertainty is introduced when the data deviate from the analytical and numerical deterministic, ideal models. The typical approach for evaluating hydrogeologic test data is referred to as "curve matching". Curve matching is professionally subjective, particularly when the data are influenced by perturbations such as barometric effects and outside pumping as discussed previously. Poor curve matches may develop because the analytical and numerical assumptions do not fit the geologic situation being evaluated. In addition, poor curve matches may occur because of poor quality control during the collection of data and the maintenance of designated discharge rates from the pumping well.

Uncertainty also can be incorporated in the analysis during the interpretation of boundary conditions from the test data. Uncertainties introduced in this manner are caused by the fact that the interpretation of boundary conditions from test data is seldom unique. Professional judgment is required to assess the possible impacts of boundary conditions that may be suspected based on geologic data. A quantitative analysis usually can be performed by proper application of theory but the necessary professional judgment introduces uncertainty.

## 4.6 Application of Coefficients

The selection of the size of the volume to which calculated values of coefficients are applied rates as a principal source of uncertainty (category "A"). The scale of the test is not always evident from the data collected during the test. Consequently, the selection of the representative volume that the test represents is not always self-evident. Some uncertainty arises from defining the hydrostratigraphic units to which the data should be assigned. The locations of the boundaries of the designated hydrostratigraphic units are not always clear.

Additional uncertainty is inevitable during the selection of distributions or ranges of values for the coefficients which will be used in the groundwater travel time analysis. The ranges of values of hydraulic conductivity that are based on calculated values of transmissivity are particularly troublesome. The thickness of the strata that contributed the majority of flow during testing must be measured in order to calculate a hydraulic conductivity value that is valid. The standard procedure for calculating hydraulic conductivity is to divide the transmissivity by the thickness of the test zone. In fractured rock this procedure results in the calculation of a value of hydraulic conductivity that by definition may be lower than the true value. A more appropriate manner for calculating hydraulic conductivity is based on the evaluation of auxiliary data which indicates the thickness of the water producing zones within the test interval. The hydraulic conductivity that is calculated based on the thickness of the water producing zones is higher and produces a more conservative (safer) value to be used in the calculation of groundwater travel time.

Additional uncertainty occurs each time a particular coefficient is assigned a range or distribution of values. Different sample sizes among the different hydrogeologic coefficients creates uncertainty. The size of the samples influences the distribution of the sample. The number of samples used to estimate effective porosity will be much smaller than that used to estimate hydraulic conductivity. Combining the different sample sizes creates uncertainty because of the differences in scale and the differences in the number of values that will be used to determine the distribution of a coefficient. It will not be practical to conduct the same number of tests for each hydrogeologic coefficient required for the prediction of groundwater travel time.

## 4.7 Sufficiency of Testing

Uncertainty always exists regarding the question of how much testing is sufficient. This item ranks in category "B". It is not always easy to decide when adequate testing has been conducted. The decision as to whether the testing is sufficient inevitably will vary depending upon the point of view of the investigator.

## 4.8 Hydrochemical and Isotopic Data

Uncertainty exists in the interpretation of the relationship between hydrochemical and isotopic data and the groundwater flow system that was interpreted based on other hydrogeologic data. This factor ranks in the "B" category. The uncertainty derives from a number of factors that depend upon the subjective interpretation of a professional hydrogeologist. The interpretation of hydrochemical and isotopic data must be made independently of the interpretation of the groundwater flow system. The interpretation of the separate data sets should be coincident. However, they may not be coincident because of a lack of data or because of misinterpretation of one set or both sets of data. Uncertainty arises because of the subjectivity of several aspects of the interpretation of both sets of data.

# 5. UNCERTAINTY IN MODEL PREDICTIONS OF GROUNDWATER TRAVEL TIME

The uncertainties outlined previously regarding the conceptual model and the calculation of hydrogeologic coefficients coalesce in the mathematical models used to predict groundwater travel time. Model predictions rank in the "A" category.

## 5.1 Deterministic Model Predictions

A deterministic model can be used to predict groundwater travel time; the use of a deterministic model deserves ranking in category "A". Uncertainties are inherent in the mathematical approximations and numerical factors that include error of truncation and roundoff in the model. These instabilities and errors rank in category "B". Significant uncertainties may be created by "lumping" values for the coefficients in the hydrogeologic model. The lumping (category "B") occurs because of restrictions in the size of model that can be used and because of inadequate data. Lumping frequently combines hydrostratigraphic units that exhibit similar but nevertheless different characteristics; the determination that the units have similar characteristics usually is based largely on professional judgment. The uncertainty caused by the lumping may be significant if the evaluation of an inadequate data base allows lumping of coefficient values for units that in fact should not be grouped together.

