3.3.4 Radionuclide Release Rates and Solubility Limits

3.3.4.1 Description of Issue

The Radionuclide Release Rates and Solubility Limits Integrated Subissue addresses the release of radionuclides from the engineered barrier subsystem to the geosphere. The relationship of this integrated subissue to other subissues are depicted in Figure 3.3.4-1. The overall organization and identification of all the integrated subissues are depicted in Figure 1.2-2. This section provides a review of the abstractions of radionuclide release rates and solubility limits incorporated by the DOE in its Total System Performance Assessment–Site Recommendation (CRWMS M&O, 2000a,t).

3.3.4.2 Relationship to Key Technical Issue Subissues

The Radionuclide Release Rates and Solubility Limits Integrated Subissue incorporates subject matter previously captured in the following key technical issue subissues:

- Container Life and Source Term: Subissue 3—The Rate at Which Radionuclides in Spent Nuclear Fuel Are Released from the Engineered Barrier Subsystem Through the Oxidation and Dissolution of Spent Nuclear Fuel (NRC, 2001)
- Container Life and Source Term: Subissue 4—The Rate at Which Radionuclides in High-level Waste Glass Are Leached and Released from the Engineered Barrier Subsystem (NRC, 2001)
- Container Life and Source Term: Subissue 5—The Effect of In-package Criticality on Waste Package and Engineered Barrier Subsystem Performance (NRC, 2001)
- Container Life and Source Term: Subissue 6—The Effects of Alternate Engineered Barrier Subsystem Design Features on Container Lifetime and Radionuclide Release from the Engineered Barrier Subsystem (NRC, 2001)
- Evolution of the Near-Field Environment: Subissue 3—Effects of Coupled Thermal-hydrologic-chemical Processes on the Chemical Environment for Radionuclide Release (NRC, 2000a)
- Evolution of the Near-Field Environment: Subissue 4—Effects of Coupled Thermal-hydrologic-chemical Processes on Radionuclide Transport Through Engineered and Natural Barriers (NRC, 2000a)
- Evolution of the Near-Field Environment: Subissue 5—Effects of Coupled Thermal-hydrologic-chemical Processes on Potential Nuclear Criticality in the near Field (NRC, 2000a)
- Total System Performance Assessment and Integration: Subissue 1—System Description and Demonstration of Multiple Barriers (NRC, 2000b)

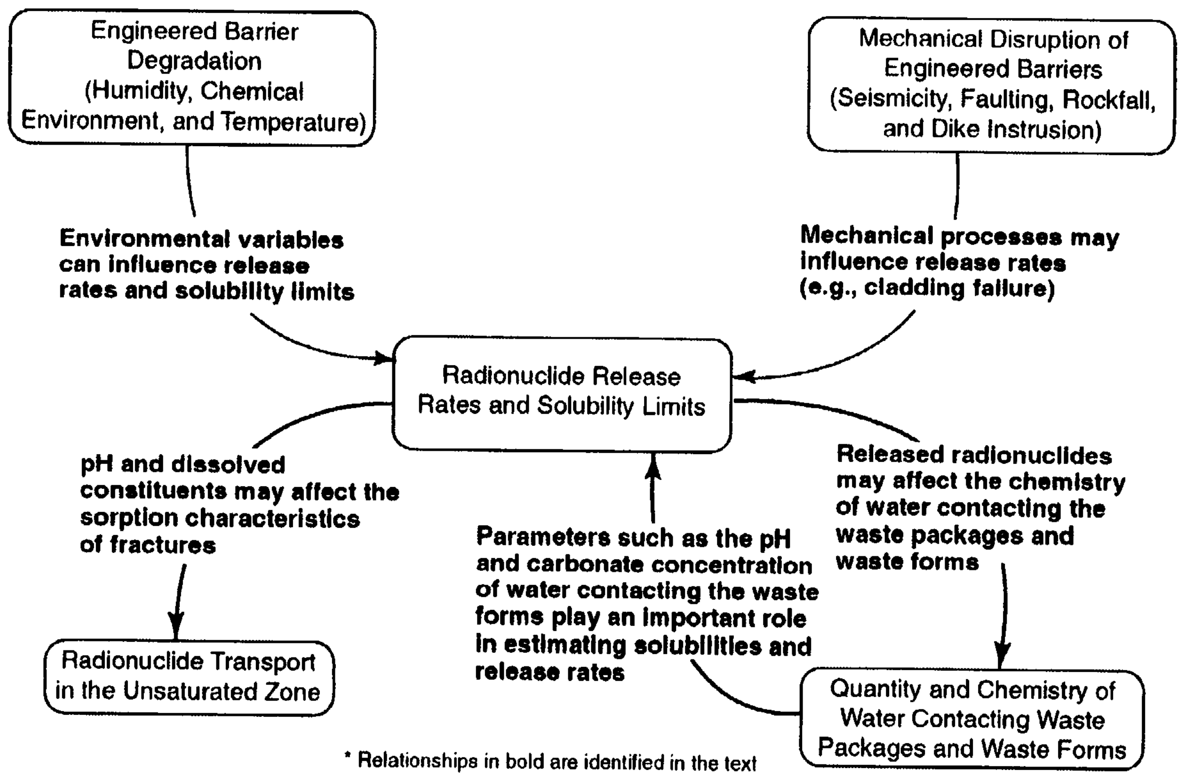

Figure 3.3.4-1. Diagram Illustrating the Relationship Between Radionuclide Release Rates and Solubility Limits and Other Integrated Subissues

- Total System Performance Assessment and Integration: Subissue 2—Scenario Analysis and Event Probability (NRC, 2000b)
- Total System Performance Assessment and Integration: Subissue 3—Model Abstraction (NRC, 2000b)
- Total System Performance Assessment and Integration: Subissue 4—Demonstration of Compliance with the Postclosure Public Health and Environmental Standards (NRC, 2000b)

The key technical issue subissues formed the bases for previous versions of the issue resolution status reports and also were the bases for technical exchanges with DOE where agreements were reached on the additional information DOE needed to provide to resolve the subissue. The resolution status of each integrated subissue is based on the resolution status of each of the contributing key technical issue subissues. Discussions of issue resolution pertaining to the subissues on nuclear criticality are presented in Sections 3.3.1 and 3.3.7 and are not repeated here. The subsequent sections incorporate applicable portions of these key technical issue subissues, however, no effort was made to explicitly identify each subissue.

3.3.4.3 Importance to Postclosure Performance

The NRC review was to determine how this integrated subissue is related to the DOE repository safety strategy. The importance of radionuclide release rates and solubility limits to repository performance at Yucca Mountain is recognized by DOE. In CRWMS M&O (2000a), limited release of radionuclides from the engineered barriers is identified as one of five system attributes most important for predicting the performance of engineered and natural barriers. DOE considered the waste form itself, such as the irradiated uranium oxide pellets or the high-level waste glass, as one of the barriers to the release of radionuclides. DOE believed the concentration limits of radionuclides in water was another factor that constrained radionuclide release. For example, many radionuclides are sufficiently insoluble that they are not mobilized even if the waste form degrades. The transport behavior of radionuclides in the waste package and the engineered barriers outside the waste package also places constraints on radionuclide release. For limited flow conditions, DOE believes that radionuclide transport is limited by diffusion out of the waste package, a process that would be affected by the waste-generated heat that elevates temperatures and removes moisture. The invert material below the waste package could also limit the migration of radionuclides in the engineered barrier subsystem.

DOE considered radionuclide concentration limits in water as one of eight principal factors of the postclosure safety case in CRWMS M&O (2000a). This factor includes the limits for both dissolved radionuclides and those associated with colloidal suspensions. Other factors identified by DOE for the postclosure safety case, though given lower importance, include cladding performance and waste form performance. Cladding performance pertains to the role of cladding in limiting water contact and subsequent dissolution of the spent nuclear fuel waste form. Waste form performance relates to the rate of mobilization of radionuclides caused by degradation of the waste form itself (e.g., the irradiated uranium oxide matrix or high-level waste glass waste form).

3.3.4.4 Technical Basis

Radionuclide release from the engineered barrier subsystem will depend on several processes: (i) contact of water with the waste form, (ii) dissolution of the waste form, (iii) solubility limit of radionuclides, (iv) transport in water, and (v) interaction with engineered barrier materials. The waste form will begin to degrade once it comes into contact with air, water vapor, or water. Transport of radionuclides away from the waste form to the geosphere, however, generally requires a water pathway. In this regard, integrity of the cladding as an additional metallic barrier is an important factor considered by DOE in delaying water contact with the fuel matrix and degradation of commercial spent nuclear fuel. Radionuclides would be released from the waste form to the water within the waste package at a rate controlled by the (i) rate of waste form degradation (i.e., congruent dissolution), (ii) rate of dissolution of secondary minerals into which the radionuclides have become incorporated (e.g., schoepite or uranyl-hydrate), or (iii) solubility of the radionuclides themselves. Rates of dissolution vary for the different waste forms (e.g., spent nuclear fuel versus high-level waste glass). The rate of water flow through the waste package and the concentration of radionuclides in waste package waters ultimately control the release rate from the waste package (although molecular diffusion might be relatively important in a situation where flow rates are small). The solubility of radionuclide-bearing minerals could limit radionuclide concentrations in waste package water if the saturation index of the radionuclide-bearing mineral is positive. Colloid formation, especially from degradation of the high-level waste glass, however, is a potential process that could result in radionuclide concentration [(dissolved + colloid load)/volume] higher than the solubility limit. Once radionuclides are released from the waste package into the waste emplacement drifts, interaction with other engineered components could affect the release of radionuclides into the geosphere.

Near-field, coupled thermal-hydrological-mechanical-chemical processes will affect the environment for radionuclide release from the engineered barrier subsystem. Composition of the water entering the waste package will evolve as a function of time as a result of thermal-hydrological-chemical processes. As water interacts with the materials inside the waste package, the water chemistry will change. The dissolution rates of the waste form and engineered materials and the precipitation rates of alteration minerals are functions of temperature. In addition, as the materials degrade and alteration minerals are formed, the amount of water that can enter or exit the degraded waste package may change. The degradation rate of the Zircaloy cladding that surrounds the spent nuclear fuel and the dissolution rates of both the spent nuclear fuel and glass waste forms are functions of water chemistry. Other engineered materials in the emplacement drifts, including backfill, if present, and the drift invert, will be affected by coupled thermal-hydrological-mechanical-chemical processes. The coupled thermal-hydrological-mechanical-chemical processes could affect both hydraulic properties of the flow path from the waste package into the geosphere and the sorptive properties of the engineered materials. In addition, coupled thermal-hydrological-mechanical-chemical processes could affect the potential of near-field criticality.

Several factors need to be considered in abstractions of radionuclide release rates and solubility limits. In the specific case of spent nuclear fuel degradation, important factors are (i) spent nuclear fuel types, (ii) radionuclide inventory and distribution in the fuel, (iii) cladding performance, (iv) dry oxidation of the spent nuclear fuel and its effects on subsequent performance in an aqueous environment, (v) dissolution in an aqueous environment, (vi) solubility of radionuclides, (vii) secondary mineral formation and coprecipitation, (viii) formation of colloids, and (ix) conceptual models for release from waste packages. In the abstraction of glass waste form degradation, several factors are important: (i) high-level waste glass dissolution processes, (ii) formation of secondary minerals, (iii) effects of colloids and microbes, and (iv) conceptual models for release from the waste packages. Finally, the abstraction of the release of radionuclides from the waste package into the geosphere must consider (i) the hydrologic, chemical, and sorptive characteristics of engineered materials beneath the waste packages, such as backfill and invert, and (ii) the changes in the sorptive and hydraulic characteristics of engineered materials beneath the waste packages caused by coupled thermal-hydrological-mechanical-chemical processes.

The release rate of uranium and other species from breached waste packages containing spent nuclear fuel is controlled by a series of processes, such as the flux of water and oxidants, oxidative dissolution of spent nuclear fuel, secondary uranyl mineral precipitation, uranyl mineral dissolution or transformation, and transport of radionuclides, and is affected by the condition of the fuel cladding. The waste dissolution rate and elemental solubilities are key technical components affecting total system performance assessment (Electric Power Research Institute, 1998; DOE, 1998). The models used to describe waste form dissolution and the extent to which cladding can protect the spent nuclear fuel from contact with water are important determinants of total system performance assessment (Jarzemba, et al., 1999; Mohanty, et al., 1999; DOE, 1998). For example, four different spent nuclear fuel dissolution models, based on different assumptions of the chemical composition of the water contacting the waste form and the presence or absence of secondary uranium minerals, predict doses at 10,000 years that vary by one order of magnitude or more (Mohanty, et al., 1999).

The release of radionuclides from the waste package and engineered barriers is dependent on the concentration of radionuclides contained in the water of breached waste packages. Radionuclide release into water contacting the waste forms is, in turn, dependent on either the solubility of the individual radionuclide or the solubility of the waste matrix. In the absence of colloids, radionuclide solubilities represent the upper limit for individual radionuclide concentrations in the in-package water and depend on the physical and chemical conditions in the near-field environment.

A typical approach to analyze the radionuclide release rates and solubility limits in total system performance assessments is as follows. Waste form leach rate, combined with the amount of water in contact with the waste form, determines the fraction of radionuclide inventory released to waste package waters (NRC, 2001). If releases of radionuclides to waste package waters result in concentrations greater than the solubility limits, the radionuclide concentrations are set equal to the solubility limits (NRC, 2001). In this manner, both radionuclide solubilities and the waste form leach rate contribute to estimates of repository performance.

Total system performance assessment models can use a bathtub model, where a volume of water accumulates within a failed waste package, or a flow-through model, where water does not collect in the waste package (Mohanty, et al., 2000). Advective and diffusive releases from the waste package are estimated; both require estimation of time-dependent radionuclide concentrations in the water inside the waste package. In advective release, the rate at which water exits the waste package is multiplied by the radionuclide concentration to obtain a release rate for radionuclides from the waste package. In diffusive release, the concentration of radionuclides in waste package waters is used to estimate the concentration gradient necessary for calculating the diffusive flux of radionuclides from the waste package. Expressions for the dissolution rate of radionuclides in the waste form are used to estimate time-dependent radionuclide concentrations inside a breached waste package, Then, a mass balance is performed for the radionuclide concentration in the waste package water. The total release rate of radionuclides of higher solubility to waste package waters is the dissolution rate multiplied by the radionuclide inventory in the waste packages.

Radionuclides exiting the waste package will travel through the material that supports the waste package and lines the floor of the emplacement drifts (NRC, 2000a). These materials could sorb the radionuclides and decrease their release rate from the engineered barrier subsystem depending on whether matrix flow or fracture flow occurs through the materials (NRC, 2000a). The physical properties and sorptive capabilities of these materials may change as a result of coupled thermal-hydrological-mechanical-chemical processes. On the other hand, the sorption capabilities of the materials could increase the potential for near-field criticality.

Radionuclide solubilities are strongly dependent on the in-package environment. The chemistry of water contacting the waste form affects the oxidation state, the solubility, and the release rate of the radionuclides. In an oxidizing environment such as the Yucca Mountain proposed repository setting, uranium in the spent nuclear fuel may ultimately exist as U_3O_8 or UO_3, which has markedly different solubilities from UO_2. Similarly, technetium is soluble during oxidizing conditions but insoluble during reducing conditions. Other parameters dictated by the in-package chemistry also affect waste form degradation rates and radionuclide solubilities. For example, equations for the dissolution rate of spent nuclear fuel could have terms dependent on pH, temperature, carbonate, silica, and calcium concentrations.

Secondary minerals could precipitate on or near the spent nuclear fuel and mitigate radionuclide release by incorporating radionuclides into their structure or by reducing the spent nuclear fuel surface in contact with the water. For example, drip tests on spent nuclear fuel conducted at Argonne National Laboratory indicate that key nuclides, such as neptunium and cesium, can be concentrated in secondary mineral phases at the surface of the spent nuclear fuel (NRC, 2001). Periodic spallation of the secondary mineral layer, however, could expose a fresh surface of spent nuclear fuel for further dissolution.

Another aspect of radionuclide release is the possibility of precipitation of fissile isotopes after their release from the waste forms and waste packages, within the invert or on the drift floor, which could increase the potential of near-field criticality. More discussion on this subject is provided in Section 3.3.4.4.10.

NRC developed a plan (2002) consistent with the acceptance criteria and review methods found in previous issue resolution status reports. A review of DOE approaches for including radionuclide release and solubility limits in total system performance assessment abstractions is provided in the following subsections. Several DOE abstractions pertain to the Integrated Subissue on Radionuclide Release Rates and Solubility Limits. For clarity, the discussions in the following subsections are organized according to the specific topic of the DOE abstractions:

(i) Radionuclide Inventory, (ii) In-Package Chemistry, (iii) Degradation of Cladding on Commercial Spent Nuclear Fuel, (iv) Commercial Spent Nuclear Fuel Dissolution, (v) DOE Spent Nuclear Fuel Dissolution, (vi) High-Level Waste Glass Dissolution, (vii) Radionuclide Solubility, (viii) Colloidal Release, and (ix) Engineered Barrier Subsystem Flow and Transport. Staff comments for each topic are organized according to the five generic acceptance criteria identified in Section 1.5: (i) System Description and Model Integration Are Adequate, (ii) Data Are Sufficient for Model Justification, (iii) Data Uncertainty Is Characterized and Propagated Through the Model Abstraction, (iv) Model Uncertainty Is Characterized and Propagated Through the Model Abstraction, and (v) Model Abstraction Output Is Supported by Objective Comparisons.

3.3.4.4.1 Radionuclide Inventory

Radionuclide inventory is used for three purposes: (i) in a radionuclide screening evaluation to determine which radionuclides should be tracked for the total system performance assessment calculations, (ii) as input to the total system performance assessment calculations to determine the fuel heat generation rates and the radionuclide release rates, and (iii) in an evaluation to determine potential reconcentration of fissile materials that could form a critical mass. DOE accounts for the radionuclide inventories in commercial spent nuclear fuel assemblies, DOE spent nuclear fuel canisters, and defense high-level waste canisters (CRWMS M&O, 2000b). DOE derived representative radionuclide inventories, one for commercial spent nuclear fuel waste packages and another for codisposal waste packages, which contain both DOE spent nuclear fuel and high-level waste. The representative waste package inventories were developed based on a weighted average of the radionuclide inventories for all potential waste package loadings.

Radionuclide screening was performed to ensure all radionuclides that could contribute significantly to the dose were tracked in the total system performance assessment. This screening was performed by summing the product of the inventory of a radionuclide in a representative waste package and the inhalation or ingestion dose conversion factor for all radionuclides. The radionuclides that composed the upper 95 percent of this sum were screened into the analysis. This screening process was conducted at times between 100 and 10,000 years for the Total System Performance Assessment–Site Recommendation (CRWMS M&O, 2000c) analyses and up to 1,000,000 years for the final environmental impact statement analyses. Also, the process was repeated for subgroups of radionuclides based on their solubility and transport properties. Radionuclides were divided into two solubility groups (soluble and insoluble) and three transport groups (highly sorbing, mildly sorbing, and nonsorbing). This categorization identifies the important radionuclides for the nominal release scenario, the igneous activity scenario, and the human intrusion scenario.

The staff review regarding the DOE abstraction of radionuclide inventory follows.

3.3.4.4.1.1 System Description and Model Integration Are Adequate

Overall, the current information, along with the agreements reached between DOE and NRC (Section 3.3.4.5), is sufficient to conclude that the necessary information will be available at the time of a potential license application to assess the effects of radionuclide inventory on radionuclide release rates and solubility limits with respect to system description and model integration.

The approach appears to account for all waste types that will be emplaced in the repository, with reasonable bases for the radionuclide source term in the various fuel types, and seems complete in this regard. Projections of radionuclide inventory include considering the current trend to increase burnup of commercial fuel in the nuclear industry.

3.3.4.4.1.2 Data Are Sufficient for Model Justification

Sufficient data are available on the inventory of radionuclides in the waste to support the numerical values used in the calculations. Fuel assembly characteristics such as burnup, enrichment, and cooling time for commercial spent nuclear fuel are derived from a 1995 data submittal from the commercial utilities that supplied historical information about reactor assembly discharges through December 1995 and forecasts about future discharges. These data were used to derive representative radionuclide inventories for commercial spent nuclear fuel waste packages. Inventory projections for DOE spent nuclear fuel were derived from ORIGEN–2 (Oak Ridge National Laboratory, 1983) runs of representative fuel types (CRWMS M&O, 1998a). Inventory projections for high-level waste are taken from the best available information for each vitrification site (DOE, 1999). With respect to sufficient data for model justification, no information (beyond that currently available) likely will be required for regulatory decision making at the time of a potential license application.

3.3.4.4.1.3 Data Uncertainty Is Characterized and Propagated Through the Model Abstraction

DOE uses values for radionuclide inventories that reasonably account for uncertainty and variability. No additional information is needed regarding the characterization and propagation of data uncertainty through the abstraction of waste inventory.

3.3.4.4.1.4 Model Uncertainty Is Characterized and Propagated Through the Model Abstraction

To generate radionuclide inventories, DOE uses models that are reasonable. No additional information is needed regarding the characterization and propagation of model uncertainty through the abstraction of the waste inventory.

3.3.4.4.1.5 Model Abstraction Output Is Supported by Objective Comparisons

The modeling of the radionuclide inventory by DOE in its total system performance assessment analyses for every type of DOE spent nuclear fuel is reasonable. No additional information is needed regarding model abstraction output that is supported by objective comparisons for the abstraction of DOE spent nuclear fuel inventory.

3.3.4.4.2 In-Package Chemistry

The estimation of the in-package chemical environment is integral to the calculations of commercial spent nuclear fuel, DOE spent nuclear fuel, high-level waste glass degradation, radionuclide solubility, and colloid availability and stability. The in-package chemistry component in the Total System Performance Assessment–Site Recommendation couples the seepage rate of water into the waste package, the degradation rate of the waste form and waste package components, and the cladding coverage of commercial spent nuclear fuel to the resulting effluent chemistry. The water chemistry parameters used in the DOE abstraction include pH, Eh, ionic strength, and total aqueous carbonate, fluoride, and chloride concentrations. DOE made two assumptions in its abstraction of the in-package chemistry. These assumptions are that the aqueous solution fills all the voids in the waste package and that solutions that drip into the package will have the composition of J–13 Well water (CRWMS M&O, 2000d). Other drip water compositions, such as evaporated J–13 Well and Drift Scale Test waters, were considered in the revised analysis and model report (CRWMS M&O, 2001a). For development of the in-package chemistry abstraction, the drip rate is assumed to range from 1.5 to 150 L/yr [0.4 to 40 gal/yr] (CRWMS M&O, 2000d) or from 0.15 to 15 L/yr [0.04 to 4 gal/yr] (CRWMS M&O, 2001a). Dripping water is assumed to enter and exit the waste package at the same rate and not interact to any significant degree with the waste package walls as it enters/exits the waste package. The interaction of water with the waste form and several waste package components, however, is considered (CRWMS M&O, 2000d; 2001a).

Two representative waste packages were modeled: a commercial spent nuclear fuel package and a DOE-owned spent nuclear fuel/high-level waste glass codisposal package (CRWMS M&O, 2000d). Commercial spent nuclear fuel waste packages are assumed to be made of several reactive components: aluminum alloy, 304L low-carbon stainless steel, A516 carbon steel, borated and nonborated Type 316 stainless steel containing $GdPO_4$, and zirconium-clad fuel rods. Commercial spent nuclear fuel is primarily UO_2. No interaction between the Zircaloy cladding and the internal environment is assumed, although sensitivity analyses include the percentage of fuel area exposed by breached cladding. Codisposal wastes compose a DOE spent nuclear fuel canister surrounded by five containers of high-level waste glass. The codisposal waste package was assumed to have the properties of a fast flux test facility waste package with six reactive components: A516 carbon steel, Type 316 stainless steel (with and without $GdPO_4$), 304L low-carbon steel, high-level waste glass, mixed oxide fuel (made of plutonium, uranium, and neptunium oxide), and UO_2 fuel.

In the in-package chemistry model, water is assumed to fill the void volume, and the waste package internal components are lumped into equivalent masses per unit volume for calculating the reaction products. EQ3/6 is used to calculate the time evolution of solution composition as a result of these interactions (CRWMS M&O, 2000d). The specific partial pressures of CO_2 and O_2 of the repository atmosphere are set to $10^{-3.0}$ and $10^{-0.7}$ atmosphere. A range of degradation rates was used for each component of the waste package.

Results of the EQ3/6 calculations indicate the reaction of waste package components with incoming fluids results in dramatic changes in solution chemistry. The pH decreases inside the waste package because of dissolution of stainless steel components, specifically because of the chromium oxidation to Cr^{6+} species. The pH increases because of the dissolution of the uranium oxide fuels, aluminum alloy, and high-level waste glass. Solution pH represents a dynamic balance between proton-producing and proton-consuming reactions. Relatively high rates of the proton-producing reactions lead to transiently low pH, whereas relatively high rates of the proton-producing reactions cause solution pH to be transiently high. Solution ionic strength for codisposal waste package effluents varied between 0.003 and ~5.8 M, however, ionic strengths of commercial spent nuclear fuel waste package effluents never exceeded 1.7 M.

Direct use of a complex code such as EQ3/6 within the Total System Performance Assessment–Site Recommendation analysis calculations was not practical because of computational constraints. Thus, DOE used abstractions of in-package processes based on a series of multiple linear regression analyses of the output from the EQ3/6 simulations (CRWMS M&O, 2000e, 2001b). Three-dimensional response surfaces establishing the pH boundary limits were determined using the extreme (high and low) values of the waste package corrosion rate. EQ3/6 simulation results were plotted in three-dimensional space, and the pH response surfaces were modeled as a planar surface. Data regression was performed using the equation of a plane: $z = y_o + ax + by$. Processes at times less than 1,000 years after breach of the waste package were abstracted separately from those at greater than 1,000 years postbreach. For each time phase and each package type (commercial spent nuclear fuel and codisposal), one pH surface was generated for a low waste package corrosion rate scenario and another pH surface was generated for a high waste package corrosion rate scenario. These surfaces constitute the boundaries of the range of in-package pH values. The waste package corrosion rates used in the Total System Performance Assessment–Site Recommendation analysis are randomly sampled from the range bounded by these low and high values (CRWMS M&O, 2000e, 2001b).

In-package chemistry parameters included in the Total System Performance Assessment–Site Recommendation abstraction are pH, Eh, ionic strength, total aqueous carbonate concentration, chloride concentration, and fluoride concentration. The pH is the most important in-package parameter. Thus, the time discretization used by DOE for all abstracted parameters was based on changes in pH. Both total carbonate and Eh are pH dependent and may be calculated directly from the abstracted pH value. The fluoride concentration and ionic strength were given a range of values to be sampled in the Total System Performance Assessment–Site Recommendation analysis. The chloride concentration and the O_2 and CO_2 fugacities were set to constant values.

The staff review regarding the DOE abstraction of in-package chemistry follows.

3.3.4.4.2.1 System Description and Model Integration Are Adequate

Overall, the current information, along with the agreements reached between DOE and NRC (Section 3.3.4.5), is sufficient to conclude that the necessary information will be available at the time of a potential license application to assess the effects of in-package chemistry on radionuclide release rates and solubility limits with respect to system description and model integration.

The process model report (CRWMS M&O, 2000b) and analysis and model reports (CRWMS M&O, 2000d,e, 2001b) provide sufficient descriptions of the process-level and mathematical models used in estimating the in-package chemical environment and how the in-package chemistry abstraction is integrated with other abstractions in the total system performance assessment analyses. Assumptions are appropriate, clearly stated, and used consistently. In general, important physical phenomena and couplings are adequately incorporated or bounded.

DOE developed an in-package chemistry abstraction for the Total System Performance Assessment–Site Recommendation (CRWMS M&O, 2000t) that used different response surfaces depending on the time from waste package breach. An early abstraction was used for conditions when the average time since the first waste package failure was less than 1,000 years. A late abstraction was used for conditions when the average time since the first waste package failure was greater than 1,000 years. The staff review found that using the aforementioned methodology for implementation in the total system performance assessment was inconsistent with supporting documentation and was likely to underestimate projected doses.

Assuming corrosion is the only mechanism for degradation of the waste packages, breach of waste packages during the thermal period will not be significant, and high-temperature phenomena need not be considered in determining the initial conditions for the in-package chemistry model. The potentials for juvenile failure and for mechanical disruption of waste packages exist, however, and DOE will need to demonstrate that the probability of these other mechanisms is not high enough to warrant evaluating the consequences of these other processes. DOE agreed[1] to update the in-package chemistry model to account for scenarios, their associated uncertainties, and implementation in the total system performance assessment model.

3.3.4.4.2.2 Data Are Sufficient for Model Justification

Overall, the current information, along with the agreements reached between DOE and NRC (Section 3.3.4.5), is sufficient to conclude that the necessary information will be available at the time of a potential license application to assess the effects of in-package chemistry on radionuclide release rates and solubility limits with respect to data sufficiency and model justification.

Sufficient data are available about the characteristics of the near-field environment and the engineered materials to establish initial and boundary conditions for conceptual models and simulations of coupled processes affecting the in-package chemical environment. Insufficient technical justification was provided by DOE for the assumed corrosion rates of waste package components, however, and the likely modes of corrosion that account for the rates were not identified. For example, the dissolution rate assumed for Type 316 stainless steel and the

[1]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Total System Performance Assessment and Integration (August 6–10, 2001)." Letter (August 23) to S. Brocoum, DOE. Washington, DC: NRC. 2001.

borated stainless steel is one order of magnitude lower than measured experimentally (Kirchheim, et al., 1989). Additionally, the lower dissolution rate assumed for the borated stainless steel compared to Type 316 stainless steel is counterintuitive. The presence of boron, in the form of second phase particles of borides, would be expected to result in a higher corrosion rate, especially in local zones around the boride particles. DOE agreed[2] to address concerns regarding the effect of corrosion rates on in-package chemistry.

3.3.4.4.2.3 Data Uncertainty Is Characterized and Propagated Through the Model Abstraction

DOE acknowledges there are large uncertainties in the thermodynamic and kinetic data and in the simplified approach used for the abstraction of in-package chemistry. DOE accounted for some uncertainties by varying the model parameters. For example, uncertainty in the dissolution rates of waste package materials is dealt with using high and low values. Drip rates onto the waste package ranged from 1.5 to 150 L/yr [0.4 to 40 gal/yr] (CRWMS M&O, 2000d) or 0.15 to 15 L/yr [0.04 to 4 gal/yr] (CRWMS M&O, 2001a). The composition of water entering the waste package was varied by using compositions similar to that of J–13 Well water, evaporated (50×) J–13 Well water, and Drift Scale Test water (CRWMS M&O, 2001a). Staff consider acceptable this approach to characterizing and propagating data uncertainty through the model abstraction.

3.3.4.4.2.4 Model Uncertainty Is Characterized and Propagated Through the Model Abstraction

Overall, the current information, along with the agreements reached between DOE and NRC (Section 3.3.4.5), is sufficient to conclude that the necessary information will be available at the time of a potential license application to assess the effects of in-package chemistry on radionuclide release rates and solubility limits with respect to model uncertainty.

In NRC (2000a, 2001), staff commented that the DOE assumption the waste package components can be lumped into a single mass for estimating the in-package chemistry may lead to highly nonconservative estimates of pH values and asked DOE for further justification of its assumption. At issue is the effect of potential spatial variation in chemistry in the waste package leading to local pH values considerably more acidic than calculated, based on a volume-averaged mass. The pH in crevices and other tight spaces differs from bulk pH values because the dissolution reactions become spatially separated from the reduction reactions. For example, Cavanaugh, et al. (1983) reported that the pH values in corroding cavities of stainless steels range between 0 and 2, with the pH increasing with increasing molybdenum and decreasing chromium concentrations. The pH in crevices of aluminum alloys can be either acidic (pH 4) or alkaline (pH 9), depending on the initial pH and surface conditions. Therefore, the pH generated by localized dissolution of aluminum most likely would be influenced by the pH resulting from the corrosion of other components. Because the internal geometry of the

[2]Schlueter, J. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Container Life and Source Term (September 12–13, 2000)." Letter (October 4) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

waste package will have many tightly packed regions, local pH may affect the dissolution rate of spent nuclear fuel locally and, hence, the local release rate of highly soluble radionuclides such as Tc-99. Staff recommended alternative models that consider electrochemical reactions coupled to transport processes should be considered by DOE.

In its revised analysis and model report (CRWMS M&O, 2001a), DOE provided additional arguments to justify its assumption that all waste package components are in communication with fluids that completely fill the waste package. DOE argues that, although bypassing specific waste package components might lead to anomalous package fluid compositions, it also would lead to limited reaction with those components and possibly not all the reaction steps necessary to cause radionuclide release. Thus, DOE states that homogeneous flow, as used in its abstraction of in-package chemistry, is conservative because it involves complete reaction and maximal release of radionuclides. Staff consider the previous argument acceptable with respect to the potential effect of bypassing of flow inside the waste package. The potential formation of locally aggressive environments in crevices and tight spaces that could enhance waste form degradation and radionuclide solubility, however, has not been addressed sufficiently by DOE. DOE agreed[3] to provide analyses justifying the use of bulk chemistry as opposed to local chemistry for solubility and waste form degradation models in an update of the in-package chemistry analysis and model report (CRWMS M&O, 2001a).

3.3.4.4.2.5 Model Abstraction Output Is Supported by Objective Comparisons

Overall, the current information, along with the agreements reached between DOE and NRC (Section 3.3.4.5), is sufficient to conclude that the necessary information will be available at the time of a potential license application to assess the effects of in-package chemistry on radionuclide release rates and solubility limits with respect to model abstraction output being supported by objective comparisons.

The EQ3/6 predictions of in-package chemistry have not been verified by empirical observations. DOE recognized the difficulties in modeling the detailed effects of geometry and corrosion reactions on the in-package chemistry. DOE did not consider, however, the potential local acidification resulting from spatially separated anodic and cathodic regions that may enhance the dissolution rate of the waste form and the solubility of radionuclides. Although there will be issues regarding the ability of experiments to adequately represent all the complexities in a waste package, experiments to simulate certain aspects of waste package geometry and materials may aid in gaining confidence in the model abstractions.

In the revised analysis and model report (CRWMS M&O, 2001a), DOE states that validation of the in-package chemistry model is incomplete. Planned DOE validation exercises will involve using EQ3/6 to model some combination of the following processes: (i) alteration observed during drip tests performed at Argonne National Laboratory; (ii) formation of ore deposits that might constitute natural analogues; and (iii) glass, mineral, and steel corrosion measurements

---

[3]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Evolution of the Near-Field Environment (January 9–12, 2001)." Letter (January 26) to S. Brocoum, DOE. Washington, DC: NRC. 2001.

performed in the laboratory. The planned DOE validation exercises are expected to address staff concerns.[4]

3.3.4.4.3 Degradation of Cladding on Commercial Spent Nuclear Fuel

DOE considered the most likely forms of degradation that may affect the integrity of the commercial spent nuclear fuel cladding during disposal conditions. DOE developed a model to evaluate cladding degradation as part of the waste form degradation model (CRWMS M&O, 2000b) to determine the rate at which the commercial spent nuclear fuel matrix is exposed to the in-package environment. This cladding degradation model represents a significant improvement with respect to that presented in the DOE (1998). The degradation of the commercial spent nuclear fuel cladding is assumed to occur in two stages (CRWMS M&O, 2000b,f). The first stage of degradation corresponds to rod failure as a result of cladding perforation. The second stage involves progressive exposure of the spent nuclear fuel matrix as a result of splitting (unzipping) of the cladding through oxidation of the irradiated UO_2 pellets either by air and moisture or by an aqueous environment.

Cladding perforation may occur before or after waste package emplacement. DOE evaluated the initial condition of the cladding and the percentage of rods perforated at the time of disposal, taking into account data obtained from reactor operation, pool storage, dry storage, and transportation, including fuel handling (CRWMS M&O, 2000g). A distribution of initially perforated Zircaloy fuel rods, expressed as a complementary cumulative distribution function, was developed from the available data. All the commercial spent nuclear fuel clad with stainless steel instead of Zircaloy (estimated to be approximately 1.1 percent of the total) was assumed initially perforated (CRWMS M&O, 2000g).

DOE used an empirical creep model developed by Matsuo (1987) to define the creep damage of the Zircaloy cladding prior to disposal. DOE computed the creep strain as a function of initial rod stress for cladding in dry storage alone and for dry storage plus transportation, using an assumed temperature history profile representative of dry storage and transportation conditions (CRWMS M&O, 2000g). DOE concluded that little creep occurs for rod stresses less than 80 MPa [11.6 ksi]. It is assumed that most creep occurs during dry storage, whereas only a small amount of creep occurs during transportation. The amount of creep strain accumulated is expected to be less than 1 percent at initial stresses less than 90 MPa [13.0 ksi] at 27 °C [81 °F]. A creep failure strain of 3.3 percent was established based on experimental results of tensile and creep tests. This creep failure strain led to a prediction of approximately 0.24 percent of failed rods by creep in dry storage and transportation, compared with an actual failure rate of 0.45 percent (CRWMS M&O, 2000g).

Cladding perforation after waste package emplacement is assumed caused by creep, stress corrosion cracking, mechanical failure (due through seismic events), and localized corrosion (CRWMS M&O, 2000f). To evaluate the possibility of creep and stress corrosion cracking for

[4]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Evolution of the Near-Field Environment (January 9–12, 2001)." Letter (January 26) to S. Brocoum, DOE. Washington, DC: NRC. 2001.

disposal conditions, DOE estimated the temperature history of the cladding during storage and transportation and the evolution of temperature after waste package emplacement, as well as estimating the distribution of internal pressure and corresponding hoop stresses (CRWMS M&O, 2000f,g). The Murty's creep-versus-strain correlation was selected to evaluate creep rupture on the basis of experimental data for unirradiated cladding. It is claimed that the Murty's creep model is more accurate than other models because it includes Coble creep, a type of creep process important at low stresses and temperatures. The approach is considered conservative because irradiated cladding has a creep rate significantly lower than that of the unirradiated material. Nevertheless, the criterion for creep failure strain was developed based on data for irradiated cladding and is conservative with respect to other creep failure criteria. Based on distribution of hoop stresses, an abstraction was developed to provide the fraction of rods that failed by creep as a function of the peak waste package surface temperature.

Stress corrosion cracking was also a possibility, based on the calculated distribution of hoop stresses. The causative species for stress corrosion cracking of commercial spent nuclear fuel cladding is considered to be iodine, found free as a fission product in the pellet-cladding gap (CRWMS M&O, 2000f). Although the iodine concentration is asserted to be negligible, conservatively it is assumed to be above a certain critical concentration required to promote iodine-stress corrosion cracking. For stress corrosion cracking to occur, a critical stress level of 180 MPa [26.1 ksi] is selected as a threshold stress. This value is relatively high and can be attained by no more than a few rods.

Localized corrosion is also considered as a process leading to the perforation of the commercial spent nuclear fuel cladding (CRWMS M&O, 2000f). Fluoride is assumed the anionic species promoting accelerated corrosion on a relatively small area of cladding approximately 10 mm [0.39 in] in rod length. The fraction of fuel cladding surface on different fuel rods inside the same waste package is considered proportional to the volume of water entering the waste package in a flow-through scenario. This approach is considered a bounding analysis because it implicitly assumed 100-percent efficiency in the chemical reaction of fluoride with Zircaloy.

The DOE analysis of delayed hydride cracking is based on a fracture mechanics approach in which the cladding stress and crack depth were used to compute the model stress intensity factor of preexisting cracks in the cladding (CRWMS M&O, 2000g). The stress intensity factor, K_I, was taken to be the driving force for delayed hydride cracking and compared against the threshold stress intensity factor, K_{IH}. Failure by delayed hydride cracking is considered not to occur when K_I is lower than K_{IH}, but failure can occur when K_I is higher than K_{IH}. The DOE extensive review of the literature DOE (CRWMS M&O, 2000g) indicated that the minimum reported value of K_{IH} for zirconium cladding is 5 MPa•m$^{1/2}$ [4.55 ksi • in$^{1/2}$]. DOE analyzed delayed hydride cracking of existing cracks using distributed stresses and crack sizes (CRWMS M&O, 2000g). It was concluded that delayed hydride cracking can be ruled out as a possible mechanism for cladding failure of spent nuclear fuel in the proposed repository because the computed mean K_I value, 0.0016–2.7 MPa•m$^{1/2}$ [0.0015–2.5•in$^{1/2}$], was too low. DOE screened out failures of cladding by hydrogen or hydride embrittlement, delayed hydride cracking, and hydride reorientation as possible events in the repository (CRWMS M&O, 2000h). DOE considered stresses and temperatures of the cladding as too low for hydride reorientation to occur, and the cladding material would maintain sufficient strength that cladding failure would be unlikely, even if hydride reorientation did occur.

The remaining process that could lead to cladding perforation is mechanical failure caused by seismic events when the frequency of the events is on the order of 1×10^{-6} per/year. This type of event, which is considered in the DOE analysis as a disruptive event, perforates the cladding and initiates unzipping. Mechanical failure of the cladding as a result of rockfall is excluded from the model abstraction (CRWMS M&O, 2000h) using the screening argument that the waste package will remain intact for more than 10,000 years.

After cladding perforation, the inventory of radionuclides in the gap and in the grain boundaries of the irradiated fuel pellets is considered to experience fast release. The gap inventory of iodine and cesium is predicted to be released in proportion to the fission gas release fractions, while that in the grain boundaries is estimated from release experiments using intact and defective (i.e., with slits and holes) fuel rod samples. A cumulative distribution function for the fast release fraction of the radionuclides is used in the model abstraction.

Unzipping of the cladding during dry conditions is excluded from the model abstraction assuming the integrity of containers is maintained during the performance period (CRWMS M&O, 2000h). Only wet unzipping is assumed to occur. The time to unzip a fuel rod during wet conditions is estimated as a function of waste package temperature. Time also is a function of the in-package water chemistry, which, for this purpose, is defined by the pH, partial pressure of O_2, and carbonate concentration. Although DOE considered these criteria are conservative, and include the consideration of uncertainties, it argued the criteria are not as conservative as in previous total system performance assessments.

The staff review regarding the DOE abstraction of cladding degradation on commercial spent nuclear fuel follows.

3.3.4.4.3.1 System Description and Model Integration Are Adequate

Overall, the current information, along with the agreements reached between DOE and NRC (Section 3.3.4.5), is sufficient to conclude that the necessary information will be available at the time of a potential license application to assess the effect of cladding degradation of commercial spent nuclear fuel on radionuclide release rates and solubility limits with respect to system description and model integration.

The system description and model integration for creep and mechanical failure are adequate. For mechanical failure, however, the abstraction is related to the evaluation of seismic events (see Section 3.2.2), and the exclusion of rockfall effects is related to the integrity of the waste package through the 10,000-year performance period (see Section 3.1.1). The system description and model integration used in the abstraction of stress corrosion cracking and localized corrosion are not sufficient because the abstraction does not consider the range of chemical conditions that may prevail in the in-package aqueous environment. DOE agreed[5] to establish a better technical basis for the abstracted in-package chemistry.

[5]Schlueter, J. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Container Life and Source Term (September 12–13, 2000)." Letter (October 4) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

Although it is a possible failure process (NRC, 2001), localized corrosion in the form of pitting promoted by chloride, DOE excluded (CRWMS M&O, 2000h) by assuming the (i) chloride concentration is lower than the minimum concentration required for pit initiation; (ii) concentrations of inhibiting anions such as nitrate, sulfate, and bicarbonate are sufficient to overcome the detrimental effect of chloride; and (iii) concentration of dissolved Fe^{3+} ions, considered to be the single species that may increase the corrosion potential of the cladding to more than the pitting potential, is assumed insufficient for the range of expected pH of the in-package water. Instead, DOE proposed accelerated corrosion by fluoride ions as the most plausible degradation process through a chemical reaction controlled by the volume of water entering the waste package in a flow-through scenario, the flow rate, and the concentration of fluoride in the water (CRWMS M&O, 2000f). The chloride concentration inside breached waste packages, however, has not been properly bounded in DOE analyses, and the presence of Fe^{3+} ions cannot be considered an absolute requirement because corrosion potentials higher than the pitting potential can be attained in the presence of other oxidizing species including radiolytic products such as H_2O_2. A detailed discussion, based mostly on data about commercial purity zirconium relevant to chemical processes and industry applications, has been provided in the analysis and model report devoted to localized corrosion (CRWMS M&O, 2000i) questioning the occurrence of pitting corrosion induced by chloride during repository conditions. It is claimed in the discussion that acidic pHs are not attained to maintain sufficient concentration of Fe^{3+} ions in solution. This analysis, however, contradicts screening arguments in several features, events, and processes (CRWMS M&O, 2000h) in which the existence of acidic conditions inside the waste packages is assumed to justify the screening arguments that acidic pHs may affect the occurrence of localized corrosion. DOE agreed[6] to address concerns of the effects of in-package chemistry on cladding degradation.

Stress corrosion cracking of Zircaloy cladding may occur in the presence of hoop stresses of sufficient magnitude for the same environmental and electrochemical conditions that promote pitting corrosion by chloride (NRC, 2001). As noted, instead of chloride, DOE considers iodine as the causative species for stress corrosion cracking (CRWMS M&O, 2000f). The possibility of stress corrosion cracking induced by iodine discussed in the process model report (CRWMS M&O, 2000b), however, does not appear so important because it is limited by the availability of iodine. The mechanism as such has been postulated as the cause of pellet cladding interaction failure for reactor operating conditions following steep power ramps, but it does not seem plausible for disposal conditions. The technical bases to support modeling of cladding degradation as a result of both the corrosion by fluoride and the internal stress corrosion cracking by iodine are limited (NRC, 2001). DOE agreed[7] to address concerns of the effects of in-package chemistry on cladding degradation.

In the process model report (CRWMS M&O, 2000b), the role of fluoride is emphasized as a species promoting accelerated corrosion in local areas, but insufficient technical basis is offered in CRWMS M&O (2000i). In addition, the analysis of the flow and volume of water contacting

---

[6]Schlueter, J. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Container Life and Source Term (September 12–13, 2000)." Letter (October 4) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

[7]Ibid.

the fuel rods to evaluate the local attack by fluoride is limited and requires additional justification. Again, inconsistencies exist regarding evaluation of the in-package pH. A low pH is assumed for the attack by fluoride, whereas it is not taken into account to estimate the concentration in solution of Fe^{3+} ions that may promote the oxidizing conditions required for pitting corrosion in chloride solutions. DOE agreed[8] to address concerns of the effects of in-package chemistry on cladding degradation.

3.3.4.4.3.2 Data Are Sufficient for Model Justification

Overall, the current information, along with the agreements reached between DOE and NRC (Section 3.3.4.5), is sufficient to conclude that the necessary information will be available at the time of a potential license application to assess the effect of cladding degradation of commercial spent nuclear fuel on radionuclide release rates and solubility limits with respect to sufficient data for model justification.

Currently, insufficient data have been presented to justify that accelerated corrosion by fluoride or internal stress corrosion cracking by iodine are the appropriate degradation processes that need to be included in the model abstraction for radionuclide release. DOE agreed[9] to address concerns of the effects of in-package chemistry on cladding degradation caused by localized corrosion and stress corrosion cracking.

Corrosion data, generated outside the Yucca Mountain program by Teledyne Wah Chang (a producer of zirconium alloys) and reported by Yau and Webster (1987), are presented in the analysis and model report (CRWMS M&O, 2000i) to support the localized corrosion failure model for Zircaloy-2 or -4 cladding. Most data provided are for commercial purity zirconium instead of Zircaloy. In the report, it is noted that the behavior of commercial purity zirconium (containing hafnium and lacking the Zircaloy alloying elements) is comparable to that of Zircaloy. Although an acceptable statement in general terms, there are no specific data provided for environments postulated to simulate the in-package water chemistry. Although data on localized corrosion by chloride anions are presented, it is claimed this process cannot occur because the pH is too high to maintain sufficient concentration of Fe^{3+} ions in solution, which implicitly assumes this cation is the single species able to increase the corrosion potential more than beyond the pitting potential. Instead, corrosion is assumed to be caused by fluoride anions only. Corrosion rate data from 24- to 72-hour tests in aqueous solutions containing fluoride and chloride were used to generate a parametric equation relating the corrosion rate to the concentration of these anionic species (CRWMS M&O, 2000i). The equation is not used in the model abstraction, however. In the analysis and model report (CRWMS M&O, 2000f), corrosion by fluoride to stoichiometrically form ZrF_4 is conservatively assumed to be determined by its concentration in the J–13 Well water, the volume of water entering the waste package, and the flow rate; however, the attack is confined to a small 1-cm [0.39-in] long cladding ring portion of the fuel rod.

---

[8]Schlueter, J. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Container Life and Source Term (September 12–13, 2000)." Letter (October 4) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

[9]Ibid.

As noted in the analysis and model report (CRWMS M&O, 2000f), the model abstraction for stress corrosion cracking is based on the assumption that iodine as a fission product is the causative species. As a conservative approach, it is assumed that iodine concentration in the fuel matrix-cladding gap is higher than the threshold value of 5×10^{-6} g/cm^2 [7.1×10^{-8} lb/in^2] required for stress corrosion cracking. If the hoop stress is higher than 180 MPa [26.1 ksi], this form of internal stress corrosion cracking is assumed to occur. Although these values seem appropriate for evaluating iodine stress corrosion cracking and represent a lower bound, the data obtained for test conditions are not necessarily applicable to disposal conditions where stress corrosion cracking on the cladding outer surface may begin by other species present in the modified groundwater. In addition, an adequate technical basis should be provided for selection of the critical stress relevant to the environment in which external stress corrosion cracking may occur. DOE agreed[10] to address concerns of the effects of in-package chemistry and stress on cladding degradation caused by stress corrosion cracking.