As discussed in the preceding sections questions usually exist about boundary conditions in the conceptual hydrogeologic model. These questions carry over into the mathematical model; uncertainties develop when these boundary conditions are represented mathematically in the mathematical model. Boundary conditions rank in the "B" category. Uncertainties occur because of the necessity to assign coefficient values to these boundary conditions that may not be appropriate for the features that are being modeled. Adequate testing will minimize this uncertainty; however, the characteristics of the boundary may not be incorporated easily into the selected mathematical model.

Uncertainty is inherent in the designation of initial conditions in a model. Initial conditions rank in the "B" category. Initial conditions may vary between steady state conditions to nonsteady state conditions. Nonsteady state flow may be the result of man's influences or the result of natural processes. The designation of initial conditions for the mathematical model must be based on very short term data (a few years) whereas groundwater travel time must be extrapolated to at least 1,000 years and perhaps to 10,000 years. The uncertainty in the designation of initial conditions may be magnified by the necessity to extrapolate to such long time periods.

Uncertainty is introduced by the subjective selection of the element geometry used in the mathematical model. This variable is ranked in the "B" category. The element geometry may affect simulated groundwater flow paths because the geometry controls the extent to which the distribution of hydrogeologic coefficient values can approximate the distribution measured in the field. These values may be assigned based on an inadequate data base; frequently these values are assigned based on an assumed distribution of a range of values developed from testing within the area of interest. Model element geometry frequently is based on interpretations of geologic data which may indicate the presence of potential boundary conditions. Transitions between geologic units may be coincident with hydrostratigraphic unit boundaries. Some insensitivity and uncertainty in model output occurs if the element geometry is too coarse. Finer meshes are used frequently in areas where recharge or discharge is suspected in order to minimize errors and uncertainties associated with these features.

The coefficients that are allowed to vary in the model may create uncertainties. The variability of results places this impact in the "A" category. Inappropriate conceptual hydrogeologic models may evolve based on the selection of ranges of values and the selection of the coefficients that are allowed to vary.

Additional uncertainty is inherent in the prediction process because of the subjective nature of the selection of acceptable ranges (category "A") of mathematical model outputs and groundwater travel times. The selection process is dependent upon professional assessment of the range of groundwater travel times that are reasonable based on the accepted conceptual hydrogeologic models. The subjective nature of this process may be weighted by personal prejudices regarding the conceptual hydrogeologic models that fit the existing data base.

## 5.1 Stochastic Model Predictions

Uncertainty is introduced by the selection of the stochastic procedures that are used to predict groundwater travel time. This selection is ranked in the "A" category. The uncertainties presented in the preceding discussion of conceptual hydrogeologic model, three-dimensional distribution of head, and appropriateness of testing methodologies and procedures (items 2, 3, and 4) carry over into this category. Additional uncertainty occurs because of mathematical approximations and numerical instabilities that occur in the prediction process (category "B"). The differences that may occur between the geometry and scale of the deterministic model adopted for testing and the geometry and scale of the deterministic model to which the stochastic analysis is applied introduces additional uncertainty. The importance of scale ranks in category "A". As noted previously scale is a very important question that must be considered in the groundwater travel time prediction process. The scale of the field tests and the scale of the stochastic prediction modeling process should be compatible.

Some uncertainty also is introduced by the selection of the model element geometry (category "B") used in the deterministic/stochastic analysis procedure. The selection process is dependent upon professional judgment; that judgment will be affected by preconceived notions about the conceptual hydrogeologic model.

Some uncertainty also may be introduced into the prediction process when deciding which coefficients and the number of coefficients that are to be treated stochastically in the deterministic model. The importance of this item ranks in category "A". One coefficient (such as hydraulic conductivity) may be allowed to vary in the process or all the relevant coefficients may be allowed to vary, including hydraulic conductivity, effective porosity, and hydraulic head (hydraulic gradient). The stochastic analysis procedure also may create additional uncertainties because of the mathematical process by which values are selected for use in the prediction of groundwater travel time (category "A"). A stochastic simulation process may create conceptual groundwater flow paths that are not realistic from a geological point of view.