In the assessment of hydride reorientation and delayed hydride cracking (CRWMS M&O, 2000j), the stress distribution reported for cladding corresponds to 27 °C [81 °F], which appeared to be the basis leading to the conclusion that stresses and temperatures in the cladding were too low to cause hydride reorientation. There is a concern that the proper cladding stress might not have been used in the analysis. For hydride reorientation, the relevant stress to consider is the cladding hoop stress at temperatures just below the solvus temperature, which is in the range 260–300 °C [500–572 °F], depending on the hydrogen content (Northwood and Kosasih, 1983). The peak cladding temperature for the design basis waste package was estimated to be 325 °C [617 °F] (CRWMS M&O, 2000j). The hydrogen solubility in Zircaloy-2 and -4 is approximately 90 ppm. Consequently, some of the circumferential hydrides in Zircaloy cladding would dissolve into the matrix and subsequently reorient and reprecipitate as radial hydrides for a tensile (hoop) stress when the cladding cools slowly in repository conditions below the solvus temperature. The DOE analysis of delayed hydride cracking is based on the properties of Zircaloys that contain circumferential hydrides, which would not be applicable if hydride reorientation occurs. The prediction of the lack of susceptibility to delayed hydride cracking based on a K_{IH} of 5 MPa•m$^{1/2}$ [4.55 ksi•in$^{1/2}$] might not be conservative if hydride reorientation occurs in the cladding. Thus, it is important to consider the distribution of cladding stresses and temperatures and their evolution following waste package emplacement in the repository. DOE agreed[11] to address concerns regarding hydrogen embrittlement as a mode of cladding degradation.

3.3.4.4.3.3 Data Uncertainty Is Characterized and Propagated Through the Model Abstraction

Overall, the current information, along with the agreements reached between DOE and NRC (Section 3.3.4.5), is sufficient to conclude that the necessary information will be available at the time of a potential license application to assess the effect of cladding degradation of

---

[10]Schlueter, J. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Container Life and Source Term (September 12–13, 2000)." Letter (October 4) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

[11]Ibid.

commercial spent nuclear fuel on radionuclide release rates and solubility limits with respect to the characterization and propagation of data uncertainty through the model abstraction.

Data uncertainty regarding stresses and temperatures of the cladding may affect the consideration of hydride reorientation and subsequent hydride embrittlement as potential cladding failure mechanisms that need to be included in the model abstraction for radionuclide release.

DOE considers that stresses and temperatures of the cladding are too low for hydride reorientation to occur and that the cladding material would maintain sufficient strength even if hydride reorientation occurred, hence, cladding failure would be unlikely (CRWMS M&O, 2000b,h). The DOE arguments are not consistent, however, with the cladding temperatures and stresses documented in the analysis and model report (CRWMS M&O, 2000f, pp.19 and 20). According to DOE analyses, the center rod in an average waste package will reach 308 °C [586 °F], and the outer rods will peak at 291 °C [556 °F]. The temperature uncertainty is assumed uniformly distributed throughout a range of ±13.5 percent. Thus, the hottest center rod in an average waste package could peak at 350 °C [662 °F], while the hottest outer rod could peak at 314 °C [597 °F]. Solubility values of hydrogen in Zircaloy are 80 and 120 ppm at 314 °C [597 °F] and 350 °C [662 °F] (CRWMS M&O, 2000h, p. 57), whereas the average hydrogen content in commercial spent nuclear fuel rods is approximately 400 ppm in the form of hydrides. As the fuel rod temperature increases to the peak temperature, some precipitated hydrides would dissolve, and hydrogen will return to solid solution. The dissolved hydrogen will reprecipitate as radial hydrides if the cladding stress exceeds a critical value during the precipitation process. The tensile stress for hydride reorientation is estimated to be between 69 and 208 MPa [10 and 30.2 ksi]. CRWMS M&O (2000j) and the DOE calculations of the cladding stresses for the temperature range 250–385 °C [482–725 °F] result in values ranging between 55 and 120 MPa [7.8 and 17.4 ksi]. This range of stresses is well within the minimum tensile stress for hydride reorientation to occur when the cladding cools slowly below the solvus temperature in the repository. Uncertainties regarding the calculated values of cladding temperatures and stresses, including uncertainties related to the temporal and spatial variations expected for thousands of waste packages, must be taken into account when considering hydride reorientation and hydride-induced failure. The DOE analysis of delayed hydride cracking was based on properties of Zircaloys that contain circumferential hydrides, which would not be applicable if hydride reorientation occurs. The prediction of the lack of potential for delayed hydride cracking based on a K_{IH} of 5 MPa•m$^{1/2}$ [4.55 ksi•in$^{1/2}$] might not be conservative if hydride reorientation occurs in the cladding. Thus, it is important to consider the distributions of cladding stresses and temperatures and their evolution on disposal in the repository considering spatial variations. The accuracy and validity of the stress and temperature data will determine if hydride embrittlement should be considered as an important failure process for spent nuclear fuel cladding to be incorporated into the model abstraction for radionuclide release. DOE agreed[12] to address concerns regarding cladding temperature and stress related to hydrogen embrittlement.

[12]Schlueter, J. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Container Life and Source Term (September 12–13, 2000)." Letter (October 4) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

3.3.4.4.3.4 Model Uncertainty Is Characterized and Propagated Through the Model Abstraction

Overall, the current information, along with the agreements reached between DOE and NRC (Section 3.3.4.5), is sufficient to conclude that the necessary information will be available at the time of a potential license application to assess the effect of cladding degradation of commercial spent nuclear fuel on radionuclide release rates and solubility limits with respect to the characterization and propagation of model uncertainty through the model abstraction.

Current model uncertainty characterization and use are insufficient for certain aspects of commercial spent nuclear fuel cladding degradation. In particular, alternative models or consideration of model uncertainties are not sufficiently used for localized corrosion and stress corrosion cracking.

The DOE abstraction considered most forms of degradation that may affect the integrity of commercial spent nuclear fuel cladding during disposal conditions, including creep, localized corrosion, stress corrosion cracking, hydride reorientation and embrittlement, and mechanical failure (CRWMS M&O 2000b), which agree with the evaluation NRC conducted (2001). After comparing the results with various alternative creep models to define the creep damage in zirconium cladding on disposal, DOE used an empirical creep model developed by Matsuo (1987) and computed the creep strain as a function of initial rod stress for cladding in dry storage alone and in dry storage with transportation. An assumed temperature history profile representative of dry storage and transportation conditions was used (CRWMS M&O, 2000g). After an evaluation of six creep models against five sets of experimental data, DOE elected Murty's creep model rather than one of other five models, including the one by Matsuo (CRWMS M&O, 2000f). DOE claimed that Murty's creep equations are accurate at low stresses and low temperatures because the equations incorporate Coble creep, which is dominant at low stresses and low temperatures. In addition to Coble creep, Murty's creep equations include primary and steady-state creep by dislocation glide—the same creep mechanisms treated in Matsuo's model. [Model uncertainty in creep correlations of all five sets of experimental data as given by the weighted average of the relative error is 0.487 for Matsuo's model and 0.557 for Murty's model (CRWMS M&O, 2000f).] A critical strain criterion was used for creep failure. Upper and lower limits of rod failure by creep were computed based on creep failure strain limits of 0.4 and 11.7 percent. These creep failure strains were supported by experimental data of unirradiated Zircaloy and corresponded to an average creep failure strain of 3.3 percent used in an earlier analysis concerning cladding failure by creep during dry storage and transportation (CRWMS M&O, 2000g). The Murty's model and the creep strain criteria are acceptable because they both lead to conservative failure estimates.

In excluding hydride reorientation, DOE also argued that the fracture strength of zirconium cladding with reoriented hydrides remains high. There is a concern that a global stress failure based on fracture strength might not be appropriate for treating hydride embrittlement. The tensile ductility of zirconium is known to decrease with the length of radial hydrides. Puls (1988, Table IV) reported the tensile ductility of Zr-2.5 wt % Nb decreased from 12.8 to 1 percent when the hydride length increased from 20 to 150–450 μm [0.79 to 5.9–18 mils], even though the ultimate fracture strength only decreased from 866 to 715 MPa [125 to 104 ksi]. The slow cooling rate in the repository is conducive to the formation of long radial hydrides and a continuous hydride network (Chan, 1996). DOE should include hydride reorientation in its analyses of cladding failure and consider the possibility that hydride reorientation might lower the upper limit of the failure strain (11 percent) in the creep failure criterion and the K_{IH} {5 MPa•m$^{1/2}$ [4.55 ksi•in$^{1/2}$]} in delayed hydride cracking. In conclusion, the DOE analyses of delayed hydride cracking relied solely on a large crack fracture mechanics approach. In addition, no consideration was given to crack initiation at large hydrides. DOE discounted the importance of this failure event on the basis that this failure process can occur only for Zircaloy-4 cladding of pressurized water reactor fuel assemblies with a burnup exceeding 55 MWd/Kg [25 MWd/lb] uranium (CRWMS M&O, 2000f). The percentage of pressurized water reactor assemblies with burnup exceeding 55 MWd/Kg [25 MWd/lb] uranium, however, is approximately 15 percent (CRWMS M&O, 2000g). The possible failure rate of these high burnup fuel rods has not been considered. DOE agreed[13] to address concerns of hydrogen embrittlement.

Finally, no alternative models have been considered for localized corrosion and external stress corrosion cracking. This lack of alternative models can be acceptable if DOE demonstrates in the analysis and model report that the environmental conditions are not conducive to localized corrosion or stress corrosion cracking induced by chloride because (i) the chloride concentration is too low, (ii) the corrosion potential is lower than the pitting potential, or (iii) anionic species, such as nitrate, are present at a sufficiently high concentration ratio with respect to chloride that can act as efficient localized corrosion inhibitors. The hoop stress calculations used to evaluate creep are applicable to the assessment of chloride-induced stress corrosion cracking. DOE agreed[14] to address concerns of the effects of in-package chemistry on cladding degradation caused by localized corrosion and stress corrosion cracking.

3.3.4.4.3.5 Model Abstraction Output Is Supported by Objective Comparisons

Overall, the current information, along with the agreements reached between DOE and NRC (Section 3.3.4.5), is sufficient to conclude that the necessary information will be available at the time of a potential license application to assess the effect of cladding degradation of commercial spent nuclear fuel on radionuclide release rates and solubility limits with respect to model abstraction output being supported by objective comparisons.

To date, adequate verification of the model abstraction for cladding degradation is not available. As noted before, DOE has not provided empirical demonstration through experiments, using simulated in-package environments, to verify that localized corrosion by fluoride anions is a valid process to be modeled and abstracted for incorporation into the DOE Total system Performance Assessment Code or at least bound the rate at which other corrosion processes may perforate the cladding. A similar argument is valid for the model abstraction of stress corrosion cracking in which only iodide is considered the causative agent for stress corrosion cracking. This internal stress corrosion cracking process has not been verified for the

[13]Schlueter, J. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Container Life and Source Term (September 12–13, 2000)." Letter (October 4) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

[14]Ibid.

conditions expected in the repository. DOE agreed[15] to provide a technical basis for the various modes of cladding degradation.

3.3.4.4.4 Commercial Spent Nuclear Fuel Dissolution

The commercial spent nuclear fuel dissolution rates have been measured using a wide range of techniques, including flow-through experiments using spent nuclear fuel and UO_2 pellets, static tests in autoclaves, and unsaturated drip tests with spent nuclear fuel pellets contained in zirconium. Only data from the flow-through tests, however, are used to derive the dissolution rate model for total system performance assessment (CRWMS M&O, 2000b,j). Two regression equations are used in the DOE abstraction of the commercial spent nuclear fuel dissolution rate presented in the process model report (CRWMS M&O, 2000b):

for pH > 7,

$$\mathrm{Log(Rate)} = 4.69 - \frac{1085}{T} + 0.12\log_{10}[\mathrm{CO_3}]_{\mathrm{Total}} + 0.32\log_{10}[P_{\mathrm{O_2}}] \quad (3.3.4\text{-}1)$$

and for pH ≤ 7,

$$\mathrm{Log(Rate)} = 7.13 - \frac{1085}{T} + 0.32\log_{10}[P_{\mathrm{O_2}}] - 0.41\mathrm{pH} \quad (3.3.4\text{-}2)$$

where rate is expressed in $mg/m^2 \bullet day$, T is the absolute temperature in K, carbonate concentration is in moles/liter, and oxygen partial pressure is in atmospheres. The abstracted equations are derived so the rates from the two equations are equal at pH 7. The burnup in these tests ranged from 0 to 50 MWd/kg [0 to 23 MWd/lb] uranium.

It must be noted that Eq. (3.3.4-1) is an empirical regression model loosely based on irreversible thermodynamic reasoning (Stout and Leider, 1998a,b). The regression coefficient, adjusted R^2, for the high pH equation is 0.5014 (CRWMS M&O, 2000k), indicating the model does not represent a significant portion of the variance in the experimental data. A more elaborate model, with cross terms and a term involving burnup, was proposed by Stout and Leider (1998a,b) and has a much better statistical fit to the data (adjusted R^2 = 0.8174).

Equation (3.3.4-2) is derived by assuming that the dependence of dissolution rate on oxygen partial pressure and temperature is the same at pH values below 7 as it is above this pH. The term involving carbonate is neglected based on the reasoning that surface adsorption of carbonate ions is negligible below this pH. Additionally, one experimental data point at pH 3 and the calculated rate at pH 7 from Eq. (3.3.4-1) are used to derive the slope of the pH dependence for pH values between 3 and 7. The statistical significance of the abstraction for the acid environment is difficult to estimate because it is based on only two data points, one of

[15]Schlueter, J. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Container Life and Source Term (September 12–13, 2000)." Letter (October 4) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

which is a calculated value. The model is then compared to other rate measurements and found to predict higher rates than the experiments, thus justifying its use as a bounding model. The fuel burnup is also not considered directly in the abstracted model, although a variety of burnups was used in the flow-through tests.

Unsaturated drip tests were performed by DOE during the past 8 years. The tests involved spent nuclear fuel contained in Zircaloy holders exposed to dripping water or a moist environment. The drip rates used, 0.0078–0.078 L/yr [0.0021–0.021 gal/yr], are much lower than those assumed in the in-package calculations, 1.5–150 L/yr [0.40–40 gal/yr]. The drip rates used should scale to the surface area of reacting media exposed. Based on 1 cm^2 [0.155 in^2] of fuel surface, the low end of the drip rate would correspond to approximately 8 cm/yr [3.1 in/yr] of dripping, which is much larger than the seepage rates predicted in the Total System Performance Assessment–Site Recommendation model (CRWMS M&O, 2000t). This scaling relationship remains poorly understood—it may depend on the manner in which dripping water contacts the fuel (Wronkiewicz, et al., 1992). The release rates of various radionuclides were monitored. The release rates of Tc-99 and Sr-90 were used to derive the intrinsic dissolution rate of the spent nuclear fuel (CRWMS M&O, 2000b,k) The dissolution rates measured in the high-drip-rate tests are lower than that predicted by Eq. (3.3.4-1) if a surface roughness factor of three is assumed in the drip tests (CRWMS M&O, 2000k). The low-drip-rate tests exhibited lower dissolution rates. The drip tests showed that Np-237 and Pu-239 are retained in the corrosion products after an initial period of high release (CRWMS M&O, 2000b).

The staff review regarding the DOE abstraction of commercial spent nuclear fuel dissolution follows.

3.3.4.4.4.1 System Description and Model Integration Are Adequate

Overall, the current information, along with the agreements reached between DOE and NRC (Section 3.3.4.5), is sufficient to conclude that the necessary information will be available at the time of a potential license application to assess the effect of commercial spent nuclear fuel dissolution on radionuclide release rates and solubility limits with respect to system description and model integration.

DOE provided a detailed description of the commercial spent nuclear fuel characteristics, numbers, and design of the waste package internal components (CRWMS M&O, 2000b). An empirical model is used in the Total System Performance Assessment–Site Recommendation that is based on extensive measurements of spent nuclear fuel and unirradiated UO_2 dissolution in flow-through tests (CRWMS M&O, 2000k). DOE also cites measurements of the spent nuclear fuel dissolution rate using other test techniques, notably batch tests for fully immersed conditions and drip tests in partially saturated conditions. These tests and the measurement of mineral assemblages in the natural analog site at Peña Blanca are used appropriately as supporting evidence rather than to derive alternate spent nuclear fuel dissolution models for total system performance assessment. In the Total System Performance Assessment–Site Recommendation, the in-package chemistry calculation is linked to the spent nuclear fuel dissolution model.

The DOE integration of the dissolution rate model in the overall total system performance assessment is sufficient. DOE agreed[16] to provide additional information and analyses on the in-package chemistry critical to determining the commercial spent nuclear fuel dissolution rate. DOE stated that, in a future revision of the analysis and model report (CRWMS M&O, 2000d), specific NRC questions on radiolysis, chemistry of incoming water, localized corrosion, corrosion products, and transient effects will be addressed. A sensitivity study on differing dissolution rates of components will be included, as well as a more detailed calculation of the in-package chemistry effects of radiolysis, the effects of engineered materials on the chemistry of water used for input to in-package abstractions, and the applicability of abstractions for incoming water, taking into account information from a future revision of the analysis and model report (CRWMS M&O, 2000l). DOE stated current planning provides for additional analysis for in-package chemistry model support. This analysis will determine which parts of the model are amenable to additional support by testing and which parts are amenable to sensitivity analysis or use of analogues.

3.3.4.4.4.2 Data Are Sufficient for Model Justification

Overall, the current information, along with the agreements reached between DOE and NRC (Section 3.3.4.5), is sufficient to conclude that the necessary information will be available at the time of a potential license application to assess the effect of commercial spent nuclear fuel dissolution on radionuclide release rates and solubility limits with respect to data being sufficient for model justification.

Insufficient data have been presented to justify the abstracted model of spent nuclear fuel dissolution in the acid range of the model. Furthermore, the abstracted model eliminated the term related to burnup of fuel, without considering results from high burnup fuels. The DOE model for spent nuclear fuel dissolution evolved from a 12-parameter model (involving burnup, temperature, pH, oxygen, and carbonate and their interaction terms) to a 4-parameter model (involving temperature, pH, carbonate, and oxygen). The effect of burnup is suggested insignificant (Shoesmith, 1999) in comparison to other factors. Tests continue on high burnup fuel, however, which may alter the abstracted model. The linear regression model used with the limited number of parameters explains only a portion of the observed variance in the experimental data (adjusted $R^2 = 0.5014$), although it is argued that the model represents a bounding case. The reason for going from a more complex model to a simpler model is not clear. Furthermore, the statistical significance of the abstraction of the acid side of the model is difficult to estimate because it is based on only two data points, one of which is a calculated value. In deriving the abstracted model for commercial spent nuclear fuel dissolution, the flow-through corrosion test data for commercial spent nuclear fuel spans the pH range 8–10. Tests on the unirradiated UO_2 test data span the pH range 3.5–11.6 (CRWMS M&O, 2000k),

[16]Schlueter, J. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Container Life and Source Term (September 12–13, 2000)." Letter (October 4) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

but the acid test data are used only for confirmation purposes. DOE agreed[17] to address these concerns.

3.3.4.4.4.3 Data Uncertainty Is Characterized and Propagated Through the Model Abstraction

Overall, the current information, along with the agreements reached between DOE and NRC (Section 3.3.4.5), is sufficient to conclude that the necessary information will be available at the time of a potential license application to assess the effect of commercial spent nuclear fuel dissolution on radionuclide release rates and solubility limits with respect to the characterization and propagation of data uncertainty through the model abstraction.

DOE has not provided adequate information about how the uncertainties in spent nuclear fuel dissolution rate data and the various parameters used in the calculation of in-package chemistry are propagated through model abstractions and predictions of radionuclide release rates from spent nuclear fuel. The commercial spent nuclear fuel dissolution model is coupled to the calculated in-package chemistry. The in-package chemistry calculation abstraction (CRWMS M&O, 2000e) suggests that the in-package chemistry is likely to be near-neutral or alkaline during the long time period. The in-package chemistry model has data uncertainties related to the spent nuclear fuel dissolution rates, the dissolution rates of other in-package components, and the local chemical changes in crevices between cladding and fuel, between fuels, or between basket material and fuel. Additionally, uncertainties exist regarding incoming water chemistry. Similarly, there are uncertainties in the dissolution rates of spent nuclear fuel, especially in the acid side, where data are sparse. Finally, DOE is currently testing the high burnup fuel, and the data have not been included in the model abstraction. DOE agreed[18] to provide an update on the in-package chemistry effects on dissolution rates.

3.3.4.4.4.4 Model Uncertainty Is Characterized and Propagated Through the Model Abstraction

Overall, the current information, along with the agreements reached between DOE and NRC (Section 3.3.4.5), is sufficient to conclude that the necessary information will be available at the time of a potential license application to assess the effect of commercial spent nuclear fuel dissolution on radionuclide release rates and solubility limits with respect to the characterization and propagation of model uncertainty through the model abstraction.

DOE relied primarily on flow-through test data to construct its abstracted model for commercial spent nuclear fuel dissolution rate (CRWMS M&O, 2000b,k). The electrochemical mechanism was used to justify the dissolution rate data derived from flow-through tests (Shoesmith, 1999).

---

[17]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Total System Performance Assessment and Integration—Features, Events, and Processes (May 15–17, 2001)." Letter (May 30) to S. Brocoum, DOE. Washington, DC: NRC. 2001.

[18]Schlueter, J. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Container Life and Source Term (September 12–13, 2000)." Letter (October 4) to S. Brocoum, DOE. Washington, DC: NRC. 2000

DOE also suggested that the flow-through test results form an upper bound of dissolution rates measured by other techniques. DOE has not considered alternate models derived from the unsaturated drip tests, the immersion tests, or natural analogues. Although the drip test model and natural analog data may provide more realistic assessments of the spent nuclear fuel dissolution rate, the choice of the conservative flow-through test to support commercial spent nuclear fuel dissolution is acceptable.

3.3.4.4.4.5 Model Abstraction Output Is Supported by Objective Comparisons

Overall, the current information, along with the agreements reached between DOE and NRC (Section 3.3.4.5) is sufficient to conclude that the necessary information will be available at the time of a potential license application to assess the effect of commercial spent nuclear fuel dissolution on radionuclide release rates and solubility limits with respect to model abstraction output being supported by objective comparisons.

The model abstraction used for the commercial spent nuclear fuel dissolution rate in the Total System Performance Assessment–Site Recommendation (CRWMS M&O, 2000t) is based on experimental measurements. The flow-through experiments used to derive the model are considered bounding because the dissolution process is not limited by transport of species, corrosion products, or back reactions. The flow-through tests, however, do not adequately simulate the geometries and material interactions that can occur in the waste package. The flow-through experiments also do not correspond to natural analogs because of the lack of secondary minerals in the former, which are expected to lower the dissolution rate. Therefore, the model abstraction cannot be verified by long-term experiments or natural analogues but can be shown to be conservative.

3.3.4.4.5 DOE Spent Nuclear Fuel Dissolution

DOE spent nuclear fuel consists of more than 250 distinct spent nuclear fuel types divided into 11 groups. In addition, the process model report (CRWMS M&O, 2000b) considered immobilized ceramic plutonium waste. This waste form will consist of disks of a plutonium-containing, titanium dioxide-based ceramic enclosed in stainless steel cans. The process model report evaluated the following 12 types of fuels and waste forms:

Group 1	—	Naval spent nuclear fuel
Group 2	—	Plutonium/uranium alloy
Group 3	—	Plutonium/uranium carbide
Group 4	—	Mixed oxide and plutonium oxide fuels
Group 5	—	Thorium/uranium carbide
Group 6	—	Thorium/uranium oxides
Group 7	—	Uranium metal
Group 8	—	Uranium oxide
Group 9	—	Aluminum-based spent nuclear fuel
Group 10	—	Unknown
Group 11	—	Uranium-zirconium-hydride
Group 12	—	Immobilized ceramic plutonium waste

The process model report considered three types of degradation models for DOE spent nuclear fuel and waste forms: upper limit, conservative, and best estimate. The upper-limit model predicts release rates that are always well in excess of actual dissolution rates. The conservative degradation model provides an estimate of a dissolution rate that reflects the higher end of available dissolution data for the spent nuclear fuel groups or similar materials. Presently, there are no directly relevant experimental dissolution/degradation data for many DOE spent nuclear fuel waste forms. Only limited test data are available on some DOE spent nuclear fuel waste forms. Because of the lack of available data, various surrogate spent nuclear fuels were evaluated for degradation behavior to develop the conservative and best-estimate models. A full instantaneous release of radionuclides was assumed for the upper-limit model for all waste forms except Group 1. Models for the Group 1 fuel—Naval spent nuclear fuel—will be provided later by the U.S. Navy.

Because of the large effort expected for qualifying the conservative and best-estimate models, DOE conducted total system performance assessment sensitivity analyses for DOE spent nuclear fuel. Initial results indicate the performance of the repository is insensitive to DOE spent nuclear fuel degradation kinetics. That is, use of the upper-limit model, which predicts instantaneous release of radionuclides, for DOE spent nuclear fuel in the total system performance assessment still resulted in a calculated dose to the receptor group well within safety requirements. For its Total System Performance Assessment–Site Recommendation (CRWMS M&O, 2000t) model, DOE conservatively assumed the dissolution rate is a constant value equal to the rate for uranium-metal-based fuel (CRWMS M&O, 2000m). The assumed rate results in the complete dissolution of the fuel in a single timestep and in the release of the entire DOE spent nuclear fuel inventory in the waste package as soon as the package is breached (CRWMS M&O, 2000m).

The staff review regarding the abstraction of DOE spent nuclear fuel dissolution follows.

3.3.4.4.5.1 System Description and Model Integration Are Adequate

Description of the characteristics, dissolution processes, and integration of the dissolution rates for DOE spent nuclear fuel types is limited. Additional information regarding system description and model integration for DOE spent nuclear fuel degradation is not needed, however, because DOE uses the upper-limit model, which predicts instantaneous release of radionuclides for every type of DOE spent nuclear fuel. Thus, the impact of DOE spent nuclear fuel on the performance of the repository would depend only on the total inventory of the radionuclides in DOE spent nuclear fuel (CRWMS M&O, 2000b,m), and that inventory is adequately defined.

3.3.4.4.5.2 Data Are Sufficient for Model Justification

Data on the characteristics of the large number of DOE spent nuclear fuel types presented in the process model report (CRWMS M&O, 2000b) are limited. Additional data to support abstraction of DOE spent nuclear fuel degradation are not needed, however, because DOE uses the upper-limit model, which predicts instantaneous release of radionuclides, in its total system performance assessment analyses for every type of DOE spent nuclear fuel.

3.3.4.4.5.3 Data Uncertainty Is Characterized and Propagated Through the Model Abstraction

Use of the upper-limit model by DOE in its total system performance assessment analyses for every type of DOE spent nuclear fuel is reasonable. No additional information is needed regarding the characterization and propagation of data uncertainty through the abstraction of DOE spent nuclear fuel dissolution.

3.3.4.4.5.4 Model Uncertainty Is Characterized and Propagated Through the Model Abstraction

The use of the upper-limit model by DOE in its total system performance assessment analyses for every type of DOE spent nuclear fuel is reasonable. No additional information is needed regarding the characterization and propagation of model uncertainty through the abstraction of DOE spent nuclear fuel dissolution.

3.3.4.4.5.5 Model Abstraction Output Is Supported by Objective Comparisons

The use of the upper-limit model, by DOE in its total system performance assessment analyses for every type of DOE spent nuclear fuel is reasonable. No additional information is needed regarding model support for the abstraction of DOE spent nuclear fuel dissolution.

3.3.4.4.6 High-Level Waste Glass Dissolution

The basic form of the rate expression adopted by DOE (CRWMS M&O, 2000n) to describe the dissolution of waste glass immersed in water is given by a form of transition state rate law as

$$\text{Rate} = S\left\{k_o \bullet 10^{\eta \cdot \text{pH}} \bullet \exp\left(\frac{-E_a}{RT}\right) \bullet \left[1 - \frac{Q}{K}\right]\right. \qquad (3.3.4\text{-}3)$$

where

S	—	surface area of glass immersed in water, in units of area
k_o	—	intrinsic dissolution rate, which depends only on glass composition, in units of mass/(area • time)
η	—	pH dependence coefficient
E_a	—	effective activation energy, in units of kJ/mol
R	—	gas constant, which is 8.314 J/(mol • K) [1.987 cal/(mol • K)]
T	—	absolute temperature in K
Q	—	concentration of dissolved silica in the solution, in units of mass/volume
K	—	a quasi-thermodynamic fitting parameter for glass equal to the apparent silica saturation value for the glass, in units of mass/volume

Equation (3.3.4-3) contains two main factors. The first factor is the forward rate, $k_o \bullet 10^{\eta \cdot \text{pH}} \bullet \exp(-E_a/RT)$, which represents the dissolution rate in the absence of concentration effects of dissolved silica (and other aqueous species), and the other factor is the reaction affinity term $1-(Q/K)$, which quantifies such effects. Because of the complexity in defining parameters and associated uncertainties, a simpler bounding approach was adopted that combined $1-(Q/K)$ with k_o, and the following abstraction was developed for aqueous degradation of high-level waste:

$$\text{Rate} = S\left\{k_{eff} \bullet 10^{\eta\,\text{pH}} \bullet \exp\left(\frac{-E_a}{RT}\right)\right\} \tag{3.3.4-4}$$

where

$$k_{eff} = k_o \bullet (1 - \frac{Q}{K}) \tag{3.3.4-5}$$

This bounding approach reduces the abstracted model to an equation involving four parameters (η, E_a, S, and k_{eff}) and two variables (pH and T). The forward rate was measured in flow-through experimental conditions where the affinity term can be maintained close to one because of the absence of concentration effects from the products of the glass dissolution. Test results indicated that the rate dependence on pH and temperature was independent of the glass composition, within the range of the glass compositions tested, and, therefore, the same values were used for all waste glasses. The log of the dissolution rate exhibited a V-shaped curve when plotted versus pH. The value of k_{eff} was determined through experimental observations. Several options were evaluated to conservatively bound the three stages of glass corrosion. Based on this evaluation, data from the product consistency test (PCT)-A test were used to obtain bounding values for k_{eff}. The exposed surface area was estimated based on 20 times the surface area of the glass log and assumed that the entire surface corrodes at the same rate when exposed to water. In addition, the DOE model assumes the surface area remains constant during the corrosion process.

Because of the discontinuity in the log of the dissolution rate as a function of pH at intermediate pHs, separate rate expressions were obtained for the acid range and the alkaline range, as shown by Eqs. (3.3.4-6) and (3.3.4-7) (CRWMS M&O, 2000o).

For the low pH range (pH < pH_m)

$$\frac{\text{Rate}}{S}(\text{gm} \bullet \text{m}^2/\text{day}) = 10^{(14\pm0.5)} \bullet 10^{(-0.6\pm0.1)\bullet\text{pH}} \bullet \exp\left(\frac{-80\pm10}{RT}\right) \tag{3.3.4-6}$$

For the high pH range (pH ≥ pH_m)

$$\frac{\text{Rate}}{S}(\text{gm} \bullet \text{m}^2/\text{day}) = 10^{(6.9\pm0.5)} \bullet 10^{(0.4\pm0.1)\bullet\text{pH}} \bullet \exp\left(\frac{-80\pm10}{RT}\right) \tag{3.3.4-7}$$

where pH_m, equal to 7.1, is the pH at which a minimum dissolution rate occurs.

The staff review regarding the DOE abstraction of high-level waste glass dissolution follows.

3.3.4.4.6.1 System Description and Model Integration Are Adequate

Overall, the current information, along with the agreements reached between DOE and NRC (Section 3.3.4.5), is sufficient to conclude that the necessary information will be available at the time of a potential license application to assess the effect of high-level waste glass dissolution on radionuclide release rates and solubility limits with respect to system description and model integration.

DOE has not accounted for the range of environmental conditions expected inside breached waste packages in its abstraction of high-level waste glass degradation. Many studies and reviews have been reported on the effects of γ- and α-radiations on the dissolution or alteration of glass waste in the moist-air systems (Burns, et al., 1982; Wronkiewicz, et al., 1994, 1997). Wronkiewicz, et al. (1997) reported that although both γ- and α-radiations have no adverse effects on the dissolution of nuclear glass waste form immersed in water in contact with air, the radiation exposure of the glass waste form to humid air resulted in a four-to-tenfold increase of alteration layer thickness relative to samples reacted without radiation exposure. Wronkiewicz, et al. (1994, 1997) suggested increases for the irradiated humid-air experiments appear to result from condensation of radiolytic acids into the thin film of water contacting the glass surface. The radiolytic acids increased the rate of ion exchange between the glass and the thin film of condensate, resulting in accelerated corrosion rates for the glass. DOE should consider this finding in its evaluation of the dissolution of glass waste form because, after the failure of the waste package, the glass waste form may be exposed to a thin film of water in dripping conditions, and the radiation dose rate from the long-lasting alpha-emitters in the glass waste form still may be high enough to produce a significant effect. On the other hand, the radiolysis-induced nitric acid is a stable product with repository conditions and, therefore, may accumulate on the surface of the glass waste form and produce an acidic film of water even if the radiation field is low after failure of the waste package. DOE agreed[19] to provide an update on the in-package chemistry effects on dissolution rates.

DOE conducted limited analyses of high-level waste glass degradation in the presence of corrosion products from the dissolution of waste package internal components, such as FeOOH, $FeCl_2$, and $FeCl_3$, that could influence glass corrosion processes. DOE stated (CRWMS M&O, 1998b) that dissolution rates of glass strongly decrease in the presence of dissolved magnesium, lead, and zinc, but are strongly enhanced in some conditions by dissolved iron. The potential effect of dissolved iron is particularly important because corrosion of the stainless steel inner barrier of the Enhanced Design Alternative-II design could provide significant quantities of iron. DOE agreed[20] to provide an update on the in-package chemistry effects on dissolution rates.

[19]Schlueter, J. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Container Life and Source Term (September 12–13, 2000)." Letter (October 4) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

[20]Ibid.

3.3.4.4.6.2 Data Are Sufficient for Model Justification

Overall, the current information, along with the agreements reached between DOE and NRC (Section 3.3.4.5), is sufficient to conclude that the necessary information will be available at the time of a potential license application to assess the effect of high-level waste glass dissolution on radionuclide release rates and solubility limits with respect to data being sufficient for model justification.

Based on review of the DOE abstraction of high-level waste glass degradation presented in the process model report (CRWMS M&O, 2000b) and in the analysis and model reports (CRWMS M&O, 2000n,o), the data and technical bases used to support the model abstraction are not sufficient.

- The analysis and model report (CRWMS M&O, 2000n, p. 9, Bullet #1) assumes the high-level waste glass dissolution rate based on the boron release rate can be used to provide an upper bound for the radionuclide release rate. The analysis for determining the coefficients for the pH dependence violates this assumption. While the dissolution rate based on the boron release rate was used for calculating k_{eff}, the coefficients for the pH dependence of the dissolution rate were determined using the silica release rate. Silica has limited solubility, and high-level waste glass dissolution rates could be significantly underestimated if based on measured silica release rates. This closed-pending agreement was addressed in the revised analysis and model report (CRWMS M&O, 2000o).

- The pH coefficients for high-level waste glass degradation rates were determined from experiments that used pH buffers to prepare aqueous solutions. DOE conducted limited experiments to determine the possible effect on glass dissolution of corrosion products that could result from dissolution of waste package internal components. Corrosion products, such as FeOOH, $FeCl_2$, and $FeCl_3$, could influence the mechanisms and rates of glass corrosion (Pan, et al., 2001). DOE stated that glass dissolution rates are strongly enhanced in some conditions by dissolved iron. The potential effect of iron is particularly important because corrosion of the stainless steel inner barrier of the Enhanced Design Alternative–II design could provide significant quantities of dissolved iron.

- The work of Advocat, et al. (1991), cited in the analysis and model report for the effect of pH on release rate, indicates the presence of potassium ions on the surface of the corroded glass. Because the glass had no potassium, the presence of potassium ions is attributed to the ion exchange from KOH or KH_2PO_4 used for adjusting the pH of the solutions. The potassium ion, by virtue of its larger size, could lower the release rate from glass by retarding the migration of hydrogen ions in the glass matrix. Such comparisons could lead to erroneous conclusions.

- DOE assumed the release rate is independent of high-level waste glass composition. At best, one can state the intrinsic dissolution rate, k_o, can be represented as an expected value of a distribution based on the expected variation in glass compositions using a risk-informed, performance-based evaluation. In addition, the coefficients for pH and E_a

are assumed to be independent of glass composition. Again, pH and E_a values should bound the variability expected from glass compositions. This analysis is acceptable as long as it captures the expected variability in glass composition.

DOE agreed[21] to provide revised documentation on in-package water chemistry modeling for waste forms. The revised documentation will include an assessment of the chemical form and concentration of iron corrosion products and their effects on glass dissolution rates.

3.3.4.4.6.3 Data Uncertainty Is Characterized and Propagated Through the Model Abstraction

Overall, the current information, along with the agreements reached between DOE and NRC (Section 3.3.4.5), is sufficient to conclude that the necessary information will be available at the time of a potential license application to assess the effect of high-level waste glass dissolution on radionuclide release rates and solubility limits with respect to data uncertainty characterized and propagated through the model abstraction.

The DOE model for high-level waste glass dissolution is based on a single set of experiments conducted by Knauss, et al. (1990). This experiment defines the glass dissolution dependence on pH and temperature for a single, simple glass composition. Although DOE bounded the forward reaction-rate term in the model by performing several sets of experiments using various glass compositions, the uncertainties associated with pH and temperature dependence have not been evaluated using anticipated glass compositions. The DOE model lacks evaluation of data and model uncertainties. Because DOE bounded high-level waste glass dissolution rates using a conservative forward reaction rate, no additional information is needed regarding the characterization and propagation of data uncertainty through the abstraction of the high-level waste glass dissolution.

3.3.4.4.6.4 Model Uncertainty Is Characterized and Propagated Through the Model Abstraction

Overall, the current information, along with the agreements reached between DOE and NRC (Section 3.3.4.5), is sufficient to conclude that the necessary information will be available at the time of a potential license application to assess the effect of high-level waste glass dissolution on radionuclide release rates and solubility limits with respect to the characterization and propagation of model uncertainty through the model abstraction.

3.3.4.4.6.5 Model Abstraction Output Is Supported by Objective Comparisons

Overall, the current information, along with the agreements reached between DOE and NRC (Section 3.3.4.5), is sufficient to conclude that the necessary information will be available at the time of a potential license application to assess the effect of high-level waste glass dissolution

[21]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Evolution of the Near-Field Environment (January 9–12, 2001)." Letter (January 26) to S. Brocoum, DOE. Washington, DC: NRC. 2001.

on radionuclide release rates and solubility limits with respect to model abstraction output being supported by objective comparisons.

3.3.4.4.7 Radionuclide Solubility

The DOE approach to calculate bounds on the aqueous concentration of radionuclides in water that reacted with the waste form is initially to derive the concentrations from the waste form dissolution model. Subsequently, a comparison is made between the waste form dissolution-based aqueous concentration of the radionuclides and a value for the solubility limit, thermodynamically derived or based on a bounding assumption, for each radionuclide considered. If the solubility-limited value is lower for a given radionuclide than its concentration derived from the waste form dissolution, the aqueous concentration is set to the solubility-limited value, and the difference in mass is assumed to precipitate out of solution. The solubility-limited values place constraints on the aqueous concentration of the particular radionuclide element considered with each isotope of that element present in proportion to its isotopic abundance (CRWMS M&O, 1998b).

The concentration usually is constrained by the solubility limit of the solid phases that contains the radioisotopes (either solid phases with the radioisotope as the dominant element or solid phases with trace amounts of the radionuclide, as in coprecipitated species). The solid phases that form depend on temperature, redox conditions, and chemical composition of the groundwater. Because of uncertainty in the precise values for these variables in the waste package and near-field environment, there is a wide range of possible radionuclide concentration limits.

For the Total System Performance Assessment–Site Recommendation (CRWMS M&O, 2000t) the dissolved concentration limits calculation builds on three primary feeds: (i) estimates of in-package fluid chemistry (pH, Eh, ionic strength, and carbonate concentration), (ii) measured (and estimated) thermodynamic parameters describing the stabilities of aqueous species and solid radioisotope phases, and (iii) determinations of the likely solubility controlling phases for the radionuclides of concern (CRWMS M&O, 2000b). For the Total System Performance Assessment–Site Recommendation analysis, pure phases were chosen because, in general, they yield higher dissolved concentrations compared to coprecipitated phases. The specific phase selected for a particular radionuclide is based on information from geologic and experimental observations or from crystallochemical arguments. Where no information can be gleaned from field or experimental observations, the most amorphous and hydrated form of the radionuclide believed the most soluble was selected. For uranium, schoepite was assumed the solubility-controlling phase. For neptunium, plutonium, americium, and nickel, the solubility-controlling solids chosen were Np_2O_5 [or $Np(OH)_4$(am) for reducing conditions], $Pu(OH)_4$(am), $AmOHCO_3$, and NiO (CRWMS M&O, 2000p).

Thermodynamic data available for the different radionuclides, the sensitivity of solubilities to fluid chemistry, and the importance of the different radionuclides to total system performance assessment are uneven. Thus, DOE used three approaches to implement solubility limits within the Total System Performance Assessment–Site Recommendation analysis (CRWMS M&O, 2000m,b,p): (i) multitermed functions of chemistry for uranium, neptunium, americium, actinium, curium, and samarium; (ii) distributions for plutonium, protactinium, lead, and nickel;

and (iii) constant bounding values for technetium, iodine, thorium, cesium, strontium, chlorine, carbon, niobium, zirconium, radium, and tin. The concentration of uranium for the Total System Performance Assessment–Site Recommendation analysis was calculated using an equation fit to EQ3-derived schoepite solubility as a function of pH, CO_2 fugacity, and temperature. The solubility of neptunium for the Total System Performance Assessment–Site Recommendation analysis was calculated from a pH-dependent equation fit to Np_2O_5 solubilities calculated with EQ3 for a pH range 4.5–8.5. A log-uniform distribution was assigned for plutonium solubility, with a minimum of 1.0×10^{-10} and a maximum of 2.0×10^{-4} M, based on EQ3 calculations of $Pu(OH)_4$ solubility in J–13 Well waters for a range of pH, Eh, and CO_2 fugacity. To calculate americium concentrations for the Total System Performance Assessment–Site Recommendation analysis, an equation with pH and CO_2 fugacity terms was used, and similar equations were used to calculate the solubilities of actinium, curium, and samarium. The solubilities of technetium, carbon, chlorine, iodine, and cesium were set to 1.0 M, which lets the waste inventory control release, because no solubility-limiting solids are predicted to form for these radioelements. The solubility of strontium was also set to 1.0 M to simplify the analysis. A log-uniform distribution was proposed for nickel solubility, assumed controlled by the solubility of NiO with a minimum of 1.4×10^{-6} M and a maximum of 3.1 M. For lead solubility, a log-uniform distribution was recommended for the Total System Performance Assessment–Site Recommendation with a minimum of 1.0×10^{-10} M and a maximum of 1.0×10^{-5} M. In the case of protactinium solubility, a log-uniform distribution was recommended, with a minimum of 1.0×10^{-10} M, a maximum of 1.0×10^{-5} M, and a mean of 3.2×10^{-8} M. Constant values of 1.0×10^{-7} M for the solubilities of niobium, 2.3×10^{-6} M for radium, 5.0×10^{-8} M for tin, 1.0×10^{-5} M for thorium, and 6.8×10^{-10} M for zirconium were recommended (CRWMS M&O, 2000b,p).

The staff review regarding the DOE abstraction of radionuclide concentration limits follows.

3.3.4.4.7.1 System Description and Model Integration Are Adequate

Overall, the current information, along with the agreements reached between DOE and NRC (Section 3.3.4.5), is sufficient to conclude that the necessary information will be available at the time of a potential license application to assess radionuclide solubility limits with respect to system description and model integration.

For most of the 21 radionuclides considered in the abstraction, the process model report (CRWMS M&O, 2000b) and analysis and model reports (CRWMS M&O, 2000p), provide sufficient descriptions of the approach and technical bases for estimating the solubility limit of the radionuclides and the integration of the radionuclide concentration limits into the total system performance assessment analyses. The use of 1 M as a conservative upper bound for the solubility limit of technetium, carbon, iodine, chlorine, cesium, and strontium is considered acceptable. The technical basis, however, is inadequate for the solubility limits of some radionuclides. In particular, actinium, curium, and samarium are all assumed to be analogous to americium and use the same pH- and fCO_2-dependent equation and parameter values, except the first one, as americium. No technical basis was provided, however, for the differences in the value of the first parameter in the equation.

DOE recognizes that solubility of an element varies as the environmental conditions within a repository change, and evaluation of solubility limits requires knowledge of changes in this environment and the dependence of radionuclide solubility on the environment. For several radionuclides considered (e.g., zirconium, nickel, tin, and radium), however, the abstraction relied on EQ3 equilibrium modeling that assumed the water had a composition similar to that of J–13 Well water. For those radionuclides, the pH range (6–9) used in the EQ3 calculations does not encompass the reasonable range of pH inside breached waste packages. The analysis and model report (CRWMS M&O, 2000d) indicates that pH inside commercial spent nuclear fuel waste packages can range from 3.6 to 8.1, whereas pH inside DOE spent nuclear fuel/high-level waste glass (codisposal) waste packages can range from 4.8 to 10.0. In addition, although the EQ3 results show that neptunium solubility varies with fCO_2 at pH > 7, DOE selected an equation dependent only on pH to represent the solubility of neptunium. DOE justified its neglect of fCO_2 dependence by claiming in-package chemistry calculations show the maximum pH inside breached waste packages is 8.1, which is true only for the commercial spent nuclear fuel waste packages, not for the codisposal packages. In the analysis and model report (CRWMS M&O, 2000p), DOE stated that analysis of in-package chemistry and analysis of solubility limits were conducted in parallel. The in-package chemistry calculated for the codisposal waste packages, which exhibit higher pH levels and ionic strengths than either J–13 Well water or commercial spent nuclear fuel waste packages, was not considered because commercial spent nuclear fuel is the dominant waste, and the resources for this analysis are constrained (CRWMS M&O, 2000p). Thus, the results of the in-package chemistry calculations were not fully used in evaluating the solubility limits. Also, the temperature dependence of radionuclide solubilities was generally ignored, except for uranium. Thus, DOE has not reasonably accounted for the range of environmental conditions expected inside breached waste packages in its abstraction of radionuclide concentration limits.
DOE agreed[22,23] to provide revised documentation on the effects of in-package water chemistry on radionuclide solubility.

3.3.4.4.7.2 Data Are Sufficient for Model Justification

Overall, the current information, along with the agreements reached between DOE and NRC (Section 3.3.4.5), is sufficient to conclude that the necessary information will be available at the time of a potential license application to assess radionuclide solubility limits with respect to sufficient data for model justification.

For radionuclides with adequate experimental data, DOE provided an adequate description how the experimental data and EQ3 modeling results were used, interpreted, and synthesized into the abstraction of radionuclide concentration limits. For radionuclides with inadequate experimental data, the assumption of 1 M as a conservative bounding limit is considered

---

[22]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Evolution of the Near-Field Environment (January 9–12, 2001)." Letter (January 26) to S. Brocoum, DOE. Washington, DC: NRC. 2001.

[23]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Total System Performance Assessment and Integration (August 6–10, 2001)." Letter (August 23) to S. Brocoum, DOE. Washington, DC: NRC. 2001.

acceptable. In several cases, however, inadequate justification is provided for parameters used in the solubility equation. For example, the equation for the solubility of actinium, curium, and samarium has the same form as that of americium, and six of the seven parameters in the equations have the same value. The first parameter in the equations is different for actinium, curium, samarium, and americium, but no technical basis was provided for the different values, and, as stated in the analysis and model report (CRWMS M&O, 2000p), no separate solubility evaluation has been conducted for actinium, curium, and samarium.

Also, data are lacking or inadequate to support the parameters used in the abstraction of concentration limits for several radionuclides. For example, the solubility of zirconium calculated using EQ3 is uncertain because, as stated in the analysis and model report (CRWMS M&O, 2000p), some data for zirconium complexes in the EQ3 database are suspect. There are no thermodynamic data available for the pertinent aqueous niobium species, and published niobium solubility data vary by several orders of magnitude. Furthermore, in several cases, DOE used data supplemented by EQ3 calculations to support its abstraction of solubility limits. The EQ3 calculations, however, did not encompass the potential range of chemical conditions that could be present inside breached waste packages.

In addition, the analysis and model report (CRWMS M&O, 2000q) states that the analysis did not use a uniform EQ3/6 data file because the data file was still being developed. Moreover, CRWMS M&O (2000q) states that unqualified data were used in the analysis. Thus, data DOE used to justify model abstraction of dissolved concentration limits are considered inadequate. DOE agreed[24] to provide documentation of all deviations from the reference EQ3/6 database and justification for those deviations.

3.3.4.4.7.3 Data Uncertainty Is Characterized and Propagated Through the Model Abstraction

Overall, the current information, along with the agreements reached between DOE and NRC (Section 3.3.4.5), is sufficient to conclude that the necessary information will be available at the time of a potential license application to assess radionuclide solubility limits with respect to the characterization and propagation of data uncertainty through the model abstraction.

The bounding values used by DOE for the solubility limits of technetium, carbon, iodine, chlorine, cesium, and strontium reasonably account for uncertainties and variabilities of the solubility of those radionuclides. The parameter values used in the solubility equations for several of the radionuclides do not adequately reflect the range of environmental conditions expected inside breached waste packages. DOE has not adequately considered the uncertainties in the in-package chemical environment in deriving the abstracted equations for

---

[24]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Total System Performance Assessment and Integration (August 6–10, 2001)." Letter (August 23) to S. Brocoum, DOE. Washington, DC: NRC. 2001.

the solubility limits of several radionuclides. DOE agreed[25] to provide revised documentation on the effects of in-package water chemistry on radionuclide solubility.

3.3.4.4.7.4 Model Uncertainty Is Characterized and Propagated Through the Model Abstraction

Overall, the current information, along with the agreements reached between DOE and NRC (Section 3.3.4.5), is sufficient to conclude that the necessary information will be available at the time of a potential license application to assess radionuclide solubility limits with respect to the characterization and propagation of model uncertainty through the model abstraction.

The effects of thermal-hydrological-chemical coupled processes that may occur inside waste packages and that may change the in-package chemistry are not appropriately considered in the DOE abstraction of dissolved radionuclide concentration limits. DOE agreed[26] to provide revised documentation on the effects of in-package water chemistry on radionuclide solubility.

3.3.4.4.7.5 Model Abstraction Output Is Supported by Objective Comparisons

Overall, the current information, along with the agreements reached between DOE and NRC (Section 3.3.4.5), is sufficient to conclude that the necessary information will be available at the time of a potential license application to assess radionuclide solubility limits with respect to model abstraction output being supported by objective comparisons.

DOE has not adequately supported, by objective comparisons with empirical data, the range of chemical conditions it used in deriving the abstracted equations for the solubility limits for several radionuclides. As noted in Section 3.3.4.4.2.5, in the revised analysis and model report (CRWMS M&O, 2001a), DOE states that planned validation of the in-package chemistry model will involve using EQ3/6 to model some combination of the following processes: (i) alteration observed during drip tests performed at Argonne National Laboratory; (ii) formation of ore deposits that might constitute natural analoges; and (iii) glass, mineral, and steel corrosion measurements taken in the laboratory. The planned DOE validation exercises are expected to address staff concerns about model abstraction of radionuclide solubility limits being supported by objective comparisons.

3.3.4.4.8 Colloidal Release

Colloidal radionuclide release from waste forms is addressed in two analysis and model reports: one, (CRWMS M&O, 2000r) describing the abstraction to be incorporated into the DOE total system performance assessment; the second, in support of the first (CRWMS M&O, 2000s). This colloid release abstraction is limited to defining colloid-associated concentrations of certain radionuclides in water as these leave the waste package. No retardation in the waste package

[25]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Evolution of the Near-Field Environment (January 9–12, 2001)." Letter (January 26) to S. Brocoum, DOE. Washington, DC: NRC. 2001.

[26]Ibid.

is assumed, and transport outside the waste package is not within the scope of the release model. For high-level waste glass, the abstraction allows reversible and irreversible radionuclide attachment to colloids. For spent nuclear fuel waste forms, irreversible attachment was not included in the abstraction.

The DOE abstraction of colloidal radionuclide release uses empirical data on release and colloid stability to formulate a dependence of colloidal radionuclide release on in-package ionic strength and pH. The abstraction analysis and model report (CRWMS M&O, 2000r) uses literature and Yucca Mountain project data to support the construction of an algorithm for calculating colloid-associated radionuclide concentrations in solutions leaving the waste package. No credit is taken for colloid retardation within the waste package. Direct input for conceptual models and parameters was obtained from Yucca Mountain project laboratory studies and from a few literature sources. The abstraction takes output from in-package geochemical models and uses pH, ionic strength, and dissolved radionuclide concentration to calculate colloid concentrations, irreversibly colloid-bound radionuclide concentrations, and reversible colloid binding of radionuclides. The results are combined to provide a total colloid-associated source term for a given radionuclide. The abstraction classifies colloids as waste form, groundwater (preexisting), or iron oxyhydroxide (from corrosion) colloids. True colloids (i.e., products of radionuclide precipitation) are not included.

The following key input are used in the colloid release abstraction (CRWMS M&O, 2000r):

- Solution ionic strength, pH, and radionuclide concentration from separate total system performance assessment in-package geochemical calculations
- Effect of ionic strength on water concentration of waste form colloidal plutonium, including a maximum colloidal plutonium concentration of 6×10^{-8} M at ionic strength <0.01 M and a minimum of 1×10^{-11} M at ionic strength >0.05 M, from data in an analysis and model report (CRWMS M&O, 2000s)
- Maximum stability limits for waste form colloids as a function of pH, ranging from ionic strength of 0.01 M at pH 2 to ionic strength of 0.05 M at pH $\geq$6, based on montmorillonite data from Tombacz, et al. (1990) and an analysis and model report (CRWMS M&O, 2000s)
- Maximum stability limits for iron oxyhydroxide colloids as a function of pH, ranging from ionic strength of 0.05 M at pH <6 and >11 to a minimum ionic strength of 0.01 M at pH 8–9, from Liang and Morgan (1990)
- Relationship between ionic strength and mass of groundwater colloids, ranging between a minimum of 3×10^{-6} mg/L and a maximum of 3×10^{-2} mg/L (CRWMS M&O, 1998b)
- Range of distribution coefficients for reversible sorption onto colloids using literature and Yucca Mountain project laboratory data

The order of calculation is

- Water concentration of radionuclide irreversibly sorbed to waste form colloids, using ionic strength and pH
- Mass concentration of waste form colloids, using experimental relationship between concentrations of colloids and radionuclide irreversibly sorbed to them
- Radionuclide reversibly sorbed to waste form colloids, using distribution coefficient
- Mass concentration of iron oxyhydroxide colloids, using ionic strength and pH
- Radionuclide reversibly sorbed to iron oxyhydroxide colloids, using distribution coefficient
- Mass concentration of groundwater colloids, using ionic strength
- Radionuclide reversibly sorbed to groundwater colloids, using distribution coefficient
- Summed colloidal radionuclide concentration and summed colloid mass concentration output to exterior of waste package

The analysis and model report (CRWMS M&O, 2000s) contains literature and previous Argonne National Laboratory data from static- and drip-corrosion tests on high-level waste glass and spent nuclear fuel supporting a model of irreversible plutonium colloid attachment used in the analysis and model report (CRWMS M&O, 2000r). The direct input to the adopted abstraction—all based on Argonne National Laboratory work—are (i) a relationship between colloidal plutonium concentration and ionic strength based on static high-level waste glass corrosion tests, (ii) the effect of ionic strength on colloid stability, and (iii) a direct relationship between colloidal plutonium concentration and colloid concentration. The adopted abstraction uses data only from the high-level waste glass tests, however, spent nuclear fuel results were included in the development of a model in the Argonne National Laboratory analysis and model report that was used in the abstraction analysis and model report as an alternative model.

The staff review regarding the DOE abstraction of colloidal release follows.

3.3.4.4.8.1 System Description and Model Integration Are Adequate

Overall, the current information, along with the agreements reached between DOE and NRC (Section 3.3.4.5), is sufficient to conclude that the necessary information will be available at the time of a potential license application to assess the effect of colloid release on radionuclide solubility limits with respect to system description and model integration.

DOE has not yet assembled the information relating to system description and model integration for colloid release abstraction needed for a potential license application, but has a reasonable approach to do so by the time of license application, based on DOE agreements to provide additional documentation.[27]

The technical basis for selecting radionuclides for release modeling through reversible and irreversible colloidal attachment is not transparent and traceable in all cases. The Evolution of the Near-Field Environment Technical Exchange agreements matrix[28] states this issue is resolved in Section 3.5.6.1 of CRWMS M&O (2000m); the relevant section is actually in the Total System Performance Assessment–Site Recommendation report (CRWMS M&O, 2000t). This discussion does not address the possibility that waste form colloids (irreversible attachment) could significantly transport radioelements other than plutonium and americium, despite observations of other elements, such as uranium and thorium, irreversibly attached on colloids in waste corrosion tests (CRWMS M&O, 2000s). In addition, the argument neglects the potential for a contribution to release by the reversible colloid attachment of less sorbing radioelements such as neptunium and uranium. These issues also are not addressed adequately in the analysis and model report (CRWMS M&O, 2000r). DOE agreed[29] to provide the technical basis for selection of radionuclides released and transported via colloids in the total system performance assessment.

The technical basis for the exclusion of irreversible radionuclide attachment onto spent nuclear fuel colloids is not adequate. It is noted in CRWMS M&O (2000r) that the lack of observed attachment of this type may be an effect of the spent nuclear fuel test configuration, and that fewer data were obtained from the commercial spent nuclear fuel testing than from the high-level waste glass testing. In addition, CRWMS M&O (2000r) discusses the possibility that a plutonium-rich alteration layer on corroded spent nuclear fuel may be released by spallation, though this has not yet been observed. According to NRC (2000a, p. 224), several reports discuss evidence for irreversible plutonium attachment to corrosion product colloids. For other waste types such as DOE spent nuclear fuel, DOE needs to either screen out colloid-associated radionuclide release or develop modeling approaches for them. In CRWMS M&O (2000r), N-Reactor fuel is specifically discussed as requiring an assessment of importance to performance and possible inclusion in the abstraction. DOE agreed[30] to provide the technical basis for selection of waste forms for which irreversible colloidal release is modeled.

According to CRWMS M&O (2000m), only plutonium, americium, thorium, and protactinium are modeled as colloidally released, but other radioelements are included in unsaturated and

[27]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Evolution of the Near-Field Environment (January 9–12, 2001)." Letter (January 26) to S. Brocoum, DOE. Washington, DC: NRC. 2001.

[28]Ibid.

[29]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Radionuclide Transport (December 5–7, 2000)." Letter (December 12) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

[30]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Evolution of the Near-Field Environment (January 9–12, 2001)." Letter (January 26) to S. Brocoum, DOE. Washington, DC: NRC. 2001.

saturated zone transport models. This apparent lack of model integration may be justified but should be clarified. In addition, confusion exists among the various reports cited in this section regarding the disposition of specific radioelements in colloid modeling. DOE agreed[31] to provide the technical basis for selection of radionuclides released and transported via colloids in the total system performance assessment.

3.3.4.4.8.2 Data Are Sufficient for Model Justification

Overall, the current information, along with the agreements reached between DOE and NRC (Section 3.3.4.5), is sufficient to conclude that the necessary information will be available at the time of a potential license application to assess the effect of colloid release on radionuclide solubility limits with respect to sufficient data for model justification.

Site- and waste-specific data on colloid release parameters are not sufficient. For example, DOE needs to more strongly support the maximum concentration of colloidal waste form plutonium (i.e., $CRN_{coll,wf,irrev,max} = 6 \times 10^{-8}$ M) (CRWMS M&O, 2000r), which is constrained by the results of experiments on only one high-level waste glass sample. No basis is provided for the assertion in CRWMS M&O (2000r) that the values for the concentration range of iron oxide corrosion product colloids ($M_{coll,FeOx,max}$ and $M_{coll,FeOx,min}$) are reasonable and conservative. CRWMS M&O (2000r) asserts that plutonium and americium behave similarly enough during high-level waste glass colloid irreversible attachment that a constant concentration ratio may be assumed, however, supporting test data are not described or cited. Similarly, the colloid analysis and model reports do not demonstrate that the samples studied are sufficiently representative of the range of waste types. DOE agreed[32] to demonstrate that colloidal release and transport model parameters are sufficiently supported.

3.3.4.4.8.3 Data Uncertainty Is Characterized and Propagated Through the Model Abstraction

Overall, the current information, along with the agreements reached between DOE and NRC (Section 3.3.4.5), is sufficient to conclude that the necessary information will be available at the time of a potential license application to assess the effect of colloid release on radionuclide solubility limits with respect to the characterization and propagation of data uncertainty through the model abstraction.

DOE has not demonstrated that its selection of colloid release model parameters (e.g., K_c) bound the uncertainty associated with data limitations, the special chemical environment in the waste package, and possible coupled thermal-hydrological-chemical processes (NRC, 2000a). For example, laboratory data were obtained for a limited range of chemical and thermal conditions {e.g., at 90 °C [194 °F]} (CRWMS M&O, 2000s), and it is not clear that adopted parameters, such as colloidal plutonium concentration, reflect the associated uncertainties. As

---

[31]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Radionuclide Transport (December 5–7, 2000)." Letter (December 12) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

[32]Ibid.

another example, the maximum colloidal plutonium concentration of 6×10^{-8} M, as measured during corrosion tests, is also the maximum value used in the model abstraction (CRWMS M&O, 2000r). No additional uncertainty is reflected in this value. In modeling chemical effects on colloid concentrations and radionuclide attachment, the DOE considers only pH and ionic strength; potential uncertainties associated with neglecting other effects are not explicitly addressed. DOE agreed[33] to demonstrate that colloidal release and transport model parameters are suitably bounding.

3.3.4.4.8.4 Model Uncertainty Is Characterized and Propagated Through the Model Abstraction

Overall, the current information, along with the agreements reached between DOE and NRC (Section 3.3.4.5), is sufficient to conclude that the necessary information will be available at the time of a potential license application to assess the effect of colloid release on radionuclide solubility limits with respect to the characterization and propagation of model uncertainty through the model abstraction.

Section 6.3.4.6 of CRWMS M&O (2000m) describes implementation for codisposal packages of the colloid release and invert transport model abstractions in Total System Performance Assessment–Site Recommendation. The following issues concerning the characterization and propagation of uncertainty arising from model abstraction were identified in this review.

- Calculation of the concentration of iron (hydr)oxide colloids available to sorb radionuclides (CRWMS M&O, 2000m, p. 326) depends on pH and ionic strength. Determination of iron (hydr)oxide colloid stability involves comparison of solution pH and ionic strength against a plot of regions of colloid stability and instability (CRWMS M&O, 2000r, Figure 11). As demonstrated in the model verification discussion and in Figure 6-144 of CRWMS M&O (2000m), small changes in pH or ionic strength in the ranges plausible for in-package conditions can result in an abrupt change in modeled iron (hydr)oxide colloid concentration by a factor of 1,000; there are no intermediate values. This result demonstrates marked sensitivity to the adopted stability boundaries and to modeled solution parameters unlikely to be simulated accurately or precisely. In the example case of a codisposal package, the minimum iron (hydr)oxide colloid concentration results for the waste package, that is, far less radionuclide can be mobilized by reversible attachment. DOE should perform analyses to show if this high model sensitivity—which is not reflected in model uncertainty—has implications for modeled dose.

- Similar model sensitivity exists for the pH dependence of stability of waste form colloids. A functional relationship defines the variation of waste form colloid concentration with ionic strength for the range 0.01–0.05 M, but, at ionic strength above 0.05 M, the concentration drops abruptly by three orders of magnitude to 10^{-11} M (CRWMS M&O,

---

[33]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Radionuclide Transport (December 5–7, 2000)." Letter (December 12) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

2000r, Figure 13). In-package and invert chemistry models suggest this sensitivity will not affect results because ionic strength stays below 0.05 M after waste package failure (CRWMS M&O, 2000m). A stability boundary in ionic strength versus pH space, however, introduces an abrupt concentration boundary (CRWMS M&O, 2000r, Figure 12), which is revealed in a model result that shows a one-time step drop by a factor of 6,000 in concentration of irreversibly bound plutonium (CRWMS M&O, 2000a, Figure 6-139). Although the concentration then rebounds to near maximum value for the remainder of the model, high sensitivity to modeled pH (which is uncertain) is evident. DOE should perform analyses showing if this high model sensitivity—which is not reflected in model or parameter uncertainty—has implications for modeled dose.

- The modeled concentration of groundwater colloids (which facilitate reversible attachment) also shows an abrupt pH dependence, using the same stability fields as for waste form colloids (CRWMS M&O, 2000r, Figure 12). In this case, an abrupt change in concentration by a factor of 10^4 can result from a shift in ionic strength versus pH space; behavior similar to that of waste form colloids results (CRWMS M&O, 2000m). DOE should perform analyses showing if this high model sensitivity—which is not reflected in model or parameter uncertainty—has implications for modeled dose.

DOE agreed[34] to demonstrate that colloidal release and transport model parameters are suitably bounding. In addition, DOE agreed[35] to provide a sensitivity analysis of these potentially abrupt changes in modeled colloid concentration.

3.3.4.4.8.5 Model Abstraction Output Is Supported by Objective Comparisons

Overall, the current information, along with the agreements reached between DOE and NRC (Section 3.3.4.5), is sufficient to conclude that the necessary information will be available at the time of a potential license application to assess the effect of colloid release on radionuclide solubility limits with respect to model abstraction output being supported by objective comparisons.

Section 6.3.4.6 of CRWMS M&O (2000m) discusses model verification for the colloid release and invert transport model abstractions for a codisposal package. In one case—calculation of invert iron (hydr)oxide colloid concentration—an independent analysis did not agree with the reports results. It may be deduced from Figure 6-143 of CRWMS M&O (2000m) that modeled invert water pH after 100,000 years is approximately 7.7. This pH, combined with ionic strength of 0.01 M places this water within the iron (hydr)oxide colloid stability field of Figure 11 of CRWMS M&O (2000r), contradicting the Total System Performance Assessment–Site Recommendation verification result that these colloids will be at their minimum concentration of

---

[34]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Radionuclide Transport (December 5–7, 2000)." Letter (December 12) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

[35]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Total System Performance Assessment and Integration (August 6–10, 2001)." Letter (August 23) to S. Brocoum, DOE. Washington, DC: NRC, 2001.

0.001 mg/L (CRWMS M&O, 2000m, p. 332). That the invert water lies in the stability field is also shown in Figure 6-143 of CRWMS M&O (2000m) by the location of the ionic strength curve below the curve for the stability boundary equation, 0.02 • pH + 0.17 (note that the equation is incorrect in the figure legend). Thus, the iron (hydr)oxide colloid concentration should be at its maximum value of 1 mg/L, three orders of magnitude higher than the conclusion of CRWMS M&O (2000m). That invert ionic strength is above the 0.02 • pH – 0.17 curve is irrelevant because pH is not between 9 and 11.

The inconsistent results could be related to a potential problem noted with the definition of Condition B in CRWMS M&O (2000m). As stated on page 326, Condition B in the abstraction is equal to one if ionic strength in the waste package is greater than *either* of two values calculated to represent portions of the stability boundaries linear with pH. It is more correct to say that the condition is one if ionic strength is greater than the value calculated using the particular equation for the relevant pH range of 6 to 8 or 9 to 11 (CRWMS M&O, 2000r, Figure 11). Ionic strength may be below one calculated value and above another and still be in the region of stability. The way Condition B is described on page 326, a combination of Conditions A and B both being equal to one is not sufficient to conclude the colloids are unstable. If the description of Condition B in CRWMS M&O (2000m) is as intended, DOE should correct the description so that erroneous stability conclusions will not be drawn. Such a conclusion could lead to a three-order-of-magnitude underestimate of iron (hydr)oxide colloid concentration. DOE agreed[36] to provide revised documentation on the effects of in-package water chemistry on colloid release.

3.3.4.4.9 Engineered Barrier Subsystem Flow and Transport

The release of radionuclides from the engineered barrier subsystem can occur primarily through transport either as dissolved constituents in water or as bound to colloids. Both dissolved and colloidal radionuclides can diffuse and advect through the water within the waste package and through the invert below the waste packages. Before radionuclide transport can occur, however, the waste package must be breached, the cladding must fail (for commercial spent nuclear fuel packages), and the waste forms must degrade. Thus, radionuclide transport from the engineered barrier subsystem into the unsaturated zone is dependent on a complex series of events in the potential repository (CRWMS M&O, 2000u). Several factors will affect the mobilization and transport of radionuclides through the engineered barrier subsystem: (i) drip shield performance, (ii) waste package performance, (iii) cladding performance, (iv) waste form dissolution rates, (v) entry and movement of water through the waste package, (vi) solubility limit for each radionuclide, (vii) radionuclide transportation through and out of the waste package, (viii) radionuclide transportation through the invert, and (ix) radionuclide transportation via colloids.

The DOE conceptual model for engineered barrier subsystem flow abstraction relies on several key elements. Flow through the engineered barrier subsystem is abstracted to a

[36]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Evolution of the Near-Field Environment (January 9–12, 2001)." Letter (January 26) to S. Brocoum, DOE. Washington, DC: NRC. 2001.

one-dimensional network of flow pathways, and the flow system is assumed to be quasi-steady (i.e., fluid immediately flows through the system and does not accumulate within the engineered barrier subsystem). The abstraction also uses a flow-through model for the waste package (i.e., fluid does not accumulate in the waste package). The type, number, and timing of breaches in the drip shield and waste package are predicted by the WAPDEG code. Separation of the drip shields in response to rock fall, seismic events, or thermal expansion is assumed not to occur.

The DOE conceptual model for engineered barrier subsystem transport abstraction has several key elements. Advective transport of radionuclides may occur through patches and pits created by various corrosion mechanisms in the waste package. Patches can be created by general corrosion, and pits can be created by localized corrosion. Both patches and pits are conceptualized to have a large enough cross-sectional area to provide a pathway for advective flow and transport through the waste package. Radionuclides also can be transported by diffusion through any breach in the waste package (i.e., through stress corrosion cracks, patches, or pits).

DOE recognizes potentially large uncertainties in the response of a complex engineered barrier subsystem through long periods of time. To bound the uncertainties in the model parameters used in its abstraction of flow and radionuclide transport processes in the engineered barrier subsystem, DOE made several assumptions, as discussed in the analysis and model report (CRWMS M&O, 2000u). These assumptions include

- The fluid flux is assumed to pass through any patch or stress corrosion crack on the surface of the waste package, independent of its location on the upper or lower surface of the waste package. DOE states this is a conservative assumption for the patches and pits on the lower half of the waste package, where little inflow is expected to occur, and for flow-through stress corrosion cracks because fluid is unlikely to reach any stress corrosion cracks on the upper half of the lid.

- The fluid flux onto the closure lid of the waste package (where stress corrosion cracks can occur) is reasonably bounded by assuming the waste package is tilted at the maximum angle possible beneath the drip shield.

- All fluid that flows as a film on the closure lid of the waste package flows through a stress corrosion crack, if present.

- Radionuclide transport through a stress corrosion crack is assumed limited to diffusive transport through a thin, continuous film that is always present (meaning radionuclide diffusion out of the waste package is possible as soon as a stress corrosion crack forms on the canister lid). Advective flux through a stress corrosion crack is considered negligible because of the small cross-sectional area of the stress corrosion crack.

- Advective transport occurs only in the vertical direction and is always downward.

- The effects of longitudinal and transverse dispersion are ignored.

- The diffusion coefficient of all relevant radionuclides is bounded by the self-diffusion coefficient for water.
- Sorption of dissolved radionuclides to stationary phases in the waste package and invert is negligible.
- The flux of water into the waste package is equal to the flux out of the waste package and into the invert (flow-through system).

The staff review regarding the DOE abstraction of engineered barrier subsystem flow and transport follows.

3.3.4.4.9.1 System Description and Model Integration Are Adequate

Overall, the current information, along with the agreements reached between DOE and NRC (Section 3.3.4.5), is sufficient to conclude that the necessary information will be available at the time of a potential license application to assess engineered barrier subsystem flow and transport with respect to system description and model integration.

Sufficient description is provided on the approach and technical basis for the abstraction of engineered barrier subsystem flow and transport and the integration into total system performance assessment analyses. The assumptions are clearly stated, used consistently, and are technically defensible. In general, important design features, processes, and couplings are incorporated or bounded.

DOE has not provided a satisfactory evaluation of floor buckling and the potential effects on the rates of water flow and radionuclide release through the invert. DOE proposed to screen out floor buckling (CRWMS M&O, 2000u,v) based on results presented in CRWMS M&O (1998c), which indicate floor heave from thermal-mechanical effects would not exceed approximately 10 mm. The NRC staff (2000c),[37] however, have expressed concern about the appropriateness of the thermal-mechanical parameters used in the DOE assessment of rock-mass behavior around the emplacement drifts (CRWMS M&O, 1998c, 2000w). Stress conditions induced by thermal loading would favor reverse-faulting-style slip on subhorizontal fractures beneath the floor of the emplacement drifts (Ofoegbu, 2001). The occurrence of such fracture slip, which depends on thermal-load magnitude and rock-mass, thermal-mechanical properties, would lead to buckling of the emplacement-drift floor and a change in the hydrological characteristics of the invert and underlying rock. DOE agreed[38] to revise its analysis of thermal-mechanical behavior around the emplacement drifts to include site-specific, thermal-mechanical properties and spatial and temporal variations of the property values.

---

[37]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Thermal Effects on Flow (January 8–9, 2001)." Letter (January 26) to S. Brocoum, DOE. Washington, DC: NRC. 2001.

[38]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Repository Design and Thermal-Mechanical Effects (February 6–8, 2001)." Letter (February 28) to S. Brocoum, DOE. Washington, DC: NRC. 2001.

3.3.4.4.9.2 Data Are Sufficient for Model Justification

The DOE abstraction of engineered barrier subsystem flow and transport relies on input from other total system performance assessment abstractions. Thus, staff evaluation with respect to sufficient data for model justification is discussed in Sections 3.3.6 and 3.3.7.

3.3.4.4.9.3 Data Uncertainty Is Characterized and Propagated Through the Model Abstraction

DOE made several assumptions in its abstraction of flow and radionuclide transport processes in the engineered barrier subsystem to bound the uncertainties in the model parameters. The DOE approach to incorporating data uncertainty by making conservative assumptions in its abstraction is reasonable.

3.3.4.4.9.4 Model Uncertainty Is Characterized and Propagated Through the Model Abstraction

Overall, the current information, along with the agreements reached between DOE and NRC (Section 3.3.4.5), is sufficient to conclude that the necessary information will be available at the time of a potential license application to assess engineered barrier subsystem flow and transport with respect to the characterization and propagation of model uncertainty through the model abstraction.

DOE made several assumptions in its abstraction of flow and radionuclide transport processes in the engineered barrier subsystem to bound the uncertainties in the conceptual models. The DOE approach to incorporating model uncertainty by making conservative assumptions in its abstraction is reasonable. DOE, however, has not considered the potential effect of floor buckling on the rates of water flow and radionuclide release through the invert. Stress conditions induced by thermal loading could result in reverse-faulting-style slip on subhorizontal fractures beneath the floor of the emplacement drifts, which would lead to buckling of the emplacement-drift floor and a change in the hydrological characteristics of the invert and underlying rock. DOE agreed[39] to revise its analysis of thermal-mechanical behavior around the emplacement drifts to include site-specific, thermal-mechanical properties and spatial and temporal variations of the property values.

3.3.4.4.9.5 Model Abstraction Output Is Supported by Objective Comparisons

The DOE abstraction of engineered barrier subsystem flow and transport relies on input from other total system performance assessment abstractions. Thus, staff evaluation of DOE information to support its abstraction of engineered barrier subsystem flow and transport is discussed in Sections 3.3.6 and 3.3.7.

---

[39]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Repository Design and Thermal-Mechanical Effects (February 6–8, 2001)." Letter (February 28) to S. Brocoum, DOE. Washington, DC: NRC. 2001.

3.3.4.4.10 Near-Field Criticality

Using the Total System Performance Assessment–Site Recommendation (based on no waste package breach or failure at any time during the first 10,000 years of postclosure), DOE screened the occurrence of nuclear criticality for commercial spent nuclear fuel for normal conditions and seismic events (CRWMS M&O, 2000r). The NRC concerns regarding the DOE screening argument for nuclear criticality are delineated in Section 3.2.2. As agreed during the DOE and NRC Technical Exchange on Criticality,[40] DOE agreed to perform a what-if analysis, to analyze the probability and consequences of a criticality event given an early waste package failure using the topical report methodology.

This topical report (DOE, 1998) describes the methodology to be used to assess the probability and consequences of criticality events within the repository system for all fuel types, except Naval fuels, in all locations (i.e., in package, near field, and far field). In this topical report, DOE proposed to use a systematic approach for identifying scenarios and configurations that could result in a criticality event. Included are the configurations within which fissile material is precipitated in the vicinity of the waste package inside the drift or within the invert on release from the waste package.

NRC reviewed this topical report and documented the results of its review in a safety evaluation report (NRC, 2000c). This safety evaluation report contains 28 open items on the methodology, which, when closed, will document NRC acceptance of the proposed methodology to address criticality in the repository system. According to an agreement made during the DOE and NRC Technical Exchange on Criticality,[41] DOE provided NRC with Revision 1 of this topical report, which is intended to address 27 of the open items (DOE, 2000). The remaining open item on burnup measurements was discussed at the DOE and NRC Technical Exchange on Pre-Closure Safety.[42] On December 10, 2001, the NRC staff notified DOE that NRC accepted Revision 1 of the topical report for detailed technical review. If found acceptable, NRC will have confidence that DOE will be able to address the effects of criticality on the performance of the repository system in any potential license application, even if DOE is not able to support its arguments for screening criticality from the total system performance assessment.

Criticality in Naval fuel has been addressed in a separate addendum, which, for security reasons, is not discussed in this report.

---

[40]Schlueter, J.R. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Criticality (October 23–24, 2000)." Letter (October 27) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

[41]Ibid.

[42]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Pre-Closure Safety (July 24–26, 2001)." Letter (August 14) to S. Brocoum, DOE. Washington, DC: NRC. 2001.

3.3.4.4.10.1 System Description and Model Integration Are Adequate

Overall, the current information, along with the agreements reached between DOE and NRC (Section 3.3.4.5), is sufficient to conclude that the necessary information will be available at the time of a potential license application to assess near-field criticality with respect to system description and model integration.

In Revision 0 of the topical report (DOE, 2000), identified five near-field (NF) scenarios with potentials for a criticality event: (i) NF–1: solute transport of fissile material from the waste package and accumulation in the invert; (ii) NF–2: slurry transport of fissile material from the waste package and accumulation on the invert; (iii) NF–3: colloidal transport of fissile material from the waste package and accumulation in the invert; (iv) NF–4: collection of water ponds in drift, degradation of waste package and waste form, and accumulation of fissile material in clays at the bottom of the drift; and (v) NF–5: collection of water ponds in drift, degradation of waste package, and settlement of intact waste package in pond. All scenarios require—in addition to release and transport of fissile material—a degree of separation of fissile material from neutron absorbers, and mechanisms for this process are, therefore, included. Each scenario encompasses one or more configuration classes, which further specify the processes and settings that define the potentially critical configuration. For example, scenario NF–3 includes three configuration classes—NF–3a, NF–3b, and NF–3c—that specify whether colloids accumulate in waste package corrosion products, invert fractures, or degraded concrete.

In its evaluation of the near-field criticality scenarios, except for the igneous-activity-induced criticality scenario, the staff found that—contingent on the topical report revisions promised in the DOE responses to the request for additional information—DOE comprehensively identified generic and site-specific near-field criticality scenarios. With respect to igneous-activity criticality, DOE provided an approach in the topical report (DOE, 2000, Revision 01, Section 3.3.4) for identifying potential critical configurations following a volcanic event. The staff will evaluate the DOE approach and document the results in the amendment to the safety evaluation report. On the other hand, DOE screened the occurrence of igneous-induced criticality based on a low probability of formation of a critical configuration. The basis for this screening was documented in the probability of criticality within 10,000 years calculation report (CRWMS M&O, 2000h). Staff concerns with this report are discussed in Section 3.2.2.

For identifying near-field criticality configuration within each scenario, DOE proposed to quantify parameter ranges for each configuration class. Formulation of a configuration is based on parameters consistent with repository features, taking into consideration current design and site characterization. Examples include drift floor materials and host rock fracture density. DOE proposed a six-step determination for formulating a configuration: (i) fissile material source term using information generated by waste package internal configuration; (ii) water flow rates and patterns; (iii) sorption along flow paths; (iv) mineral precipitates along flow paths; (v) alternate paths when primary rock fractures are filled, including possible coalescence of contaminant plumes from several waste packages; and (vi) reaction products resulting from the plume encountering a reducing zone.

In performing the previous steps, DOE proposed to use a geochemistry transport and a geochemistry computer code to calculate fissile material accumulation external to the waste package. These models will include relevant geochemical processes and will incorporate transport. DOE indicated that the geochemical transport code PHREEQC, supplemented by a modification of EQ3/6, will be used.

Another component of near-field configuration modeling will be the configuration generator code. This code will provide bookkeeping for the transport between sites of application of a detailed geochemistry code and, in some situations, provide more rapid calculation when the detailed geochemistry code results can be used to develop heuristic models for the most significant ions for a few solution parameters.

The NRC staff accepted the DOE use of a geochemistry-transport code, a geochemistry code used in a mode that simulates transport, or both, to calculate fissile material accumulation external to the waste package, provided these are properly applied and validated.

3.3.4.4.10.2 Data Are Sufficient for Model Justification

Overall, the current information, along with the agreements reached between DOE and NRC (Section 3.3.4.5), is sufficient to conclude that the necessary information will be available at the time of a potential license application to assess near-field criticality with respect to sufficient data for model justification.

Data sufficiency for calculation of k_{eff} for near-field configurations is addressed in the safety evaluation report (NRC, 2000c). For example, one open item states that DOE needs to use the cross-sectional data corresponding to the temperature for the waste package or critical benchmarks. If a critical configuration is credible while near-field temperatures are elevated, this item would also apply to external accumulations. Revision 1 of the topical report is intended to address the open items (DOE, 2000). NRC review of this revision of the topical report will be documented in a revision to the safety evaluation report on the topical report. Additionally, DOE indicated at the DOE and NRC Technical Exchange on Criticality that additional data would be located in the validation reports for computer codes that will be used in the criticality modeling. DOE agreed[43] to provide these validation reports to the NRC before submission of a license application for the proposed Yucca Mountain repository.

With respect to geochemical models for external near-field critical configurations, NRC (2000c) did not address data sufficiency because the review was focused on methodology. DOE stated that geochemical transport modeling for external near-field critical configurations will be consistent with models supporting total system performance assessment. Therefore, data sufficiency for models of near-field release and transport for total system performance assessment (see elsewhere in this section, as well as Section 3.3.9) will, in general, ensure data sufficiency for near-field criticality models. Some exceptions to this correspondence exist. For example, the DOE model validation report on external accumulation relies on satisfactory

[43]Schlueter, J.R. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Criticality (October 23–24, 2000)." Letter (October 27) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

characterization of fracture and lithophysae distributions immediately below the drift (Bechtel SAIC Company, LLC, 2001a). The aspects of this report have not yet been reviewed.

3.3.4.4.10.3 Data Uncertainty Is Characterized and Propagated Through the Model Abstraction

Overall, the current information, along with the agreements reached between DOE and NRC (Section 3.3.4.5), is sufficient to conclude that the necessary information will be available at the time of a potential license application to assess near-field criticality with respect to the characterization and propagation data uncertainty through the model abstraction.

Data uncertainty issues with respect to calculation of k_{eff} for near-field configurations are addressed in the safety evaluation report (NRC, 2000c). For example, two relevant open items are include (i) DOE must include the cross dependency of configuration parameters for k_{eff} regression equations and (ii) DOE must include the isotopic bias and uncertainty in developing the critical limit. Revision 1 of the topical report (DOE, 2000) is intended to address the open items including those related to data uncertainty. The NRC review of this revision of the topical report will be documented in a revision to the safety evaluation report. In the DOE and NRC Technical Exchange on Criticality, DOE indicated[44] that quantification of data uncertainty would be located in the validation reports for computer codes that will be used in the criticality modeling. DOE agreed to provide these validation reports to NRC before submission of any license application for the proposed Yucca Mountain repository (NRC, 2000a).

With respect to geochemical models for external near-field critical configurations, the topical report safety evaluation report (NRC, 2000c) did not address data uncertainty because the review was focused on methodology. It is expected that data uncertainty issues not covered in other geochemical modeling applications in total system performance assessment will be addressed in future criticality reports. Reports currently available (Bechtel SAIC Company, LLC, 2001a,b) have not yet been reviewed with respect to this issue.

3.3.4.4.10.4 Model Uncertainty Is Characterized and Propagated Through the Model Abstraction

Overall, the current information, along with the agreements reached between DOE and NRC (Section 3.3.4.5), is sufficient to conclude that the necessary information will be available at the time of a potential license application to assess near-field criticality with respect to the characterization and propagation of model uncertainty through the model abstraction.

Model uncertainty issues with respect to calculation of k_{eff} for near-field configurations are addressed in the safety evaluation report (NRC, 2000c). The relevant open item states: DOE must demonstrate the adequacy of using one-dimensional calculations to capture three-dimensional neutron spectrum effects in their point-depletion calculation or use

[44]Schlueter, J.R. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Criticality (October 23–24, 2000)." Letter (October 27) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

two/three-dimensional calculations for determining the neutron spectra during the depletion cycles to be used in the depletion analyses. This open item is intended to be addressed in Revision 1 of the topical report (DOE, 2000). NRC review of this revision of the topical report will be documented in a revision to the safety evaluation report. In the DOE and NRC Technical Exchange on Criticality, DOE indicated the validation reports will support use of the inventory computer code that will be used in the criticality modeling. DOE[45] agreed to provide these validation reports to NRC prior to submission of any license application for the proposed Yucca Mountain repository.

With respect to geochemical models for external near-field critical configurations, the topical report safety evaluation report (NRC, 2000c) did not explicitly evaluate model uncertainty issues because the review was focused on methodology. It is expected that model uncertainty issues not covered in other geochemical modeling applications in total system performance assessment will be addressed in future criticality reports. Reports currently available (Bechtel SAIC Company, LLC, 2001a,b) have not yet been reviewed with respect to this issue.

3.3.4.4.10.5 Model Abstraction Output Is Supported by Objective Comparisons

Overall, the current information, along with the agreements reached between DOE and NRC (Section 3.3.4.5), is sufficient to conclude that the necessary information will be available at the time of a potential license application to assess near-field criticality with respect to model abstraction output being supported by objective comparisons.

Model verification issues with respect to calculation of k_{eff} for near-field configurations are addressed in the safety evaluation report (NRC, 2000c). Open items include: (i) DOE must present a validation methodology or work scope for external criticality models, and (ii) DOE must verify the regression equation or look-up table for all ranges of configuration and waste form parameters affecting k_{eff}. Revision 1 of the topical report is intended to address the open items (DOE, 2000), including those related to model support. NRC review of Revision 1 of the topical report will be documented in an amendment to the NRC safety evaluation report. In the DOE and NRC Technical Exchange on Criticality, DOE indicated justification of the models used in the criticality analyses would be located in the validation reports for the inventory and neutronics computer codes. DOE agreed[46] to provide these validation reports to NRC prior to submission of a license application for the proposed Yucca Mountain repository (NRC, 2000a).

DOE provided two of these reports—the Geochemistry Model Validation Report: Material Degradation and Release Model (Bechtel SAIC Company, LLC, 2001b) and Geochemistry Model Validation Report: External Accumulation Model (Bechtel SAIC Company, LLC, 2001a). These two report are currently being reviewed by staff.

---

[45]Schlueter, J.R. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Criticality (October 23–24, 2000)." Letter (October 27) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

[46]Ibid.

3.3.4.5 Status and Path Forward

Table 3.3.4-1 provides the status of all key technical issue subissues referenced in Section 3.3.4.2 and the related DOE and NRC agreements for the Radionuclide Release Rates and Solubility Limits Integrated Subissue. The agreements listed in the table are associated with one or all five generic acceptance criteria discussed in Section 3.3.4.4. Note the status and detailed agreements (or path forward) pertaining to all the key technical issue subissues are provided in Table 1.1-3 and Appendix A.

The DOE-proposed approach, together with the DOE agreements to provide NRC with additional information (through specified testing, analyses, and the like), acceptably addresses the NRC questions so that no information beyond that provided, or agreed to, will likely be required at the time of a potential license application.

Table 3.3.4-1. Related Key Technical Issue Subissues and Agreements

Key Technical Issue	Subissue	Status	Related Agreements*
Container Life and Source Term	Subissue 3—The Rate at Which Radionuclides in Spent Nuclear Fuel Are Released from the Engineered Barrier Subsystem Through the Oxidation and Dissolution of Spent Nuclear Fuel	Closed-Pending	CLST.3.01 through CLST.3.10
	Subissue 4—The Rate at Which Radionuclides in High-level Waste Glass Are Leached and Released from the Engineered Barrier Subsystem	Closed-Pending	CLST.4.01 through CLST.4.11
	Subissue 5—The Effect of In-package Criticality on Waste Package and Engineered Barrier Subsystem Performance	Closed-Pending	CLST.5.01 CLST.5.04 CLST.5.05 CLST.5.07
	Subissue 6—The Effects of Alternate Engineered Barrier Subsystem Design Features on Container Lifetime and Radionuclide Release from the Engineered Barrier Subsystem	Closed-Pending	None
Evolution of the Near-Field Environmental	Subissue 3—Effect of Coupled Thermal-Hydrologic-Chemical Processes on the Chemical Environment for Radionuclide Release	Closed-Pending	ENFE.3.03 ENFE.3.04 ENFE.3.05

Table 3.3.4-1. Related Key Technical Issue Subissues and Agreements (continued)

Key Technical Issue	Subissue	Status	Related Agreements*
Evolution of the Near-Field Environmental	Subissue 4—Effects of Coupled Thermal-Hydrologic-Chemical Processes on Radionuclide Transport Through Engineered and Natural Barriers	Closed-Pending	ENFE.4.06
	Subissue 5—Effects of Coupled Thermal-Hydrologic-Chemical Processes on Potential Nuclear Criticality in the Near Field	Closed-Pending	None
Total System Performance Assessment and Integration	Subissue 1—System Description and Demonstration of Multiple Barriers	Closed-Pending	None
	Subissue 2—Scenario Analysis and Event Probability	Closed-Pending	TSPAI.2.01 TSPAI.2.02
	Subissue 3—Model Abstraction	Closed-Pending	TSPAI.3.14 through TSPAI.3.17 TSPAI.3.42
	Subissue 4—Demonstration of Compliance with the Postclosure Public Health and Environmental Standards	Closed-Pending	None

*Related DOE and NRC agreements are associated with one or all five generic acceptance criteria.

Note: Key Technical Issue Agreement GEN.1.01 pertains to multiple integrated subissues, as well as some specific issues related to this integrated subissue.

3.3.4.6 References

Advocat, T., J.L. Crovisier, E. Vernaz, G. Ehret, and H. Charpentier. "Hydrolysis of R717 Nuclear Waste Glass in Dilute Media: Mechanisms and Rate: A Function of pH." Scientific Basis for Nuclear Waste Management XIV. Symposium Proceedings 212. T.J. Abrajano and L.H. Johnson, eds. Pittsburgh, Pennsylvania: Materials Research Society. pp. 57–64. 1991.

Bechtel SAIC Company, LLC. "Geochemistry Model Validation Report: External Accumulation Model." ANL–EBS–GS–00002. Las Vegas, Nevada: Bechtel SAIC Company, LLC. 2001a.

———. "Geochemistry Model Validation Report: Material Degradation and Release Model." ANL–EBS–GS–00001. Las Vegas, Nevada: Bechtel SAIC Company, LLC. 2001b.

Burns, W.G., A.E. Hughes, J.A.C. Marples, R.S. Nelson, and A.M. Stoneham. "Effects of Radiation on the Leach Rates of Vitrified Radioactive Waste." *Journal of Nuclear Materials*. Vol. 107. pp. 245–270. 1982.

Cavanaugh, M.A., J.A. Kargol, J. Nickerson, and N.F. Fiore. "The Anodic Dissolution of a Ni-base Superalloy." *Corrosion.* Vol. 39, No.4. pp. 144–150. 1983.

Chan, K.S. "A Micromechanical Model for Predicting Hydride Embrittlement in Nuclear Fuel Cladding Material." *Journal of Nuclear Materials.* Vol. 227. pp. 220–236. 1996.

CRWMS M&O. "U.S. Department of Energy Spent Nuclear Fuel Information in Support of TSPA-VA." DOE/SNF/REP–027. Idaho Falls, Idaho: Idaho National Engineering and Environmental Laboratory. 1998a.

———. "Total System Performance Assessment–Viability Assessment (TSPA-VA) Analyses Technical Basis Document." B00000000–01717–4301. Revision 01. Las Vegas, Nevada: CRWMS M&O. 1998b.

———. "Repository Ground Support Analysis for Viability Assessment." BCAA00000–01717–0200–00004. Revision 01. Las Vegas, Nevada: CRWMS M&O. 1998c.

———. "Repository Safety Strategy: Plan to Prepare the Safety Case to Support Yucca Mountain Site Recommendation and Licensing Considerations." TDR–WIS–RL–000001. Revision 4 ICN 01. Las Vegas, Nevada: CRWMS M&O. 2000a.

———. "Waste Form Degradation Process Model Report." TDR–WIS–MD–000001. Revision 00 ICN 01. Las Vegas, Nevada: CRWMS M&O. 2000b.

———. "Inventory Abstraction." ANL–WIS–MD–000006. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000c.

———. "Summary of In-Package Chemistry for Waste Forms." ANL–EBS–MD–000050. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000d.

———. "In-Package Chemistry Abstraction." ANL–EBS–MD–00037. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000e.

———. "Clad Degradation—Summary and Abstraction." ANL–WIS–MD–000007. Revision 00 ICN 01. Las Vegas, Nevada: CRWMS M&O. 2000f.

———. "Initial Cladding Condition." ANL–EBS–MD–000048. Revision 00 ICN 01. Las Vegas, Nevada: CRWMS M&O. 2000g.

———. "Clad Degradation—FEPs Screening Arguments." ANL–WIS–MD–000008. Revision 00 ICN 01. Las Vegas, Nevada: CRWMS M&O. 2000h.

———. "Clad Degradation—Local Corrosion of Zirconium and Its Alloys Under Repository Conditions." ANL–EBS–MD–000012. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000i.

———. "Hydride Related Degradation of SNF Cladding Under Repository Conditions." ANL–EBS–MD–000011. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000j.

———. "CSNF Waste Form Degradation Summary Abstraction." ANL–EBS–MD–000015. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000k.

———. "Environment on the Surfaces of the Drip Shield and Waste Package Outer Barrier." ANL–EBS–MD–000001. Revision 00 ICN 01. Las Vegas, Nevada: CRWMS M&O. 2000l.

———. "Total System Performance Assessment (TSPA) Model for Site Recommendation." MDL–WIS–PA–000002. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000m.

———. "Defense High-Level Waste Glass Degradation." ANL–EBS–MD–0016. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000n.

———. "Defense High-Level Waste Glass Degradation." ANL–EBS–MD–0016. Revision 00 ICN 01. Las Vegas, Nevada: CRWMS M&O. 2000o.

———. "Summary of Dissolved Concentration Limits." ANL–WIS–MD–000010. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000p.

———. "Pure Phase Solubility Limits—LANL." ANL–EBS–MD–000017. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000q.

———. "Waste Form Colloid-Associated Concentration Limits: Abstraction and Summary." ANL–WIS–MD–000012. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000r.

———. "Colloid-Associated Radionuclide Concentration Limits." ANL–EBS–MD–000020. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000s.

———. "Total System Performance Assessment (TSPA) for the Site Recommendation." MDL–WIS–PA–000002. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000t.

———. "EBS Radionuclide Transport Abstraction." ANL–WIS–PA–000001. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000u.

———. "EBS FEPs/Degradation Modes Abstraction." ANL–WIS–PA–000002. Revision 00 ICN 1. Las Vegas, Nevada: CRWMS M&O. 2000v.

———. "Ground Control for Emplacement Drifts for SR." ANL–EBS–GE–000002. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000w.

———. "In-Package Chemistry for Waste Forms." ANL–EBS–MD–000056. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2001a.

———. "In-Package Chemistry Abstraction." ANL–EBS–MD–00037. Revision 01. Las Vegas, Nevada: CRWMS M&O. 2001b.

DOE. "Viability Assessment of a Repository at Yucca Mountain. Vol. 3: Total System Performance Assessment." DOE/RW–0508/3. Las Vegas, Nevada: DOE, Office of Civilian Radioactive Waste Management. 1998.

———. "Draft Environmental Impact Statement for a Geologic Repository for the Disposal of Spent Nuclear Fuel and High-Level Radioactive Waste at Yucca Mountain, Nye County, Nevada." DOE/EIS–0250D. Las Vegas, Nevada: DOE, CRWMS M&O. 1999.

———. "Disposal Criticality Analysis Methodology Topical Report." YMP/TR–004Q. Revision 01. Las Vegas, Nevada: DOE, Office of Civilian Radioactive Waste Management. 2000.

Electric Power Research Institute. "Yucca Mountain Performance Assessment, Phase 4." Palo Alto, California: Electric Power Research Institute. 1998.

Kirchheim, R., B. Heine, H. Fischmeister, S. Hofmann, H. Knote, and U. Stoltz. "The Passivity of Iron-Chromium Alloys." *Corrosion Science*. Vol. 30, No. 7. pp. 899–917. 1989.

Knauss, K.G., W.L. Bourcier, K.D. McKeegan, C.I. Merzbacher, S.N. Nguyen, F.J. Ryerson, D.K. Smith, and H.C. Weed. "Dissolution Kinetics of a Simple Analogue Nuclear Waste Glass As a Function of pH, Time, and Temperature." Scientific Basis for Nuclear Waste Management XIII. V.M. Oversby and P.W. Brown, eds. Symposium Proceedings. Warrendale, Pennsylvania: Materials Research Society. pp. 176, 371–381. 1990.

Liang, L. and J.J. Morgan. "Chemical Aspects of Iron Oxide Coagulation in Water: Laboratory Studies and Implications for Natural Systems." *Aquatic Sciences*. Vol. 52. pp. 32–55. 1990.

Matsuo, Y. "Thermal Creep of Zircaloy-4 Cladding Under Internal Pressure." *Journal of Nuclear Science and Technology*. Vol. 24. pp. 111–119. 1987.

Mohanty, S., R. Codell, R.W. Rice, J. Weldy, Y. Lu, R.M. Byrne, T.J. McCartin, M.S. Jarzemba, and G.W. Wittmeyer. "System-Level Repository Sensitivity Analyses Using TPA Version 3.2 Code." CNWRA 99-002. San Antonio, Texas: CNWRA. 1999.

Mohanty, S., T.J. McCartin, and D.W. Esh. "Total-system Performance Assessment (TPA) Version 4.0 Code: Module Descriptions and User's Guide." San Antonio, Texas: CNWRA. 2000.

Northwood, D.O. and U. Kosasih. "Hydrides and Delayed Hydrogen Cracking in Zirconium and Its Alloys." *International Metals Review*. Vol. 28, No. 2. pp. 92–121. 1983.