Technical limitations on defining and applying correlation structure(s) within and among hydrogeologic coefficients for the stochastic portion of the prediction process also may introduce additional uncertainty. The importance of correlation structure places this item in the "A" category. This uncertainty may be created by differences in scale of different testing techniques which are required for quantifying hydrogeologic coefficients. These coefficients are required for the prediction of groundwater travel time, yet the scale at which these tests are conducted may vary greatly depending upon the site that is being investigated. This problem may be especially relevant to Yucca Mountain because of the nature of the testing that can be conducted in the unsaturated zone. The ability to obtain large scale values for hydrogeologic coefficients in the unsaturated zone is limited. Conversely the correlation structure may be defined with little difficulty because all of the values may be of similar small scale.

Uncertainty may occur because of the assumption that the data point values are fixed (have no associated uncertainty) during kriging and conditional simulation (category "B"). The assumption that data point values are precise values is not valid at some of the sites.

Some uncertainty may be created by introducing different sample sizes (number of samples) for different hydrogeologic coefficients. The importance of this item is reflected in its rank in the "A" category. The sample sizes for effective porosity may be smaller than the sample sizes for hydraulic conductivity. The disparity in the sample sizes may be caused by practical limitations in conducting tracer tests. Uncertainty is introduced by combining a small sample size with a large sample size as discussed at other points in this topical report.

Uncertainty also is introduced into the prediction of groundwater travel time because of the need to use professional judgment in identifying that portion of the groundwater travel time output from the stochastic procedure that is defensible in a hydrogeologic context. This important item is placed in category "A". The conceptual hydrogeologic model must be maintained when evaluating the groundwater travel time output from the stochastic procedure; output that represents nonrealistic conceptual models should be eliminated from the output data set. The final data set that is evaluated should represent all conceptual models that are reasonable based on the existing data base. The ability to select the portions of the groundwater travel time output that reflect realistic conceptual models requires the application of professional judgment.

Uncertainty is introduced into the groundwater travel time prediction process because the deterministic/stochastic modeling procedure for predicting groundwater travel time produces a cumulative frequency distribution (category "A") of model outputs. The cumulative frequency distribution of model output must be evaluated to determine whether it is at least a reasonable representation of the true groundwater travel time probability distribution. The model itself cannot exactly represent the true physical system. Uncertainty occurs because of the potential disparity that can occur between the output as a cumulative frequency distribution and the actual but unknown probability distribution of groundwater travel times. The true probability distribution is a function of the conceptual model(s), the data base, and the assumed probability distribution of the coefficients.

# 6. ADDRESSING UNCERTAINTIES INHERENT IN THE PREDICTION OF GROUNDWATER TRAVEL TIME

This report outlines the uncertainties that are inherent in developing the hydrogeologic data base required for the prediction of groundwater travel time by either deterministic or deterministic/stochastic processes. The categories of uncertainty that have been discussed encompass a number of fields of expertise. An associated second topical report is entitled "Evaluation of Methodologies to Quantify and Reduce Uncertainty During Site Characterization in Order to Demonstrate Compliance with 10 CFR 60.113(a)(2): Pre-Waste-Emplacement Groundwater Travel Time". This second topical report will address the conceptual model and the testing methodologies and procedures; its purpose will be to outline methods for quantifying the uncertainty and reducing and/or minimizing uncertainty.

A third topical report entitled "Evaluation of Methodologies to Express Uncertainty When Quantifying Groundwater Travel Time in Order to Demonstrate Compliance with 10 CFR 60.113(a)(2): Pre-Waste-Emplacement Groundwater Travel Time" will evaluate methodologies and procedures that are available to express and quantify the uncertainty produced by the different components required for predicting groundwater travel time.

OUTLINE OF TOPICAL REPORT NO. 1
CATEGORIZING UNCERTAINTY IN ORDER TO DEMONSTRATE
COMPLIANCE WITH 10 CFR 60.113(A)(2):
PRE-WASTE-EMPLACEMENT GROUNDWATER TRAVEL TIME

1. INTRODUCTION

1.1. A ranking system is employed, which includes three categories of importance

A. Essential for quantifying GWTT.
B. May be essential for quantifying GWTT.
C. Not essential for quantifying GWTT.

The ranking system is applied to the three following broad subject areas.

1.1.1. Conceptual model--incorporates knowledge about distribution of K, $n_e$, and gradient (location of recharge and discharge area) in the saturated zone and flow processes and rate of flux in the unsaturated zone.