NRC. NUREG–1688, "NRC Sensitivity and Uncertainty Analyses for a Proposed High-Level Waste Repository at Yucca Mountain, Nevada, Using TPA 3.1." Vol. 2. Washington, DC: NRC. March 1999.

———. "Issue Resolution Status Report, Key Technical Issue: Evolution of the Near-Field Environment." Revision 3. Washington, DC: 2000a.

———. "Issue Resolution Status Report, Key Technical Issue: Total System Performance Assessment and Integration." Revision 3. Washington, DC: NRC. 2000b.

———. "Safety Evaluation Report for Disposal Criticality Analysis Methodology Topical Report." Revision 0. Washington, DC: NRC. 2000c.

———. "Issue Resolution Status Report, Key Technical Issue: Container Life and Source Term." Revision 3. Washington, DC: NRC. 2001.

———. NUREG–1804, "Yucca Mountain Review Plan—Draft Report for Comment." Revision 2. Washington, DC: NRC. March 2002.

Oak Ridge National Laboratory. "ORIGEN2.1: Isotope Generation and Depletion Code—Matrix Exponential Method." C00371. Oak Ridge, Tennessee: Oak Ridge National Laboratory. 1983.

Ofoegbu, G.I. "Hydrological Implications of Thermally Induced Geomechanical Response at Yucca Mountain, Nevada." Proceedings of the 38th U.S. Rock Mechanics Symposium. San Antonio, Texas: CNWRA. 2001.

Pan, Y.M., V. Jain, M. Bogart, and P. Deshpande. "Effect of Iron Chlorides on the Dissolution Behavior of Simulated High-Level Waste Glasses." *Ceramic Transactions of the Environmental Issues and Waste Management Technologies in the Ceramic and Nuclear Industries.* Vol. 119. D. Spearing, et al., eds. Westerville, Ohio: American Ceramic Society. 2001.

Puls, M.P. "The Influence of Hydride Size and Matrix Strength on Fracture Initiation at Hydrides in Zirconium Alloys." *Metallurgical Transactions A.* 19A. pp. 1,507–1,522. 1988.

Shoesmith, D.W. "Fuel Corrosion Processes Under Waste Disposal Conditions." AECL–12034. Pinawa Manitoba, Canada: AECL Technologies, Inc. 1999.

Stout, R.B. and H.R. Leider. "Waste Form Characteristics Report." UCRL–ID–108314. Version 1.3. Livermore, California: Lawrence Livermore National Laboratory. 1998a.

———. "Waste Form Characteristics Report." UCRL–ID–132375, CD-ROM Version. Livermore, California: Lawrence Livermore National Laboratory. 1998b.

Tombacz, E., I. Abraham, M. Gilde, and F. Szanto. "The pH-Dependent Colloidal Stability of Aqueous Montmorillonite Suspensions." *Colloids and Surfaces.* Vol. 49. pp. 71–80. 1990.

Wronkiewicz, D.J., J.K. Bates, T.J. Gerding, and E. Veleckis. "Uranium Release and Secondary Phase Formation During Unsaturated Testing of UO_2 at 90 °C." *Journal of Nuclear Materials.* Vol. 190. pp. 107–126. 1992.

Wronkiewicz, D.J., C.R. Bradley, J.K. Bates, and L.M. Wang. "Effect of Radiation Exposure on SRL 131 Composition Glass in a Steam Environment." Scientific Basis for Nuclear Waste Management XVII. Symposium Proceedings 333. A. Barkatt and R.A. Van Konynenburg, eds. Pittsburgh, Pennsylvania: Materials Research Society. pp. 259–267. 1994.

Wronkiewicz, D.J., J.K. Bates, E.C. Buck, J.C. Hoh, J.W. Emery, and L.M. Wang. "Radiation Effects in Moist-Air Systems and the Influence of Radiolytic Products on Formation of Nuclear Waste Glass Corrosion." ANL–97/15. Argonne, Illinois: Argonne National Laboratory. 1997.

Yau, T.L. and R.T. Webster. "Corrosion of Zirconium and Hafnium." *Metals Handbook: Vol. 13—Corrosion Materials*. Park, Ohio: ASM International. 1987.

3.3.5 Climate and Infiltration

3.3.5.1 Description of Issue

The Climate and Infiltration Integrated Subissue addresses the near-surface hydrologic processes, such as precipitation, temperature, climate change, and rates of infiltration. Climate strongly influences the rates of shallow infiltration, which in turn, correlates with the amount of water entering the waste emplacement drifts. Relationship of this integrated subissue to other integrated subissues is depicted in Figure 3.3.5-1. The overall organization and identification of all the integrated subissues are depicted in Figure 1.1-2. The DOE description and technical basis for abstractions of climate and infiltration are documented in CRWMS M&O (2000a) and numerous supporting analysis and model reports. This section reviews the abstractions of climate and infiltration incorporated by DOE in its total system performance assessment. Portions of additional analysis and model reports are reviewed to the extent that they contain data or analyses that support the total system performance assessment abstractions for climate and infiltration.

3.3.5.2 Relationship to Key Technical Issue Subissues

The Climate and Infiltration Integrated Subissue incorporates subject matter previously captured in the following key technical issue subissues:

- Unsaturated and Saturated Flow Under Isothermal Conditions: Subissue 1—Climate Change (NRC, 1999)
- Unsaturated and Saturated Flow Under Isothermal Conditions: Subissue 2—Hydrologic Effects of Climate Change (NRC, 1999)
- Unsaturated and Saturated Flow Under Isothermal Conditions: Subissue 3—Present-Day Shallow Infiltration (NRC, 1999)
- Structural Deformation and Seismicity: Subissue 3—Fracturing and Structural Framework of the Geological Setting (NRC, 2000a)
- Total System Performance Assessment and Integration: Subissue 1—System Description and Demonstration of Multiple Barriers (NRC, 2000b)
- Total System Performance Assessment and Integration: Subissue 2—Scenario Analysis and Event Probability (NRC, 2000b)
- Total System Performance Assessment and Integration: Subissue 3—Model Abstraction (NRC, 2000b)
- Total System Performance Assessment and Integration: Subissue 4—Demonstration of Compliance with the Postclosure Public Health and Environmental Standards (NRC, 2000b)

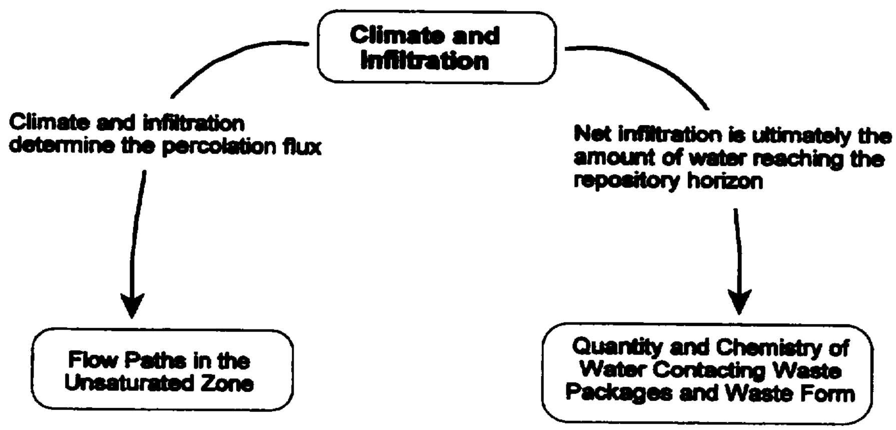

Figure 3.3.5-1. Diagram Illustrating the Relationship Between Climate and Infiltration and Other Integrated Subissues

The key technical issue subissues formed the bases for the previous versions of the issue resolution status reports and also were the bases for technical exchanges with DOE where agreements were reached for potential future resolution of subissues. The resolution status of this integrated subissue is based on the resolution status of each of the contributing key technical issue subissues. The subsequent sections incorporate applicable portions of these key technical issue subissues, however, no effort was made to explicitly identify each subissue.

3.3.5.3 Importance to Postclosure Performance

One aspect of risk-informing NRC review was to determine how this integrated subissue is related to the DOE repository safety strategy. The importance of shallow infiltration to repository performance at Yucca Mountain is recognized by DOE by identifying seepage into emplacement drifts as one of the eight principal factors in the repository safety strategy for the postclosure safety case (CRWMS M&O, 2000b) for the 10,000-year performance period. Because there is little evidence to support lateral movement of water between the ground surface and the repository, shallow infiltration determines the percolation flux at the repository horizon. The total system performance assessment abstraction for the seepage into emplacement drifts relies on seepage as a function of percolation rate. Because infiltration is the primary source of water in the unsaturated zone at Yucca Mountain, it is the first in a series of natural-system processes that must be considered to evaluate the quantity of water that could seep into emplacement drifts and to evaluate the flow paths and rates for transporting radionuclides below the repository to the water table.

Climate changes must also be considered in total system performance assessment because long-term changes in precipitation and temperature will significantly affect shallow infiltration rates (CRWMS M&O, 1999). Hence, during the 10,000-year compliance period, climate changes in the Yucca Mountain region are expected to produce (i) changes in precipitation and temperature that will affect the amount of deep percolation at the proposed repository horizon, (ii) increases in water table elevation that will reduce the distance from the repository horizon to the water table, and (iii) changes in saturated zone groundwater fluxes and flow paths from beneath the repository to the compliance boundary.

3.3.5.4 Technical Basis

The NRC has developed a Yucca Mountain Review Plan (NRC, 2002) that is consistent with the acceptance criteria and review methods found in previous issue resolution status reports. A review of DOE approaches for including climate and infiltration in total system performance assessment abstractions is provided in the following subsections. The review is organized according to the five acceptance criteria identified in Section 1.5 as follows: (i) System Description and Model Integration Are Adequate, (ii) Data Are Sufficient for Model Justification, (iii) Data Uncertainty Is Characterized and Propagated Through the Model Abstraction, (iv) Model Uncertainty Is Characterized and Propagated Through the Model Abstraction, and (v) Model Abstraction Output Is Supported by Objective Comparisons.

3.3.5.4.1 System Description and Model Integration Are Adequate

Overall, the current information, along with agreements reached between DOE and NRC (Section 3.3.5.5), is sufficient to conclude that the necessary information will be available at the time of a potential license application to assess climate and infiltration with respect to system description and model integration.

The DOE technical bases for including or excluding the features, events, and processes related to climate and infiltration are provided primarily in CRWMS M&O (2000c). A list of features, events, and processes, for which screening arguments by DOE are not adequate or require verification, is provided in Section 3.2.1 of this report. The following paragraphs provide a brief description of the conceptual and modeling approach developed by DOE to integrate features, events, and processes that affect climate and infiltration into the total system performance assessment abstraction.

The approach and technical basis for the abstraction of climate change are documented by DOE in CRWMS M&O (2000d), herein referred to as the climate analysis and model report. Key assumptions are that (i) climate is cyclical, (ii) climate change cycles can be timed with an orbital clock (i.e., Milankovitch forcing) calibrated with the Devils Hole chronology, and (iii) past climate cycles repeat themselves in sequential order. The DOE features, events, and processes database[1] was reviewed in NRC (2000b). Based on these assumptions, a 10,000-year climate history, beginning from approximately 400,000 years before the present, was selected as the most probable analog for the next 10,000 years. During this period, three different climate states have been identified: (i) present-day climate for the first 600 years; (ii) a monsoon climate that is warmer and wetter than present day for the following 1,400 years; and (iii) a glacial transition climate that is cooler and wetter than present for the balance of the 10,000-year period (CRWMS M&O, 2000a,d).

Changes in precipitation rates and temperature from one climate state to the next are estimated and integrated as boundary conditions for the shallow infiltration process model. For each climate state, time-varying precipitation and temperature boundary conditions were derived from measurements at local and climate analog sites. The basis for the choices of analog sites in Washington, Utah, Nevada, Arizona, and New Mexico is the relationship between climate change and the movement of the jet stream across the western United States (CRWMS M&O, 2000d). For the shallow infiltration abstraction, DOE has also added consideration of climate-induced changes in vegetation during future climates (CRWMS M&O, 2000e). The DOE abstraction of climate in total system performance assessment also includes an assumed climate-induced water table rise of 120 m [394 ft], which reduces transport path lengths from the proposed repository level to the water table during the monsoon and glacial-transition climate states.

The scope of the DOE shallow-infiltration process model is limited to surficial hydrological processes, with estimates of net infiltration limited to depth of the root zone only. As described in CRWMS M&O (2000a), the infiltration model covers a domain of 123.7 km^2 [47.8 mi^2] with 30 × 30 m [98 × 98 ft] computational cells. The important portions of the infiltration model domain are the 4.7-km^2 [1.8-mi^2] area of the repository footprint, which is dominated by Tiva Canyon bedrock covered by a thin layer of soil or no soil and the 38.7-km^2 [14.9-mi^2] area of the three-dimensional unsaturated zone site-scale model domain that uses the shallow infiltration estimates as steady-state boundary conditions. The shallow infiltration model is documented in CRWMS M&O (2000e).

Processes considered in the shallow infiltration model are precipitation, infiltration, evapotranspiration, snow accumulation and snowmelt, and surface water run-on. These processes are incorporated into a watershed-scale, volume-balanced model using a one-dimensional (vertical), root-zone infiltration submodel; an evaporation and net radiation submodel; a snowpack submodel; and a two-dimensional (horizontal) surface-water flow-routing submodel. Depending on the climate state, synthetic or measured meteorological data from local or climate analog sites are used as the boundary conditions for the shallow infiltration model. Combinations of a 15-year precipitation and temperature record developed from multiple local meteorological stations and two 100-year stochastically generated records are used to simulate mean, lower-, and upper-bound modern climate net infiltration. Measured meteorological data from the future climate analog sites described in CRWMS M&O (2000d) are used for lower- and upper-bound monsoon and glacial transition climate net infiltration. The

[1]DOE. "Yucca Mountain Features, Events, and Processes Database." Revision 00b. Washington, DC: DOE. Preliminary version. September 1999.

meteorological boundary conditions are spatially distributed based on empirical correlations to elevation. In the infiltration model, water that exceeds the infiltration capacity of a soil column is routed to lower elevation nodes for subsequent infiltration or further downgradient routing. Potential evapotranspiration is determined by an energy balance that depends on net radiation, air temperature, ground heat flux, a saturation-specific humidity curve, and wind.

Calibration of the shallow infiltration is accomplished on a subwatershed basis using two storm events with concurrent stream gage measurements. Important parameters, fixed before calibration, include the soil thickness and equivalent bedrock permeability. Where soil is thin {0.5 m [1.6 ft]}, which is particularly true for the repository footprint, bedrock permeability becomes a sensitive parameter. Important parameters adjusted during the calibration process are root zone depth and percent area contributing to runoff. DOE agreed[2] to demonstrate that effects of near surface lateral flow on the spatial variability of net infiltration are appropriately considered.

It is reasonable to assume that vegetation density will increase and vegetation types will change during wetter and colder future climates. However, the infiltration analysis and model report indicates that these changes in vegetation are only considered for the upper-bound climate scenarios (CRWMS M&O, 2000e, Section 6.9.4). For the upper-bound monsoon climate, the root-zone weighting parameters were adjusted to approximate a 40-percent vegetation cover (compared with 20 percent for modern climate) and the maximum thickness of the bedrock root zone layer was increased from 2 to 2.5 m [6.5 to 8.2 ft]. For the upper-bound glacial-transition climate, the root-zone weighting parameters were adjusted to approximate a 60-percent vegetation cover and the maximum thickness of the bedrock root-zone layer was increased to 3 m [9.84 ft]. These increases in vegetation cover and root-zone depth increase evapotranspiration and, hence, decrease net infiltration. Increases in root-zone depth also increase the water-holding capacity of the soil and bedrock, which decreases shallow infiltration. It is reasonable to assume that the large increases in precipitation assumed for the upper-bound future climate scenarios would support increased vegetation cover and vegetation types with greater root-zone depth. No basis nor sensitivity analysis, however, was presented for the magnitude of the changes that account for increased vegetation and root-zone depth, hence, it is difficult to access the reasonableness of the magnitude of these changes. DOE agreed[3] to provide justification for use of the evapotranspiration model, and justify the use of the analog site temperature data.

Output from the DOE infiltration model is used to define spatially distributed, time-averaged estimates of net infiltration, which provide the necessary steady-state flux boundary conditions for the site-scale unsaturated zone flow model. Nine boundary conditions for the unsaturated zone flow model are developed, including low-, medium-, and high-infiltration scenarios for each of the three climate states. This integration of the infiltration model with the site-scale unsaturated zone flow model requires spatial averaging because the unsaturated zone flow

---

[2]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Total System Performance Assessment and Integration (August 6–10, 2001)." Letter (August 23) to S. Brocoum, DOE. Washington, DC: NRC. 2001.

[3]Ibid.

model grid is coarser than that of the infiltration model. Temporal averaging is also used to convert the time-varying infiltration model output into an equivalent steady-state flux. DOE justifies spatial averaging and use of a steady-state flux boundary because the sparsely fractured, highly sorptive Paintbrush nonwelded tuff layer beneath the surface at Yucca Mountain is postulated to attenuate episodic surface infiltration pulses and spatially smooth localized zones of high infiltration. As discussed in Section 3.3.6, the assumption of steady-state flow caused by the Paintbrush nonwelded tuff requires further basis, which DOE has agreed to provide.

In summary, the unsaturated zone process model report, supporting analysis and model reports, and DOE and NRC agreements generally provide sufficient descriptions of the conceptual models, model formulations, and methods of integrating the models into total system performance assessment analyses. The climate and infiltration abstractions are generally consistent with the available data, and important physical phenomena and couplings are adequately incorporated or bounded. Assumptions are clearly stated and used consistently. The unsaturated zone process model report and supporting analysis and model reports provide sufficient descriptions of (i) the technical basis for estimating climate conditions during the compliance period, (ii) integration of the future climate conditions with the shallow-infiltration process, (iii) the approach and technical basis for the shallow-infiltration model, and (iv) integration of the shallow-infiltration process model into total system performance assessment analyses.

3.3.5.4.2 Data Are Sufficient for Model Justification

Overall, the current information, along with agreements reached between DOE and NRC (Section 3.3.5.5), is sufficient to conclude that the necessary information will be available at the time of a potential license application to assess climate and infiltration with respect to data being sufficient for model justification.

Detailed descriptions of the climate data sets and how they can be used to justify the abstraction approach are provided in CRWMS M&O (2000d). Three data sets are crucial to development of the DOE approach: (i) Devils Hole calcite deposits, (ii) Owens Lake microfossil records, and (iii) meteorologic records from climate analog sites.

Devils Hole is located approximately 90 km [56 mi] south of Yucca Mountain in the Paleozoic limestone that comprises the regional aquifer. Calcite has precipitated on the walls of Devils Hole during the last 500,000 or more years, leaving a record of $\delta^{18}O$ that provides insights about long-term changes in average annual groundwater temperatures (i.e., climate change) (CRWMS M&O, 2000d). Because the calcites in Devils Hole have been dated, they provide a chronology of climate that reflects a cyclic change from interglacial to glacial climates. A relation between Devils Hole data and orbital precession is evident where maximal values of precession mark the ends of the Devils Hole interglacials and other warm periods (CRWMS M&O, 2000d). This relation was developed to provide a rationale for timing future climate change in terms of the Devils Hole chronology of climate change in the Yucca Mountain region. Thus, the Devils Hole data set provides a reasonable basis for forecasting the cyclical timing of climate change.

To reconstruct the climatological conditions that existed in the Yucca Mountain region for each climate state, microfossil records of diatoms and ostracodes from cores drilled at Owens Lake were used (CRWMS M&O, 2000d). Owens Lake is located on the eastern side of the Sierra Nevada Mountains, east of Los Angeles. The known environmental tolerances of ostracode and diatom species provide a way to interpret the relative total dissolved solids of the Owens paleolake, and the relative temperature of its water. The total dissolved solids and water-temperature information are then used to qualitatively infer a range of likely climate conditions—namely precipitation and temperature—during the Owens Lake stage 11 (interglacial period about 400,000 years ago) to stage 10 (glacial period) transition. In this manner, monsoon and glacial-transition climate states were identified as the sequence of climate states most likely to follow present-day climate in the Yucca Mountain region during the 10,000-year compliance period.

Once qualitative descriptions of future climate states were obtained from the Owens Lake record, it was necessary to identify analog sites where present-day climate conditions were qualitatively consistent with those inferred for the monsoon and glacial-transition climates (CRWMS M&O, 2000d). Meteorological stations within these analog areas were then selected to obtain precipitation and temperature data to be used as analog input to the infiltration process model. For the monsoon climate, meteorological stations from two analog sites (Nogales, Arizona, and Hobbs, New Mexico) were chosen to represent an upper bound; the modern climate meteorological record was used as a lower bound. For the glacial transition climate, lower- and upper-bound analog sites (Beowawe, Nevada; Delta, Utah; Rosalia, Washington; Spokane, Washington; and St. John, Washington) were chosen. Shallow infiltration simulation results using lower- and upper-bound meteorological records as inputs were averaged to create a mean net infiltration estimate for the future climates. The meteorological inputs for estimating mean shallow infiltration for the modern climate, however, were a synthetic 15-year record developed from local Yucca Mountain stations and a stochastically developed 100-year precipitation and temperature record developed from Yucca Mountain and Nevada Test Site weather stations.

There are no direct measurements of shallow infiltration at Yucca Mountain. The infiltration model relies on matrix pore water geochemical data to support and constrain the long-term shallow infiltration results. The infiltration model uses a plug-flow, or bucket, approach to model one-dimensional movement of water vertically into the soil and bedrock (CRWMS M&O, 2000e). Two-dimensional runoff routing is incorporated by tracking the amount of water flux that cannot be stored or transmitted vertically downward by the top layer. The plug-flow approximation for vertical flow ignores the effect of capillarity in the unsaturated zone, though this may be offset by the coarse vertical grids of the one-dimensional infiltration model. DOE agreed[4] to provide a technical basis that the water-balance plug-flow model adequately represents the nonlinear flow processes represented by Richard's equation, particularly over the repository where there is thin soil.

---

[4]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Total System Performance Assessment and Integration (August 6–10, 2001)." Letter (August 23) to S. Brocoum, DOE. Washington, DC: NRC. 2001.

Data collected at Yucca Mountain to support infiltration modeling include soil and bedrock hydrological properties, meteorological data, soil and bedrock water-content profiles, soil and bedrock water chemistry and temperature, and streamflow measurements. These data reveal the episodic nature of precipitation events at Yucca Mountain. Short periods of heavy precipitation (including an occasional snowmelt) may produce fleeting surface run-on and stream flow events. The data also indicate that areas with thin soils and highly fractured bedrock permit rapid infiltration of water below the root zone. Meteorological measurements indicate that the average annual potential evapotranspiration rate is approximately six times greater than the average annual precipitation rate for the current climate, resulting in the arid condition of Yucca Mountain between episodic precipitation events (CRWMS M&O, 2000e). These data and observations are generally consistent with the conceptual model for infiltration at Yucca Mountain on which the process model is based and show the importance of considering processes such as surface runoff and evapotranspiration.

Estimation of equivalent bedrock permeability for a fractured tuff for the one-dimensional bucket model is highly uncertain. Bedrock permeability is a sensitive parameter for net infiltration estimates where soils are thin or nonexistent (NRC, 1999). The approach described in CRWMS M&O (2000e) to estimate equivalent bedrock properties for the one-dimensional infiltration model did not change from that used for the viability assessment. Rough estimates of properties were developed from laboratory measurements of cores and assumed fracture properties. A range of estimates for each lithologic unit was developed because matrix scaling and unknown fracture properties led to a large uncertainty in hydraulic property estimates. Six different assumptions about fracture characteristics were used to estimate six different columns of equivalent permeability. Geometric averaging of core permeability values was used to upscale the matrix permeability to the infiltration grid scale. The column of values chosen to be used in the infiltration model was determined by modeling changes in water content profiles over time as measured by neutron probes installed in shallow boreholes. Because neutron probes measure water content in the rock matrix, equilibration of bedrock matrix and fractures must be assumed. Near the ground surface, however, this equilibration is unlikely for moderate to densely welded tuffs because of preferential or focused flow in fracture networks. Alcove 1 is the only area where large-scale infiltration measurements into the soil and bedrock have been made at Yucca Mountain. Steady-state influx rates at the ground surface in the Alcove 1 tests can be used to approximate the equivalent bedrock permeability. The influx rates are an aspect of the test that have not been formally documented. However, informal communication of the rates indicate that the equivalent permeability of the fractured bedrock is 35 times greater than the bedrock permeability value used in the model.

Though fracture properties were not directly used in the final choice of equivalent hydraulic properties, the available fracture data from surface exposures could be used to support the assumed fracture characteristics used to develop the columns of potential values. Analysis in the Tiva Canyon upper lithophysal unit indicates that normalized fracture area is 30 to 50 times greater, and fracture porosity is 2 to 10 times greater[5] than assumed for the

[5]Fedors, R.W., D.A. Ferrill, and A.P. Morris. "Integration of Fracture Data into Shallow Infiltration Models." *Presentation to Geological Society of America, November 13–17, 2000.* Reno, Nevada. 2000.

infiltration model. This fracture porosity is relevant to surface infiltration at the ground surface (i.e., two-dimensional porosity along the ground surface plane).

To calibrate the model, streamflow measurements have been collected for selected subwatersheds as calibration targets; data from two storms were used (CRWMS M&O, 2000e). As part of this calibration, geochemical data were used to constrain estimates of net infiltration. Although this approach could lead to a well-calibrated model, it may lack the ability to accurately estimate net infiltration because the data are not sufficient to derive a unique best set of model parameters. For example, important calibrated parameters such as root zone depth, porosity, and area of watershed contributing to runoff may simply compensate for errors in fixed parameters such as bedrock permeability and soil depth.

The DOE infiltration model does not consider variations in bedrock saturation. Bedrock dryout zones beneath areas of thin or no soil cover, however, would tend to lessen rates of shallow infiltration. Thus, the predicted high net infiltration rates in areas of thin soil cover may be partly the result of neglecting variability in bedrock saturation. Another factor to consider is that water potential, saturation, and chloride content data from the Exploratory Studies Facility and East-West Cross Drift suggest that the runoff/run-on component of shallow infiltration is underpredicted beneath stream channels over the repository footprint.[6] So, there are indications that the DOE infiltration model may tend to overpredict net infiltration on ridges with thin soils and underpredict it in stream channels. The overall effect may be that net infiltration is more variable spatially than is predicted by the model.

For the concerns discussed previously, DOE agreed[7] to provide justification and documentation of Monte Carlo analyses. This would include the uncertain input parameters from the Analysis of Infiltration Uncertainty analysis and model report (e.g., reconciling the Alcove 1 test results with the bedrock permeability in the infiltration model).

Net infiltration is highly sensitive to soil depth, particularly when the soil layer covering the bedrock is thin. The repository footprint is dominated by thin soils. Measurements of soil thickness for a 30-m [98-ft] pixel—the grid size for the net infiltration model—are extremely difficult on the highly irregular bedrock surface. On steep slopes, point measurement of soil thickness can vary from 0 to 1 m [3.3 ft] in a 1-m^2 [11-ft^2] area. In small wash channels alone, the soil thickness can vary from 0 to 2 m [6.5 ft] for a 30-m [98-ft] distance. The approach described in CRWMS M&O (2000e) for estimating soil thickness values for the net infiltration grid is based on empirical equations for different geomorphic categories and different depth classes. Each equation assumes a slope angle-soil depth correlation. Although equations for thicker soils are constrained by information from borehole logs, thin soil thicknesses can only be constrained by qualitative visual observations in the field because of the highly irregular bedrock surface. Although the DOE approach leads to qualitatively reasonable results,

---

[6]Flint, L. "Measuring Flow and Transport in Unsaturated Fractured Rocks: A Large-Scale Unsaturated Flow Experiment." *Presentation to Geological Society of America, November 13–17, 2000.* Reno, Nevada. 2000.

[7]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Unsaturated and Saturated Flow Under Isothermal Conditions (October 31–November 2, 2000)." Letter (November 17) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

uncertainty in soil thickness estimates should not be ignored over the repository footprint where the soils are dominantly thin. This uncertainty, combined with the uncertainty in the constraints on the model results described in Section 3.3.5.4.5, leads to uncertain model results, particularly for future climate conditions. Instead of choosing to establish a better basis for the parameter values and constraints, DOE agreed[8] to propagate uncertainty through the abstraction in the total system performance assessment as described in Sections 3.3.5.4.3 and 3.3.5.4.4.

In summary, much of the available data at Yucca Mountain has been collected using acceptable techniques, and the conceptual models for climate and infiltration are generally consistent with the available site-specific data. The review of the paleoclimate data for the Yucca Mountain region and meteorological data from climate analog sites indicate that they have been collected using acceptable techniques. Although the DOE shallow-infiltration model adequately includes important features and processes, direct measurements of shallow infiltration are lacking, and a basis for the parameter values lacks supporting data. The missing data needed to fully support the shallow infiltration estimates, however, can be compensated for by propagating data uncertainty through the model, which is discussed in the following section. Thus, with the caveat that data uncertainty must be propagated through the shallow infiltration abstraction (see Section 3.3.5.4.3), adequate DOE and NRC agreements and sufficient data exist to support development of the shallow-infiltration process model for Yucca Mountain.

3.3.5.4.3 Data Uncertainty Is Characterized and Propagated Through the Model Abstraction

Overall, the current information, along with agreements reached between DOE and NRC (Section 3.3.5.5), is sufficient to conclude that the necessary information will be available at the time of a potential license application to assess climate and infiltration with respect to data uncertainty being characterized and propagated through the model abstraction.

CRWMS M&O (2000a) identifies several sources of data uncertainty. First, there is uncertainty in knowing whether changes in $\delta^{18}O$ values are directly correlated with changes in mean annual precipitation and mean annual temperature or if there is a lead or a lag time between changes in regional climate. Second, each Devils Hole sample integrates a particular thickness of carbonate in a continuous sample series and represents about 1,000 years. Consequently, the data would not reveal changes in regional climate with durations much less than 1,000 years. Third, there is uncertainty in the sediment accumulation rate that was used to infer relative ages of the microfossils obtained from cores in Owens Lake. There is no simple nor objective way of assessing the nature of any of these three sources of uncertainty. A fourth source of uncertainty is the standard deviation associated with age estimates of Devils Hole calcite samples. Although the standard deviation of Devils Hole ages is itself an estimate of uncertainty, that estimate was not incorporated into the abstraction because the other sources of uncertainty cannot be estimated, and hence, their relation to standard deviation is unknown. A final source of uncertainty is the choice of a starting point, at 400,000 years before the

---

[8]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Total System Performance Assessment and Integration (August 6–10, 2001)." Letter (August 23) to S. Brocoum, DOE. Washington, DC: NRC. 2001.

present, assumed equivalent to modern climate for purposes of projecting forward. Though possible, the choice is somewhat arbitrary, considering the lack of data from Devils Hole over the last 8,000 years.

To address data uncertainty in the shallow infiltration model, DOE developed distributions for values of 12 input parameters to the infiltration process model (CRWMS M&O, 2000f, Table 4-1). These input parameters were stochastically sampled using a Latin hypercube sampling algorithm in a 100-realization Monte Carlo analysis of infiltration for a glacial-transition climate state. CRWMS M&O (2000f) did not, however, provide tangible evidence that 100 realizations would adequately represent the uncertainty distribution. The parameters chosen for development of uncertainty distributions were effective bedrock porosity, bedrock root zone thickness, soil depth, precipitation, potential evapotranspiration, bulk bedrock saturated hydraulic conductivity, soil saturated hydraulic conductivity, two parameters associated with bare soil evaporation, and effective surface-water flow area. Two additional parameters are related to sublimation and melting of snow cover.

Upper and lower bounds for the 12 infiltration model parameters were estimated partly by using physical limits and partly by judgment based on existing bounds within the available data. The logic and the data used to deduce reasonable limits, however, are not clearly described in CRWMS M&O (2000f), and the methods used to deduce these parameter distributions are not transparent to NRC staff. In fact, some of the parameter ranges listed in the infiltration uncertainty analysis and model report are physically impossible (e.g., a value of −10 for the lower bound of the precipitation multiplier). DOE indicated there are typographic errors that will be corrected in a future revision of the infiltration analysis and model report. DOE also agreed[9] to provide additional justification for the 12 stochastic parameters identified in CRWMS M&O (2000f, Table 4-1).

The range and distribution of net infiltration rates obtained from these Monte Carlo analyses of parameter uncertainty were used as the basis for estimating probability weighting factors of 0.17, 0.48, and 0.35 for low-, medium-, and high-infiltration scenarios, respectively (CRWMS M&O, 2000f, Table 6-2). For example, for a total system performance assessment realization with stochastically sampled inputs, there is a 48-percent chance that the unsaturated zone flow fields obtained from the medium-infiltration case will be selected. In this manner, data uncertainty is propagated through the total system performance assessment abstraction. It should be noted that values of the probability weighting factors are expected to change as a result of an NRC concern that the DOE upper-bound net infiltration estimates for the three climate states do not incorporate parameter uncertainty. DOE agreed[10] to provide the documentation sources and schedule for the Monte Carlo method for analyzing infiltration.

In summary, there are several concerns related to the propagation of data uncertainties in the abstraction of climate and infiltration. In each case, however, either the current DOE approach

---

[9]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Unsaturated and Saturated Flow Under Isothermal Conditions (October 31–November 2, 2000)." Letter (November 17) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

[10]Ibid.

is reasonably bounding, the uncertainty is not expected to be of significant importance to performance predictions, or DOE agreed to provide additional information or analyses to support the abstraction approach. Uncertainty is not incorporated into the deterministic approach used to estimate magnitude, type, and duration of climate change. Although CRWMS M&O (2000g) relies on robust canisters (no failures over 10,000 years) to justify that climate uncertainty is not important in total system performance assessment analyses, the duration of the glacial transition climate (i.e., covering 80 percent of the 10,000-year performance period) is, nonetheless, a reasonable conservative bound. DOE agreed that parameter uncertainty should be reflected in the lower- and upper-bound infiltration scenarios. The DOE approach to incorporating data uncertainty into the infiltration process model and total system performance assessment abstraction through Monte Carlo analysis will provide sufficient information for review.

3.3.5.4.4 Model Uncertainty Is Characterized and Propagated Through the Model Abstraction

Overall, the current information, along with agreements reached between DOE and NRC (Section 3.3.5.5), is sufficient to conclude that the necessary information will be available at the time of a potential license application to assess climate and infiltration with respect to model uncertainty being characterized and propagated through the model abstraction.

Perhaps the most significant model uncertainty lies in not knowing what the magnitude will be of changes in precipitation and temperature for each climate state. This uncertainty is addressed in the climate model abstraction by using several analog sites for each climate state. The locations of these analog sites are described in CRWMS M&O (2000d, Table 2). Upper- and lower-bound values for precipitation and temperature are quantified by selecting meteorological stations at locations in areas with some or all of the common ostracodes and diatoms found in Owens Lake, thus integrating the biology, hydrology, and climate linkages that were expressed in the past at Owens Lake. Mean (expected) values of precipitation and temperature are determined by averaging the upper- and lower-bounding values obtained from the analog sites. DOE estimates of annualized mean, lower-, and upper-bound values of precipitation and temperature for the three climate states are listed in Table 3.3.5-1. These annualized values are for comparison only; actual inputs to the infiltration process model are time varying on a daily basis (CRWMS M&O 2000e). Model uncertainty that DOE did not directly consider is the variation of climate, on the scale of decades to centuries, that could lead to greater estimates of net infiltration.

It can be seen in Table 3.3.5-1 that the ranges of precipitation between lower- and upper-bounds for all climate states is quite large; hence, a large range of model uncertainty is incorporated into the abstraction. Note also that the increase in precipitation from modern to the monsoon and glacial transition climates is also quite large. These precipitation estimates for future climates are consistent with those previously estimated by DOE for the viability assessment (DOE, 1998) and found to be acceptable by NRC (1999) but have a more rigorous technical basis linking the approach to Devils Hole calcite and Owens Lake microfossil data.

Infiltration process model uncertainty results from the combined model parameter uncertainty, uncertainty in boundary conditions defined by the climate abstraction, and general uncertainty in the validity of various conceptual model assumptions. It is thus important that the ranges of infiltration estimates—the low, medium, and high cases—for each postulated climate state are sufficient to reasonably bound this combined uncertainty. The approach described in CRWMS M&O (2000a), however, falls short of this goal because the estimated low-, medium-, and high-infiltration scenarios are based only on consideration of climate uncertainty. That is, the low-, medium-, and high-infiltration estimates for each climate scenario are determined by setting model parameters to their expected values and simply running the model with the mean, lower-bound, and upper-bound climate boundary conditions (see Table 3.3.5-1). The DOE approach yields a set of nine infiltration scenarios used as constant-flux boundary inputs to the site-scale unsaturated zone flow model (CRWMS M&O, 2000a). The nine unsaturated zone flow model net infiltration scenarios are summarized in Table 3.3.5-2. Note that net infiltration flux to the unsaturated zone flow model is spatially variable; the values in Table 3.3.5-2 are averaged over the unsaturated zone flow model domain and are used for comparison only. A specific concern with the DOE approach is that model parameter uncertainty is not propagated into the range of net infiltration estimates, which should reflect both model and data uncertainties. Additionally, the current estimates for the upper-bound net infiltration scenarios are significantly lower than those the NRC staff considers acceptable for the viability

Table 3.3.5-1. Annualized Precipitation and Temperature Estimates Used in the Climate Abstraction for the Three Climate States*

Climate	Mean Annual Precipitation and Temperature		
	Lower Bound	**Mean**	**Upper Bound**
Modern (Note: temperature not provided for modern)	186.8 mm/yr [7.35 in/yr]	190.6 mm/yr [7.50 in/yr]	268.4 mm/yr [10.57 in/yr]
Monsoon	190.6 mm/yr [7.50 in/yr] 17.3 °C [63.1 °F]	302.7 mm/yr [11.92 in/yr] 17.2 °C [63.0 °F]	414.8 mm/yr [16.33 in/yr] 17.0 °C [62.6 °F]
Glacial Transition	202.2 mm/yr [7.96 in/yr] 10.2 °C [50.4 °F]	317.8 mm/yr [12.51 in/yr] 9.8 °C [49.6 °F]	433.5 mm/yr [17.07 in/yr] 9.4 °C [48.9 °F]

*CRWMS M&O. "Unsaturated Zone Flow and Transport Model PMR." Section 3.5.1.8. TDP–NBS–HS–000002. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000.

Table 3.3.5-2. Area-Averaged Mean Annual Infiltration Estimates for the Unsaturated Zone Site-Scale Flow Model Area*

Climate	Low-Infiltration Case (mm/yr)	Medium-Infiltration Case (mm/yr)	High-Infiltration Case (mm/yr)
Modern Climate	1.3 [0.051 in/yr]	4.6 [0.18 in/yr]	11.1 [0.44 in/yr]
Monsoon Climate	4.6 [0.18 in/yr]	12.2 [0.48 in/yr]	19.8 [0.78 in/yr]
Glacial-Transition Climate	2.5 [0.10 in/yr]	17.8 [0.70 in/yr]	33.0 [1.30 in/yr]

*CRWMS M&O. "Unsaturated Zone Flow and Transport Model PMR." Table 3.5-4. TDP–NBS–HS–000002. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000.

assessment (DOE, 1998). The DOE plan to address this NRC concern includes three elements: (i) develop an upper-bound infiltration case based on the 90th percentile from the Monte Carlo analysis of the glacial-transition climate documented in CRWMS M&O (2000f), (ii) develop upper-bound infiltration cases for the monsoon and modern climates by proportional scaling based on the ratio between upper-bound and mean cases for the glacial-transition climate, and (iii) calculate new probability weighting factors into the total system performance assessment analyses using the same methodology developed in CRWMS M&O (2000f).

At a technical exchange,[11] DOE staff conveyed preliminary estimates for the revised high-infiltration scenarios for the glacial-transition and monsoon climates as being 53 and 30 mm/yr [2.1 and 1.2 in/yr]; the estimate for modern climate is not expected to change. Probability weighting factors also need to be recalculated, DOE staff explained, because selecting the high-infiltration scenario from the end of the Monte Carlo distribution translates to a decreased probability that this scenario would occur. It was stated that the revised probability weighting factor for the high-infiltration scenario will be about 20 percent. Although the weighting factor is lower, total system performance assessment simulations would still sample a reasonably large proportion of high-infiltration scenarios. NRC staff agreed that this concern regarding infiltration model uncertainty is resolved, pending incorporation of these proposed changes into total system performance assessment calculations used to support the license application.

In summary, the use of multiple analog sites results in a wide range of mean annual precipitation estimates for the monsoon and glacial-transition climate states. The estimated climate conditions are consistent with those previously found acceptable by NRC staff (NRC, 1999) and are considered acceptable for the current abstraction. Staff are concerned that the range of net infiltration estimates used for the abstraction does not adequately bound the model and parameter uncertainty in the shallow infiltration process model. In response, DOE agreed to use Monte Carlo analyses of model parameters to revise the upper-bound infiltration scenario for the total system performance assessment abstraction.

[11]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Unsaturated and Saturated Flow Under Isothermal Conditions (October 31–November 2, 2000)." Letter (November 17) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

3.3.5.4.5 Model Abstraction Output Is Supported by Objective Comparisons

Overall, the current information, along with agreements reached between DOE and NRC (Section 3.3.5.5), is sufficient to conclude that the necessary information will be available at the time of a potential license application to assess climate and infiltration with respect to model abstraction being supported by objective comparisons.

Predictions of future climate are derived from meteorological conditions recorded at analog sites across the western United States. The sites were chosen based on their consistency with the Owens Lake record. In the climate analysis and model report, it is reasoned that climate conditions at Owens Lake are similar to those at the top of Yucca Mountain and subject to the same climate cycles. Regional changes to climate are driven by shifts in the jet stream pattern. Thus, an objective comparison exists between modern climate conditions at Yucca Mountain and Owens Lake. Although the comparisons are subjective between future climate conditions (based on the Owens Lake record) and those climate conditions that may occur at Yucca Mountain, confidence is gained because uncertainty is incorporated through the use of upper-bound precipitation and temperature estimates for the climate abstraction.

Estimates of precipitation and temperature during past glacial climates in the Yucca Mountain region have been derived from a study of the plant macrofossils found in packrat middens (Thompson, et al., 1999). These observations were interpreted to show that, during the last full-glacial climate at Yucca Mountain, mean annual precipitation was approximately 266–321 mm [10.5–12.6 in.], and mean annual temperature was about 7.9–8.5 °C [46.2–47.3 °F]. Although these estimates are uncertain, they provide an independent and objective basis for comparison showing that a precipitation estimate for the last full glacial climate at Yucca Mountain is consistent with the mean estimated for the glacial-transition climate (Table 3.3.5-1). In addition, the uncertainty in the estimates from packrat middens is conservatively bounded by upper-bound glacial-transition estimates (Table 3.3.5-1).

For validation of the shallow-infiltration abstraction, CRWMS M&O (2000e) cites a 7–14-mm/yr [0.28–0.55-in/yr] estimate of recharge to the saturated zone beneath Yucca Mountain, based on measurements of chloride from saturated zone boreholes (CRWMS M&O, 2000h) and an assumed long-term average annual precipitation rate of 170 mm/yr [6.7 in/yr]. Using a chloride mass balance approach, net infiltration has also been estimated from matrix pore water samples in the Exploratory Studies Facility; samples obtained from the North Ramp, Main Drift, and Cross Drift correspond to infiltration rates of 5–14 mm/yr [0.20–0.55 in/yr]; samples from the South Ramp yielded estimates of 1–2 mm/yr [0.04–0.08 in/yr] (CRWMS M&O, 2000h). These estimates are broadly consistent with the DOE estimates for spatial distributions of infiltration for the modern climate (CRWMS M&O, 2000e). It should be noted, however, these values were revised downward by approximately 50 percent from previously reported values (CRWMS M&O, 1998) because of a reinterpretation of the chloride input from precipitation and wind-blown processes. The reduction was accomplished by a reinterpretation of the chloride input from precipitation and wind-blown processes. The previously assumed chloride concentration of precipitation and wind-blown soil particles (0.62 mg/L) [3.58×10^{-7} 07/in^3] was revised downward (0.30 mg/L) [1.73×10^{-7} 07/in^3] based on historical interpretation of Cl-36 data. Temporal aspects, both in the precipitation and in the dating of bedrock matrix water and its geochemical composition, clearly are important.

There are uncertainties and potential biases associated with recharge estimates obtained from the chloride mass balance method. For example, the chloride mass balance applies to one-dimensional plug flow in a homogeneous porous medium. Chloride measurements are obtained from matrix pore water, yet the conceptual model for flow in the unsaturated zone at Yucca Mountain is that flow occurs predominantly in fractures; fracture-matrix interactions are not taken into account in the chloride mass balance method. Based on the assumptions for the method, chloride mass balance should lead to an estimate of the lower bound on percolation, not the mean value. Thus, to gain additional confidence in chloride-based infiltration estimates, the site-scale unsaturated zone flow and transport model, which includes fracture-matrix interactions, used pore water chloride concentrations in the Exploratory Studies Facility and East-West Cross Drift as calibration targets. Model results indicate a range of net infiltration rates from 3–10 mm/yr [0.12–0.39 in/yr] (CRWMS M&O, 2000a, Figure 3.8-4). Though this range of infiltration estimates is generally consistent with infiltration model calculations, the meaning of the results are not clear. The results may demonstrate (i) that the model is self-consistent with its calibration to those same infiltration rates, (ii) that the assumed chloride fluxes at the ground surface can be matched with the matrix chloride concentrations, and (iii) that a deficiency in using a simple mixing model approach exists. Chloride content in the subsurface depends on the flux at the ground surface and also on the spatially variant evaporation history in the subsurface, particularly in the Tiva Canyon where barometric pumping is likely prominent.

Neutron probe profiles collected during a 4-year period were used to estimate shallow infiltration at approximately 98 locations covering a range of geomorphic sites. The range of shallow infiltration estimates is 0–80 mm/yr [0–3.1 in/yr] for all geomorphic areas (CRWMS M&O, 2000e); an approximate average of 33 mm/yr [1.3 in/yr] is estimated for ridges and slideslopes only, which dominate the repository footprint (CRWMS M&O, 2000e, Figure 6-5). The high value of shallow infiltration may reflect the correspondence with wetter than average climatic conditions during the short period of measurements collected in the 1990s. Conversely, neutron probe data reflect minimum estimates because the probes estimate bedrock matrix water content; flow bypassing in fractures may be missed by the probe.

In an independent analysis, Winterle, et al. (1999) estimated an infiltration rate of 6.7 mm/yr [0.26 in/yr], for an area comparable to the unsaturated zone flow model area, based on a fit of infiltration estimates obtained from borehole temperature profiles to a lognormal statistical distribution. Uncertainty in shallow infiltration estimates based on temperature profiles is reflected in (i) the bias of geomorphic locations of boreholes, (ii) the bias created by elimination of boreholes with high values of percolation because they must be affected by a fault system, and (iii) the bias caused by the small number of point estimates.

The uncertainty in the parameter values and the uncertainty in the constraints on the model results described in this section, lead to uncertain model results, particularly for future climate conditions. DOE agreed[12] to propagate uncertainty through the abstraction in the total system

[12]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Total System Performance Assessment and Integration (August 6–10, 2001)." Letter (August 23) to S. Brocoum, DOE. Washington, DC: NRC. 2001.

performance assessment. In addition, DOE agreed[13] to provide justification and documentation of Monte Carlo analyses. This would include the uncertain input parameters from the analysis of infiltration uncertainty (CRWMS M&O, 2000f).

In summary, the climate and infiltration abstractions of Yucca Mountain are generally consistent with the DOE interpretations of empirical observations. Interpretation of past climate conditions based on plant macrofossils in packrat middens is used to verify DOE climate forecasts for Yucca Mountain. For the shallow infiltration model, there is generally good agreement—well within one order of magnitude—between the infiltration model estimates and those obtained from geochemical data, flow and transport modeling, and borehole thermal profiles. Considering the manifold uncertainties in model boundary conditions, parameter values, and conceptual model assumptions, however, it is important for DOE to assess repository performance using ranges of future climate conditions and net infiltration estimates that reasonably bound those uncertainties. The agreements reached between DOE and NRC (discussed in the preceding section), when implemented, will ensure that the range of uncertainty in climate change and in the spatial and temporal distributions of infiltration at Yucca Mountain will be adequate for inclusion in a potential license application.

3.3.5.5 Status and Path Forward

Table 3.3.5-3 provides the status of all key technical issue subissues, referenced in Section 3.3.5.2, for the Climate and Infiltration Integrated Subissue. The table also provides the related DOE and NRC agreements pertaining to the Climate and Infiltration Integrated Subissue. The agreements listed in the table are associated with one or all five generic acceptance criteria discussed in Section 3.3.5.4. Note that the status and the detailed agreements (or path forward) pertaining to all the key technical issue subissues, are provided in Table 1.1-3 and Appendix A.

The DOE-proposed approach, together with the DOE agreements to provide NRC with additional information (through specified testing, analyses, and the like), acceptably addresses the NRC questions so that no information beyond that provided, or agreed to, will likely be required at the time of a potential license application.

Table 3.3.5-3. Related Key Technical Issue Subissues and Agreements

Key Technical Issue	Subissue	Status	Related Agreements*
Unsaturated and Saturated Flow Under Isothermal Conditions	Subissue 1—Climate Change	Closed	None
	Subissue 2—Hydrologic Effects of Climate Change	Closed	None
	Subissue 3—Present-Day Shallow Infiltration	Closed-Pending	USFIC.3.01 USFIC.3.02

[13]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Unsaturated and Saturated Flow Under Isothermal Conditions (October 31–November 2, 2000)." Letter (November 17) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

Table 3.3.5-3. Related Key Technical Issue Subissues and Agreements (continued)			
Key Technical Issue	Subissue	Status	Related Agreements*
Structural Deformation and Seismicity	Subissue 3—Fracturing and Structural Framework of the Geologic Setting	Closed-Pending	None
Total System Performance Assessment and Integration	Subissue 1—System Description and Demonstration of Multiple Barriers	Closed-Pending	None
	Subissue 2—Scenario Analysis and Event Probability	Closed-Pending	TSPAI.2.01 TSPAI.2.02
	Subissue 3—Model Abstraction	Closed-Pending	TSPAI.3.18 TSPAI.3.19 TSPAI.3.20 TSPAI.3.21
	Subissue 4—Demonstration of Compliance with the Postclosure Public Health and Environmental Standards	Closed-Pending	None
*Related DOE and NRC agreements are associated with one or all five generic acceptance criteria.			

3.3.5.6 References

CRWMS M&O. "Chapter 2: Unsaturated Zone Hydrology Model. Total System Performance Assessment—Viability Assessment (TSPA-VA) Analyses Technical Basis Document." B00000000–01717–4301–0002. Revision 01. Las Vegas, Nevada: TRW Environmental Safety Systems, Inc. 1998.

———. "Total System Performance Assessment—Site Recommendation Methods and Assumptions." TDR–MGR–MD–000001. Revision 00. Las Vegas, Nevada: CRWMS M&O. 1999.

———. "Unsaturated Zone Flow and Transport Model PMR." TDP–NBS–HS–000002. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000a

———. "Repository Safety Strategy: Plan to Prepare the Safety Case to Support Yucca Mountain Site Recommendation and Licensing Considerations." TDRL–WIS–RL–000001. Revision 04. Las Vegas, Nevada: CRWMS M&O. 2000b.

———. "Features, Events, and Processes in UZ Flow and Transport." ANL–NBS–MD–000001. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000c.

———. "Future Climate Analysis." ANL–NBS–GS–000008. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000d.

———. "Simulation of Net Infiltration for Modern and Potential Future Climates." ANL–NBS–GS–000032. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000e.

———. "Analysis of Infiltration Uncertainty." ANL–NBS–HS–000027. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000f.

———. "Total System Performance Assessment for the Site Recommendation." TDR–WIS–PA–000001. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000g.

———. "Analysis of Geochemical Data for the Unsaturated Zone." ANL–NBS–GS–000004. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000h.

DOE. "Viability Assessment of a Repository at Yucca Mountain." Overview and all five volumes. DOE/RW–0508. Las Vegas, Nevada: DOE, Office of Civilian Radioactive Waste Management. 1998.

NRC. "Issue Resolution Status Report, Key Technical Issue: Unsaturated and Saturated Flow Under Isothermal Conditions." Revision 2. Washington, DC: NRC. 1999.

———. "Issue Resolution Status Report, Key Technical Issue: Structural Deformation and Seismicity." Revision 3. Washington, DC: NRC. 2000a.

———. "Issue Resolution Status Report, Key Technical Issue: Total-System Performance Assessment and Integration." Revision 3. Washington, DC: NRC. 2000b.

———. NUREG–1804, "Yucca Mountain Review Plan—Draft Report for Comment." Revision 2. Washington, DC: NRC. March 2002.

Thompson, R.S., K.H. Anderson, and P.J. Bartlein. "Quantitative Paleoclimatic Reconstructions from Late Pleistocene Plant Macrofossils of the Yucca Mountain Region." U.S. Geological Survey Open-File Report 99-338. 1999.

Winterle, J.R., R.W. Fedors, D.L. Hughson, and S. Stothoff. "Review of the Unsaturated Zone Models Used to Support the Viability Assessment of a Repository at Yucca Mountain." San Antonio, Texas: CNWRA. 1999.

3.3.6 Flow Paths in the Unsaturated Zone

3.3.6.1 Description of Issue

The Flow Paths in the Unsaturated Zone Integrated Subissue addresses effects of subsurface geology and hydrologic processes on the distribution and velocity of flow between the shallow subsurface and the water table at Yucca Mountain. Relationship of this integrated subissue to other integrated subissues is depicted in Figure 3.3.6-1. The overall organization and identification of all the integrated subissues are depicted in Figure 1.1-2. The DOE description and technical basis for abstractions of flow paths in the unsaturated zone are documented in CRWMS M&O (2000a) and numerous supporting analysis and model reports. This section reviews the abstractions of flow paths in the unsaturated zone incorporated by DOE in its total system performance assessment.

3.3.6.2 Relationship to Key Technical Issue Subissues

The Flow Paths in the Unsaturated Zone Integrated Subissue incorporates subject matter previously captured in the following key technical issue subissues:

- Unsaturated and Saturated Flow Under Isothermal Conditions: Subissue 4—Deep Percolation (NRC, 1999)
- Radionuclide Transport: Subissue 1—Radionuclide Transport Through Porous Rock (NRC, 2000a)
- Radionuclide Transport: Subissue 3—Radionuclide Transport Through Fractured Rock (NRC, 2000a)
- Structural Deformation and Seismicity: Subissue 3—Fracturing and Structural Framework of the Geologic Setting (NRC, 2000b)
- Thermal Effects on Flow: Subissue 1—Features, Events, and Processes Related to Thermal Effects on Flow (NRC, 2000c)
- Thermal Effects on Flow: Subissue 2—Thermal Effects on Temperature, Humidity, Saturation, and Flux (NRC, 2000c)
- Repository Design and Thermal-Mechanical Effects: Subissue 2—Design of the Geologic Repository Operations Area for the Effects of Seismic Events and Direct Fault Disruption (NRC, 2000d)
- Repository Design and Thermal-Mechanical Effects: Subissue 3—Thermal-Mechanical Effects on Underground Facility Design and Performance (NRC, 2000d)
- Evolution of the Near-Field Environment: Subissue 1—Importance to Performance of Coupled Thermal-Hydrological-Chemical Effects on Seepage and Flow (NRC, 2000e)

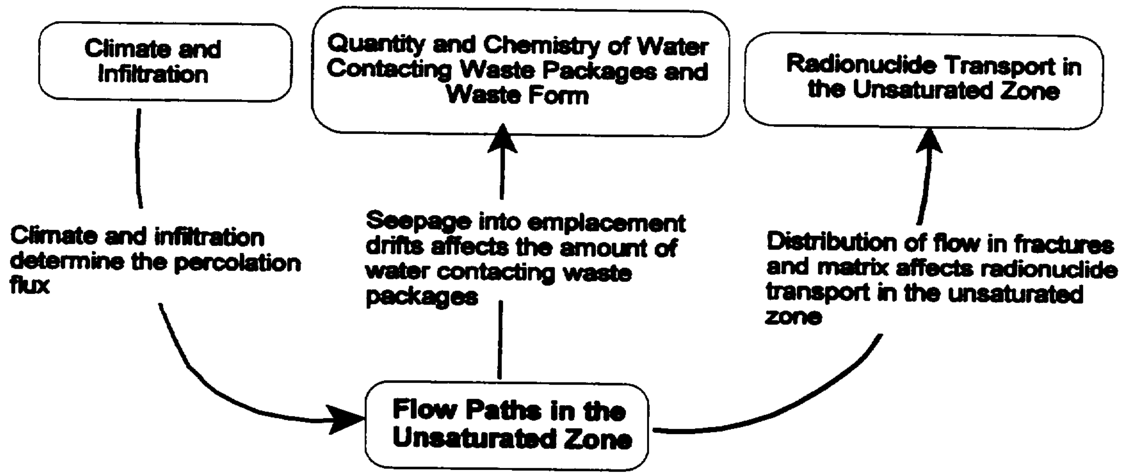

Figure 3.3.6-1. Diagram Illustrating the Relationship Between Flow Paths in the Unsaturated Zone and Other Integrated Subissues

- Total System Performance Assessment and Integration: Subissue 1—System Description and Demonstration of Multiple Barriers (NRC, 2000f)
- Total System Performance Assessment and Integration: Subissue 2—Scenario Analysis and Event Probability (NRC, 2000f)
- Total System Performance Assessment and Integration: Subissue 3—Model Abstraction (NRC, 2000f)
- Total System Performance Assessment and Integration: Subissue 4—Demonstration of Compliance with the Postclosure Public Health and Environmental Standards (NRC, 2000f)

The key technical issue subissues formed the bases for the previous versions of the issue resolution status reports and also were the bases for technical exchanges with DOE where agreements were reached on what additional information DOE needed to provide to resolve the subissue. The resolution status of this integrated subissue is based on the resolution status of each of the contributing key technical issue subissues. The subsequent sections incorporate applicable portions of these key technical issue subissues, however, no effort was made to explicitly identify each subissue.

3.3.6.3 Importance to Postclosure Performance

One aspect regarding risk-informing the NRC review was to determine how this integrated subissue is related to the DOE repository safety strategy. The importance of considering flow paths in the unsaturated zone at Yucca Mountain is directly related to two of the principal factors in the current postclosure safety case identified by DOE in the repository safety strategy (CRWMS M&O, 2000b)—seepage into emplacement drifts and radionuclide delay through the unsaturated zone. Above the proposed repository horizon, the spatial distribution of hydrologic properties in the unsaturated zone can affect the spatial and temporal distribution of flow intersecting repository drifts. For example, flow of a given volume of water uniformly distributed in space and time is less likely to drip into an underground opening than if the same volume of water was channeled or focused into a small area above a drift or if the water was to arrive as a transient pulse. Within the proposed repository horizon, host-rock properties and engineering design features will affect the quantity of water that may contact drip shields or waste packages, which may affect waste package corrosion and mobilize radionuclides in the event of a waste package failure. Below the repository horizon, it is necessary to understand how the spatial distribution of hydrologic properties may affect the flow paths from the proposed repository horizon to the water table. For example, flow diverted into fast pathways along faults will have short travel times to the water table, and less mineral surface area will be available for sorption of radionuclides. Conversely, flow through sparsely fractured, vitric, nonwelded tuffs will occur mainly in rock matrix with much slower transport velocity and greater exposure of the surface area of mineral grains for radionuclide sorption.

Sensitivity analyses DOE conducted for the site recommendation (CRWMS M&O, 2000c) show that proposed repository performance at Yucca Mountain can be affected by flow focusing in fracture networks and seepage into drifts. Because of the assumed high diffusive releases from the waste packages, however, neither of these two processes had a significant effect on performance, particularly at simulation times prior to 40,000 years when the drip shield is mostly intact and Tc-99 dominates the dose estimate.

3.3.6.4 Technical Basis

NRC has developed a Yucca Mountain Review Plan (NRC, 2002) that is consistent with the acceptance criteria and review methods found in previous issue resolution status reports. A review of DOE approaches for including flow paths in the unsaturated zone in total system performance assessment abstractions is provided in the following subsections. The review is organized according to the five acceptance criteria identified in Section 1.5: (i) System Description and Model Integration Are Adequate, (ii) Data Are Sufficient for Model Justification, (iii) Data Uncertainty Is Characterized and Propagated Through the Model Abstraction, (iv) Model Uncertainty Is Characterized and Propagated Through the Model Abstraction, and (v) Model Abstraction Output Is Supported by Objective Comparisons.

3.3.6.4.1 System Description and Model Integration Are Adequate

Overall, the current information, along with agreements reached between DOE and NRC (Section 3.3.6.5), is sufficient to conclude that the necessary information will be available at the time of a potential license application to assess flow paths in the unsaturated zone with respect to system description and model integration.

The site-scale unsaturated zone flow model is a three-dimensional, dual-continuum, unsaturated flow model used to estimate the flow rates and spatial distribution of flow reaching the proposed repository horizon and to evaluate potential contaminant transport pathways to the water table. For the mountain-scale unsaturated zone flow model, outputs from nine infiltration process model scenarios were used to develop an equal number of steady-state flux boundaries for discrete flow model realizations corresponding to the low, medium, and high net-infiltration scenarios for each of the three climate states. The numerical model grid represents the complex geology and stratigraphy using 32 layers with differing hydrologic properties. These layers dip to the east and are offset by numerous faults that are explicitly considered in the model. The area of the proposed repository transects three different model layers of the Topopah Spring welded tuff unit: about 10 percent is in the middle nonlithophysal layer, 78 percent in the lower lithophysal layer, and 12 percent in the lower nonlithophysal layer (CRWMS M&O, 2000d).

Each layer in the site-scale unsaturated zone flow model is assigned homogenous hydrologic properties, with the exception of the layers in the Calico Hills nonwelded unit, which are assigned hydrologic properties for either vitric or zeolitically altered rock types. The intralayer variability of hydrologic properties for the Calico Hills nonwelded unit is necessary to reproduce observations of perched water bodies found primarily in the northern part of the proposed repository area where lower-permeability, sparsely fractured zeolitic rock units predominate. The presence of the perched water bodies creates potential for the lateral flow of water to nearby high-permeability faults. Three-dimensional simulations of flow and radionuclide transport in the northern part indicate that flow in faults increases with depth below the repository horizon so that, over the unsaturated zone model domain, 35 percent of the deep percolation reaches the water table through faults (CRWMS M&O, 2000a). The percentage of flow from the repository horizon that reaches the water table through faults is not clear in the related process model report and analysis and model report. However, radionuclide transport studies using unsaturated zone flow fields from the mean modern infiltration scenario clearly show that rapid flow in fault zones contributes substantially to the calculated arrival of nonsorbing species at the water table (e.g., CRWMS M&O, 2000e, Section 6.12). DOE agreed[1] to provide the analysis of geochemical data used for support of the flow field below the repository.

Output from the site-scale unsaturated zone flow model is integrated into total system performance assessment analyses in two ways. First, estimates of flow reaching the proposed repository horizon in fractures are used to develop maps of percolation flux that are input to the drift seepage abstraction, which calculates the fraction of waste canisters that receive drips and the fraction of water that seeps into repository drifts. Second, calculated flow vectors in both fracture and matrix continua are used to delineate nine sets of unsaturated zone flow fields

---

[1]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Total System Performance Assessment and Integration (August 6–10, 2001)." Letter (August 23) to S. Brocoum, DOE. Washington, DC: NRC. 2001.

used as input for the abstraction of radionuclide transport in the unsaturated zone. The drift seepage abstraction is discussed in the following paragraphs; the abstraction of radionuclide transport in the unsaturated zone is discussed in Section 3.3.7 of this report.

DOE acknowledges that accurate prediction of seepage from fractures into underground openings is an extremely difficult endeavor, and many of the physical processes that may affect seepage rates are poorly understood. Hence, DOE does not expect to accurately predict either individual seepage events or the precise spatial distribution along the emplacement-drift axis or the drift ceiling. Rather, the approach taken is aimed at yielding robust, conservative seepage estimates for a wide range of hydrologic conditions (CRWMS M&O, 2000a). The seepage abstraction begins with the Seepage Calibration Model (CRWMS M&O, 2000f), which incorporates results from air-permeability and liquid-release tests from Niche 3650 of the Exploratory Studies Facility to develop a methodology for the subsequent development of seepage process models. The Seepage Calibration Model is used to develop methodology and provide some confidence in the conceptual model for the performance assessment abstraction. The calibrated properties estimated from this model, however, are not used directly in the seepage abstraction. Rather, the seepage model for performance assessment (CRWMS M&O, 2000g) was developed as a stochastic approach to provide seepage estimates for a variety of hydrologic properties, percolation fluxes, and drift shapes. These stochastic results are then used in the seepage abstraction (CRWMS M&O, 2000h) to develop a simplified transfer function approach to include drift seepage in total system performance assessment simulations.

The seepage model for total system performance assessment is a three-dimensional, single-continuum, drift-scale unsaturated flow model used to develop transfer functions to estimate the fraction of wetted waste packages and the rate of seepage onto the wetted packages as functions of percolation flux at the repository horizon. This drift seepage process model represents a 5.23-m [17.2-ft] drift segment and is used to develop two transfer functions for use in the seepage abstraction. The first transfer function is a relationship between percolation flux and the fraction of waste package locations onto which seepage occurs (seepage fraction). The second transfer function describes a relationship between percolation flux and the seepage flux that enters those drift segments that receive seepage (seepage flux). An adjustment to the seepage flux transfer function was made to account for the effects of changes in the drift shape caused by rockfall. DOE simulations using the seepage model for total system performance assessment suggested a moderate increase of drift seepage as a result of partial drift degradation. Accordingly, seepage flow rates were increased by a factor of 1.55 to account for the effects from partial drift degradation and rock bolts. Seepage flow rates were further increased by 10 percent to account for potential correlation between fracture network permeability and the van Genuchten α parameter (related to capillary retention). These adjustment factors are based on results obtained from alternative scenario modeling (CRWMS M&O, 2000g). For example, seepage estimates from alternative models with correlated permeability and α parameters were 0–10 percent higher than the uncorrelated model; thus, rather than incorporate the correlated seepage model into the abstraction, DOE simply increased the current abstraction estimates by 10 percent, the upper end of this range.

The seepage abstraction for total system performance assessment makes use of the transfer functions for seepage fraction and seepage flux using maps of percolation flux estimates from the site-scale unsaturated zone flow model that are divided into six subregions. DOE recognizes that flow within the hundreds-of-meters scale of the six subregions may occur as localized weeps that focus flow from scales of several tens of meters into the scales smaller than the 15-m × 5.23-m [49-ft × 17.2-ft] scale of the drift seepage model. To account for this potential focusing, the area-averaged flux to each subregion is modified in the seepage abstraction using a flow-focusing factor (CRWMS M&O, 2000h, Section 6.3.3). The adjusted percolation fluxes are then used to obtain seepage fraction and seepage flux estimates for each subregion from the aforementioned transfer functions. Seepage fraction estimates are then reduced by dividing by the focusing factor to account for the fact that focusing of flow in one area needs to be balanced by a reduction of flow to other areas (CRWMS M&O, 2000h, Section 6.3.3).

Thermal-hydrological effects on seepage are accounted for by using the flux time histories from the thermal-hydrology abstraction (CRWMS M&O 2000i, Section 6.3) as input to the seepage abstraction. During the thermal pulse, increased percolation flux estimated from the drift-scale thermal-hydrological model is used as input to the seepage fraction and seepage flow rate transfer functions.

Depending on stress states and fracture orientations, various changes to fracture aperture could occur as a result of waste-generated thermal effects. DOE presently assumes that thermal-mechanical effects can be neglected in the drift seepage abstraction (CRWMS M&O, 2000j). To justify this assumption, DOE evaluated thermal-mechanical effects on hydrological properties through analyses of localized thermally induced rock response near a heated drift (CRWMS M&O, 2000k). However, an important case of a potential increase in the aperture of subhorizontal fractures in pillars between drifts was not considered. Such aperture increases may result from thermal-mechanical effects and could be important to cross-repository water flow because of the potential diversion of water flux from pillars to adjacent drifts, thereby focusing flux toward the drift (Ofoegbu, et al., 2001). To address this concern, DOE agreed[2] to provide (i) sensitivity analyses of thermal-mechanical effects on fracture permeability, including the effects of boundary conditions, coefficient of thermal expansion, fracture distributions, rock mass and fracture properties, and drift degradation, consistent with site-specific data and integrated with appropriate models; and (ii) the results of additional validation analysis of field tests related to the thermal-mechanical effects on fracture permeability.

DOE proposes to neglect thermal-hydrological-chemical-induced changes to hydrological properties based on numerical simulations of the Topopah Spring welded tuff that show that any such changes will have a negligible effect on seepage and flow paths (CRWMS M&O, 2000a,c). However, seepage and flow paths also can be affected by thermal-hydrological-chemical-induced changes to hydrological properties of the nonwelded Paintbrush Tuff and Calico Hills formations, for which no numerical simulations or analyses have been provided. The technical basis has not been provided for neglecting thermal alteration of the nonwelded

---

[2]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Thermal Effects on Flow (January 8–9, 2001)." Letter (January 26) to S. Brocoum, DOE. Washington, DC: NRC. 2001.

Paintbrush Tuff and Calico Hills hydrogeologic units. To address this concern, DOE agreed[3] to provide (i) additional documentation of results of thermal-hydrological-chemical simulations showing negligible porosity and permeability changes in the nonwelded Paintbrush Tuff and Calico Hills hydrogeological units; and (ii) additional technical bases for the treatment of the effects of cementitious materials on hydrologic properties, including an evaluation of the potential effects on hydrologic properties and radionuclide transport characteristics of the unsaturated zone.

The identification and screening of features, events, and processes are discussed in Section 3.2 of this report. Features, events, and processes for which DOE screening arguments were not adequate or required verification are discussed, as are their associated path forward. Several features, events, and processes are excluded from the Total System Performance Assessment–Site Recommendation abstraction of unsaturated zone flow based on screening arguments that the features, events, and processes are of low probability or low consequence to performance predictions. The screening arguments pertaining to the abstraction of flow paths in the unsaturated zone are outlined by CRWMS M&O (2000l). The adequacy of features, events, and processes integration into the total system performance assessment abstractions is discussed in Section 3.2.1.

In summary, the unsaturated zone process model report, supporting analysis and model reports, and DOE and NRC Agreements generally provide sufficient descriptions of the conceptual models, model formulations, and methods of integrating the unsaturated zone flow and drift seepage models into total system performance assessment analyses. Important design features, physical phenomena, and couplings are adequately incorporated or bounded for inclusion in a potential license application. Assumptions are clearly stated and used consistently throughout the abstraction of flow paths in the unsaturated zone.

3.3.6.4.2 Data Are Sufficient for Model Justification

Overall, the current information, along with agreements reached between DOE and NRC (Section 3.3.6.5), is sufficient to conclude that the necessary information will be available at the time of a potential license application to assess flow paths in the unsaturated zone with respect to data being sufficient for model justification.

An extensive database is available for rock matrix properties at Yucca Mountain. These properties include moisture retention characteristics, permeability, porosity, and rock density, which are all measured in the laboratory on samples and cores collected from bedrock transects, surface-based boreholes, and alcove, drift, and niche boreholes in the Exploratory Studies Facility (e.g., Flint, 1998).

Pneumatic pressure signals between boreholes, core saturation data from laboratory measurements, and *in-situ* moisture potential profiles from boreholes were used to calibrate

---

[3]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Evolution of the Near-Field Environment (January 9–12, 2001)." Letter (January 26) to S. Brocoum, DOE. Washington, DC: NRC. 2001.

the unsaturated zone flow model (CRWMS M&O, 2000m). Observations of perched water also are used for unsaturated zone flow model calibration. Perched water bodies exist in the north below the potential repository horizon and in the south in the vicinity of Ghost Dance fault. Perched water bodies have been encountered in boreholes at both the vitrophyre between the Topopah Spring welded tuff and Calico Hills nonwelded units and at the vitric-zeolitic interface within the Calico Hills nonwelded unit. Data from pumping tests were collected to evaluate the spatial extent of the perched water bodies, and water samples were collected for age dating.

Subsurface studies in the underground Exploratory Studies Facility include data from four alcoves in the North Ramp: Alcove 1 provides access to the upper Tiva Canyon welded tuff unit, Alcove 2 to the Bow Ridge fault, Alcove 3 to the upper Paintbrush nonwelded tuff contact, and Alcove 4 to the lower Paintbrush nonwelded tuff contact. These alcoves were largely used to collect cores, measure air permeability, and sample gases. Alcoves 6 and 7, along the Main Drift, were designed to measure the properties of the Ghost Dance fault. Alcoves 4 and 6 were used to conduct fracture-matrix and fault-matrix interaction tests. Alcove 1 was instrumented with seepage collectors and wall sensors for a large-scale infiltration and seepage test. Bomb-pulse Cl-36 data have verified the existence of fast flow from the land surface to the potential repository horizon. A majority of the bomb-pulse signal locations in the Exploratory Studies Facility and East-West Cross Drift can be linked with locations where faults cross the Paintbrush nonwelded tuff, though several of these locations have no clear association with faults. It should be noted that investigators at Lawrence Livermore National Laboratory and Los Alamos National Laboratory appear to have collected conflicting data regarding the presence of bomb-pulse Cl-36 in the Exploratory Studies Facility. The U.S. Nuclear Waste Technical Review Board suggested that high priority be given to resolving this conflict.[4] DOE agreed[5] to reconcile the differences between the Cl-36 studies. Until the conflict is resolved, however, it is conservative to continue conceptual model development assuming the earlier findings that bomb-pulse Cl-36 has penetrated to repository depths.

Geochemical data such as total chloride, nonbomb-pulse Cl-36, and calcite fillings in fractures are used to build confidence in the conceptual and numerical models of flow and transport processes occurring in the mountain and to constrain the predictions of local and global percolation fluxes. This type of model validation is discussed further in Section 3.3.5.

Data from Niche 3650 seepage tests help to evaluate the capillary barrier and seepage threshold (zero seepage below a threshold percolation flux) conceptual models and provide estimates of fracture-network, moisture-retention properties. These data include air permeability and measurements of injected aqueous dye tracers released as pulses above the ceiling of Niche 3650 (CRWMS M&O, 2000n). The observed distribution of tracers arriving at the ceiling of the niche was sampled to evaluate spatial distributions of flow paths

---

[4]Cohon, J.L. Letter (June 16) to Dr. Ivan Itkin, Director, Office of Civilian Radioactive Waste Management, DOE. Arlington, Virginia: U.S. Nuclear Waste Technical Review Board. <www.nwtrb.gov/corr/jlc076.pdf> 2000.

[5]Schlueter, J.R. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Unsaturated and Saturated Flow Under Isothermal Conditions (August 16–17, 2000)." Letter (September 8) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

associated with the wetting-front movement through the fractures. These data are used in inverse models to estimate hydrologic properties for fracture networks surrounding drifts.

DOE researchers interpret the seepage test data to indicate that seepage thresholds may be much larger than the percolation fluxes predicted by the unsaturated zone flow model (CRWMS M&O, 2000f). NRC previously commented, however, that conclusions drawn from Niche 3650 seepage tests potentially could be biased by ventilation dryout, the close proximity of the injection boreholes to the Niche ceiling, and by injection rates much greater than ambient percolation flux (e.g., NRC, 1999). Several ongoing tests at Yucca Mountain, if conducted carefully, may address these concerns. These tests include the Alcove 8–Niche 3 test and the East-West Cross Drift passive monitoring test. In the Alcove 8–Niche 3 test, tracer-bearing water is to be applied to areas in Alcove 8 of the East-West Cross Drift, about 10 m [33 ft] directly above Niche 3 of the Exploratory Studies Facility. This test encompasses a relatively large volume (compared to previous tests) and is sealed off from ventilation. Of perhaps greater interest are ongoing passive monitoring tests in an approximately 1-km [0.62-mi] section of the East-West Cross Drift and in Alcove 7, which have been sealed off from ventilation (except for periodic entry to maintain equipment) and are continuously monitored to evaluate when ambient conditions have returned. DOE agreed[6] to complete the planned and ongoing testing in the underground at Yucca Mountain to address this issue.

Ongoing seepage and transport tests in the drifts, niches, and alcoves at Yucca Mountain are being used to evaluate seepage and solute transport properties at Yucca Mountain. If and when repository construction occurs, it may not be feasible to conduct new seepage and transport studies for each repository drift. Rather, performance confirmation of seepage and transport properties may be based largely on examination of fracture patterns that intersect drift walls to evaluate whether they are consistent with fracture patterns in the drifts, niches, and alcoves used to develop and validate the total system performance assessment abstraction. Therefore, an approach needs to be in place to relate observed fracture patterns to possible drift seepage and transport properties. Although such an approach may be largely qualitative, it would nonetheless provide a useful basis for performance confirmation. DOE agreed[7] that observations of seepage need to be related to observed fracture patterns. Accordingly, observations of seepage in the passive test in the East-West Cross Drift will be related to full periphery fracture maps and other fracture data; fracture characterization data from the Alcove 8–Niche 3 test will also be provided.

Seepage into drifts also may be affected by thermally driven redistribution of water caused by waste-generated heat. An objective of the current design (Enhanced Design Alternative II) is to maintain temperatures below boiling in the pillars between drifts to allow condensate drainage between drifts. The ability to achieve this design objective depends, in part, on the efficacy of

---

[6]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Total System Performance Assessment and Integration (August 6–10, 2001)." Letter (August 23) to S. Brocoum, DOE. Washington, DC: NRC. 2001.

[7]Schlueter, J.R. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Structural Deformation and Seismicity (October 11–12, 2000)." Letter (October 27) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

the ventilation system. The CRWMS M&O (2000o) ventilation model shows 70-percent heat removal by drift ventilation flow rates between 10 and 15 m^3/s [353 and 530 ft^3/s]. Several simplifying assumptions used in this model are not supported by experimental data, however. To address this concern, a quarter-scale ventilation test is being conducted at the Engineered Barrier Subsystem Test Facility in North Las Vegas, Nevada (CRWMS M&O, 2000p). DOE agreed[8] to provide results of the ventilation test in an update to the ventilation model.

Another concern related to thermal effects on flow is the lack of data to support modeling of fracture saturations, extent of dryout, formation of heat pipes, liquid fluxes in heat pipes, and, ultimately, the fate of thermally mobilized water in the drift-scale heater test. This concern is important because a key aspect of the proposed repository (Enhanced Design Alternative II) is the intention for thermally mobilized water to condense and drain through the pillars between drifts. Given uncertainties of the drift-scale heater test, such as in the losses of moisture through the bulkhead, and the lack of quantitative measurements of condensation and drainage in fractures, it is not clear whether the results of the drift-scale heater test can be used to determine the fate of thermally mobilized water. Measurements of mass losses through the drift-scale heater test bulkhead may help to reduce this uncertainty somewhat, but, if significant losses have occurred through the bulkhead during the past 3 years, it may be too late to assess those losses. To address this concern, DOE agreed[9] to provide a white paper on the technical basis for the current DOE understanding of heat and mass losses through the drift-scale heater test bulkhead and the effects of such losses on the test results. The white paper will include the technical basis for the decision to not monitor heat and mass losses through the drift-scale heater test bulkhead. The white paper will also address uncertainty in the fate of thermally mobilized water in the drift-scale heater test and the effect this uncertainty has on conclusions drawn from the drift-scale heater test results.

In summary, much of the available data on geology, hydrology, and geochemistry at Yucca Mountain have been collected using acceptable techniques, and the conceptual models for unsaturated zone flow and drift seepage are generally consistent with the available site-specific data. DOE has agreed to provide additional information and results from several ongoing and planned tests to validate conceptual models for relationships between seepage into drifts and fracture patterns, thermal and thermal-mechanical effects on flow and seepage, and effects of ventilation on the distribution of heat and water in pillars between drifts.

3.3.6.4.3 Data Uncertainty Is Characterized and Propagated Through the Model Abstraction

Overall, the current information, along with agreements reached between DOE and NRC (Section 3.3.6.5), is sufficient to conclude that the necessary information will be available at the time of a potential license application to assess flow paths in the unsaturated zone with respect to data uncertainty being characterized and propagated through the model abstraction.

---

[8]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Thermal Effects on Flow (January 8–9, 2001)." Letter (January 26) to S. Brocoum, DOE. Washington, DC: NRC. 2001.

[9]Ibid.

Uncertainties generally exist in the estimated rock and fracture hydrologic properties because of sparse data and limitations of the estimation procedures used. This is particularly true for fracture and fault properties, such as moisture retention parameters and porosity. Because these properties cannot be readily measured, they were indirectly estimated from other measurements such as air permeability and fracture spacing. Site data are used for initial estimates of most matrix and fracture properties (CRWMS M&O, 2000q). Matrix porosity, fracture porosity, and residual saturation were fixed before calibration, whereas the remaining properties were further adjusted during the model calibration process. Thus, many of the parameter values used in the flow model are more a product of calibration than of site data analysis (CRWMS M&O, 2000m). DOE agreed[10] to use the field test data to provide additional confidence in the seepage abstraction and associated parameter values.

A concern with the treatment of data uncertainty in the abstraction of flow paths in the unsaturated zone is that measurement error, bias, and scale dependence in the saturation, water potential, and pneumatic pressure test data are not adequately accounted for in the process model used to predict flow paths in the unsaturated zone for total system performance assessment. For example, standard deviations of saturation data from cores were used to estimate weights for the weighted-least-squares inverse algorithm (CRWMS M&O, 2000m), but the effect of measurement errors on the resulting calibrated properties was not evaluated. Three types of data (matrix saturation from cores, water potential from boreholes, and pneumatic pressures) were obtained on different scales ranging from a few centimeters for cores to several tens of meters or more for pneumatic pressures. Matrix saturations from core data were upscaled by arithmetic averaging, a process that may tend to smooth out variability. It is not clear how the scale dependence of the water potentials and pneumatic pressure data were treated. Pneumatic pressure data are known to be scale-dependent because fracture permeabilities estimated from barometric pumping responses tend to be about two orders of magnitude greater than those determined from air-injection testing (CRWMS M&O, 2000b). The nonlinear least-squares maximum likelihood inverse method implemented in ITOUGH2 is essentially used only to obtain single parameter values and fails to properly account for all sources of variability and uncertainty and to propagate those sources through the calibrated model. Thus, the measurement error must be generalized to include such things as scale-dependence and modeling errors, because there is no other way to account for uncertainty in the least-squares inverse approach (e.g., McLaughlin and Townley, 1996). To address this concern, DOE agreed[11] to represent the full variability and uncertainty of data in the results of the thermal effects on flow simulations used for the abstraction of thermodynamic variables for other models or to provide technical bases that a reduced representation is appropriate, considering risk significance.

---

[10]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Total System Performance Assessment and Integration (August 6–10, 2001)." Letter (August 23) to S. Brocoum, DOE. Washington, DC: NRC. 2001.

[11]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Thermal Effects on Flow (January 8–9, 2001)." Letter (January 26) to S. Brocoum, DOE. Washington, DC: NRC. 2001.

The conceptual model used to develop the calibrated property sets for the site-scale unsaturated zone flow model is described in CRWMS M&O (2000m), which treats each geological layer in the model as homogeneous. The resulting average layer-calibrated drift-scale property sets for the basecase show fracture permeability in the Tsw34 unit to be 2.76×10^{-13} m^2 and in the Tsw35 unit to be 1.29×10^{-12} m^2. For the upper bound infiltration map these change to 4.63×10^{-13} m^2 and 5.09×10^{-12} m^2 and for the lower bound to 4.99×10^{-13} m^2 and 1.82×10^{-12} m^2 for the Tsw34 and Tsw35 units, respectively. Thus, variability and uncertainty in model layer fracture permeability for these two units range within approximately one order of magnitude. A statistical analysis of air-injection data collected from the niches in the Exploratory Studies Facility, however, found fracture permeabilities ranging from 1.53×10^{-15} m^2 to 7.15×10^{-10} m^2. These data, all collected in the Tsw34 unit, indicate that heterogeneity of fracture permeability can span at least four orders of magnitude within a single geological layer. It is not clear how using homogeneous layer properties in a model, with variability spanning only one order of magnitude, can adequately represent variability and uncertainty that may range several orders of magnitude within a single geological layer. CRWMS M&O (2000m) recommends that future studies consider the use of Monte Carlo simulations to evaluate the appropriateness of the prior information uncertainty for the calibrated properties. Such exercises would be useful for evaluating the propagation of uncertainty through the least-squares inverse approach as discussed previously. This would not, however, address the uncertainty inherent in spatial heterogeneity nor would it adequately address the uncertainty in the equally valid but significantly different models and property sets of the Thermal Tests Thermal-Hydrological Model (CRWMS M&O, 2000r). Additional studies applying generally accepted methods of stochastic subsurface hydrology, sensitivity, and bounding analyses would be required to address the data and model uncertainty. DOE agreed[12] to provide documentation of analyses of spatially heterogeneous fracture permeability using refinement of the grid for the heterogeneous fields in three dimensions and to evaluate the effect of high-permeability features (e.g., faults) crossing the drifts. DOE will also provide an update to CRWMS M&O (2000m) to incorporate uncertainties from all significant sources.

Data to support the values of assigned hydrologic properties of faults are also lacking. Because data from Borehole USW UZ–7a, used to characterize Ghost Dance fault, represent the most complete data set from within a fault zone at Yucca Mountain, these data are applied to all faults in the Unsaturated Zone Model (CRWMS M&O, 2000a). Additional data on the hydrologic and transport properties are presently being collected from the Alcove 8–Niche 3 test, which is intersected by a fault. One Alcove8–Niche 3 test objective is to characterize the fault and fractures across the lithophysal-nonlithophysal interface. DOE agreed[13] to provide the documentation for the Alcove 8–Niche 3 testing.

---

[12]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Thermal Effects on Flow (January 8–9, 2001)." Letter (January 26) to S. Brocoum, DOE. Washington, DC: NRC. 2001.

[13]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Radionuclide Transport (December 5–7,2000)." Letter (December 12) to S. Brocoum, DOE. Washington, DC: NRC. 2001.

Another potentially important source of data uncertainty is the measurement of *in-situ* rock matrix saturations and water potentials used as calibration targets. Saturation data used in the calibration were obtained from rock cores collected *in situ* but analyzed *ex situ*. Corresponding field-based measurements of water content and water potential indicate that laboratory-derived estimates of the water retention relations underpredict saturations. Preliminary monitoring results from the East-West Cross Drift indicate the rock mass in the proposed repository horizon is wetter (i.e., water potentials are higher) and that moisture is more uniformly distributed than was expected based on earlier rock-core analyses.[14] Also, measurements of water potential taken in surface-based boreholes have gradually reequilibrated to ambient conditions that are much wetter than the data used to calibrate the three-dimensional unsaturated zone model. Of concern is that if the more recent measurements are validated, the calibrated unsaturated zone site-scale model should be consistent with these findings. Previous difficulties in matching saturations and water potentials may be alleviated by use of the ambient data in the calibration. Because of the complexity of the model and the large number of hydraulic parameters (matrix, fracture, or matrix/fracture parameter values) whose values could change during calibration to match the ambient, wetter conditions, it is not clear what the effect will be on the calibrated property data sets and predicted distributions of flow between fractures and matrix. DOE agreed[15] to use recent data on saturations and water potentials when calibrating the unsaturated zone flow model; thus, this uncertainty is expected to be reduced in future model iterations.

Input data from CRWMS M&O (2000s) are used to develop the unsaturated zone flow model grid. The unsaturated zone model numerical grids attempt to closely match the Geologic Framework Model 3.1 layers. However, because borehole data used to construct Geologic Framework Model 3.1 are limited, there is uncertainty in the assumptions regarding lateral continuity and thickness trends of layers at Yucca Mountain. Although layers in Geologic Framework Model 3.1 represent a valid interpretation, the effect of greater lateral discontinuity resulting from the inclusion of small faults on flow could be significant, especially in areas where little or no information has been collected. Areas of sparse data are generally outside the proposed repository area, however, so the effect of this data uncertainty is mitigated. Numerous fault zones and associated layer offsets within the proposed repository area are explicitly included in the unsaturated zone model grid. Hence, although considerable uncertainty exists in the accuracy of unsaturated zone model grids at any particular location, the model grid sufficiently allows for consideration of important effects on flow of faults and layer discontinuities at the scale and location of the proposed repository.

For the drift seepage model, spatial variability of air permeability data and the inability to directly measure moisture-retention properties of fracture networks produce uncertainty in the parameters k and α used in the seepage model for total system performance assessment, where k is fracture network permeability and α is a moisture-retention parameter (called

[14]Craig, R. "Progress Report, March 1999." Letter (April 14, 1999) to W. Kozai, Yucca Mountain Site Characterization Office. Denver, CO: U.S. Geological Survey, Yucca Mountain Project Branch. 1999.

[15]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Total System Performance Assessment and Integration (August 6–10, 2001)." Letter (August 23) to S. Brocoum, DOE. Washington, DC: NRC. 2001.

van Genuchten's alpha) related inversely to air-entry pressure. In addition to the uncertainty in the appropriate range of values for these parameters is the uncertainty in their spatial distribution. Accordingly, uncertainty in two additional model parameters is considered: the standard deviation, σ, of the logarithm of fracture network permeability; and the spatial correlation length, λ, for fracture permeability. These two parameters are used to generate random spatial heterogeneity for permeabilities assigned to the seepage model grid cells.

The range of fracture permeability considered for *k* in the seepage model is from 0.9×10^{-14} to 0.9×10^{-11} m^2. This range is based on data from air permeability tests at Niche 3650, which indicate a mean permeability of 2.2×10^{-12} m^2. The low end of the range is consistent with host permeability measurements measured elsewhere in the Exploratory Studies Facility not affected by drift excavation; the high end of the range accounts for uncertainty in the degree of enhanced permeability from excavation effects (CRWMS M&O 2000g, Section 6.3.2). This range of *k* values is also consistent with the range of permeability measurements reported by LeCain (1997) for the Topopah Spring welded tuff middle nonlithophysal layer and, thus, seems reasonably to bound uncertainty in this parameter for the seepage process model. It is not yet established, however, if this range also includes or appropriately bounds variability in the lower lithophysal unit. DOE agreed[16] to use the field test data to provide additional confidence in, or a basis for, revising the total system performance assessment seepage abstraction and associated parameter values or provide a technical basis for not using it.

To incorporate uncertainty in the α parameter, four values were used: $1/\alpha$ = 30, 100, 300, and 1,000 Pa. This range of values is somewhat arbitrary, but as discussed in the analysis and model report, it brackets values used in previous modeling studies (CRWMS M&O, 2000g, Section 6.3.4). Spatial variability of α is not considered for total system performance assessment abstraction. That is, for any particular process model realization used to develop the total system performance assessment abstraction, α was assumed constant throughout the entire model domain. DOE researchers did, however, investigate the sensitivity to spatial variability of α by evaluating a limited number of cases with α correlated to permeability. It is interesting to note that the correlated α condition yielded higher seepage by 0–10 percent (CRWMS M&O, 2000g). For this reason, seepage values used for the total system performance assessment abstraction are increased by 10 percent to allow for possible spatial correlation. One factor that should be considered is that the value of α at the drift-fracture interface is a function of fracture aperture and, hence, can vary considerably within scales of only a few centimeters. Because dripping is more likely to occur where water encounters an increased fracture aperture, DOE should demonstrate that the values of α used to develop the abstraction are consistent with the largest apertures typical for the grid-block scale. From the information presented by DOE thus far, it is not clear that the uncertainty in this important parameter has been incorporated adequately into the total system performance assessment abstraction. Test results from the Alcove 8–Niche 3 test and the East-West Cross Drift passive

[16]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Total System Performance Assessment and Integration (August 6–10, 2001)." Letter (August 23) to S. Brocoum, DOE. Washington, DC: NRC. 2001.

test should help resolve this concern. DOE agreed[17] to use the field test data to provide additional confidence in the seepage abstraction and associated parameter values.

Three alternatives, $\sigma = 1.66$, 1.93, and 2.5, were used to account for uncertainty in the standard deviation in fracture permeability used to incorporate random heterogeneity. The low value is based on data from Niche 3650 tests (CRWMS M&O, 2000f, Table 5); the two higher values span a value of 2.1 estimated in a modeling study by Birkholzer, et al. (1999). Note that higher values of σ represent stronger heterogeneity that would produce greater opportunity for local seepage. The values of σ seem reasonable to bound uncertainty. For example, the σ value of 2.5 would produce a distribution of permeability values that could vary spatially by 10 orders of magnitude (i.e., approximately 95 percent of assigned permeability values will be within a range of $\pm 2\sigma$ from the mean log-*k* value). Niche 3650 air permeabilities ranged from 1.53×10^{-15} m^2 to 1.27×10^{-10} m^2—about 5 orders of magnitude (CRWMS M&O, 2000f, Table 5).

Uncertainty in the correlation length scale, λ, for heterogeneity in fracture network permeability is not propagated through drift seepage model abstraction for total system performance assessment. In CRWMS M&O (2000f, Section 6.3.2), DOE investigators suggest that permeability is essentially random without a noticeable spatial correlation. Thus, to develop the total system performance assessment abstraction, heterogeneous fields for the seepage model were developed with λ equal to a grid size of 0.5 m [1.6 ft] (CRWMS M&O, 2000g). To further support this approach, process-level sensitivity studies were conducted with values of $\lambda = 1$ and 4 m [3.3 and 13 ft]. Results suggest that seepage increases with increased λ; hence, the DOE approach of neglecting spatial correlation of permeability may bias seepage predictions to be too low. Although DOE researchers cite data suggesting no spatial correlation beyond the grid-block scale, those data represent only one small niche and, owing to the data uncertainty, also have been interpreted to show a correlation scale of nearly 4 m [3.3 ft] (CRWMS M&O, 2000f). Another potentially important uncertainty is the presence of spatial correlation anisotropy caused by the presence of subvertical high-permeability fractures. The presence of subvertical high-permeability fractures could provide conduits for preferential flow toward drifts with a potentially reduced capacity for lateral capillary diversion—not considered in the DOE abstraction. Here also, test results from the Alcove 8–Niche 3 test and the East-West Cross Drift passive test should help resolve this concern. DOE agreed[18] to use the field test data to provide additional confidence in the seepage abstraction and associated parameter values.

A total of 576 seepage model scenarios was developed to represent the range of parameter uncertainty in the drift seepage model. These scenarios correspond to four values of α, four average-*k* values, three σ values, three realizations of random heterogeneity, and four percolation fluxes. The results of these numerous model scenarios were used to define transfer functions for seepage fraction and seepage flux as functions of percolation flux (CRWMS M&O, 2000h). It should be noted that only three realizations of random heterogeneity

---

[17]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Total System Performance Assessment and Integration (August 6–10, 2001)." Letter (August 23) to S. Brocoum, DOE. Washington, DC: NRC. 2001.

[18]Ibid.

may not give a statistically meaningful range of results. DOE agreed[19] to evaluate spatial heterogeneity of hydrologic properties within hydrostratigraphic units and the effect this heterogeneity has on model results of unsaturated flow, seepage into the drifts, and transport.

Thermal-chemical effects on seepage are also neglected in the current abstraction approach (CRWMS M&O, 2000j), based on numerical simulations that show that any such changes will have a negligible effect on seepage and flow (CRWMS M&O, 2000m,q). However, uncertainties in the hydrological, thermal, and geochemical parameter values used in these simulations have not been adequately addressed in the drift-scale coupled processes model (CRWMS M&O, 2000t). DOE agreed[20] to evaluate the various sources of uncertainty in the thermal-hydrological-chemical process model, including details regarding how the propagation of various sources of uncertainty is calculated in a systematic uncertainty analysis; this evaluation will be documented in a revision to CRWMS M&O (2000t) or in another future document.

In summary, there are several concerns related to the propagation of data uncertainties in the abstraction of flow paths in the unsaturated zone. In each case, however, either the current DOE approach is reasonably bounding, the uncertainty is not expected to be of significant importance to performance predictions, or DOE agreed to provide additional information or analyses to support the abstraction approach.

3.3.6.4.4 Model Uncertainty Is Characterized and Propagated Through the Model Abstraction

Overall, the current information, along with agreements reached between DOE and NRC (Section 3.3.6.5), is sufficient to conclude that the necessary information will be available at the time of a potential license application to assess flow paths in the unsaturated zone with respect to model uncertainty being characterized and propagated through the model abstraction.

To account for combined data and model uncertainty in the site-scale unsaturated zone flow model, 18 flow fields were originally defined for the basecase Total System Performance Assessment–Site Recommendation calculations (CRWMS M&O, 2000a). These flow fields consisted of three infiltration cases (lower, mean, and upper) within each of the three climate states (present-day, monsoon, and glacial transition), along with two different perched-water conceptual model: (i) a permeability-barrier model with reduced permeability in both fracture and matrix elements in the vicinity of the perched water and (ii) an unfractured zeolite model that eliminated fractures in all zeolitic units. Preliminary DOE calculations showed the difference between the two perched-water models was not significant (CRWMS M&O, 2000a, Figure 3.7-17), with the first model being slightly more conservative in predicting early arrival of

---

[19]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Total System Performance Assessment and Integration (August 6–10, 2001)." Letter (August 23) to S. Brocoum, DOE. Washington, DC: NRC. 2001.

[20]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Evolution of the Near-Field Environment (January 9–12, 2001)." Letter (January 26) to S. Brocoum, DOE. Washington, DC: NRC. 2001.

contaminants. Hence, only the nine flow fields based on the first perched-water model are carried forward to the Total System Performance Assessment–Site Recommendation.

Other sources of site-scale unsaturated zone flow model uncertainty are associated with the many assumptions and simplifications that must be made to model such a complex environment. For example, the assumption of homogenous layers implies that the model grid-block scale is larger than the scale of variability in hydrologic properties (heterogeneity). It is thus assumed that all grid blocks within any layer capture a comparable range of heterogeneity and, therefore, have the same average properties. DOE contends that the calibration process upscales the core-based measurements to the grid scale, thus accounting for intralayer heterogeneity at the subgrid scale. Based on the sparse data available, heterogeneity is not indicated in the Paintbrush nonwelded tuff at scales larger than the grid scale near the repository. Except for the Calico Hills nonwelded unit, the only heterogeneities considered in the model occur at layer interfaces and where layers are offset by faults. Within the Calico Hills nonwelded unit, layers are divided into either vitric or zeolitic rock types—which have significantly different hydrologic properties—based on borehole data and observations of perched water.

Staff are presently evaluating potential effects of lateral heterogeneity in the Paintbrush nonwelded tuff layer on the distribution of flow into the Topopah Spring welded tuff. Work by Ofoegbu, et al. (2001) indicated heterogeneity in the Paintbrush nonwelded tuff properties, caused by either depositional or secondary overprinting processes (e.g., small fault or slumping), could lead to increases in localized fluxes at the repository horizon. Currently, however, no field evidence exists that such effects dominate flow patterns at Yucca Mountain. The present DOE model indicates considerable lateral variability in the percolation flux reaching the proposed repository horizon (CRWMS M&O, 2000a, Figures 3.7-11 and 3.7-12), mainly as a result of the predicted spatial variability in net surface infiltration. DOE agreed[21] to evaluate spatial heterogeneity of hydrologic properties within hydrostratigraphic units and the effect this heterogeneity has on model results of unsaturated flow, seepage into the drifts, and transport.