1.1.2. Basic coefficients required for calculating GWTT (K, $n_e$, and gradient)--ranking.

1.1.3. Predicting groundwater travel time

| Category | | |
|---|---|---|
| A | 2. | CONCEPTUAL HYDROGEOLOGIC MODEL(S) |
| A | 2.1. | Uncertainty about delineation of geologic framework (layers, facies, zones, fold axes, faults). |
| A | 2.2. | Uncertainty about the distribution of hydrogeologic coefficients within the geologic framework or flow domain (layers, zones, anisotropy, heterogeneity, discontinuities created by geological processes). |
| A | 2.3. | Uncertainty about the boundary conditions of the hydrogeologic framework. |
| B | 2.3.1. | Uncertainty about the definition of geologic boundaries (faults, facies changes, fold axes, collapse breccia structures, sedimentary features, groundwater divides). |
| C | 2.3.2. | Uncertainty about the location of the recharge areas. |
| C | 2.3.3. | Uncertainty about the location of the discharge areas. |
| C but A at NTS | 2.3.4. | Uncertainty about the recharge and discharge rates |
| C | 2.3.5. | Uncertainty about whether the upgradient and downgradient boundaries can be assumed constant head or constant flow boundaries. |
| B but A at NTS | 2.3.6. | Uncertainty about whether steady or unsteady flow conditions are operable. |
| B but A at NTS | 2.3.7. | Uncertainty about initial conditions. |
| A | 2.4. | Uncertainty about flow processes (saturated flow, unsaturated liquid water flow, water vapor flow, variable density fluids). |
| B | 2.5. | Uncertainty about the hydrochemical and isotopic characteristics of the ground water system. |
| | 2.5.1. | Uncertainty about the hydrochemical and isotopic distinctness or lack of distinctness of the groundwater from different portions of the flow system. |

Category

2.5.2. Uncertainty about the hydrochemical and isotopic equilibration of the groundwater with the geologic environment.

2.5.3. Uncertainty about the hydrochemical and isotopic evolution of the groundwater.

2.5.4. Uncertainty about the correlation of groundwater flow paths and travel times with the hydrochemistry and isotopic characteristics.

Category

A 3. UNCERTAINTY IN KNOWLEDGE ABOUT THE THREE-DIMENSIONAL DISTRIBUTION OF HYDRAULIC HEAD.

A 3.1. Uncertainty in head measurements in saturated and unsaturated zones (uphole or downhole transducer position, tape, tensiometer, psychrometer, effect of borehole location and depth).

A 3.2. Uncertainty about direction of horizontal and vertical gradients.

B 3.3. Uncertainty about sources of and importance of energy fields other than fluid potential energy (temperature, chemical, electrical fields and potential free convection or coupled flow phenomena [thermal diffusion, streaming potentials, Soret effect, etc.]).

Category

A 4. UNCERTAINTY IN APPROPRIATENESS OF TESTING METHODOLOGIES AND PROCEDURES

B 4.1. Uncertainty about whether geologic conditions required for application of solutions to fundamental flow equations are met.

A 4.2. Uncertainty about whether the scale of the hydrogeologic conceptual model(s) is compatible with the scale of the deterministic mathematical model(s) used for testing.

B 4.3. Uncertainties due to limitations in data collection:

4.3.1. Measurement error (downhole or uphole transducer position, tape).

4.3.2. Errors in running test:

4.3.2.1. Was pumping rate constant or variable?

4.3.2.2. Were head changes corrected for temperature or salinity changes during test?

4.3.2.3. Were incompatible head patterns measured during tracer tests? (i.e., an order of magnitude difference was noted between the head build-up and head drawdown in the injection and withdrawal wells during the BWIP recirculation tracer test)

B 4.3.3. Uncertainty created by the collection and selection of "representative" core samples for laboratory analysis.

A 4.3.4. Uncertainty introduced by selection of depths and locations of boreholes.

4.3.4.1. Uncertainty about whether locations of boreholes are appropriate with respect to lithologic, structural, and stratigraphic features.

4.3.4.2. Uncertainty introduced by non-random procedure used for selecting borehole sites.

Category

4.3.4.3. Uncertainty introduced by vertical and horizontal distances between boreholes that are inappropriate for analytical methods.

4.3.4.4. Uncertainty introduced by construction of piezometers (e.g., fracturing of formations during drilling, hydration of formation minerals upon contact with drilling fluid, integrity of packer or cement seals, integrity of tubing, etc.)

4.3.4.5. Uncertainty introduced by existing open boreholes that cause interunit (cross-formational) flow of groundwater.

B 4.4. Uncertainty about whether the numerical or analytical deterministic model(s) selected for coefficient calculation reflects field conditions.

4.4.1. Uncertainty in the degree to which assumed conditions as required by the selected analytical or numerical deterministic model(s) are present in the hydrogeologic framework being tested.