Another important model uncertainty lies in the use of a steady-state infiltration boundary, which rests on the assumption that the Paintbrush nonwelded tuff layer acts to completely attenuate the infrequent pulses of infiltration predicted by the infiltration model. Indeed, DOE researchers have conducted modeling to demonstrate the validity of this assumption (e.g., CRWMS M&O, 1998, Section 2.4.2.8). Although these transient-flux models support the steady-state assumption, those presented to date have not used infiltration pulses that average more than 5 mm/yr [0.2 in/yr] during the long-term; yet infiltration during future climates may exceed 30 mm/yr [1.2 in/yr] over the proposed repository (CRWMS M&O, 2000a, Figure 3.7-11). Preliminary results of modeling conducted at the CNWRA indicate that, although the Paintbrush nonwelded tuff layer greatly attenuates episodic infiltration, transient percolation flux may occur at repository depth for infiltration pulses that occur every 5 years and average 10 mm/yr

[21]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Total System Performance Assessment and Integration (August 6–10, 2001)." Letter (August 23) to S. Brocoum, DOE. Washington, DC: NRC. 2001.

[0.4 in/yr] for the long term. To address this concern, DOE agreed[22] to provide additional documentation for the steady-state infiltration assumption.

A potential concern related to the grid scale of the site-scale unsaturated zone flow model is that the vertical length of model grid blocks at layer interfaces is typically much greater than the capillary-rise length scale (approximately the inverse of the van Genuchten α parameter). As a result, the numerical model may not be able to represent adequately lateral capillary diversion at layer interfaces. This concern pertains to the Paintbrush nonwelded tuff–Topopah Spring welded tuff interface, where capillary retention in the Paintbrush nonwelded tuff matrix may be greater than that of the Topopah Spring welded tuff fracture network. Preliminary modeling by Lawrence Berkeley National Laboratory staff using refined vertical grid discretization has simulated lateral capillary diversion in the Paintbrush nonwelded tuff.[23] However, there is little objective evidence that this phenomenon is occurring at the site (e.g., high matrix saturation or perched water above the Paintbrush nonwelded tuff–Topopah Spring welded tuff interface has not been observed). In fact, elevated matrix saturations occur in the uppermost welded unit of the Topopah Spring welded tuff. The difference noted between the highly discretized Lawrence Berkeley National Laboratory preliminary model and on-site observations may be that the model does not incorporate intralayer heterogeneity in the Paintbrush nonwelded tuff and Topopah Spring welded tuff that could interrupt lateral diversion or that the model does not represent adequately the gradational contact between the Paintbrush nonwelded tuff and the Topopah Spring welded tuff. Alternatively, the difference may be caused by the lack of direct flow connections in the model between the Paintbrush nonwelded tuff matrix and the underlying Topopah Spring welded tuff fractures. Thus, with present conditions, it is not expected that capillary lateral diversion in the lowermost Paintbrush nonwelded tuff layer would occur for scales larger than the model grid-block scale. If large-scale lateral diversion was to occur, possibly during future periods of greater infiltration, the likely effect would be to focus the flow into faulted zones. Such an effect could benefit performance if DOE could identify faulted zones at depth and avoid placement of waste packages in those areas. Both DOE and CNWRA researchers continue to investigate the potential for and possible effects of lateral capillary diversion in the Paintbrush nonwelded tuff. The permeability barrier at the contact between the Tiva Canyon welded unit and the Paintbrush nonwelded tuff is also being analyzed to assess the potential for lateral diversion above the Paintbrush nonwelded tuff where core data from surface-based boreholes indicate significantly elevated matrix saturations, including local saturation, in the lowermost Tiva Canyon welded unit layer. At present, however, it does not appear that exclusion of this process will result in overly optimistic performance estimates.

There are many model uncertainties in the drift seepage process model and drift seepage abstraction for total system performance assessment. The process model consists of uniformly sized grid cells of 0.5 m × 0.5 m × 0.5 m [1.6 ft × 1.6 ft × 1.6 ft], which implies an assumption that this volume contains a sufficient number of interconnected fractures to treat the fracture

---

[22]Schlueter, J.R. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Unsaturated and Saturated Flow Under Isothermal Conditions (August 16–17, 2000)." Letter (September 8) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

[23]Bodvarsson, G.S. Presentation at the DOE and NRC Technical Exchange and Management Meeting on Radionuclide Transport, December 5–7, 2000. Berkeley, California. 2000.

network as a three-dimensional continuum. The validity of this assumption is diminished in areas where spacings between water-bearing fractures are greater than a few tens of centimeters or where fractures tend to be near parallel with few intersections. As a result, the model may not calculate dripping that would occur in areas where seepage may be controlled more by fracture geometry than by fracture hydraulic properties. It is thus necessary to develop an improved understanding of the role of fracture characteristics in predicting drift seepage. Toward that goal, DOE agreed to relate any observed seepage in the passive East-West Cross Drift tests to full periphery maps of fractures and to provide a three-dimensional representation of fracture characterization in documentation of ongoing Alcove 8–Niche 3 seepage testing.[24] A desirable outcome of this effort is that drift seepage studies at Yucca Mountain will be fracture- informed so the rates and spatial distributions of drift seepage can be related, at least qualitatively, to observed fracture characteristics (e.g., aperture variability, trace length, density, interconnectedness, orientation, and location of intersection with drifts). Thus, if construction of a repository at Yucca Mountain proceeds, a qualitative basis would exist for evaluating whether fracture patterns in drifts are consistent with those used in the seepage studies used to validate the drift seepage abstraction for total system performance assessment.

Another important model uncertainty in the drift seepage process model is whether the use of the van Genuchten–Mualem model for moisture retention and relative permeability is adequate to model unsaturated flow in a fracture network. For the rather low unsaturated zone percolation fluxes predicted for Yucca Mountain, film flow may be the dominant flow regime. Film flow is a term used to describe flow on fracture surfaces that does not bridge the fracture aperture. Conditions that affect capillary diversion and dripping may be quite different for film flow than are currently modeled. One reason for concern is that parameter estimates obtained from the relatively high flow rate injection tests in Niche 3650 may not be applicable to ambient repository conditions. To address this concern, DOE agreed to either consider film flow processes in the seepage abstraction or to provide justification that the current model approach is adequate to bound this uncertainty.[25] Results from the Alcove 8–Niche 3 test and the East-West Cross Drift passive test may also help resolve this concern.

Modeling assumptions used to evaluate potential effects on seepage flux of rock bolts and changes in drift-geometry represent another source of model uncertainty. The DOE simulations (CRWMS M&O, 2000g) suggested a moderate increase of drift seepage as a result of partial drift degradation. Accordingly, seepage flow rates are increased by a factor of 1.55 in the seepage abstraction to account for the combined effects from partial drift degradation and rock bolts (CRWMS M&O, 2000d). A concern is that the grid scale of the process model used to estimate this adjustment factor is not sufficiently small to account for the scale of asperities in drift geometry caused by rockfall. Scales comparable to the inverse of the van Genuchten α parameter are appropriate, so seepage is not underpredicted for small-scale asperities. To

---

[24]Schlueter, J.R. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Structural Deformation and Seismicity (October 11–12, 2000)." Letter (October 27) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

[25]Schlueter, J.R. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Unsaturated and Saturated Flow Under Isothermal Conditions (August 16–17, 2000)." Letter (September 8) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

address NRC concerns related to the scale of the model grid used to assess the effects of drift collapse on seepage, DOE agreed[26] to consider smaller-scale tunnel irregularities or, alternatively, to provide justification that the current approach is adequate. Recent observations in the passive seepage test in the East-West Cross-Drift[27] suggest that rock bolts (and other foreign objects such as ventilation ducts and utility lines) appear to attract moisture, and several plate-sized puddles were observed beneath rock bolts.[28] It does not appear that these objects need to be in direct contact with the rock, thus, the observed moisture may be caused by vapor condensation. DOE agreed[29] to provide a technical basis for representation of or the neglect of dripping from rockbolts in performance assessment models.

DOE explicitly considers uncertainty regarding the conceptual model for flow focusing within unsaturated zone subregions in the drift seepage abstraction for total system performance assessment. Two different conceptual models for flow focusing are used to estimate upper- and lower-bounds weep spacings. The upper-bound weep spacing is based on an assumption that actively flowing fractures are saturated (CRWMS M&O, 2000h, Section 6.3.3.1); the lower-bound weep spacing is based on partially saturated fractures using the active-fracture conceptual model of Liu, et al. (1998). Based on analyses of potential weep spacings for the two different conceptual models, DOE developed statistical distributions from which the values of the flow focusing factors are sampled for individual total system performance assessment simulations (CRWMS M&O, 2000h, Section 6.3.3.2). Three different distributions for the focusing factor were developed, corresponding to total system performance assessment analyses for the low-, medium-, and high-infiltration scenarios. All three distributions are log-uniform with a lower bound of 1.0. The upper-bound values for the focusing factor distributions are 47, 22, and 9.7 for the low-, medium-, and high-infiltration scenarios, respectively. One concern with this approach is that the focusing factor distributions are based purely on theoretical considerations, and no consideration is given to how flow focusing may be affected by fracture patterns in the proposed repository host horizon. The DOE agreement to relate analyses of ongoing seepage studies to observed fracture parameters[30] should

---

[26]Schlueter, J.R. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Unsaturated and Saturated Flow Under Isothermal Conditions (August 16–17, 2000)." Letter (September 8) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

[27]Observations from Cross-Drift Bulkheads Opening January 22–25, 2001, compiled by David Hudson, U.S. Geological Survey.

[28]Glenn, C. Personal communication (February 2001) to N. Coleman, NRC Project Manager. Las Vegas, Nevada: NRC. 2001.

[29]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Total System Performance Assessment and Integration (August 6–10, 2001)." Letter (August 23) to S. Brocoum, DOE. Washington, DC: NRC. 2001.

[30]Schlueter, J.R. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Structural Deformation and Seismicity (October 11–12, 2000)." Letter (October 27) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

address this concern. In addition, DOE agreed[31] to use the field test data to provide additional confidence in the seepage abstraction and associated parameter values.

Based on measurements of air permeability, DOE suggests the process of seepage into drifts may be influenced by a 1-m [3.3-ft] thick excavation-induced disturbed zone with increased permeability around drifts (CRWMS M&O, 2000f). This zone of enhanced permeability is postulated to be the effect of dilation of existing fractures rather than the formation of new fractures. No technical basis has been presented, however, to indicate the presence or extent of excavation-induced fractures or new fracture connections. To address this concern, DOE agreed[32] to document data and interpretations regarding excavation-induced fractures in the Exploratory Studies Facility and in the Enhanced Characterization of the Repository Block Cross Drift.

DOE process modeling predicts seepage fractions to be higher when percolation flux is episodic (CRWMS M&O, 2000g, Section 6.6.7), but the unsaturated zone process model report suggests high-frequency fluctuations of infiltration will not reach the potential repository because the Paintbrush nonwelded tuff layers attenuate transient flow. As discussed in Section 3.3.4 of this report, however, the process models used to support this suggestion use average infiltration rates much lower than those expected for future climates. Thus, the validity of the steady-state flow assumption in seepage process models remains an important source of uncertainty that is not propagated through total system performance assessment abstraction. As previously mentioned, DOE agreed[33] to provide additional justification for the steady-state flow assumption, and the effectiveness of the Paintbrush nonwelded tuff to dampen episodic flow. DOE described an approach by which consideration of episodic flow can be considered in the seepage abstraction if the necessary additional justification cannot be provided (CRWMS M&O, 2000h, Section 6.3.4).

Below the proposed repository, where perched water occurs above and within the Calico Hills nonwelded unit, the unsaturated zone model predicts significant lateral diversion of water toward faults where flow to the water table is relatively rapid. The model predicts 35 percent of flow within the entire unsaturated zone model domain reaching the water table via fast flow in faults (CRWMS M&O, 2000a). If a similar percentage is applicable to the proposed repository footprint, it would be reasonable to conclude the total system performance assessment model abstraction does not benefit from undue credit for matrix flow below the proposed repository.

---

[31]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Total System Performance Assessment and Integration (August 6–10, 2001)." Letter (August 23) to S. Brocoum, DOE. Washington, DC: NRC. 2001.

[32] Schlueter, J.R. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Structural Deformation and Seismicity (October 11–12, 2000)." Letter (October 27) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

[33]Schlueter, J.R. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Unsaturated and Saturated Flow Under Isothermal Conditions (August 16–17, 2000)." Letter (September 8) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

To further reduce this source of uncertainty, DOE agreed[34] to provide an analysis of data used to support model predictions of the flow field below the repository, particularly in the nonwelded vitric portions of the Calico Hills, Prow Pass, and Bullfrog hydrostratigraphic units.

The DOE multiscale thermohydrologic model (CRWMS M&O, 2000u) uses only the drift-scale property sets to calculate thermohydrologic variables, and it is not clear how this captures the variability and uncertainty seen in predictions using other property sets or the uncertainty in comparisons to actual test results. Note that all thermal tests to date at Yucca Mountain have been conducted in the Tsw34 unit so that all conclusions from the thermal tests thermal-hydrological model (CRWMS M&O, 2000r) apply only to that unit. If the analyses were performed on the remaining geological units, the predicted variability would be greater. To address this concern, DOE agreed[35] to represent the full variability/uncertainty in results of the thermal effects on flow simulations in the abstraction of thermodynamic variables to other models or provide technical basis that a reduced representation is appropriate. DOE also agreed[36] to provide a revision to the unsaturated zone flow and transport process model report that includes consideration of model uncertainties: (i) types of model uncertainty, (ii) flow conceptualization for ambient conditions, (iii) flow conceptualization for thermal conditions, (iv) fracture flow for ambient and thermal conditions, (v) fracture matrix interaction model evolution, (vi) discrete fracture description, and (vii) reduction of model uncertainty.

As previously mentioned, the DOE abstractions of unsaturated zone flow and drift seepage neglect thermal-hydrological-chemical-induced changes to hydrological properties based on numerical simulations that show such changes will have a negligible effect on seepage and flow (CRWMS M&O, 2000a,c). Conceptual model uncertainties in these simulations have not been adequately addressed in the Drift-Scale Coupled Processes Model (CRWMS M&O, 2000t). To address this concern, DOE agreed[37] to provide an evaluation of the various sources of uncertainty in the thermal-hydrological-chemical process model, including details how the propagation of various sources of uncertainty are calculated in a systematic uncertainty analysis. In addition, DOE agreed[38] to provide additional information about the treatment of fully dry conditions in the reactive transport simulations, including information about the amount

---

[34]Schlueter, J.R. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Unsaturated and Saturated Flow Under Isothermal Conditions (August 16–17, 2000)." Letter (September 8) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

[35]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Thermal Effects on Flow (January 8–9, 2001)." Letter (January 26) to S. Brocoum, DOE. Washington, DC: NRC. 2001.

[36]Ibid.

[37]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Evolution of the Near-Field Environment (January 9–12, 2001)." Letter (January 26) to S. Brocoum, DOE. Washington, DC: NRC. 2001.

[38]Ibid.

of unreacted solute mass trapped in the dryout zone, as well as how this would affect precipitation of solutes and the resulting change in hydrological properties.

In summary, there are several concerns related to the consideration of model uncertainties in the abstraction of flow paths in the unsaturated zone. To address these concerns, DOE agreed to provide additional information or analyses to support the abstraction approach. This additional information includes justification for using a steady-state infiltration boundary; an evaluation of data to support the flow fields below the repository; consideration of fracture patterns, low flow-regime processes, and small-scale tunnel irregularities in the seepage abstraction; and consideration of parameter and model uncertainty in the multiscale thermohydrologic model and in the thermal-hydrological-chemical process model. NRC continues to evaluate the potential effects of heterogeneity in the unsaturated zone, which will be of greater importance if DOE used its refined-grid model with enhanced capillary diversion in the Paintbrush Tuff in the performance assessment abstraction.

3.3.6.4.5 Model Abstraction Output Is Supported by Objective Comparisons

Overall, the current information, along with agreements reached between DOE and NRC (Section 3.3.6.5), is sufficient to conclude that the necessary information will be available at the time of a potential license application to assess flow paths in the unsaturated zone with respect to model abstraction output being supported by objective comparisons.

The low-, medium-, and high-infiltration scenarios for the unsaturated zone flow model are calibrated using one- and two-dimensional inverse methods to match observations of pneumatic signals between boreholes, core saturation data from laboratory measurements, and *in-situ* moisture potential profiles (CRWMS M&O, 2000m). Additional fine-tuning of the model was performed to match observations of perched water associated with the Calico Hills nonwelded unit layer. Thus, the flow model scenarios are reasonably consistent with those observations. However, supporting data for the predicted flow vectors within, adjacent to, and below the perched water were not presented in the process model report of analysis and model reports. DOE agreed[39] to provide documentation of the analysis of available data to validate the predicted three-dimensional unsaturated zone model flow fields below the repository footprint, particularly below the perched water or through the vitric Calico Hills nonwelded unit, Prow Pass, and Bullfrog hydrostratigraphic units.

DOE obtained additional model validation from two modeling exercises to show the unsaturated zone flow model is broadly consistent with the observed distribution of calcite minerals in Well WT–24 and with chloride concentrations in the subsurface. Geochemical modeling of calcite precipitation was conducted to provide validation of deep percolation rates simulated in the unsaturated zone flow model (CRWMS M&O, 2000v). The result for a range of infiltration rates 2–20 mm/yr [0.08–0.8 in/yr] was that simulated calcite distributions agree reasonably well with measured data from Well WT–24 cuttings. The DOE modelers assume the amount of

---

[39]Schlueter, J.R. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Unsaturated and Saturated Flow Under Isothermal Conditions (August 16–17, 2000)." Letter (September 8) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

calcite precipitation generally increases as percolation increases. The simulated calcite abundances also are sensitive to the assumed water and gas chemistry, vapor movement, reaction kinetics, and mineralogy. The analysis provides some constraints on hydrological parameters, percolation flux, and additional evidence for validation of the flow and transport model. This analysis cannot give a definite value or a narrow range of values, however, because of the dependence of calcite deposition on the other factors. DOE agreed[40] to document the results of the calcite filling observations.

Another simulation was conducted to compare the basecase unsaturated zone flow model with observed chloride data from the Exploratory Studies Facility and East-West Cross Drift. Chloride concentrations from the steady-state transport simulation were compared with measured pore water chloride concentration data (CRWMS M&O, 2000v). The results indicate that measured chloride concentrations show a smaller range than predicted by the modern infiltration rates during steady-state conditions (CRWMS M&O, 2000a, Figure 3.8-3). However, because many measured chloride concentrations are fit closely by the model results, it appears the mean infiltration rate is approximately correct. Differences between measured and modeled chloride concentrations in the high- and low-infiltration regions suggest the time-averaged infiltration rates may be more uniform than predicted by the unsaturated zone flow model. Conversely, L. Flint[41] correlated the systematic measurements of water potential in the East-West Cross Drift and the chloride concentration of matrix pore water to shallow infiltration estimates. It was found percolation estimates from water potential data and from the chloride mass balance method both matched the magnitude and heterogeneity of the highly discretized shallow infiltration model results, except under washes where the model underpredicted percolation estimates from the East-West Cross Drift data.

A rigorous demonstration that the seepage model for total system performance assessment abstraction is valid for its intended purpose would require testing model results against relevant data not used in the original development of the model. For the seepage model for total system performance assessment, these data should include percolation flux at low flow rates for periods of years, even hundreds of years, in many locations in the repository. Unfortunately, such data are not available. Further, data for adequate validation would need to include the wide range of conditions such as drift degradation and collapse with time; those data are not available either. As previously mentioned, DOE agreed[42] to conduct and provide results from several ongoing field studies and modeling studies to increase confidence for the abstraction approach. Of particular importance is an ongoing field test in the East-West Cross Drift in which an approximately 1-km [0.62-mi] section of the tunnel has been sealed off from

---

[40]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Total System Performance Assessment and Integration (August 6–10, 2001)." Letter (August 23) to S. Brocoum, DOE. Washington, DC: NRC. 2001.

[41]Flint, L. "Measuring Flow and Transport in Unsaturated Fractured Rocks: A Large-Scale Unsaturated Flow Experiment." *Presentation to Geological Society of America November 13–17, 2000.* Reno, Nevada. 2000.

[42]Schlueter, J.R. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Unsaturated and Saturated Flow Under Isothermal Conditions (August 16–17, 2000)." Letter (September 8) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

ventilation and is being allowed to return to ambient conditions. DOE agreed[43] to consider smaller scale tunnel irregularities in drift collapse or justify that the current approach is adequate. DOE also agreed[44] to consider the NRC suggestion of comparing the numerical model results with the Phillips (1996) analytical solution as a means of model validation.

In summary, the site-scale unsaturated zone flow model of Yucca Mountain is broadly consistent with DOE interpretations of empirical observations. Because of model complexity, however, alternate interpretations of these observations are possible and model parameters can be adjusted to match a wide range of possible results. Consequently, DOE agreed to propagate data and model uncertainty through the abstraction, as discussed in the preceding sections.

3.3.6.5 Status and Path Forward

Table 3.3.6-1 provides the status of all key technical issue subissues, referenced in Section 3.3.6.2, for the Flow Paths in the Unsaturated Zone Integrated Subissue. The table also provides the related DOE and NRC agreements pertaining to the Flow Paths in the Unsaturated Zone Integrated Subissue. The agreements listed in the table are associated with one or all five generic acceptance criteria discussed in Section 3.3.6.4. Note that the status and the detailed agreements (or path forward) pertaining to all the key technical issue subissues are provided in Table 1.1-3 and Appendix A.

The DOE-proposed approach, together with the DOE agreements to provide NRC with additional information (through specified testing, analyses, and the like), acceptably addresses the NRC questions so that no information beyond that provided, or agreed to, will likely be required at the time of a potential license application.

---

[43]Schlueter, J.R. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Unsaturated and Saturated Flow Under Isothermal Conditions (August 16–17, 2000)." Letter (September 8) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

[44]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Thermal Effects on Flow (January 8–9, 2001)." Letter (January 26) to S. Brocoum, DOE. Washington, DC: NRC. 2001.

Table 3.3.6-1. Related Key Technical Issue Subissues and Agreements			
Key Technical Issue	**Subissue**	**Status**	**Related Agreements***
Unsaturated and Saturated Flow Under Isothermal Conditions	Subissue 4—Deep Percolation	Closed-Pending	USFIC.4.01 through USFIC.4.07
Radionuclide Transport	Subissue 1—Radionuclide Transport Through Porous Rock	Closed-Pending	RT.1.01
	Subissue 3—Radionuclide Transport Through Fractured Rock	Closed-Pending	RT.3.02 RT.3.05 RT.3.06
Structural Deformation and Seismicity	Subissue 3—Fracturing and Structural Framework of the Geologic Setting	Closed-Pending	SDS.3.01 SDS.3.02 SDS.3.04
Thermal Effects on Flow	Subissue 1—Features, Events, and Processes Related to Thermal Effects on Flow	Closed-Pending	None
	Subissue 2—Thermal Effects on Temperature, Humidity, Saturation, and Flux	Closed-Pending	TEF.2.01 TEF.2.06 TEF.2.07 TEF.2.08 TEF.2.10 TEF.2.11 TEF.2.12 TEF.2.13
Evolution of the Near-Field Environment	Subissue 1—Effects of Coupled Thermal-Hydrological-Chemical Processes on Seepage and Flow	Closed-Pending	ENFE.1.03 ENFE.1.04 ENFE.1.05
Repository Design and Thermal-Mechanical Effects	Subissue 2—Design of the Geologic Repository Operations Area for the Effects of Seismic Events and Direct Fault Disruption	Closed-Pending	None
	Subissue 3—Thermal-Mechanical Effects on Underground Facility Design and Performance	Closed-Pending	RDTME.3.14 RDTME.3.20 RDTME.3.21
Total System Performance Assessment and Integration	Subissue 1—System Description and Demonstration of Multiple Barriers	Closed-Pending	None
	Subissue 2—Scenario Analysis and Event Probability	Closed-Pending	TSPAI.2.01 TSPAI.2.02

Table 3.3.6-1. Related Key Technical Issue Subissues and Agreements (continued)			
Key Technical Issue	**Subissue**	**Status**	**Related Agreements***
Total System Performance Assessment and Integration	Subissue 3—Model Abstraction	Closed-Pending	TSPAI.3.07 TSPAI.3.11 TSPAI.3.22 through TSPAI.3.27
	Subissue 4—Demonstration of Compliance with the Postclosure Public Health and Environmental Standards	Closed-Pending	None
*Related DOE and NRC agreements are associated with one or all five generic acceptance criteria. Note: Key Technical Issue Agreement GEN.1.01 pertains to multiple integrated subissues, as well as to some specific issues related to this integrated subissue.			

3.3.6.6 References

Birkholzer, J., G. Li, C.F. Tsang, and Y. Tsang. "Modeling Studies and Analysis of Seepage into Drifts at Yucca Mountain." *Journal of Contaminant Hydrology.* Vol. 38. pp. 349–384. 1999.

CRWMS M&O. "Chapter 2: Unsaturated Zone Hydrology Model. Total System Performance Assessment—Viability Assessment (TSPA-VA) Analyses Technical Basis Document." B00000000–01717–4301–00011. Revision 00. Las Vegas, Nevada: TRW Environmental Safety Systems, Inc. 1998.

———. "Unsaturated Zone Flow and Transport Model PMR." TDR–NBS–HS–000002. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000a.

———. "Repository Safety Strategy: Plan to Prepare the Safety Case to Support Yucca Mountain Site Recommendation and Licensing Considerations." TDR–WIS–RL–000001. Revision 04. Las Vegas, Nevada: CRWMS M&O. 2000b.

———. "Total System Performance Assessment (TSPA) for the Site Recommendation." TDR–WIS–PA–000001. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000c.

———. "Development of Numerical Grids for UZ Flow and Transport Modeling." ANL–NBS–HS–000015. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000d.

———. "Radionuclide Transport Models Under Ambient Conditions." MDL–NBS–HS–000008. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000e.

———. "Seepage Calibration Model and Seepage Test Data." MDL–NBS–HS–000004. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000f.

———. "Seepage Model for PA Including Drift Collapse." MDL–NBS–HS–000004. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000g.

———. "Abstraction of Drift Seepage." ANL–NBS–HS–000005. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000h.

———. "Abstraction of NFE Drift Thermodynamic Environment and Percolation Flux." ANL–EBS–HS–000003. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000i

———. "Total System Performance Assessment (TSPA) Model for Site Recommendation." MDL–WIS–PA–000002. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000j.

———. "Calculation of Permeability Change Due to Coupled Thermal-Hydrological-Mechanical Effects." CAL–NBS–MD–000002. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000k.

———. "Features, Events, and Processes in UZ Flow and Transport." ANL–NBS–MD–000001. Revision 01. Las Vegas, Nevada: CRWMS M&O. 2000l.

———. "Calibrated Properties Model." ANL–NBS–HS–000003. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000m.

———. "*In-Situ* Field Testing of Processes." ANL–NBS–HS–000005. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000n.

———. "Ventilation Model." ANL–EBS–MD–000030. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000o.

———. "Development Plan or the Ventilation Test." TWP–EBS–MD–000001. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000p.

———. "Analysis of Hydrologic Properties Data." ANL–NBS–HS–000002. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000q.

———. "Thermal Tests Thermal-Hydrological Analyses/Model Report." ANL–NBS–TH–000001. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000r.

———. "Geologic Framework Model (GFM3.1)." MDL–NBS–GS–000002. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000s.

———. "Drift-Scale Coupled Processes (Drift-Scale Test and Thermal-Hydrological-Chemical Seepage) Models." MDL–NBS–HS–000001. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000t.

———. "Multi-scale Thermohydrologic Model." ANL–EBS–MD–000049. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000u.

———. "Analysis of Geochemical Data for the Unsaturated Zone." ANL–NBS–GS–000004. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000v.

Flint, L.E. "Characterization of Hydrogeologic Units Using Matrix Properties, Yucca Mountain, Nevada." U.S. Geological Survey Water Resources Investigations Report 97-4243. 1998.

LeCain, G.D. "Air-Injection Testing in Vertical Boreholes in Welded and Nonwelded Tuff, Yucca Mountain, Nevada." U.S. Geological Survey Water Resources Investigations Report 96-4262. 1997.

Liu, H.H., C. Doughty, and G.S. Bodvarsson. "An Active Model for Unsaturated Flow and Transport in Fractured Rocks." *Water Resources Research.* Vol. 34, No. 10. pp. 2,633–2,646. 1998.

McLaughlin, D. and L.R. Townley. "A Reassessment of the Groundwater Inverse Problem." *Water Resources Research.* Vol. 32, No. 5. pp. 1,131–1,161. 1996.

NRC. "Issue Resolution Status Report, Key Technical Issue: Unsaturated and Saturated Flow Under Isothermal Conditions." Revision 2. Washington, DC: NRC. 1999.

———. "Issue Resolution Status Report, Key Technical Issue: Radionuclide Transport." Revision 2. Washington, DC: NRC. 2000a.

———. "Issue Resolution Status Report, Key Technical Issue: Structural Deformation and Seismicity." Revision 3. Washington, DC: NRC. 2000b.

———. "Issue Resolution Status Report, Key Technical Issue: Thermal Effects on Flow." Revision 3. Washington, DC: NRC. 2000c.

———. "Issue Resolution Status Report, Key Technical Issue: Repository Design and Thermal-Mechanical Effects." Revision 3. Washington, DC: NRC. 2000d.

———. "Issue Resolution Status Report, Key Technical Issue: Evolution of the Near-Field Environment." Revision 3. Washington, DC: NRC. 2000e.

———. "Issue Resolution Status Report Key Technical Issue: Total System Performance Assessment and Integration." Revision 3. Washington, DC: NRC. 2000f.

———. NUREG–1804, "Yucca Mountain Review Plan—Draft Report for Comment." Revision 2. Washington, DC: NRC. March 2002.

Ofoegbu, G.I., S. Painter, R. Chen, R.W. Fedors, and D.A. Ferrill. "Geomechanical and Thermal Effects on Moisture Flow at the Proposed Yucca Mountain Nuclear Waste Repository." *Nuclear Technology*. Vol. 13, No. 3. pp. 241–262. 2001.

Phillips, O.M. "Infiltration of a Liquid Finger Down a Fracture into Superheated Rock." *Water Resources Research*. Vol. 32, No. 6. pp. 1,665–1,670. 1996.

3.3.7 Radionuclide Transport in the Unsaturated Zone

3.3.7.1 Description of Issue

The radionuclide transport in the unsaturated zone model abstraction addresses the migration of radionuclides through the unsaturated zone below the repository to the water table after waste package failure. The transport path through the unsaturated zone is defined to begin at the edge of the drift/invert part of the engineered barrier subsystem. The rate radionuclides migrate through the unsaturated zone depends on the medium through which the radionuclides travel—fractured rock or porous rock. This migration rate also depends on the water chemistry and mineralogy of the system because these control retardation processes. The relationship of this integrated subissue to other subissues is depicted in Figure 3.3.7-1. This figure shows the relationship between the radionuclide transport in the unsaturated zone model abstraction, the radionuclide release rates and solubility limits (see Section 3.3.4), and flow paths in the unsaturated zone (see Section 3.3.6) model abstractions. The overall organization and identification of all the integrated subissues are depicted in Figure 1.2-2.

3.3.7.2 Relationship to Key Technical Issue Subissues

Radionuclide transport in the Unsaturated Zone Integrated Subissue incorporates subject matter previously captured in the following key technical issue subissues:

- Radionuclide Transport: Subissue 1—Radionuclide Transport Through Porous Rock (NRC, 2000a)
- Radionuclide Transport: Subissue 2—Radionuclide Transport Through Fractured Rock (NRC, 2000a)
- Radionuclide Transport: Subissue 3—Radionuclide Transport Through Fractured Rock (NRC, 2000a)
- Radionuclide Transport: Subissue 4—Nuclear Criticality in the Far Field (NRC, 2000a)
- Unsaturated and Saturated Flow Under Isothermal Conditions: Subissue 4—Deep Percolation [Present and Future (Post-thermal Period)] (NRC, 2000b)
- Unsaturated and Saturated Flow Under Isothermal Conditions: Subissue 6—Matrix Diffusion (NRC, 2000b)
- Evolution of the Near-Field Environment: Subissue 3—The Effects of Coupled Thermal-Hydrologic-Chemical Processes on Chemical Environment for Radionuclide Release (NRC, 2000c)
- Evolution of the Near-Field Environment: Subissue 4—The Effects of Coupled Thermal-Hydrologic-Chemical Processes on Radionuclide Transport through Engineered and Natural Barriers (NRC, 2000c)

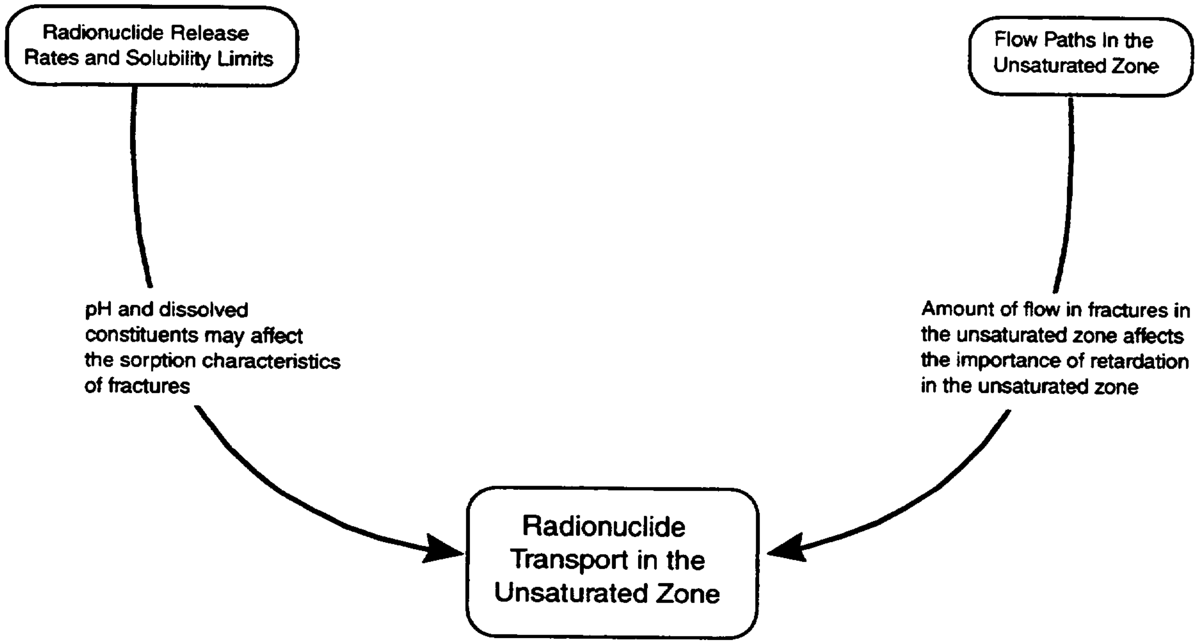

Figure 3.3.7-1. Diagram Illustrating the Relationship Between Radionuclide Transport in the Unsaturated Zone and Other Model Abstractions

- Structural Deformation and Seismicity: Subissue 3—Fracturing and Structural Framework of the Geological Setting (NRC, 2000d)
- Thermal Effects on Flow: Subissue 2—Is the DOE Thermohydrologic Modeling Approach Sufficient to Predict the Nature and Bounds of Thermal Effects on Flow in the Nearfield?(NRC, 2000e)
- Total System Performance Assessment and Integration: Subissue 1—System Description and Demonstration of Multiple Barriers (NRC, 2000f)
- Total System Performance Assessment and Integration: Subissue 2—Scenario Analysis and Event Probability (NRC, 2000f)
- Total System Performance Assessment Integration: Subissue 3—Model Abstraction (NRC, 2000f)

- Total System Performance Assessment and Integration: Subissue 4—Demonstration of Compliance with the Postclosure Public Health and Environmental Standards (NRC, 2000f)

The key technical issue subissues formed the bases for the previous versions of the issue resolution status reports and also were the bases for technical exchanges with DOE where agreements were reached on what additional information DOE needed to provide to resolve the subissue. The resolution status of this integrated subissue is based on the resolution status of each of the contributing key technical issue subissues. The subsequent sections incorporate applicable portions of these key technical issues subissues, however, no effort was made to explicitly identify each subissue.

3.3.7.3 Importance to Postclosure Performance

One aspect of risk informing the NRC review was to determine how this integrated subissue is related to the DOE repository safety strategy. DOE identifies radionuclide transport in the unsaturated zone at Yucca Mountain in Revision 4.0 of the repository safety strategy (CRWMS M&O, 2000a) as a principal factor of the current postclosure safety case. In the DOE model abstraction, radionuclide transport in fractures in the volcanic tuffs is conservatively considered to be unretarded because of limited characterization regarding the distribution of fracture-lining minerals (CRWMS M&O, 2000b). The DOE conceptual model for radionuclide transport in the unsaturated zone in total system performance assessment is that delay of radionuclide migration by sorption onto minerals in the volcanic tuffs occurs only within the rock matrix where solutes enter only by matrix diffusion. Sorption parameters are based on a combination of batch experiments and expert elicitation (CRWMS M&O, 2000c).

The DOE approach for considering radionuclide transport in the unsaturated zone is essentially the same approach used previously in DOE (1998a). Transport parameter values, represented by sorption coefficient (K_d) probability distribution functions, have been modified slightly from CRWMS M&O (2000c). Other changes include using updated parameter values and inputs from the unsaturated zone flow model and incorporation of the active-fracture conceptual model.

Because the conceptual model only provides for retardation in the matrix, the process of matrix diffusion is an important factor in the abstraction of radionuclide transport in the unsaturated zone. In sensitivity analyses performed by the DOE for the Total System Performance Assessment–Site Recommendation, the mean dose rate from the undisturbed basecase was compared with a case with no matrix diffusion in the unsaturated zone and with a case where anion and cation matrix diffusion coefficients were set at 100 times the matrix diffusion coefficients in the basecase (CRWMS M&O, 2000b, Section 5.2.6.1). Results showed that matrix diffusion in the unsaturated zone has a moderate effect on the dose history, especially between 20,000 and 30,000 years, where dose rates predicted for the no-matrix-diffusion case exceed those for the basecase by as much as two orders of magnitude. Conversely, differences in predicted dose rates are negligible between the basecase and the case with matrix diffusion coefficients 100 times the basecase values.

3.3.7.4 Technical Basis

NRC developed a plan (2002) consistent with the acceptance criteria and review methods found in previous issue resolution status reports. A review of DOE approaches for including radionuclide transport in the unsaturated zone in total system performance assessment abstractions is provided in the following subsections. The review is organized according to the five acceptance criteria identified in Section 1.5: (i) System Description and Model Integration Are Adequate, (ii) Data Are Sufficient for Model Justification, (iii) Data Uncertainty Is Characterized and Propagated Through the Model Abstraction, (iv) Model Uncertainty Is Characterized and Propagated Through the Model Abstraction, and (v) Model Abstraction Output Is Supported by Objective Comparisons.

3.3.7.4.1 System Description and Model Integration Are Adequate

Overall, the current information, along with the agreements reached between DOE and NRC (Section 3.3.7.5), is sufficient to conclude that the necessary information will be available at the time of a potential license application to assess radionuclide transport in the unsaturated zone with respect to system description and model integration.

DOE is handing the abstraction of unsaturated zone radionuclide transport for the total system performance assessment (CRWMS M&O, 2000d) through a residence-time transfer function adapted to the FEHM particle-tracking algorithm (Zyvoloski, et al. 1997). The residence-time transfer function approach is a particle-tracking method that describes a cumulative probability distribution function of particle residence times that accounts for the influence of advective transport in fracture networks and rock matrix and diffusive transport of solutes from fractures into rock matrix. The travel time of any given particle through a particular cell is computed by generating a random number between 0 and 1 and determining the corresponding residence time from the residence-time transfer function. On average, if a large number of particles travel through this portion of the model domain, the cumulative residence time distribution of particles will reproduce the shape of the transfer function (CRWMS M&O, 2000d). After spending the assigned residence-time in a model cell, a particle then moves from the resident cell to an adjoining cell, randomly, with the probability of entering an adjoining cell set according to the proportion of efflux from the resident cell into each of the adjoining cells (CRWMS M&O, 2000e), as determined by flow fields derived from the site-scale unsaturated zone flow model.

The residence-time transfer function used to assign particle residence times for transport in the fracture continuum is based on the analytical solution of Sudicky and Frind (1982), which takes into account advective transport in the fractures, molecular diffusion from the fracture to the porous matrix, adsorption on the fracture face, and adsorption within the matrix (CRWMS M&O, 2000c). Although this method allows consideration of solute sorption on fracture surfaces, this option is not used in the unsaturated zone transport abstraction model because of the lack of conclusive information about sorption in fractures and the anticipated small impact on model predictions (CRWMS M&O, 2000e). This approach is conservative with respect to repository performance.

A significant change from the unsaturated zone radionuclide transport model abstraction used for the Total System Performance Assessment–Viability Assessment is the incorporation of the active-fracture concept described by Liu, et al. (1998). The active-fracture concept accounts for the fact that not all fractures in an unsaturated flow system actively conduct water, and the number of active fractures in a flow system increases with increased flow rate. As described in CRWMS M&O (2000d), the active-fracture concept is implemented in the transport model by adjusting the flow interval spacing in the transport equation according to the equation

$$B = B_g S_e^{-\gamma} \tag{3.3.7-1}$$

where B is the adjusted flowing interval spacing; B_g is the geometric fracture spacing; S_e is the effective fracture saturation ($0 \leq S_e \leq 1$); and γ is the active-fracture fitting parameter ($0 \leq \gamma \leq 1$). The effect of incorporating the active-fracture conceptual model is that the effective flowing interval spacing is considerably larger when fracture saturations are low, which is generally the case for units such as the Topopah Spring Tuff. Larger flow interval spacing translates into less matrix diffusion because there is less available fracture-matrix interface area and greater isolation of the rock matrix between flowing intervals. In nonwelded vitric units, where flow is predominantly in rock matrix, the process of matrix diffusion would be of little benefit to performance. Although the active-fracture approach is a reasonable conceptual model, the methods of model parameter estimation and the numerical implementation of the transport model are not transparent in the analysis and model report (CRWMS M&O, 2000d). For example, it is not clear how fracture spacing, fracture porosity, and mean fracture aperture values in Table 3 of the analysis and model report (CRWMS M&O, 2000d) are derived. The mean fracture aperture values given in the analysis and model report seem quite large, but there is no discussion of how they relate to aperture measurements at depth; if the listed aperture values have been adjusted to account for the active-fracture concept, it is not stated in the analysis and model report. Also, it is not clear how or whether the fraction of active fractures is factored into the calculation of fluid velocity in the transport model. It would seem that velocity must increase for a given flux if the number of active fractures is reduced, but calculation of velocity is not discussed in the analysis and model report. DOE agreed[1] to provide independent lines of evidence to support the use of the active fracture model continuum concept in the transport model.

DOE relies on linear sorption isotherms and represents all retardation processes using K_d (CRWMS M&O, 2000b,c,e,f). Sorption coefficients for the radionuclides of interest are selected based on an initial and informal expert elicitation conducted for Total System Performance Assessment–1993, involving three experts (Wilson, et al., 1994). The sorption parameters probability distribution functions were constrained, assuming that water from saturated volcanic tuff (Well J–13) and the Paleozoic (UE–25p#1) aquifer bound the chemistry of the groundwaters at Yucca Mountain. Total System Performance Assessment–1993 used only geochemical information indirectly through expert elicitation to estimate probability distribution functions for K_d and did not explicitly incorporate geochemistry or geochemical modeling

---

[1]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Total System Performance Assessment and Integration (August 6–10, 2001)." Letter (August 23) to S. Brocoum, DOE. Washington, DC: NRC. 2001.

results. The approach has remained essentially unchanged since Total System Performance Assessment–1993, although the specific constraints on the transport parameters have been modified, particularly for uranium, neptunium, and plutonium (Wilson, et al., 1994; Triay, et al., 1997; CRWMS M&O, 2000c). Sorption probability distribution functions are abstracted into four rock types: devitrified, vitric, and zeolitic tuff, and iron oxide. The iron oxide is intended to represent waste package corrosion products and is not used to simulate retardation by fracture-lining minerals. Radionuclide retardation is related to K_d, the sorption coefficient, by the equation

$$R_f = 1 + \frac{\rho_b}{n} K_d \qquad (3.3.7\text{-}2)$$

where R_f is the retardation factor, ρ_b is the bulk density, and n is the porosity. This equation is for saturated flow. For unsaturated flow, the moisture content, θ, is substituted for n. Retardation by adsorption is assumed to occur only in the matrix, and the degree to which retardation contributes to overall repository performance depends on the nature of coupling between the matrix/fracture.

The technical basis for selecting radionuclides for transport modeling via reversible and irreversible colloid attachment is not transparent and traceable in all cases. The analysis and model report (CRWMS M&O, 2000g) identifies radionuclides for the total system performance assessment model abstraction based on contribution to dose, inventory, and mobility considerations, but does not explicitly identify those radionuclides that will be transported as colloids. Discussions in the analysis and model report (CRWMS M&O, 2000b,f,h) do not fully consider the possibility that waste form colloids could significantly transport radioelements other than plutonium and americium or the potential contribution of reversible colloid attachment to transport of less sorbing elements such as neptunium and uranium. In addition, there still exists, among the cited reports, confusion about the disposition of specific radioelements in colloid modeling. For example, CRWMS M&O (2000f) lists U-234 and Np-237 as radionuclides irreversibly attached to colloids, but CRWMS M&O (2000b) says that neptunium and uranium isotopes are not included in colloid transport models. DOE agreed[2] to address this issue.

The occurrence of nuclear criticality has been screened from Total System Performance Assessment–Site Recommendation based on its low probability of occurrence within 10,000 years (CRWMS M&O, 2000i). The basis for screening criticality from the postclosure performance assessment of the Yucca Mountain repository is contained in CRWMS M&O (2000j) which references a document (CRWMS M&O, 2000i). In the CRWMS M&O (2000i), report DOE screened out the far-field criticality, both in the unsaturated and the saturated zones, based on no waste package failure before 10,000 years. When there is no waste package, there is no release of fissile material; therefore, no fissile material to accumulate before 10,000 years in either unsaturated or saturated zones. The DOE screening argument for criticality relies heavily on the argument that the probability of a waste package failing within 10,000 years in the absence of a volcanic intrusion is very small. More recent analyses

---

[2]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Radionuclide Transport (December 5–7, 2000)." Letter (December 12) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

documented in the supplemental science and performance analyses (Bechtel SAIC Company, LLC, 2001a,b) indicate that waste package failure can occur within the first 10,000 years after repository closure because of stress corrosion cracking of welds that have been improperly heat-treated. Additional concerns about the Probability of Criticality Before 10,000 Years report are discussed in Section 3.2 of this report.

DOE described a methodology to determine the probability and consequences of a nuclear criticality event within the repository system (1998b). NRC staff accepted this methodology pending closure of 28 open items (2000g). As agreed at the DOE and NRC Technical Exchange on Criticality,[3] DOE provided NRC with Revision 1 of a topical report, which should address 27 of the open items (DOE, 2000). (The final open item on burnup verification will be addressed in the preclosure criticality analysis methodology.) Concerns relevant to criticality in the unsaturated zone are chiefly related to the methodology and validation for transport and redeposition models. To address these concerns, DOE agreed to update the topical report (2000). If this new revision of the topical report (2000) is acceptable, it will provide confidence that DOE will be able to address far-field criticality in the unsaturated zone in a potential license application even if DOE chooses to perform consequence analysis for far-field criticality to support its arguments for screening such criticality from the total system performance assessment.

DOE used arguments based on low probability and/or low consequence to exclude a number of features, events, and processes from the radionuclide transport in the unsaturated zone Total System Performance Assessment–Site Recommendation abstraction. The screening arguments are outlined in the process model report (CRWMS M&O, 2000e) and the features, events, and processes in another analysis and model report (CRWMS M&O, 2000k, 2001a). In general, the geochemical description of radionuclide transport in the unsaturated zone, including features, events, and processes, requires either a stronger technical basis for exclusion and verification of assumptions or needs to be included in the performance assessment calculations. In a number of cases, the screening arguments are adequate, and the exclusion of a particular feature, event, and process is appropriate. In other cases, however, the DOE argument is incomplete, based on assumptions that are to be verified or are otherwise inadequate at this time. Also, in some cases, DOE has not identified a feature, event, or process as either included or excluded. Scenario analysis and the NRC assessment of the DOE screening arguments are provided in Section 3.2 of this report. DOE agreed[4] to address these concerns relating to the features, events, and processes. Some specific examples of NRC concerns related to features, events, and processes are provided next.

The DOE (CRWMS M&O, 2001b) states that particles larger than colloids (2.1.09.21.00) will be included and treated as colloids, but this radionuclide transport process is not identified as

---

[3]Schlueter, J.R. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Criticality (October 23–24, 2000)." Letter (October 27) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

[4]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Total System Performance Assessment and Integration (May 15–17, 2001)." Letter (May 30) to S. Brocoum, DOE. Washington, DC: NRC. 2001.

either included or excluded from the Total System Performance Assessment–Site Recommendation abstraction of Radionuclide Transport in the Unsaturated Zone (CRWMS M&O, 2000e,k, 2001a). In the preliminary features, events, and processes database (Swift, et al., 1999), this process was excluded based on the assumption that, although particles may be transported through fractures in the unsaturated zone, low groundwater velocities through the saturated zone would lead to particle settling, suggesting inconsistency in the screening analysis. Qualitative comparison to colloid size distributions from wells in the Yucca Mountain region was also used as part of the exclusion rationale suggesting inconsistency in the screening analysis. This process is also noted as excluded under two other model components in the features, events, and processes database (CRWMS M&O, 2001c). Because DOE includes colloid formation processes in its screening analysis, and because of the large amounts of iron particles that may be introduced in the engineered barrier subsystem, particle transport through the engineered barrier subsystem into the unsaturated zone is plausible. Exclusion of the particle transport process may be acceptable but will remain open until DOE provides a more complete technical basis and calculations to support an assumption of low consequence. DOE should also consider the possible effects of settled or trapped particles acting as sources of dissolved radionuclide.