4.4.2. Uncertainty in the compatibility of scale of test(s) with scale of model selected.

4.4.3. Uncertainty in applying equivalent porous media deterministic models to fractured rocks.

4.4.4. Uncertainty introduced by combining results of different types and scales of tests.

A 4.5. Uncertainty in the professional subjective judgment required for the calculation of distributions or ranges of values of hydrogeologic coefficients.

4.5.1. Uncertainty introduced by treatment of externally produced perturbations (e.g., barometric effects, earth tides, external pumping such as irrigation).

4.5.2. Uncertainty in emphasis placed on selected portions of the data base.

4.5.3. Uncertainty introduced by deviations of data from analytical or numerical deterministic model expectations (poor curve matches).

Category

4.5.4. Uncertainty in interpretation of boundaries from the results of the tests (as opposed to mapped geologic features).

A 4.6. Utilization of calculated coefficients.

4.6.1. Uncertainty in the selection of the size of area to which calculated values of coefficients are applied.

4.6.2. Uncertainty in the definition of the hydrostratigraphic unit to which the data are applied.

4.6.3. Uncertainty in selecting distributions or ranges of values of hydraulic conductivity from values of transmissivity.

4.6.4. Uncertainty in calculating distributions or ranges of effective thickness or other parameters from borehole flow logs, borehole geophysical logs and tracer test results.

4.6.5. Uncertainty caused by different sample sizes among different hydrogeologic coefficients. Size of sample influences distribution and range of resulting data (e.g., effective porosity versus hydraulic conductivity).

B 4.7. Uncertainty in deciding how much testing is sufficient.

B 4.8. Uncertainty in interpreting the relationship between hydrochemical and isotopic data and the groundwater flow system that is interpreted based on field determined hydrogeologic coefficients.

Category

A 5. UNCERTAINTY IN MODEL PREDICTIONS OF GWTT.

A 5.1. Uncertainty resulting from utilizing deterministic model(s) for predicting GWTT.

5.1.1. All the uncertainties under items 2, 3, and 4 carry through.

B 5.1.2. Uncertainty due to mathematical approximations and numerical instabilities (including errors of truncation and round-off).

B 5.1.3. Uncertainty caused by the lumping of the coefficients in the hydrogeologic conceptual model(s).

B 5.1.4. Uncertainty about whether boundaries in the hydrogeologic conceptual model can be portrayed mathematically in the deterministic mathematical model.

B 5.1.5. Uncertainty in the designation of initial conditions.

B 5.1.6. Uncertainty introduced by the subjective selection of the model element geometry used in the deterministic (numerical) analysis.

A 5.1.7. Uncertainty introduced by the designation of coefficients for input into the deterministic model(s).

A 5.1.8. Uncertainty in the subjective selection of the acceptable range of deterministic model outputs of GWTT.

A 5.2. Uncertainty resulting from utilizing deterministic model(s) with stochastic analyses (deterministic/stochastic model(s)) for predicting GWTT.

5.2.1. Uncertainties listed in items 2, 3, and 4 carry through.

B 5.2.2. Uncertainties due to mathematical approximations and numerical instabilities.

A 5.2.3. Uncertainty introduced by the differences between the geometry and scale of the deterministic model(s)

| Category | | |
|---|---|---|
| | | adopted for testing and the geometry and scale of the deterministic model to which stochastic analysis is applied. |
| B | 5.2.4. | Uncertainty introduced by the subjective selection of the model element geometry used in the deterministic/stochastic analysis. |
| A | 5.2.5. | Uncertainty in the decision of which coefficients and the number of coefficients that are to be treated stochastically in the deterministic model framework. |
| A | 5.2.6. | Uncertainty introduced by the stochastic analysis itself. |
| A | 5.2.7. | Uncertainty due to technical limitations on defining and applying correlation structure(s) within and among hydrogeologic coefficients for the stochastic portion of the model(s). |
| B | 5.2.8. | Uncertainty about the validity of data point values that are considered to be fixed during kriging and conditional simulation. |
| A | 5.2.9. | Uncertainty caused by different sample sizes of hydrogeologic coefficients. |
| A | 5.2.10. | Uncertainty in the professional judgement used in the identification of the portion of the GWTT output from the stochastic procedure which is defensible in a hydrogeologic context. |
| A | 5.2.11. | Uncertainty in determining whether the output of a deterministic/stochastic modeling procedure for GWTT is a true probability distribution or simply a cumulative frequency distribution. |

Category

6. ADDRESSING UNCERTAINTIES INHERENT IN THE PREDICTION OF GROUNDWATER TRAVEL TIME