Radionuclide solubility limits in the geosphere (2.2.08.07.00) are excluded from the Total System Performance Assessment–Site Recommendation abstraction of radionuclide transport in the unsaturated zone on the basis of low consequence (CRWMS M&O, 2000e,k, 2001a). The DOE screening argument assumes that radionuclide solubility limits in the geosphere may be different from the near-field environment but indicates that this process is conservatively ignored with respect to solubility reduction in the far field (CRWMS M&O, 2000e). Although this argument makes valid points, the possibility of either creating a secondary source or increasing solubility limits should also be considered. Solubility limits in the geosphere will be determined by interaction between the contaminant plume and the host rock. Neglecting processes that control radionuclide sorption in the geosphere has not been demonstrated to be a conservative assumption and should be constrained by calculations including sensitivity analyses, bounding calculations, and comparison with natural analog systems.

Naturally occurring gases in the geosphere (2.2.11.01.00) are excluded from the Total System Performance Assessment–Site Recommendation abstraction of radionuclide transport in the unsaturated zone on the basis of both low consequence and low probability (CRWMS M&O, 2000e,k, 2001a). Screening arguments for this process expect naturally occurring gases to escape to the atmosphere through a well-connected unsaturated zone, preventing buildup in the repository. Although carbon dioxide is mentioned, its potential effects on water chemistry are not evaluated as part of the screening argument. Near-field modeling (CRWMS M&O, 2000l) suggests that thermal effects on carbon dioxide partial pressures and aqueous carbonate concentrations are small. This minimal effect would suggest that changes in the far field may also be small and have a minimal effect on radionuclide transport in the unsaturated zone (CRWMS M&O, 2000k, Assumption 11), and the exclusion is appropriate with regard to radionuclide transport.

Changes to rock properties caused by igneous activity (1.2.04.02.00) are excluded from the Total System Performance Assessment–Site Recommendation abstraction of radionuclide transport in the unsaturated zone on the basis of low consequence (CRWMS M&O, 2000e,k, 2001a). Although several of the arguments presented (scale, duration) may be reasonable, no specific technical basis, such as comparison with a natural analog (Matyskiela, 1997), is provided in the screening argument for this process. This discussion also does not include the effect of plugging of pores with remobilized silica or the effect of intruding a low-permeability igneous feature on hydrologic flow. Probability may also be an aspect to use in the screening argument for this process, provided it is consistent with the probabilities used for the igneous disruptive scenario.

Advection and dispersion are included in the radionuclide transport in the saturated zone model abstraction (CRWMS M&O, 2000b,f, 2001b) but are not identified as either included or excluded from the Total System Performance Assessment–Site Recommendation abstraction of radionuclide transport in the unsaturated zone (CRWMS M&O, 2000e,k, 2001a). Because advection and dispersion are key components of the DOE radionuclide transport in the unsaturated zone model abstraction, these processes should be included.

DOE included the current ambient groundwater chemistry (2.2.08.01.00) and composition conditions in the Total System Performance Assessment–Site Recommendation abstraction of radionuclide transport in the unsaturated zone but excluded future changes (CRWMS M&O, 2000e,k, 2001a). The thermal effects from waste emplacement in the repository are expected to be larger than any effects caused by climate change (CRWMS M&O, 2000k, Assumptions 10 and 11). These assumptions seem to be reasonable, but they are identified as to be verified in CRWMS M&O (2000k) and need to be verified. DOE asserts that the thermal effects on chemistry are minimal, but this assertion focuses mainly on the effects of dissolution and precipitation on hydrologic properties. Predicted changes in key geochemical parameters (pH and total carbon) are large enough to have an effect on sorption coefficients. It is assumed that the K_d uncertainty ranges bound possible variations from chemistry variations (CRWMS M&O, 2001a). The discussion of total system performance assessment disposition, however, does not address the potential for covariation among radioelement K_ds and possible performance effects. Furthermore, CRWMS M&O (2000m) states that K_d values derived from experiments are not considered to be influenced by microbial and precipitation and dissolution processes. The technical basis for this exclusion is not satisfactory. Without the details on how expert judgment was used to derive the Total System Performance Assessment–Site Recommendation sorption parameters, it is not clear how the effects of changes in the ambient system chemistry are incorporated in the transport calculations. DOE agreed to provide documentation of how its K_d distributions were derived.[5] The argument that K_d uncertainty accounts for microbial and precipitation and dissolution effects needs to be reconciled with the suggestion elsewhere that these effects were not considered in deriving K_ds.

Radionuclide transport in a carrier plume in the geosphere (2.2.08.02.00) is excluded from the Total System Performance Assessment–Site Recommendation abstraction of radionuclide transport in the unsaturated zone on the basis of low consequence. The key assumption (CRWMS M&O, 2000k, Assumption 11) is that results from the near-field thermal-hydrological-

[5]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Radionuclide Transport (December 5–7, 2000)." Letter (December 12) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

chemical coupled processes model (CRWMS M&O, 2000l) can be used to bound the effects of similar coupled processes on far-field flow and transport. This assumption is to be verified. Because the screening argument for this process is focused primarily on thermal effects on the chemistry of seepage water entering the emplacement drifts, it does not appear to include other potential effects (colloids, interactions with waste forms, and engineered barrier subsystem materials). This argument also ignores the aspects of retardation that suggest sorption is dominated by solution chemistry rather than rock type and that these chemical changes may be either beneficial or adverse. It seems that carrier plume chemistry should be explicitly modeled as it evolves in the geosphere. Also, the properties of a carrier plume in the engineered barrier subsystem are included in the engineered barrier subsystem process model report (CRWMS M&O, 2000k,l), suggesting that radionuclide transport in a carrier plume should be included in transport beyond the engineered barrier subsystem. The arguments presented for exclusion of this process (CRWMS M&O, 2000j) are not sufficient.

Geochemical interactions in the geosphere (dissolution, precipitation, and weathering) and effects on radionuclide transport (2.2.08.03.00) are excluded from the Total System Performance–Site Recommendation abstraction of radionuclide transport in the unsaturated zone on the basis of low consequence. The key assumption (CRWMS M&O, 2000k, Assumption 11) is that results from the near-field, thermal-hydrological-chemical coupled processes model (CRWMS M&O, 2000l) can be used to bound the effects of similar coupled processes on far-field flow and transport. This assumption is to be verified. Predicted mineralogical changes (CRWMS M&O, 2000l) in response to the thermal effects of the repository are small (only calcite precipitation and dissolution). Predicted changes in porosity and permeability are also small. Transport through fractures is conservatively modeled in the Total System Performance Assessment–Site Recommendation, assuming no retardation. The screening argument addresses only changes in seepage water chemistry. The argument does not address the possibility of reduced (or enhanced) matrix diffusion through precipitation and dissolution. As described in Revision 4.0 of CRWMS M&O (2000a), diffusion into the matrix and sorption on matrix minerals are important retardation mechanisms. The effect of small-volume changes on fracture armoring and diffusion into the matrix may be important. Also, this process is included in the radionuclide transport in the saturated zone model abstraction (CRWMS M&O, 2001b), suggesting inconsistency in the DOE flow and transport models. The current screening arguments are not sufficient and will depend in part on the verification of Assumption 11 that far-field changes to radionuclide transport in the unsaturated zone will be less than calculated near-field changes (CRWMS M&O, 2000k).

DOE included the effects of ambient condition complexation (2.2.08.06.00) in the Total System Performance Assessment–Site Recommendation abstraction of radionuclide transport in the unsaturated zone, but excluded future changes (CRWMS M&O, 2000e,k, 2001a). The effects of complexation are "... implicitly included in the radionuclide sorption coefficients, ..." but there is no clear technical basis regarding how the effects of organics or other ligands were used in establishing the K_d distributions (CRWMS M&O, 2000j). Experimental results, reported in Triay, et al. (1997), that form much of the basis for the sorption coefficient distributions address only the effects of organics on neptunium and plutonium sorption. The analysis and model report (CRWMS M&O, 2000c) does not provide any additional information on the effect of organics on other radionuclides. It is also not clear how the potential effects of hydrolysis or inorganic complexation on retardation were factored into the original K_ds. The current process models do not address the effects of complexation on transport parameters, and the exclusion of changes to complex formation does not have sufficient support. DOE agreed to provide documentation of how its K_d distributions were derived.[6]

DOE excluded microbial activity in the geosphere (2.2.09.01.00) from the Total System Performance Assessment–Site Recommendation abstraction of radionuclide transport in the unsaturated zone on the basis of low consequence (CRWMS M&O, 2000e,k, 2001a) because of the low amounts of organic materials anticipated to be emplaced or generated in the postclosure repository environment (CRWMS M&O, 2000k, Assumption 12). This assumption is identified as to-be-verified, so the technical basis supporting the exclusion is not sufficient.

Repository-induced thermal effects in the geosphere (2.2.10.01.00) are excluded from the Total System Performance Assessment–Site Recommendation abstraction of radionuclide transport in the unsaturated zone on the basis of low consequence (CRWMS M&O, 2000e,k, 2001a). The screening argument is only partially supported by near-field thermal-chemical modeling for a limited number of hydrochemical constituents and minerals (CRWMS M&O, 2000i) and is not directly related to temperature effects on radionuclide transport (e.g., effect of temperature on sorption coefficients). The technical basis for the screening is not sufficient, and future evaluation will depend, in part, on the DOE verification of Assumption 11 that far-field changes to radionuclide transport in the unsaturated zone will be less than calculated near-field changes (CRWMS M&O, 2000k).

Thermal-chemical alteration (solubility, speciation, phase changes, precipitation and dissolution) (2.2.10.06.99) is excluded from the Total System Performance Assessment–Site Recommendation abstraction of radionuclide transport in the unsaturated zone on the basis of low consequence and low probability (CRWMS M&O, 2000e,k, 2001a). Thermal effects on chemistry at the mountain scale are expected to be low on the basis of near-field coupled thermal-hydrological-chemical models that indicate the thermal effects of the repository result in only small changes in major hydrochemical constituents and limited changes in mineralogy. Results in the cited report (CRWMS M&O, 2000l) consider only a few components in hydrochemistry important to container life (e.g., pH, total carbon, and calcium) and are limited to calcite precipitation and dissolution. Although it is reasonable to assume that far-field changes are likely to be less than near-field changes, this assumption it is identified as to-be-verified (CRWMS M&O, 2000k). The technical basis is not sufficient to demonstrate low consequence, and the low-probability argument is not developed at all. The evaluation of this exclusion will depend, in part, on the verification of Assumption 11 that far-field changes to radionuclide transport in the unsaturated zone will be less than calculated near-field changes (CRWMS M&O, 2000k). DOE should provide a technical basis based on verified assumptions and/or analyses that thermal repository effects will have negligible effects on transport in the saturated zone. This argument should address the effects of thermal-chemical rock alteration and temperature effects on geochemical processes such as sorption. This analysis should be presented in the context of modeling results showing temperatures as high as 65–70 °C

[6]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Radionuclide Transport (December 5–7, 2000)." Letter (December 12) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

[149–158 °F] at the water table during the thermal pulse (CRWMS M&O, 2000n). If DOE is to rely on the argument that any such effects are accounted for by transport property uncertainty ranges, then DOE should provide additional documentation to explain how transport parameter distributions were derived in a manner consistent with NUREG–1563 (NRC, 1996), as agreed at the Radionuclide Transport Key Technical Issue Technical Exchange.[7]

DOE excludes thermal-chemical alteration of the Calico Hills unit (2.2.10.07.00) and the Topopah Spring basal vitrophyre from the Total System Performance Assessment–Site Recommendation abstraction of radionuclide transport in the unsaturated zone on the basis of low consequence (CRWMS M&O, 2000l). The screening argument is based on prediction of small changes in aqueous geochemistry and mineralogy in response to coupled thermal-hydrological-chemistry processes in the nearfield (CRWMS M&O, 2000l). Thermal-chemical changes in the far field, including the Calico Hills unit and Topopah Spring basal vitrophyre, are expected to be even less significant (CRWMS M&O, 2000k, Assumption 11). It is important to note that the near-field analyses (CRWMS M&O, 2000o) are performed with a focus on seepage chemistry and how it might affect container life, rather than with the purpose of considering thermal effects on radionuclide transport. The screening argument indicates that temperatures in the zeolite-bearing Calico Hills unit will not be high enough to cause significant zeolite alteration (CRWMS M&O, 2000k). Final evaluation of excluding thermal alteration effects will depend in part on the verification of Assumption 11 that far-field changes to radionuclide transport in the unsaturated zone will be less than calculated near-field changes (CRWMS M&O, 2000m). This analysis should be presented in the context of modeling results showing temperatures as high as {65–70 °C [149–158 °F]} at the water table during the thermal pulse (CRWMS M&O, 2000n). If DOE is to rely on the argument that potential thermal alteration effects are accounted for by transport property uncertainty ranges, DOE should provide additional documentation to explain how transport parameter distributions were derived in a manner consistent with NUREG–1563 (NRC, 1996), as agreed at the Radionuclide Transport Key Technical Issue Technical Exchange.[8]

In summary, system description and model integration for radionuclide transport in the unsaturated zone are not adequate. As discussed, DOE agreed[9] to address these concerns in future documents. Scenario analysis and the NRC assessment of the DOE screening arguments for features, events, and processes are provided in Section 3.2 of this report.

---

[7]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Radionuclide Transport (December 5–7, 2000)." Letter (December 12) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

[8]Ibid.

[9]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Total System Performance Assessment and Integration (August 6–10, 2001)." Letter (August 23) to S. Brocoum, DOE. Washington, DC: NRC. 2001.

3.3.7.4.2 Data Are Sufficient for Model Justification

Overall, the current information, along with the agreements reached between the DOE and NRC (Section 3.3.7.5), is sufficient to conclude that the necessary information will be available at the time of a potential license application to assess radionuclide transport in the unsaturated zone with respect to data being sufficient for model justification.

The DOE abstraction approach to radionuclide transport in the unsaturated zone requires the definition of a number of parameters to describe solute transport properties of fracture networks and rock matrix in unsaturated zone below the proposed repository. These properties include fracture aperture, fracture porosity, effective fracture spacing (more correctly, flowing interval spacing), linear groundwater velocity within the fracture, porosity of the rock matrix, sorption coefficients (K_d values), and the effective matrix diffusion coefficient. Laboratory tests include measurements of rock matrix porosity (Flint,1998) and diffusion-cell and rock-beaker experiments using tuffs from the unsaturated zone at Yucca Mountain (CRWMS M&O, 2000c). A comprehensive data set to support estimates of hydrologic properties of rock matrix in the various hydrostratigraphic units at Yucca Mountain is presented by Flint (1998); that data set is sufficient to support estimates of rock matrix porosity for the transport model.

Data to support the conceptual model of diffusive solute transfer between fracture and matrix continua are supported by laboratory and field tests. Laboratory data from diffusion-cell, rock-beaker, and fractured-core experiments are used to estimate effective matrix diffusion coefficients to model diffusive mass transport in the volcanic tuffs of Yucca Mountain. Field data to provide *in-situ* evidence for matrix diffusion in the unsaturated zone at Yucca Mountain are still preliminary or ongoing. The preliminary analysis of tracer movement in the Alcove 1 infiltration experiments shows the tracer breakthrough data are fit best by a numerical model that includes the effects of matrix diffusion.[10] Ongoing tracer tests in the Alcove 8–Niche 3 are aimed at providing additional evidence for matrix diffusion in the Topopah Springs upper lithophysal and middle nonlithophysal units. DOE agreed to complete the Alcove 8–Niche 3 test and is expected to incorporate the results, as appropriate, in the total system performance assessment abstraction.[11]

The DOE abstraction for radionuclide transport in the unsaturated zone is based on a conceptual model that assumes radionuclide sorption occurs only within rock matrix and that solutes can migrate by diffusion from flowing fractures into rock matrix, a process referred to as matrix diffusion. NRC staff are concerned that insufficient data are presently available to justify the inclusion of matrix diffusion in the abstraction of radionuclide transport in the unsaturated zone. Data from tracer studies in the Alcove 1 infiltration experiments support the matrix diffusion conceptual model. These tests, however, were not conducted in the same host-rock

---

[10]Schlueter, J.R. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Unsaturated and Saturated Flow Under Isothermal Conditions (August 16–17, 2000)." Letter (September 8) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

[11]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Radionuclide Transport (December 5–7, 2000)." Letter (December 12) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

formation proposed for possible construction of a repository. DOE agreed[12] to conduct tests of tracer transport between Alcove 8 (of the enhanced characterization of the repository block drift) and Niche 3 (of the exploratory studies facility) to provide sufficient data to justify or refute the inclusion of matrix diffusion processes in the proposed repository host rock.

The geochemical data used to support the flow field below the repository are not sufficient. Uncertainty with regard to the composition of fracture and pore water compositions (Yang, et al., 1996, 1998; Browning, et al., 2000) results from limited data sets and questions regarding whether DOE accounted for the effects of the extraction techniques on water chemistry. There is also some question with regard to Cl-36 results in the exploratory studies facility and the implications for fast paths. For example, the active-fracture model is not used to explain Cl-36 occurrence (Liu, et al., 1998) because of sparse spatial distribution. It is further hypothesized that the amount of water associated with the Cl-36 occurrences is a small part of the total flux through the mountain. The results of the study suggest active fractures are much more abundant than features associated with bomb-pulse Cl-36. In contrast, pneumatic monitoring evidence suggests that the fracture system is well-connected and can be viewed as a continuum. These types of uncertainty need to be resolved for the radionuclide transport in the unsaturated zone model abstraction. The DOE agreed[13] to provide the technical basis supporting its flow and transport models, including model calibration and *in-situ* field testing.

Faults can provide fast pathways for radionuclide transport in the unsaturated zone. Furthermore, the flow and transport characteristics of fault zone pathways can vary widely from those elsewhere in the tuff aquifer. The DOE transport parameters are assigned only by rock type and do not include any specific consideration of faults, unless they are treated explicitly as zones of fracture flow. It is not clear that DOE adequately accounted for the possible effects of these differences in formulating transport parameter distributions (CRWMS M&O, 2000c,m). DOE agreed[14] to provide a technical basis for the importance to performance of transport through fault zones below the repository and to provide the technical basis for the parameters and distributions if such transport is found to be important to performance.

DOE refers to the expert elicitation (CRWMS M&O, 2000c, p. 42) conducted for Total System Performance Assessment–1993 (Wilson, et al., 1994) as the original basis for the K_d distributions. Much of the text in a key document (Triay, et al., 1997) is virtually identical with the text in Wilson, et al., (1994), whose values were based on one elicitation session conducted with three experts involved in the DOE Yucca Mountain program. The methods used to arrive at the K_d probability distribution functions are described in general terms in Barnard, et al. (1992), but the specific process implemented for the K_d elicitation is not described. Many of the

---

[12]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Total System Performance Assessment and Integration (August 6–10, 2001)." Letter (August 23) to S. Brocoum, DOE. Washington, DC: NRC. 2001.

[13]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Radionuclide Transport (December 5–7, 2000)." Letter (December 12) to S.J. Brocoum, DOE. Washington, DC: NRC. 2000.

[14]Ibid.

methods normally used in expert elicitation (e.g., panel selection, training, mitigating bias, consensus building, incorporating dissenting opinions, aggregation of results, and documentation) are not discussed. This information is needed to understand how K_d probability distribution functions were selected, what data were used, and how the experts arrived at their conclusions. For example, Wilson, et al. (1994) notes that one of the experts believed that lead should be assigned a K_d of zero, however, a consensus value of 0–500 mL/g [0–0.05 m^3/kg], subsequently adjusted in CRWMS M&O (1998) to 100–500 mL/g [0.01–0.05 m^3/kg], was adopted. DOE agreed[15] to provide the documentation necessary to evaluate the adequacy of the DOE approach.

Subsequent changes in both K_d ranges and distribution type have been made to the Total System Performance Assessment–1993 distributions without documentation. For example, protactinium is assumed to exhibit sorption characteristics similar to neptunium (Triay, et al., 1997), but the K_d distributions are different, and the upper limits are significantly higher for protactinium 100 mL/g [0.11m^3/kg] versus 3 to 15 mL/g [0.003 to 0.015 m^3/kg] for neptunium. In addition, niobium was assigned a $K_d = 0$ in Chapter 7 of CRWMS M&O (1998), but has since been assigned high K_d values similar to americium (CRWMS M&O, 2000c). In another example, the tin K_d distribution is reportedly based on the compilation of Andersson (1988). Although there is an evaluation of tin solubility data in Andersson, there is no discussion of tin sorption. DOE agreed[16] to provide the documentation necessary to evaluate the adequacy of the DOE approach.

Despite the reference to bounding the groundwater characteristics using water from Wells J–13 and UE–25 p#1, the sorption data from the automatic technical data tracking system are limited in many instances only to experiments using J–13 water. Only uranium and plutonium have significant numbers of analyses using UE–25 p#1 water. The number of experiments at different pH values is limited: the experiments are generally controlled by CO_2 overpressuring, making it difficult to identify other effects. The support for the K_d distributions is largely empirical. Although there is discussion of chemical effects on sorption, there is no process modeling to support assertions used in selecting upper or lower bounds for K_d. Eh control is limited for much of the data. For example, in the dynamic column transport experiments, assertions are made regarding the predominance of pentavalent plutonium, without any description of how redox is controlled or how the dominant oxidation state is determined. This process is especially critical for a redox sensitive element such as plutonium. Finally, there is no apparent correlation among the different radionuclides, and the link through geochemical effects is lost. DOE agreed[17] to provide the documentation necessary to evaluate the adequacy of the DOE approach.

---

[15]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Radionuclide Transport (December 5–7, 2000)." Letter (December 12) to S.J. Brocoum, DOE. Washington, DC: NRC. 2000.

[16]Ibid.

[17]Ibid.

Documentation is necessary to determine how these types of geochemical uncertainties have been factored into the DOE total system performance assessment transport parameter distributions to support a licensing decision. The documentation should be adequate to allow an external reviewer to trace the origins of the judgments from initial assumptions through aggregation of results and parameter development. In particular, DOE should provide information that is sufficiently complete to allow the reviewer to evaluate the expert judgment(s), the technical information used to support the judgments, how the judgments are implemented in total system performance assessment, and why they are used instead of obtaining the needed objective information (NRC, 1996). DOE agreed to provide documentation of the technical basis for its expert elicitation[18] in accordance with NRC guidance in (1996).

The data used to support the screening criteria and transport parameters for colloid transport in the total system performance assessment are insufficient at this time. The radionuclides tracked in Total System Performance Assessment–Site Recommendation are identified in the analysis and model report inventory abstraction (CRWMS M&O, 2000g). The selection of radionuclides is appropriately based on considerations of dose, inventory, and mobility, but it is not clear in the inventory screening which radionuclides are to be modeled as colloids. DOE agreed[19] to document identification of radionuclides transported via colloids for total system performance assessment in an update to CRWMS M&O (2000m) and in CRWMS M&O (2000b,f).

The sources of data used to support estimates of fracture properties for the transport model are not readily apparent from the information provided by DOE in the unsaturated zone flow and transport process model report (CRWMS M&O, 2000e) or in supporting analysis and model reports (CRWMS M&O, 2000c,d). Additionally, the DOE model documentation does not provide a basis for relating effective fracture porosities, effective fracture apertures, or flowing interval spacings to observed fracture patterns. To address these shortcomings, DOE agreed[20] that results and analyses of ongoing seepage and transport studies in the Alcove 8–Niche 3 test will be fracture informed. In this regard, DOE should document how effective fracture porosities, effective fracture apertures, or flowing interval spacings used in the solute transport models for total system performance assessment (e.g., CRWMS M&O, 2000d, Table 3) compare with apertures and spacings typically observed *in situ*. The ability to relate unsaturated zone transport properties to observed fracture patterns will provide justification for extending results of underground tracer studies in niches and alcoves at Yucca Mountain to the area proposed for repository construction.

In summary, additional data are needed from DOE to support the inclusion of matrix diffusion and radionuclide sorption in the unsaturated zone transport model for the proposed Yucca Mountain repository. As discussed in the preceding paragraphs, DOE agreed to collect

[18]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Radionuclide Transport (December 5–7, 2000)." Letter (December 12) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

[19]Ibid.

[20]Ibid.

the additional data for model justification and provide it for review before a potential license application.

3.3.7.4.3 Data Uncertainty Is Characterized and Propagated Through the Model Abstraction

Overall, the current information, along with the agreements reached between the DOE and NRC (Section 3.3.7.5), is sufficient to conclude that the necessary information will be available at the time of a potential license application to assess radionuclide transport in the unsaturated zone with respect to data uncertainty being characterized and propagated through the model abstraction.

Uncertainty in the effective diffusion coefficient is a function of the uncertainty and variability in the molecular size of the radionuclide, temperature, heterogeneity of rock properties, and geochemical conditions along the transport pathway. The distributions of matrix diffusion values used to develop the total system performance assessment abstraction for radionuclide transport in the unsaturated zone are based on laboratory-measured diffusion coefficients of tritium for cationic radionuclide species and technetium for anionic species (CRWMS M&O, 2000c, Section 6.6.1). For both anionic and cationic species, the range of effective diffusion coefficients is sampled stochastically for each total system performance assessment realization from a beta-type distribution with a range of $0–10^{-9}$ m^2/s [$0–1.1 \times 10^{-8}$ ft^2/s]. The sampled distribution for the anionic species has a mean of 3.2×10^{-11} m^2/s [3.4×10^{-10} ft^2/s] and a standard deviation of 1×10^{-11} m^2/s [1.1×10^{-10} ft^2/s]. The distribution for the cationic species has a mean of 1.6×10^{-10} m^2/s [1.7×10^{-9} ft^2/s] and a standard deviation of 0.5×10^{-10} m^2/s [5.4×10^{-10} ft^2/s]. These distributions seem reasonably based on laboratory data and span a range that represents variability of centimeter-scale rock samples. Variability of diffusion coefficients can be expected to be much less for rock properties averaged over the scale of tens of meters in the transport model; hence, the ranges based on laboratory samples provide adequate bounds for model-scale diffusion coefficients.

Another important uncertainty is that of effective fracture aperture used in the total system performance assessment abstraction of unsaturated zone radionuclide transport. As discussed in the process model report (CRWMS M&O, 2000e), for a continuous, parallel fracture pattern, the inverse of the fracture aperture is half the area of contact between the fracture and matrix continua per unit volume of fracture pore space. Therefore, the larger the aperture, the less the diffusion (in a saturated system). For an unsaturated fracture, the relevant volume (per unit matrix area) is not the fracture pore volume itself, but the volume of water in the fracture. Apertures are sampled stochastically in the transport calculations for total system performance assessment. Aperture distributions are described using a log-normal distribution of apertures for all the model layers beneath the potential repository (values are listed in CRWMS M&O, 2000d, Table 4).

According to the supporting analysis and model report (CRWMS M&O, 2000d), fracture apertures used in the abstraction are derived from the fracture porosity and fracture-matrix connection area. It is not clear, however, what sources of data or analyses are used to support estimates of fracture porosity and fracture-matrix connection area. It is not clear how the active-fracture concept is factored into the estimates of fracture-matrix connection area. As previously mentioned, the mean fracture aperture values given in the analysis and model report seem quite large, and there is no discussion of how they relate to aperture measurements at depth. DOE should provide documentation to improve the transparency of how fracture aperture was determined. Fracture spacing also affects matrix diffusion because it sets the boundary for the depth of penetration from matrix diffusion. The sensitivity of transport to fracture spacing is low, however, owing to the relatively short transport distances through the unsaturated zone, so a constant value for each layer is used (CRWMS M&O, 2000e, Section 3.11.3.4). DOE agreed[21] to provide independent lines of evidence to support the use of the active-fracture model continuum concept in the transport model.

Although a significant amount of laboratory work and literature research is evident in the DOE process model report (CRWMS M&O, 2000a) and supporting analysis and model reports (CRWMS M&O, 2000c,m), the process used in conducting the expert elicitation (or expert judgment) for transport parameter distributions, particularly K_d values, is not described in sufficient detail. Many of the methods normally used in expert elicitation (panel selection, training, bias, consensus building, dissenting opinions, aggregation, and documentation) are not discussed. In addition, the information used by the expert panel is not described in a way that demonstrates how the strengths and weaknesses of different data sets were evaluated and considered to derive the K_d probability distribution functions. Also, subsequent changes from the initial elicitation are not documented in a transparent manner. This type of information is important to allow a reviewer to trace the process used to develop parameter distributions, from the original data and assumptions to the results and conclusions (NRC, 1996). Although the parameter distributions used may be appropriate without the underlying basis for the expert judgments, the radionuclide transport in the unsaturated zone model abstraction does not provide a sufficient treatment of data uncertainty. To support a licensing decision, documentation is necessary to determine how DOE developed the total system performance assessment transport parameter distributions and the type of information used to support the expert elicitation. DOE agreed to provide documentation of the technical basis for its expert elicitation[22] in accordance with NRC guidance in (1996).

DOE improved its capability to model colloid transport in recent total system performance assessment efforts (CRWMS M&O, 1998, 2000m), but many of the parameters (e.g., the colloid partitioning coefficient, K_c) used in the models are not supported by site characterization or laboratory data. DOE addressed this problem to some extent by using bounding analyses and sensitivity analyses, but there is insufficient radioelement-specific data to determine whether the uncertainty in colloid transport has been constrained in the radionuclide transport in

---

[21]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Total System Performance Assessment and Integration (August 6–10, 2001)." Letter (August 23) to S. Brocoum, DOE. Washington, DC: NRC. 2001.

[22]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Radionuclide Transport (December 5–7, 2000)." Letter (December 12) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

the unsaturated zone model abstraction. DOE agreed[23] to document the identification of radionuclides transport via colloids for Total System Performance Assessment.

The data used to support transport parameters for unsaturated zone colloid transport in the total system performance assessment are insufficient, and it is not apparent that uncertainty is reflected in parameters adopted in total system performance assessment. The four parameters that affect unsaturated zone colloid transport are the colloid size distribution, colloid K_c, colloid R_c, and colloid filtration factor; colloid matrix diffusion is neglected (CRWMS M&O, 2000f). In the unsaturated zone, R_c is conservatively set to one (i.e., there is no retardation of irreversible colloids), and the colloid filtration factor applies only to the small amount of advective flow between fracture and matrix (CRWMS M&O, 2000f). These two parameters, therefore, do not have a significant diminishing effect on unsaturated zone colloid transport. The colloid size distribution is used for calculating potentially significant colloid removal by filtration at matrix unit interfaces; it is not based on site-specific data but was chosen to be consistent with unrelated laboratory data (CRWMS M&O, 2000f). The K_c parameter, used to simulate reversible colloid attachment by lowering the radioelement K_d, is based on data for americium sorption to colloids and is applied to the K_d values for all reversibly attached radionuclides (CRWMS M&O, 2000m). Calculation of K_c also involves a term for colloid concentration in the water. The concentration adopted—0.03 mg/L [0.05 in^3/oz]—is claimed to be for conservatism, the highest observed or expected colloid concentration (CRWMS M&O, 2000f). This concentration, however, is well below the maximum values used in release models for waste form 5 mg/L [8.6 in^3/oz] and iron (hydr)oxide 1 mg/L [1.7 in^3/oz] colloids derived from the engineered barrier subsystem (CRWMS M&O, 2000h). DOE has not used any data, site-specific or not, to demonstrate that the reversible colloid attachment parameter will bound the range of possible effects of this process, nor have sensitivity analyses been employed to investigate the effects of parameter uncertainty on modeled repository performance. DOE agreed[24] to provide sensitivity analyses to test the importance of colloid transport parameters and models to performance for the unsaturated and saturated zones.

In summary, DOE used stochastic approaches to identify and constrain data uncertainty in its model abstraction on radionuclide transport in the unsaturated zone. In various cases, however, the technical basis for the probability distribution functions used to describe data uncertainty is not clear and transparent. To the extent possible, DOE needs to provide experimental and field information to constrain data uncertainty. Where it is not practical to obtain these data, DOE needs to document the expert elicitations or expert judgments used to provide uncertainty estimates in accordance with NRC guidance (1996) and its own quality assurance program. Sensitivity analyses and bounding calculations are an important means of providing a risk-informed, performance-based context for the DOE data uncertainty and

---

[23]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Radionuclide Transport (December 5–7, 2000)." Letter (December 12) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

[24]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Total System Performance Assessment and Integration (August 6–10, 2001)." Letter (August 23) to S. Brocoum, DOE. Washington, DC: NRC. 2001.

evaluating the need for additional data. DOE agreed[25] to provide technical support demonstrating appropriate handling of data uncertainty.

3.3.7.4.4 Model Uncertainty Is Characterized and Propagated Through the Model Abstraction

Overall, the current information, along with the agreements reached between the DOE and NRC (Section 3.3.7.5), is sufficient to conclude that the necessary information will be available at the time of a potential license application to assess radionuclide transport in the unsaturated zone with respect to model uncertainty being characterized and propagated through the model abstraction.

DOE evaluated how different approaches to represent matrix diffusion in the transport model could yield different transport behavior. For example, comparisons between the finite element heat and mass transfer particle-tracking approach and an alternative transport model, DCPT, were performed (CRWMS M&O, 2000o, Section 6.4.3). The two particle-tracking routines agree only if diffusion and dispersion are neglected. For the cases that include diffusion and dispersion, the median breakthrough for finite element heat and mass transfer algorithm occurs at times more than one or two orders of magnitude earlier. The difference is more pronounced for radionuclides undergoing sorption in the matrix. DOE believes these differences stem from different implementations of the diffusive mass flow between fractures and the matrix in the two codes (CRWMS M&O, 2000p, Section 7). The rather significant difference between the predictive results of the two models is troublesome. The finite element heat and mass transfer model used for total system performance assessment predicts faster breakthrough.

DOE consistently neglected radionuclide sorption in fractures and applied a linear sorption coefficient to simulate radionuclide transport through the matrix in the unsaturated zone in total system performance assessment (Wilson, et al., 1994; CRWMS M&O, 1998, 2000b,f). DOE asserts that model uncertainty is contained within the probability distribution functions defined for the retardation parameters. The potential for processes such as precipitation and colloid formation to contribute to the results from batch sorption experiments is also believed to be conservatively bounded by the K_d approach (CRWMS M&O, 2000c). The acceptability of this approach to model uncertainty will depend to a large extent on the documentation of the processes and information used in the expert judgments for sorption coefficient probability distribution functions, as discussed in the previous section. DOE agreed[26] to provide this documentation as part of its technical basis for transport parameter distributions. DOE also has *in-situ* testing planned for Alcove 8–Niche 3 and Busted Butte that is anticipated to support the characterization of model uncertainty. Laboratory column experiments will also help evaluate the uncertainty in using a linear sorption coefficient.

---

[25]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Radionuclide Transport (December 5–7, 2000)." Letter (December 12) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

[26]Ibid.

In summary, for unsaturated zone colloid transport modeling, DOE addresses model uncertainty chiefly by adopting each of two distinct attachment modes—reversible and irreversible (CRWMS M&O, 2000h). DOE has not provided sufficient evidence that its selection of colloid transport parameters bounds model uncertainties, so that the radionuclide transport in the unsaturated zone model abstraction realistically or conservatively bounds the possible effects of colloids. Although Total System Performance Assessment–Site Recommendation sensitivity analyses suggest that reversible attachment has a small effect (CRWMS M&O, 2000b), DOE needs to show, for example, that neglect of kinetic adsorption and desorption effects will not result in underestimating the effects of reversible attachment on performance. DOE agreed[27] to demonstrate adequate consideration of model uncertainty as documented in future reports.

3.3.7.4.5 Model Abstraction Output Is Supported by Objective Comparisons

Overall, the current information, along with the agreements reached between the DOE and NRC (Section 3.3.7.5), is sufficient to conclude that the necessary information will be available at the time of a potential license application to assess radionuclide transport in the unsaturated zone with respect to model abstraction output being supported by objective comparisons.

The residence-time transfer function method used to couple matrix diffusion to the FEHM (Zyvoloski et al., 1997) transfer particle-tracking transport model is supported by comparison to predictions from analytical solutions and other numerical models (CRWMS M&O, 2000d,q). For cases where large numbers of particles are used, predictions made using the residence-time transfer function particle-tracking approach compare well to one-dimensional analytical solutions (CRWMS M&O, 2000d, Section 6.3).

To check for proper implementation of the transport model in the total system performance assessment analyses, DOE tested the coupling between GoldSim, FEHM transfer, and other coupling components (CRWMS M&O, 2000f). DOE used FEHM to track 21 species through the unsaturated zone for a period of 1 million years, with a climate change sequence of present-day climate for the first 600 years, monsoonal climate from 600 to 2,000 years, and glacial-transition climate for times greater than 2,000 years. Median transport parameter values and a maximum of 525,000 particles were used. The results show that the finite element heat and mass transfer unsaturated zone outflow mass flux curves trace the corresponding engineered barrier subsystem release curves well. The results also provide support that the GoldSim–FEHM coupling worked as designed, and finite element heat and mass transfer tracked the transport of radionuclides in the unsaturated zone correctly (CRWMS M&O, 2000f, Figures 6-165 and 6-166).

In summary, DOE has not provided sufficient evidence, either through field tests or natural analogs, that results from laboratory sorption and transport experiments can be extended or used to bound transport over larger distances and longer times. Demonstration of scale effect

[27]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Total System Performance Assessment and Integration (August 6–10, 2001)." Letter (August 23) to S. Brocoum, DOE. Washington, DC: NRC. 2001.

is possible at the Alluvial Tracer Complex if the distance between the wells is varied in the cross-hole tests and the duration of the tests is varied. If credit is to be taken for radionuclide attenuation, DOE should demonstrate that nonradioactive tracers used in field tests are appropriate homologues for radioelements. DOE expects to show that nonradioactive tracers used in field tests are appropriate homologues for radioelements, but results are not yet available. Ongoing testing at Alcove 8–Niche 3 in the Exploratory Studies Facility, Busted Butte, and large block studies at Atomic Energy of Canada Limited, laboratories in Pinawa, Manitoba, will provide transport data using a suite of tracers representative of conservative and weakly sorbing radionuclides (Vandergraaf, et al., 2000a,b). DOE considers these tests to be representative of transport of conservative radionuclides, sorbing radionuclides, and colloids. For dissolved radionuclides, DOE is using these results as a means of demonstrating the appropriateness of conceptual models rather than as a source of transport parameters for total system performance assessment. DOE agreed[28] to provide pretest predictions and results of field tests to demonstrate model abstraction is supported by objective comparisons.

3.3.7.5 Status and Path Forward

Table 3.3.7-1 provides the status of all key technical issue subissues, referenced in Section 3.3.7.2, for the Radionuclide Transport in the Unsaturated Zone Integrated Subissue. The table also provides the related DOE and NRC agreements pertaining to the Radionuclide Transport in the Unsaturated Zone Integrated Subissue. The agreements listed in the table are associated with one or all five generic acceptance criteria discussed in Section 3.3.7.4. Note the status and the detailed agreements (or path forward) pertaining to all the key technical issue subissues are provided in Table 1.1-3 and Appendix A.

The DOE-proposed approach, together with the DOE agreements to provide NRC with additional information (through specified testing, analyses, and the like), acceptably addresses the NRC questions so that no information beyond that provided, or agreed to, will likely be required at the time of a potential license application.

Table 3.3.7-1. Related Key Technical Issue Subissues and Agreements

Key Technical Issue	Subissue	Status	Related Agreements*
Radionuclide Transport	Subissue 1—Radionuclide Transport through Porous Rock	Closed-Pending	RT.1.01 through RT 1.05
	Subissue 2—Radionuclide Transport through Fractured Rock	Closed-Pending	RT.2.10

[28]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Radionuclide Transport (December 5–7, 2000)." Letter (December 12) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

Table 3.3.7-1. Related Key Technical Issue Subissues and Agreements (continued)

Key Technical Issue	Subissue	Status	Related Agreements*
Radionuclide Transport	Subissue 3—Radionuclide Transport through Fractured Rock		RT.3.01 RT.3.02 RT.3.04 through RT.3.08 RT.3.10
	Subissue 4—Nuclear Criticality in the Far Field	Closed-Pending	RT.4.01 RT.4.03
Unsaturated and Saturated Flow Under Isothermal Conditions	Subissue 4—Deep Percolation	Closed-Pending	USFIC.4.01
	Subissue 6—Matrix Diffusion	Closed-Pending	USFIC.6.01 USFIC.6.02 USFIC 6.03
Thermal Effects on Flow	Subissue 2—Is the DOE Thermohydrologic Modeling Approach Sufficient to Predict the Nature and Bounds of Thermal Effects on Flow in the Near Field?	Closed-Pending	TEF.2.12 TEF.2.13
Structural Deformation and Seismicity	Subissue 3—Fracturing and Structural Framework of the Geologic Setting	Closed-Pending	SDS.3.01 SDS.3.02
Evolution of the Near-Field Environment	Subissue 3—The Effects of Coupled Thermal-Hydrological-Chemical Processes on Chemical Environment for Radionuclide Release	Closed-Pending	ENFE.3.05
	Subissue 4—The Effects of Coupled Thermal-Hydrological-Chemical Processes on Radionuclide Transport through Engineered and Natural Barriers	Closed-Pending	None
Total System Performance Assessment and Integration	Subissue 1—System Description and Demonstration of Multiple Barriers	Closed-Pending	None
	Subissue 2—Scenario Analysis and Event Probability	Closed-Pending	TSPAI.2.01 TSPAI.2.02 TSPAI.2.03
	Subissue 3—Model Abstraction	Closed-Pending	TSPAI.3.28 TSPAI.3.29
	Subissue 4—Demonstration of Compliance with the Postclosure Public Health and Environmental Standards	Closed-Pending	None

*Related DOE and NRC agreements are associated with one or all five generic acceptance criteria.

Note: Key Technical Issue Agreement GEN.1.01 pertains to multiple integrated subissues, as well as some specific issues related to this integrated subissue.

3.3.7.6 References

Andersson, K. "SKI Project-90: Chemical Data." SKI Technical Report 91: 21. Stockholm, Sweden: Swedish Nuclear Power Inspectorate. 1998.

Barnard, R.W., M.L. Wilson, H.A. Dockery, J.H. Gauthier, P.G. Kaplan, R.R. Eaton, F.W. Bingham, and T.H. Robey. "Total System Performance Assessment—1991: An Initial Total-System Performance Assessment for Yucca Mountain." SAND91–2795. Albuquerque, New Mexico: Sandia National Laboratories. 1992.

Bechtel SAIC Company, LLC. "FY01 Supplemental Science and Performance Analyses." Vol. 1: Scientific Bases and Analyses. TDR–MGR–MD–000007. Revision 00 ICN 01. Las Vegas, Nevada: Bechtel SAIC Company, LLC. 2001a.

Bechtel SAIC Company, LLC. "FY01 Supplemental Science and Performance Analyses." Vol. 2: Performance Analyses. TDR–MGR–PA–000001. Rev. 00. Las Vegas, Nevada: Bechtel SAIC Company, LLC. 2001b.

Browning, L., W.M. Murphy, B.W. Leslie, and W.L. Dam. "Thermodynamic Interpretations of Chemical Analyses of Unsaturated Zone Water From Yucca Mountain, Nevada." Symposium Proceedings. Vol. 608. R.W. Smith and D.W. Shoesmith, eds. Pittsburgh, Pennsylvania: Materials Research Society. pp. 237–242. 2000.

CRWMS M&O. "Total System Performance Assessment–Viability Assessment (TSPA-VA) Analyses Technical Basis Document." B00000000–01717–4301. Revision 01. Las Vegas, Nevada: TRW Environmental Safety Systems, Inc. 1998.

———. "Repository Safety Strategy: Plan to Prepare the Safety Case to Support Yucca Mountain Site Recommendation and Licensing Considerations." TDR–WIS–RL–000001. Revision 04. Las Vegas, Nevada: CRWMS M&O. 2000a.

———. "Total System Performance Assessment for the Site Recommendation." TDF–WIS–PA–00001. Revision 00 ICN 01. Las Vegas, Nevada: CRWMS M&O. 2000b.

———. "Unsaturated Zone and Saturated Zone Transport Properties." ANL–NBS–HS–000019. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000c.

———. "Particle Tracking Model and Abstraction of Transport Processes." ANL–NBS–HS–000026. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000d.

———. "Unsaturated Zone Flow and Transport Model Process Model Report." TDR–NBS–HS–000002. Revision 00, ICN02. Las Vegas, Nevada: CRWMS M&O. 2000e.

———. "Total System Performance Assessment (TSPA) Model for Site Recommendation." MDL–WIS–PA–000002. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000f.

———. "Inventory Abstraction." ANL–WIS–MD–000006. Revision 00. Las Vegas, Nevada. CRWMS M&O: 2000g.

———. "Waste Form Colloid-Associated Concentration Limits: Abstraction and Summary." ANL–WIS–MD–000012. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000h.

———. "Probability of Criticality Before 10,000 Years." CAL–EBS–NU–000014. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000i.

———. "Features, Events, and Processes—System Level and Criticality." ANL–WIS–MD–000019. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000j.

———. "Features, Events, and Processes in Unsaturated Zone Flow and Transport." ANL–NBS–MD–000001. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000k.

———. "Drift-Scale Coupled Processes (DST and THC Seepage) Models." MDL–NBS–HS–000001. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000l.

———. "Uncertainty Distributions for Stochastic Parameters." ANL–NBS–MD–000011. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000m.

———. "Mountain-Scale Coupled Processes (TH) Model." MDL–NBS–HS–000007. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000n.

———. "Engineered Barrier SubSystem Features, Events, and Processes/Degradation Modes Abstraction." ANL–WIS–PA–000002. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000o.

———. "Engineered Barrier SubSystem Degradation, Flow, and Transport Process Model Report." TDR–EBS–MD–000006. Revision 00, ICN 01. Las Vegas, Nevada: CRWMS M&O. 2000p.

———. "Analysis Comparing Advective-Dispersive Transport Solution to Particle Tracking." ANL–NBS–HS–000001. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000q.

———. "Analysis of the Base-Case Particle Tracking Results of the Base-Case Flow Fields." ANL–NBS–HS–000024. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000r.

———. "Features, Events, and Processes in Unsaturated Zone Flow and Transport." ANL–NBS–MD–000001. Revision 01. Las Vegas, Nevada: CRWMS M&O. 2001a.

———. "Features, Events, and Processes in Saturated Zone Flow and Transport." ANL–NBS–MD–000002. Revision 01. Las Vegas, Nevada: CRWMS M&O. 2001b.

———. "Yucca Mountain FEP Database." TDR–WIS–MD–000003. Revision 00 ICN01. Las Vegas, Nevada: CRWMS M&O. 2001c.

DOE. "Viability Assessment of a Repository at Yucca Mountain." Overview and All Five Volumes. DOE/RW–0508. Las Vegas, Nevada: DOE, Office of Civilian Radioactive Waste Management. 1998a.

———. "Disposal Criticality Analysis Methodology Topical Report." YMP/TR–004Q. Revision 00. Las Vegas, Nevada: DOE. 1998b.

———. "Disposal Criticality Analysis Methodology Topical Report." YMP/TR–004Q. Revision 01. Las Vegas, Nevada: DOE. 2000.

Flint, L.E. "Characterization of Hydrogeologic Units Using Matrix Properties, Yucca Mountain, Nevada." U.S. Geological Survey Water Resources Investigations Report 97-4243. 1998.

Liu, H.H., C. Doughty, and G.S. Bodvarsson. "An Active Fracture Model for Unsaturated Flow and Transport in Fractured Rocks." *Water Resources Research*. Vol.34. pp. 2,633–2,646. 1998.

Matyskiela, W. "Silica Redistribution and Hydrologic Changes in Heated Fractured Tuff." *Geology*. Vol. 25. pp. 1,115–1,118. 1997.

Murphy, W.M. and R.T. Pabalan. NUREG/CR–6288. "Geochemical Investigations Related to the Yucca Mountain Environment and Potential Nuclear Waste Repository." Washington, DC: NRC. 1994.

NRC. NUREG–1563, "Branch Technical Position on the Use of Expert Elicitation in the High-Level Radioactive Waste Program." Washington, DC: NRC. November 1996.

——— "Issue Resolution Status Report, Key Technical Issue: Radionuclide Transport, Revision 2." Washington, DC: NRC. 2000a.

———. "Issue Resolution Status Report, Key Technical Issue: Unsaturated and Saturated Flow Under Isothermal Conditions, Revision 3." Washington, DC: NRC. 2000b.

———. "Issue Resolution Status Report, Key Technical Issue: Evolution of the Near-Field Environment, Revision 3." Washington, DC: NRC. 2000c.

———. "Issue Resolution Status Report, Key Technical Issue: Structural Deformation and Seismicity, Revision 3." Washington, DC: NRC. 2000d.

———. "Issue Resolution Status Report, Key Technical Issue: Thermal Effects on Flow, Revision 3." Washington, DC: NRC. 2000e.

———. "Issue Resolution Status Report, Key Technical Issue: Total System Performance Assessment and Integration, Revision 3." Washington, DC: NRC. 2000f.

———. "Safety Evaluation Report for Disposal Criticality Analysis Methodology Topical Report, Revision 0." Washington, DC: NRC. 2000g.

———. NUREG–1804, "Yucca Mountain Review Plan—Draft Report for Comment." Revision 2. Washington, DC: NRC. March 2002.

Reimus, P.W., A. Adams, M.J. Haga, A. Humphrey, T. Callahan, I. Anghel, and D. Counce. "Results and Interpretation of Hydraulic and Tracer Testing in the Prow Pass Tuff at the C-Holes: Yucca Mountain Project Milestone SP32E7M4." Los Alamos, New Mexico: Los Alamos National Laboratory: 1999.

Sudicky, E.A. and E.O. Frind. "Contaminant Transport in Fractured Porous Media: Analytical Solutions for a System of Parallel Fractures." *Water Resources Research*. Vol. 18, No. 6. pp. 1,634–1,642. 1982.

Swift, P., G. Barr, R. Barnard, R. Rechard, A. Schenker, G. Freeze, and P. Burck. "Feature, Event, and Process Screening and Scenario Development for the Yucca Mountain Total System Performance Assessment." SAND98–2831C. Albuquerque, New Mexico: Sandia National Laboratories. 1999.

Triay, I.R., A. Meijer, J.L. Conca, K.S. Kung, R.S. Rundberg, and E.A. Strietelmeier. "Summary and Synthesis Report on Radionuclide Retardation for the Yucca Mountain Site Characterization Project, Milestone 3784M." LA–13262–MS. Los Alamos, New Mexico: Los Alamos National Laboratory, Chemical Science and Technology Division. 1997.

Vandergraaf, T.T., D.J. Drew, and K.V. Ticknor. "Radionuclide Migration Experiments in Non-Welded Tuff Under Unsaturated and Saturated Conditions. Bi-Monthly Report, July–August 2000." TDP–NBS–GS–000020. Pinawa, Manitoba: Atomic Energy of Canada Limited. 2000a.

———. "Radionuclide Migration Experiments in Non-Welded Tuff Under Unsaturated and Saturated Conditions. Bi-Monthly Report, September–October 2000." TDP–NBS–GS–000020. Pinawa, Manitoba: Atomic Energy of Canada Limited. 2000b.

Wilson, M.L., J.H. Gauthier, R.W. Barnard, G.E. Barr, H.A. Dockery, E. Dunn, R.R. Eaton, D.C. Guerin, N. Lu, M.J. Martinez, R. Nilson, C.A. Rautman, T.H. Robey, B. Ross, E.E. Ryder, A.R. Schenker, S.A. Shannon, L.H. Skinner, W.G. Halsey, J.D. Gansemer, L.C. Lewis, A.D. Lamont, I.R. Triay, A. Meijer, and D.E. Morris. "Total-System Performance Assessment for Yucca Mountain–SNL Second Iteration (TSPA–1993) Volume 2." SAND93–2675. Albuquerque, New Mexico: Sandia National Laboratories. 1994.

Yang I.C., G.W. Rattray, and P. Yu. "Interpretation of Chemical and Isotopic Data from Boreholes in the Unsaturated Zone at Yucca Mountain, Nevada." U.S. Geological Survey. Water Resources Investigations Report 96-4058. 1996.

Yang, I.C. P, Yu, G.W. Rattray, J.S. Ferarese, and J.N. Ryan. "Hydrochemical Investigations in Characterizing the Unsaturated Zone at Yucca Mountain, Nevada." U.S. Geological Survey. Water Resources Investigations Report 98-4132. 1998.

Zyvoloski, G.A., B.A. Robinson, Z.V. Dash, and L.L. Trease. "Summary of Models and Methods for the FEHM Application—A Finite Element Heat- and Mass-Transfer Code." LA–13307–MS. Los Alamos, New Mexico: Los Alamos National Laboratory. 1997.

3.3.8 Flow Paths in the Saturated Zone

3.3.8.1 Description of Issue

The Flow Paths in the Saturated Zone Integrated Subissue addresses features and processes that affect the saturated zone flow paths and flow velocities in the saturated zone between the area beneath the proposed repository site and the compliance boundary, and their effects on the radionuclide concentrations in the groundwater at the receptor location. The relationship of this integrated subissue to other integrated subissues are depicted in Figure 3.3.8-1. The overall organization and identification of all the integrated subissues is depicted in Figure 1.1-2. The DOE description and technical bases for abstraction of flow paths in the saturated zone are documented in CRWMS M&O (2000a) and several supporting analysis and model reports cited throughout this review. This section provides a review of the abstractions DOE developed to incorporate these features and processes in its total system performance assessment.

3.3.8.2 Relationship to Key Technical Issue Subissues

The Flow Paths in the Saturated Zone Integrated Subissue incorporates subject matter previously captured in the following key technical issue subissues:

- Unsaturated and Saturated Flow Under Isothermal Conditions: Subissue 2—Hydrologic Effects of Climate Change (NRC, 1999)
- Unsaturated and Saturated Flow Under Isothermal Conditions: Subissue 5—Saturated Zone Flow and Dilution Processes (NRC, 1999)
- Unsaturated and Saturated Flow Under Isothermal Conditions: Subissue 6—Matrix Diffusion (NRC, 1999)
- Structural Deformation and Seismicity: Subissue 1—Faulting (NRC, 2000a)
- Structural Deformation and Seismicity: Subissue 3—Fracturing (NRC, 2000a)
- Total System Performance Assessment and Integration: Subissue 1—System Description and Demonstration of Multiple Barriers (NRC, 2000b)
- Total System Performance Assessment and Integration: Subissue 2—Scenario Analysis and Event Probability (NRC, 2000b)
- Total System Performance Assessment and Integration: Subissue 3—Model Abstraction (NRC, 2000b)
- Total System Performance Assessment and Integration: Subissue 4—Demonstration of Compliance with the Postclosure Public Health and Environmental Standards (NRC, 2000b)

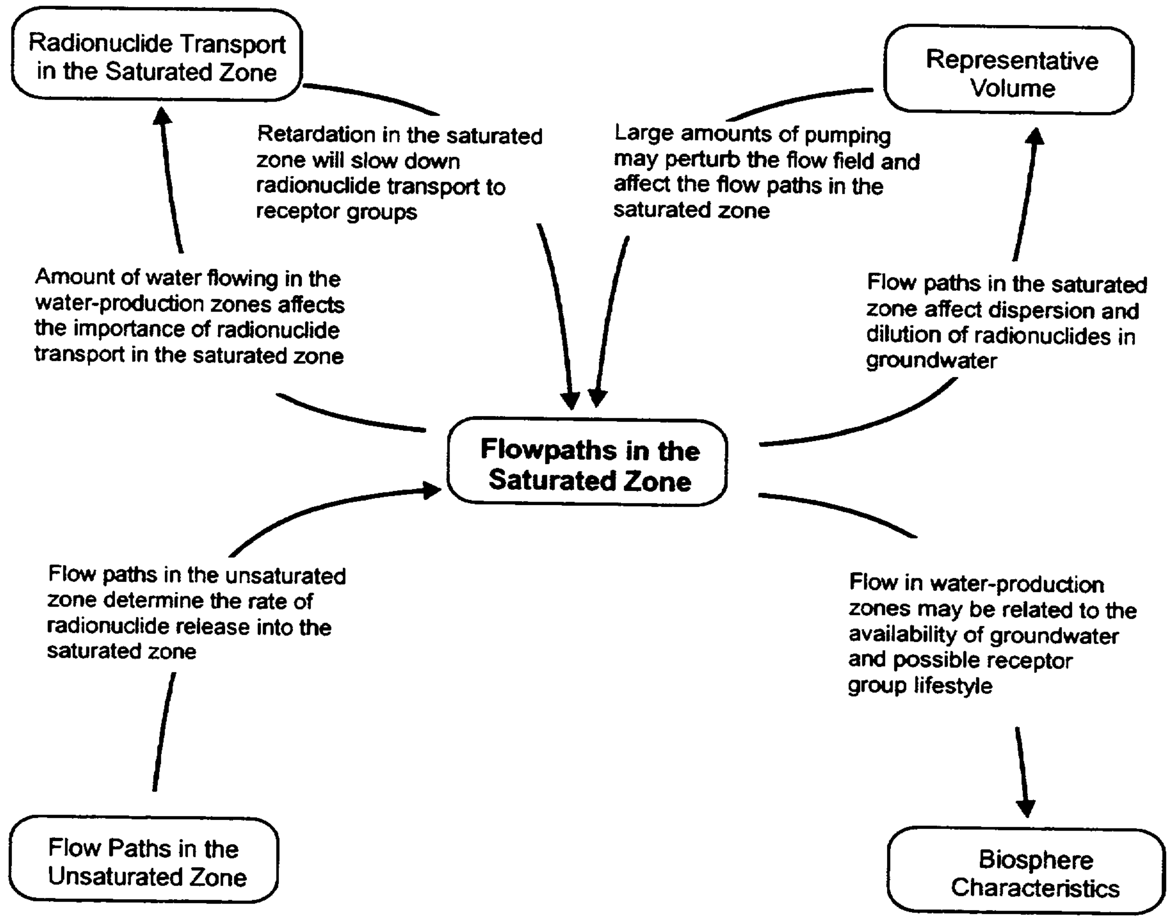

Figure 3.3.8-1. Diagram Illustrating the Relationship Between Flow Paths in the Saturated Zone and Other Integrated Subissues

- Radionuclide Transport: Subissue 1—Radionuclide Transport Through Porous Rock (NRC, 2000c)
- Radionuclide Transport: Subissue 2—Radionuclide Transport Through Fractured Rock (NRC, 2000c)
- Radionuclide Transport: Subissue 3—Radionuclide Transport Through Alluvium (NRC, 2000c)

The key technical issue subissues formed the bases for the previous versions of the issue resolution status reports and also were the bases for technical exchanges with DOE where agreements were reached on what additional information DOE needed to provide to resolve the subissue. The resolution status of this integrated subissue is based on the resolution status of each of the contributing key technical issue subissues. The subsequent sections incorporate applicable portions of these key technical issue subissues, however, no effort was made to explicitly identify each subissue.

3.3.8.3 Importance to Postclosure Performance

One aspect of risk informing the NRC review was to determine how this integrated subissue is related to the DOE repository safety strategy. DOE identified radionuclide delay through the saturated zone in CRWMS M&O (2000b) as one of eight principal factors of the current postclosure safety case for the proposed nuclear waste repository at Yucca Mountain.

DOE did not perform sensitivity analyses for individual saturated zone flow and transport parameters for the Total System Performance Assessment–Site Recommendation. Rather, analyses were performed to compare a degraded saturated zone barrier to an enhanced saturated zone barrier (CRWMS M&O, 2000c, Section 5.3.7). To evaluate degraded behavior, parameters known to increase radionuclide travel times were assigned values from the low end of their range (5th percentile), and parameters known to reduce radionuclide travel time were assigned values at the high end of their range (95th percentile). The opposite approach was used to achieve enhanced behavior. Performance estimates for 100,000 years show the difference in dose between the degraded and the enhanced cases is between one and two orders of magnitude (CRWMS M&O, 2000c, Figure 5.3-13). In this manner, it was demonstrated that the saturated zone is a potentially important barrier to radionuclide transport.

3.3.8.4 Technical Basis

NRC developed a review plan (NRC, 2002) that is consistent with the acceptance criteria and review methods found in previous issue resolution status reports. A review of DOE approaches for including flow paths in the saturated zone in total system performance assessment abstractions is provided in the following subsections. The review is organized according to the five acceptance criteria identified in Section 1.5 as follows: (i) System Description and Model Integration Are Adequate, (ii) Data Are Sufficient for Model Justification, (iii) Data Uncertainty Is Characterized and Propagated Through the Model Abstraction, (iv) Model Uncertainty Is Characterized and Propagated Through the Model Abstraction, and (v) Model Abstraction Output Is Supported by Objective Comparisons.

3.3.8.4.1 System Description and Model Integration Are Adequate

Overall, the current information, along with agreements reached between DOE and NRC (Section 3.3.8.5), is sufficient to conclude that the necessary information will be available at the time of a potential license application to assess flow paths in the saturated zone with respect to system description and model integration.

A site-scale three-dimensional, steady-state saturated zone flow model of the Yucca Mountain region was developed to support saturated zone radionuclide transport calculations for total system performance assessment (CRWMS M&O, 2000a). The flow model domain lies within the Alkali Flat-Furnace Creek groundwater basin, which is part of the larger Death Valley regional groundwater flow system. A major assumption used to develop the site-scale model is that the Death Valley Regional Groundwater Flow Model (D'Agnese, et al., 1997) provides a reasonable representation of the groundwater flow patterns within the Alkali Flat-Furnace Creek groundwater basin and thus can be used to define boundary conditions and calibration targets for the site-scale model. Accordingly, constant-potential boundary conditions and distributed vertical recharge were derived from the regional model. Recharge from the unsaturated zone site-scale model area and from Fortymile Wash also is included in the model. NRC staff concern with the use of the Death Valley Regional Groundwater Flow Model is that the model has been updated significantly since it was last published by D'Agnese, et al. (1997). The U.S. Geological Survey has not made these updates available, and, as a result, their potential impacts on the DOE three-dimensional site-scale model have not been assessed. It was noted at a DOE and NRC technical exchange on saturated zone flow[1] that documentation of the Death Valley Regional Groundwater Flow Model is a U.S. Geological Survey product anticipated to be available in late 2001, and DOE agreed to update the saturated zone process model report, as necessary, to incorporate updates to the regional flow model.

The rectangular saturated zone site-scale flow model domain is 30 km [18.7 mi] wide by 45 km [28.0 mi] long and extends vertically from the water table to a depth 2,750 m [9,022 ft] below the water table (CRWMS M&O, 2000a). The numerical model grid is discretized horizontally into uniform 500 × 500-m [1640.4 × 1640.4-ft] grid cells producing a 60 × 90-cell horizontal grid. Vertically, the grid spacing varies from as little as 10 m [32.8 ft], for more permeable layers near the top of the model, to as large as 550 m [1,804.5 ft] at the bottom of the model, with a total of 39 layers (CRWMS M&O, 2000a, Table 3-4). Hydrologic properties assigned to grid cells are based on their spatial correspondence to one of 19 hydrogeologic units defined in the Hydrogeologic Framework Model (CRWMS M&O, 2000d, Table 6-2). The Hydrogeologic Framework Model incorporates the Geologic Framework Model (CRWMS M&O, 2000e) that was developed to support, among other issues, site-scale unsaturated zone modeling. To include the entire saturated zone flow model area, the Hydrogeologic Framework Model coverage extends well beyond the Geologic Framework Model area, and integrates additional data from borehole lithologic logs, geologic maps, geologic cross sections, topographic information, and geologic cross sections and stratigraphic surfaces developed for the Nevada Test Site (CRWMS M&O, 2000d). A concern NRC staff raised at the DOE and NRC technical exchange on saturated zone flow[2] is that discontinuities may have been introduced during extrapolation from the Geologic Framework Model domain to the Hydrogeologic Framework Model domain. DOE agreed at the technical exchange to evaluate the potential effects of such modeling-induced discontinuities and to report the results in an update to the Hydrogeologic Framework Model.

The hydrologic properties (e.g., hydraulic conductivity) of the individual hydrostratigraphic layers in the Hydrogeologic Framework Model are assumed to be homogeneous in the saturated zone flow model. Although this assumption neglects subunit heterogeneity, large-scale heterogeneity is accounted for in the model. Other contributions to the large-scale heterogeneity are considered in the model by modifying properties of grid cells corresponding

[1]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Unsaturated and Saturated Flow Under Isothermal Conditions (October 31–November 2, 2000)." Letter (November 17) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

[2]Ibid.

to any of 17 hydrologic features that were added to represent faults, fault zones, areas of geochemical alteration, and an area of valley fill with large uncertainties (CRWMS M&O, 2000f, Table 6, Figure 4). Some of these features have enhanced permeability, some have reduced permeability, and some have anisotropic permeability. Each feature is said to have a significant impact on the calibration of the flow model (CRWMS M&O, 2000f, Section 6.3). Several of these hydrologic features represent faults that have enhanced permeability, are predominantly vertical, and are oriented roughly north-south. The inclusion of such features imparts to the saturated zone model an effect similar to that of a large-scale horizontal anisotropy. That is, flow can be diverted to a more southerly direction than might be inferred from the prevailing hydraulic gradient.

For the calibrated basecase saturated zone site-scale model (CRWMS M&O, 2000g), Hydrogeologic Framework Model units not associated with hydrologic features are assumed horizontally isotropic and assigned a horizontal-to-vertical anisotropy ratio of 10:1 (CRWMS M&O, 2000a). That is, horizontal permeability is independent of direction, and permeability in the vertical direction is assumed one-tenth the horizontal permeability. The reduced vertical permeability is intended to account for effects of horizontal stratification not explicitly incorporated into the model. To account for the potential effects of the preferential north-south orientation of fractures observed in boreholes penetrating saturated tuffs near Yucca Mountain (e.g., Geldon, 1996), an alternative conceptual model is considered by assigning a 5:1 anisotropy ratio to the permeability of hydrogeologic units representing fractured volcanic tuffs such that permeability in the north-south direction is five times as great as permeability in the east-west direction. This anisotropy is applied only to those tuff units located south of the repository. That is, the permeabilities of similar units north of the repository are assumed to be isotropic.

The three-dimensional saturated zone flow model was calibrated using an inverse optimization approach with the goal to minimize differences (residuals) between model estimates and observations. The observations, referred to as calibration targets, include 115 water level and head measurements (CRWMS M&O, 2000f, Table 7) and 10 side-boundary flux values derived from the Death Valley regional groundwater flow model. Weighting factors were used in the calibration to assign relative importance to each water level and head measurement. For example, weighting factors of 20 were used for water levels in wells along flow paths downstream of Yucca Mountain; factors as low as 0.05 were used for wells to the north beyond the large hydraulic gradient.

Uncertainty in both groundwater flow rates and flow directions is abstracted in total system performance assessment calculations by sampling six discrete cases of steady-state saturated zone flow fields developed using the site-scale saturated zone flow model. The first three cases are based on the isotropic conceptual model of horizontally isotropic permeability and consist of (i) the mean case (corresponding to saturated zone groundwater flux estimated from the Death Valley regional model) of the calibrated site-scale saturated zone flow model), (ii) the low-flux case (mean flux times 0.1), and (iii) the high-flux case (mean flux times 10). The other three cases represent the anisotropic conceptual model (5:1 horizontal anisotropy ratio for fractured volcanic tuffs) and include mean, low, and high fluxes. The mean-flux case for the isotropic conceptual model represents the calibrated saturated zone site-scale flow model. The other five flow model cases are not calibrated models. DOE notes, however, that only small variations exist in the simulated heads among the six flow solutions, generally less than 1 m [3.28 ft] (CRWMS M&O, 2000a, Section 3.6.3.2). In fact, the residual head differences were slightly less for the uncalibrated mean anisotropic case compared with the calibrated mean isotropic case. These differences suggest that the anisotropic conceptual model may be better suited as a basecase scenario for total system performance assessment calculations, as discussed further in Section 3.3.8.4.4.

The steady-state three-dimensional flow fields derived from the saturated zone site-scale flow model are coupled to the transport module of the saturated zone flow and transport model to generate breakthrough curves for the various radionuclides and for various stochastically sampled transport parameter sets. The breakthrough curves are then used by the abstraction model—the convolution integral method—in the total system performance assessment computer program to determine radionuclide flux to the biosphere (CRWMS M&O, 2000a, Section 3.6.3.3).

The DOE model couples climate and saturated groundwater flow through recharge. Saturated zone groundwater fluxes are expected to increase during future climates. The effects of climate change on transport of radionuclides in the saturated zone are incorporated in the total system performance assessment by scaling mass breakthrough arrival times in proportion to the estimated increase in groundwater flux during future climate conditions (CRWMS M&O, 2000a). This method treats the shift in climatic conditions as an instantaneous change from one steady-state groundwater flow condition to another. To estimate the increase in groundwater flux for future climate, simulations using inferred conditions of a past-climate state (21,000 years ago) were conducted using the Death Valley Regional Groundwater Flow Model (D'Agnese, et al., 1999). This climatic state is assumed to correspond approximately to the glacial-transition state. Results indicate a change in groundwater flux in the saturated zone near Yucca Mountain by a factor of 3.9, relative to present-day conditions. Coincidentally, the ratio of glacial-transition infiltration in the unsaturated zone model to the present-day infiltration is also about 3.9 (CRWMS M&O, 2000h). Based on this correspondence, DOE assumed that the unsaturated zone infiltration ratio provides a reasonable estimate of the flux ratio for the saturated zone. Accordingly, a value of 2.7 is used to scale the saturated zone model fluxes for the monsoon climate because it represents the ratio of predicted unsaturated zone infiltration for monsoon conditions to present-day infiltration. These inferred magnitudes of climate-induced changes in groundwater flux seem reasonable considering the range of uncertainty in groundwater flux accounted for by the mean-, low-, and high-flux cases spans two orders of magnitude (i.e., 0.1 times mean, mean, and 10 times mean). It should be noted that this approach ignores the effects of climate-induced water table rise on saturated zone flow paths. Given the scale of the saturated zone site-scale flow model, however, water table rise on the order of a few tens of meters (see Section 3.3.5) is not expected to have a significant effect on performance of the saturated zone as a natural barrier to radionuclide migration.

Several features, events, and processes are excluded from the Total System Performance Assessment–Site Recommendation abstraction of the saturated zone. These exclusions are based on screening arguments that the features, events, and processes are of low probability or of low consequence to performance estimates. The screening arguments pertaining to the abstraction of flow paths in the saturated zone are outlined in CRWMS M&O (2001). In most cases, the screening arguments are adequate and exclusion of the various features, events, and processes is appropriate. In other cases, however, DOE arguments are either incomplete, based on assumptions that are to be verified, or otherwise inadequate at this time. A list of features, events, and processes for which screening arguments proposed by DOE were not adequate or required verification, and their associated path forward (as agreed to by DOE and NRC during an August 2001 Technical Exchange Meeting on Total System Performance Assessment and Integration[3]), is provided in Section 3.2 of this report.

In summary, the technical basis for data sufficiency for model justification with respect to flow paths in the saturated zone, along with the agreements reached, will provide a sufficient basis for a satisfactory characterization of flow paths in the saturated zone and saturated zone abstraction in the total system performance assessment at the time of a potential license application.

3.3.8.4.2 Data Are Sufficient for Model Justification

Overall, the current information, along with agreements reached between DOE and NRC (Section 3.3.8.5), is sufficient to conclude that the necessary information will be available at the time of a potential license application to assess flow paths in the saturated zone with respect to data being sufficient for model justification.

To assess the extent to which radionuclides may be delayed or immobilized in the saturated zone, it is necessary to understand the ambient flow conditions and the spatial distribution of hydrologic properties from the water table beneath the proposed repository to the compliance boundary. Ambient flow conditions are affected by the subsurface geology, areal recharge patterns, water use patterns, and interbasin or interaquifer mixing of groundwaters.

The Hydrogeologic Framework Model (CRWMS M&O, 2000e) provides the conceptual foundation for the hydrostratigraphy of the site-scale three-dimensional flow model. Available hydrogeologic data used by DOE to develop the Hydrogeologic Framework Model include the Geologic Framework Model, borehole lithologic logs, geologic maps, geologic cross sections, and topographic information. The Hydrogeologic Framework Model is generally consistent with the conceptual model developed by Luckey, et al. (1996), in which saturated zone flow from below Yucca Mountain goes through gently eastward-dipping volcanic-tuff aquifers and aquitards occasionally offset by faults, transitioning to a valley-fill alluvial aquifer some distance southeast of Yucca Mountain. NRC previously reviewed the Luckey, et al. (1996) conceptual model and found it provided an adequate basis for a groundwater flow model, with the exception of uncertainty in properties of the alluvial aquifer system and location of the tuff-alluvium interface (NRC, 1999). At a technical exchange between DOE and NRC, DOE agreed to delineate the tuff-alluvium contact based on ongoing drilling and testing.[4]

---

[3]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Total System Performance Assessment and Integration (August 6–10, 2001)." Letter (August 23) to S. Brocoum, DOE. Washington, DC: NRC. 2001.

[4]Ibid.

Data to support estimates of vertical and lateral recharge used for the saturated zone site-scale flow model are derived from three sources: (i) results of the unsaturated zone flow model (CRWMS M&O, 2000h), (ii) estimates of recharge from analysis of stream flows in Fortymile Wash (Savard, 1998), and (iii) regional fluxes predicted by the Death Valley Regional Groundwater Flow Model (D'Agnese, et al., 1997). Use of such data to develop input for the site-scale saturated zone model is reasonable. Lateral recharge estimated from the Death Valley Regional Groundwater Flow Model accounts for the vast majority of groundwater inflow to the site-scale saturated zone model. It should be noted that the Death Valley Regional Groundwater Flow Model has been significantly modified and refined since the 1997 version used for the abstraction of saturated zone flow paths. At the DOE and NRC Technical Exchange on Saturated Zone Flow issues,[5] DOE agreed to update the saturated zone flow model and process model report considering the updated Death Valley Regional Flow Model.

Water-level data collected in Yucca Mountain wells (CRWMS M&O, 2000i) indicate areas of moderate and high hydraulic gradients west and north of Yucca Mountain. East and southeast of Yucca Mountain, both the hydraulic potential and the hydraulic gradient reflected in water levels are significantly lower than those to the west and north. Water levels in wells east of the Solitario Canyon fault support the conceptual model of eastward flow of groundwater directly beneath Yucca Mountain that gradually turns to southward flow in the vicinity of Fortymile Wash.

The moderate hydraulic gradient area west of Yucca Mountain is characterized by significantly higher water table elevations in wells just west of the Solitario Canyon fault, indicating the moderate gradient likely is caused by a zone of reduced permeability in the volcanic tuffs along the Solitario Canyon fault (CRWMS M&O, 2000a, Section 3.2.2.3). It was expected that hydraulic testing of a new well, SD–6, on the crest of Yucca Mountain just east of the Solitario Canyon fault, would help to characterize further the cause of the moderate hydraulic gradient. It appears, however, that SD–6 is not sufficiently productive to produce a measurable hydraulic response in observation wells on the other side of the Solitario Canyon fault. At NRC request,[6] DOE agreed to provide the data collected during the pumping tests conducted at SD–6. Although insufficient to characterize properties of the Solitario Canyon fault, the fact that Well SD–6 produces little water supports the conceptual model of a zone of reduced permeability along or adjacent to the Solitario Canyon fault. Other wells drilled on Yucca Mountain just east of the Solitario Canyon fault also show low permeability. For example, transmissivity estimates for the volcanic tuffs in Wells USW H–3 (H–3) and USW H–5 are only 1.1 m^2/d [18.8 ft^2/d] and 36 m^2/d [387.5 ft^2/d] (e.g., Thordarson, et al., 1985; Robison and Craig, 1991). West of the Solitario Canyon fault, reported transmissivities are on the order of several hundred meters squared per day; transmissivities also increase rapidly with distances east of Solitario Canyon fault, from several hundred meters squared per day on the east flank of Yucca Mountain to a few thousand meters squared per day at the C-Holes Complex (e.g., Geldon, 1996). Thus, the moderate hydraulic gradient beneath the western portion of Yucca Mountain appears related to

---

[5]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Unsaturated and Saturated Flow Under Isothermal Conditions (October 31–November 2, 2000)." Letter (November 17) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

[6]Ibid.

a zone of reduced permeability associated with, or at least coincident with, the presence of the Solitario Canyon fault.

The completion of Well USW WT–24, just southeast of Well G–2, provided new insight for the large hydraulic gradient. Data show the presence of a perched-water zone. A fairly conductive fracture was eventually encountered near the base of the Calico Hills Tuff, and the water level rose over 100 m [328.08 ft], marking the location of the potentiometric surface. The water level was reported to be rising slowly as of early June 1998. In June 1998, the water level was reported at approximately 839.5 m [2,754.27 ft], implying a lateral southerly hydraulic gradient of approximately 0.059 between Well WT–24 and Wells WT–16 and USW H–1 (H–1) (shallow zone). The data verify that heads are indeed higher north of the Yucca Mountain site, and the relatively high heads in Wells G–2 and WT–6 are not entirely the result of perched water.

The cause of the large hydraulic gradient is still uncertain, but the evidence from Wells WT–24 and USW G–2 points to a simple model with a thick, low-permeability confining unit that perches water above and within it. The Calico Hills Tuff is relatively thicker to the north and occurs within the saturated zone; whereas, it is unsaturated at the Yucca Mountain site. The Calico Hills Tuff causes perched water at WT–24 and at numerous locations further south, demonstrating that vertical permeabilities are relatively low, and any fractures present are poorly conductive. Lateral permeabilities are also low, as demonstrated through testing at Well USW G–2. These low permabilities, combined with proximity to the water table, probably cause a lateral flow barrier that restricts flow and causes heads to build up to the north. The Yucca Mountain site appears to be bounded on both the north and west by zones of relatively low permeability. The high gradients across these features provide a driving force for groundwater to move laterally in the Yucca Mountain area.

The calibrated site-scale saturated zone flow model also attempts to reproduce the upward vertical hydraulic gradient observed between the Paleozoic carbonate aquifer and the overlying volcanic tuff and valley-fill (alluvial) aquifer systems. Data to support the existence of this upward gradient come from Wells UE–25 p#1 (p#1), H–1, H–3, and NC–EWDP–2DB (2DB). Hydraulic potentials in p#1 are approximately 20 m [65.6 ft] higher in the lower part of the volcanic tuffs and in the underlying carbonate aquifer system than in the upper part of the saturated volcanic tuffs. The carbonate and volcanic tuff aquifers in the vicinity of p#1 are separated by the lowermost volcanic confining unit (Luckey, et al. 1996). Well H–1 does not penetrate to the carbonate aquifer, but reaches the lower portion of the lowermost volcanic confining unit where observed potentials are about 50 m [164 ft] greater than in the overlying tuff aquifer (e.g., Graves, et al., 1997). Similarly, hydraulic potentials in Well H–3 are nearly 30 m [98.4 ft] higher in the lower interval than in the upper interval. Well 2DB, which was completed only recently, is the second well in the vicinity of Yucca Mountain to penetrate the carbonate aquifer. Data from Well 2DB are preliminary, but a Nye County representative reported at the Saturated Zone Technical Exchange[7] that hydraulic potentials are higher in the Paleozoic carbonates in Well 2DB. DOE agreed to provide an updated potentiometric map and

[7]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Unsaturated and Saturated Flow Under Isothermal Conditions (October 31–November 2, 2000)." Letter (November 17) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

supporting data for the uppermost aquifer in an update to the analysis and model report on water-level data (CRWMS M&O, 2000i), subject to receipt of data from the Nye County program. DOE also will provide an analysis of vertical hydraulic gradients in the next revision to the analysis and model report on calibration of the site-scale flow model (CRWMS M&O, 2000f).

Pumping test and water-level data from wells are used to characterize the permeabilities of the hydrogeologic units and to provide calibration targets for the saturated zone site-scale flow model. Several wells in the vicinity of Yucca Mountain can be used to reasonably estimate these characteristics for the saturated volcanic tuff aquifer system. To achieve calibration, 26 parameters representing permeabilities of hydrogeologic units and hydrologic features were adjusted to match hydraulic potentials inferred from water-level data. Adjustment of these parameters was constrained within ranges of values based on the judgment of model developers (CRWMS M&O, 2000f, Table 8). As shown in CRWMS M&O (2000a, Figure 3-22), calibrated permeability values for the saturated zone site-scale flow model did not always fall within the range of permeabilities estimated from pumping test data, but were generally within one order of magnitude. Given the limitations on the number of pumping tests that can be conducted, the uncertainties associated with interpretation of pumping test data, and the variability of the scale of the pumping tests, the calibrated permeability values compare reasonably well with those inferred from pumping test data.

Well data are sparse from about 10 km [6.2 mi] downgradient from Yucca Mountain to the compliance boundary, making it difficult to characterize the saturated zone flow and transport properties in the valley-fill deposits. Preliminary data from Nye County wells located near the compliance boundary show the water table to be occurring within the valley-fill aquifer, indicating flow paths may transition from a tuff to a valley-fill aquifer system before reaching the proposed compliance point. The exact location of the transition from the tuff to the valley-fill aquifer system and the transmissive properties of the valley-fill aquifer remain uncertain. The complexity of flow paths in the valley fill are supported by detailed examinations of the alluvial and fluvial sediments exposed in the modern entrenched channel of Fortymile Wash, which provides the best analog for features of the valley fill within the saturated flow system. Based on studies performed in the Fortymile Wash channel, Ressler (2001) concluded that the valley fill is best conceptualized by using a braided stream model consisting of eight diagnostic lithofacies defined by grain size, sedimentary features, and sedimentary geometry. Laboratory samples collected in Fortymile Wash and analyzed by Ressler (2001) indicate porosity contrasts between hydrofacies are approximately two orders of magnitude, and hydraulic conductivity contrasts ranging more than three orders of magnitude. These range can significantly impact groundwater flow and transport within the valley-fill deposits. The data gap in the valley-fill aquifer system is presently being addressed by Nye County installing several new wells. At the site of Nye County Wells NC–EWDP–19D and NC–EWDP–19P, located in Fortymile Wash approximately 2 km [1.2 mi] north of the proposed compliance boundary, DOE developed the Alluvial Testing Complex, where hydraulic and tracer testings are ongoing. The Alluvial Testing Complex, along with several new and planned Nye County wells, could possibly yield sufficient data to support parameter estimates for conceptual and numerical models of flow and transport in the valley fill. DOE agreed[8] to provide additional information to support the uncertainty distribution for flow path lengths in valley fill used in the total system performance assessment and also to provide hydrostratigraphic cross sections that include the Nye County well data.

Groundwater pore velocities are poorly constrained for flow paths from Yucca Mountain because of the difficulty in estimating effective flow porosities in the fractured tuff aquifer and the paucity of data for the valley-fill aquifer. Average linear groundwater velocities and residence times can be inferred through groundwater dating. Numerous Yucca Mountain groundwater samples have undergone C-14 dating, but it is difficult to correct for the significant amounts of dead carbon from various sources dissolved in the groundwater. A promising new approach using dissolved organic carbon may greatly improve C-14 dating of groundwater (e.g., Thomas, 1996). This technique has been applied to groundwater near Devils Hole and indicates that groundwater residence times in the carbonate aquifer feeding Devils Hole are about 2,000–3,000 years (Winograd, et al., 1997), significantly less than earlier estimates. NRC staff proposed[9] that DOE could apply this method to samples collected along saturated zone flow paths from Yucca Mountain to independently estimate the average groundwater residence times. Although DOE did not specify a method, it agreed to provide the technical basis for estimated saturated zone residence times in an update to the analysis and model report addressing geochemical and isotopic constraints on groundwater flow (CRWMS M&O, 2000j). DOE also agreed[10] to provide further justification for the range of effective porosity assumed for alluvium, considering the possible effects of contrasts in hydrologic properties of layers observed in wells. To this end, DOE will use data obtained from the Nye County Drilling Program, available geophysical data, including the Nye County aeromagnetic data, and results from the Alluvial Testing Complex. For example, borehole gravimeter data collected at Well 2DB show total porosity within the valley fill varies from approximately 20 to 30 percent.

In summary, sources of data currently analyzed lend support to the DOE conceptual and numerical models for saturated zone site-scale flow at Yucca Mountain. Considerable data collected for the tuff and alluvial aquifer systems, however, remain to be analyzed, interpreted, and published for review (e.g., the final results of the analyses of the long-term pumping and tracer tests at the C-Holes Complex). Data collection is also ongoing in the Nye County Drilling Program and the Alluvial Testing Complex hydraulic and tracer testings. In addition, the U.S. Geological Survey is assessing geochemical constraints on groundwater flow by developing detailed stratigraphic and structural models of the subsurface of Fortymile Wash using data from Nye County wells. These data are necessary to assess the DOE conceptual model for flow paths in the valley-fill aquifer system. As mentioned in the preceding discussion, DOE agreed to provide the additional data and analyses for NRC review.

---

[8]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Unsaturated and Saturated Flow Under Isothermal Conditions (October 31–November 2, 2000)." Letter (November 17) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

[9]Ibid.

[10]DOE and NRC. Presentation at the DOE and NRC Technical Exchange and Management Meeting on Radionuclide Transport, December 5–7, 2000. Berkeley, California. 2000.

3.3.8.4.3 Data Uncertainty Is Characterized and Propagated Through the Model Abstraction

Overall, the current information, along with agreements reached between DOE and NRC (Section 3.3.8.5), is sufficient to conclude that the necessary information will be available at the time of a potential license application to assess flow paths in the saturated zone with respect to data uncertainty being characterized and propagated through model abstraction.

To reasonably account for the uncertainty in saturated zone flow paths and flow rates from beneath the proposed repository to the compliance boundary, the DOE radionuclide transport abstraction for total system performance assessment analyzes samples from among six different sets of saturated zone groundwater flow fields. These flow fields, derived from the saturated zone site-scale flow model, are intended to bound the uncertainties in groundwater fluxes and flow directions. The range of uncertainty considered for the groundwater flux (i.e., mean flux × 0.1 to mean flux × 10) is based on the results of the saturated zone expert elicitation (CRWMS M&O, 1998). Uncertainty in flow direction is treated by developing groundwater flow fields for both isotropic conditions and an alternative model that incorporates horizontally anisotropic conditions with a north-south orientated 5:1 permeability anisotropy ratio for fractured tuffs located south of the repository. The anisotropic cases result in more southerly flow, keeping the flow paths in fractured tuffs for greater distances, thus reducing transport distances through the valley-fill deposits. The six sets of flow fields are among several variables stochastically sampled to generate a set of 100 input files for the radionuclide transport model, which, in turn, is used to generate a library of unit breakthrough curves that subsequently can be sampled for total system performance assessment calculations. Of the 100 stochastically generated input files, the flow fields are sampled as follows: 24 realizations of the mean-flux isotropic case, 28 realizations of the mean-flux anisotropic case, 12 realizations each for the low-flux isotropic and anisotropic cases, 14 realizations of the high-flux isotropic case, and 10 realizations of the high-flux anisotropic case (CRWMS M&O, 2000g, Table 6). Thus, the mean-flux scenario is selected for approximately half the simulations in a stochastic total system performance assessment analysis; flow fields selected for the remainder of simulations are divided equally among low- and high-flux cases. Note, also, that while the anisotropic case is treated as an alternative conceptual model, the total system performance assessment abstraction uses an equal number of realizations representing isotropic and anisotropic flow fields.

Another important uncertainty in the saturated zone site-scale flow model is where saturated zone flow transitions from the volcanic tuff aquifer into the overlying valley-fill sediments along the flow path from Yucca Mountain to the compliance location. This uncertainty is important because the relatively slow flow anticipated in the porous valley fill is thought to have much greater potential for attenuation of radionuclide transport than fast, fracture-dominated flow in the tuffs. Uncertainty in the tuff-valley-fill contact is accounted for stochastically in the total system performance assessment. The tuff-valley-fill transition area is incorporated in the particle-tracking transport simulations for total system performance assessment as a trapezoidal region with a maximum north-south extent of approximately 10 km [6.21 mi], constrained by well log data. The east-west extent of this area averages approximately 5 km [3.1 mi] in width and is bounded by surface outcrops of volcanic units on the west (CRWMS M&O, 2000g, Figure 2). The northern boundary is varied throughout the full north-south extent of the uncertainty zone, from a full 10 km [6.21 mi] of flow in valley fill to a case with no flow in valley fill. The western boundary is varied only about 2 km [1.2 mi] from its most westerly position. Moving this latter boundary farther to the east results in longer transport distances in tuffs for those flow paths that fall to the west of the boundary. For each particle-tracking transport simulation, the locations of these boundaries are selected stochastically within their geometric constraints, assuming a uniform distribution. DOE assumes that the uniform distribution is the least biased, in the absence of more data, to constrain the zone geometry (CRWMS M&O, 2000j). As discussed in Section 3.3.8.4.2, DOE agreed to use data obtained from the Nye County Drilling Program, available geophysical data, and results from the Alluvial Testing Complex testing to justify the range of effective porosity in the valley fill, considering possible effects of contrasts in hydrologic properties of layers observed in wells along potential flow paths.[11]

The effective porosity of the saturated formations along flow paths from Yucca Mountain is another uncertain parameter. Flow velocities in the saturated zone are important in that they determine groundwater and radionuclide travel times from the repository to the compliance location. Effective porosity is defined as volume fraction of the saturated formation occupied by connected pore space in which groundwater movement is dominated by advection. For model layers that represent fractured tuffs, DOE refers to effective porosity as flowing interval porosity. Uncertainty in flowing interval porosity in the fractured tuffs is handled in the saturated zone transport model by assuming a log-uniform distribution of effective porosity from 10^{-5} to 10^{-1}. Based on a previous CNWRA review of effective porosity (Farrell, et al., 2000), this range provides a reasonable bound on the wide range of this highly uncertain parameter. Further, the log-uniform distribution for tuff porosity is skewed toward lower values, which is a conservative approach compared to a normal or uniform distribution. Uncertainty in effective porosity for the valley-fill aquifer is handled by sampling from a truncated normal distribution with a mean value of 0.18 and a standard deviation of 0.051 (CRWMS M&O, 2000j, Table 15). This distribution for effective porosity of the valley fill comes from a study of hydraulic characteristics of alluvium within the North American Basin and Range Province by Bedinger, et al. (1989). It is not clear, however, to what extent the study of Bedinger, et al. (1989) is applicable to the alluvial sediments along the saturated zone flow path from Yucca Mountain. Porosity data are needed from the Nye County wells completed in the valley fill along the flow path from Yucca Mountain. As mentioned in Section 3.3.8.4.2, DOE agreed to use data obtained from the Nye County Drilling Program, available geophysical data, aeromagnetic data, and results from the Alluvial Testing Complex testing to justify the range of effective porosity in the valley fill, considering possible effects of contrasts in hydrologic properties of layers observed in wells along potential flow paths.[12]

In summary, the DOE approach to incorporating data uncertainty into total system performance assessment abstractions by using a stochastic sampling approach is reasonable. More data are needed, however, to constrain the size of the alluvial uncertainty zone and to support the

---

[11]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Unsaturated and Saturated Flow Under Isothermal Conditions (October 31–November 2, 2000)." Letter (November 17) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

[12]Ibid

range and statistical distribution used to account for uncertainty for the effective porosity of alluvium. As mentioned in the preceding discussion, DOE agreed to provide the additional data and analyses for NRC review.

3.3.8.4.4 Model Uncertainty Is Characterized and Propagated Through the Model Abstraction

Overall, the current information, along with agreements reached between DOE and NRC (Section 3.3.8.5), is sufficient to conclude that the necessary information will be available at the time of a potential license application to assess flow paths in the saturated zone with respect to model uncertainty being characterized and propagated through model abstraction.

Model uncertainty refers to uncertainty about the validity of the conceptual models that provide the foundations for the saturated zone site-scale flow and transport models, and the numerical and mathematical approaches employed to develop total system performance assessment abstractions for consideration of flow and transport in the saturated zone. Conceptual model uncertainty requires consideration of alternative conceptual models that cannot be ruled out based on the available data. DOE agreed with this approach.[13]

A model uncertainty in the DOE approach is that changes in transport pathways could result from a potential climate-induced water table rise. This potential flow path variability is not evaluated in the current DOE site-scale saturated zone flow model. Potential water table rise on the order of a few tens of meters is inferred by the Lathrop Wells diatomite deposits that lie above a shallow water table and is likely to have only a small effect on flow patterns relative to the scale of the saturated zone flow model. Such effects might include changes in locations where the water table transitions from the tuff to the alluvial aquifer. DOE should either demonstrate that potential effects of water table rise are negligible or conservative, or incorporate water table rise into the site-scale saturated zone model. DOE researchers are presently revising the site-scale Hydrogeologic Framework Model to change the top boundary of the model from the water table to the ground surface.[14] This revision will allow consideration of water table rise with increased groundwater flux in the site-scale saturated zone flow model, if DOE determines that water table rise should be considered.

The hydraulic potentials observed in the lowermost saturated units of the volcanic tuff aquifer and in the underlying Paleozoic carbonate aquifer east of Yucca Mountain are similar in magnitude to the hydraulic potentials in the uppermost saturated units of the volcanic aquifer west of Yucca Mountain. This observation led to a proposed alternative conceptual model wherein the deep volcanic tuffs and carbonates share a good hydraulic connection with the uppermost saturated volcanic tuffs west of the Solitario Canyon fault. This conceptual model cannot be ruled out based on available data and is potentially important because the western edge of the proposed repository horizon overlies a portion of the moderate hydraulic gradient

---

[13]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Unsaturated and Saturated Flow Under Isothermal Conditions (October 31–November 2, 2000)." Letter (November 17) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

[14]Ibid.

area. It is, therefore, conceivable that potential releases of contaminants from the proposed repository could enter a flow system connected to the regional carbonate aquifer system, as opposed to the current conceptual model where potential contaminant releases are assumed to enter only the uppermost volcanic aquifer system. DOE agreed to consider an alternative conceptual model in which the assumed low permeability zone along the Solitario Canyon fault diminishes with depth, thereby allowing a significant hydraulic connection between the regional carbonate aquifer system below Yucca Mountain and the volcanic tuff aquifer system on the west side of the Solitario Canyon fault.[15]

DOE considers horizontal anisotropy in the permeability of fractured tuffs to be an alternative conceptual model (CRWMS M&O, 2000a). As mentioned in Section 3.3.8.4.1, however, calibration of the site-scale model was improved using a north-south orientated 5:1 horizontal anisotropy ratio. This result suggests the anisotropic model may be better suited as a basecase scenario for total system performance assessment calculations. Other support for assuming anisotropic conditions as the basecase include the preferential north-south orientation of fractures and faults in the area (e.g., Geldon, 1996; Luckey, et al., 1996), possible effects of *in-situ* stress field on conductivity of faults and fractures (Ferrill, et al., 1999), and the observed response in wells during the C-Holes Complex tests (e.g., Ferrill, et al., 1999; Winterle and La Femina, 1999). Whether anisotropic conditions are referred to as the basecase or an alternative model may be a matter of semantics because, as discussed in the preceding section, stochastic sampling of saturated zone flow fields produces an equal number of isotropic and anisotropic realizations. A concern NRC raised at the Technical Exchange on Saturated Zone Flow[16] is that the 5:1 ratio assumed for horizontal anisotropy is based on an analysis by Winterle and La Femina (1999), who noted this estimate was poorly constrained and highly uncertain. Unpublished data and analyses from long-term pumping at the C-Holes Complex could provide an improved technical basis for estimating horizontal anisotropy. At the technical exchange, DOE agreed to provide an analysis of horizontal anisotropy of permeability in the tuff aquifer based on observations in wells that responded to the long-term tests at the C-Holes Complex. Results of these analyses will be carried forward to the site-scale model, as appropriate.

Preliminary interpretations of data from the Nye County Early Warning Drilling Project wells and logs from wells in the town of Amargosa Valley indicate the presence of thick, horizontally continuous, low-permeability clay sediments in the alluvial aquifer system. The heterogeneous nature of juxtaposed clay layers and sand and gravel deposits could cause flow paths to be diverted above, below, or around such layers. Fast pathways also may exist in sand and gravel channels within clay sediments. Such juxtaposition could exert significant control on potential flow velocities and sorption capacities along flow paths within the valley-fill sediments. Presently, DOE is engaged in several data-collection efforts in the alluvial aquifer related to the Nye County Drilling Program and the Alluvial Testing Complex hydraulic and tracer testings. At

---

[15]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Unsaturated and Saturated Flow Under Isothermal Conditions (October 31–November 2, 2000)." Letter (November 17) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

[16]Ibid.

the previously mentioned DOE and NRC technical exchange, DOE agreed to provide additional technical bases for flow paths in alluvium, effective porosities, and transport parameters.[17]

Another alternative conceptual model is that of the potential for seismically activated geothermal perturbations of the saturated zone flow system to flood the potential location of the repository during its planned 10,000-year life. It is important to note that the State of Nevada has not provided details explaining how seismic events can trigger a significant water table rise; there are several comprehensive reviews that show water table changes from earthquakes are transitory and of a limited extent (Carrigan, et al., 1991; Gauthier, et al., 1995; Arnold and Barr, 1996). Scientists working for the State of Nevada asserted that upwelling of geothermal fluids to volcanic units above the proposed repository horizon occurred several times in the recent geologic past, including at least once within the late Quaternary (last 125,000 years). The State of Nevada scientists cite as supporting evidence abundant two-phase fluid inclusions in calcite minerals within the unsaturated zone exposed in the Exploration Studies Facility and Cross Drift, and in calcite veins found in trenches of faults (Szymanski, 1992; Archambeau and Price, 1991; Dublyansky, et al., 2001). These scientists are concerned that such geothermal activity would flood the repository with warm and chemically active fluids that would corrode the waste packages and lead to large-scale release of radionuclides to the accessible environment.

Recently, the University of Nevada, Las Vegas, concluded a 2-year study of the fluid inclusions, designed to determine the ages and temperatures of secondary mineralization at Yucca Mountain. The study focused on assemblages of two-phase fluid inclusions (gas and liquid) because such inclusions are deemed to be reasonably reliable indicators of the temperatures and pressure conditions during growth of the secondary minerals. These paleotemperatures and paleopressures are determined from measurements of the homogenization temperature, (i.e., the laboratory-heating temperature at which vapor bubbles disappear from two-phase fluid inclusions). The investigation analyzed data from the so-called two-phase fluid inclusions found in the calcite deposits beneath Yucca Mountain, and sought to determine the presence and timing of fluids with elevated temperatures that may be indicative of geothermal activity. The University of Nevada, Las Vegas, work involved collection and study of 155 samples from throughout the Exploration Studies Facility and Cross Drift. Two-phase fluid inclusion assemblages were found in secondary minerals in all areas of the Exploration Studies Facility and Cross Drift. Two-phase fluid inclusion assemblages with consistent liquid-vapor ratios were found in 78 samples. Although the study identified two-phase fluid inclusion assemblages in all minerals regardless of relative age, no two-phase fluid inclusion assemblages with consistent liquid-vapor ratios were found in the youngest (outermost) calcite in lithophysal cavities. This calcite is typically enriched in magnesium and lacks two-phase fluid inclusions (at least those two-phase fluid inclusions that have consistent liquid/vapor ratios). The magnesium-rich calcite is found in 65 percent of all samples and is dated at approximately 2 million years ago. In addition, the University of Nevada, Las Vegas, study shows that all two-phase fluid inclusion assemblages with consistent liquid-vapor ratios may be only as young as the basal portion of intermediate-age calcite, which is constrained to ages older than approximately 4 million years

[17]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Unsaturated and Saturated Flow Under Isothermal Conditions (October 31–November 2, 2000)." Letter (November 17) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

ago. Assumed maximum homogenization temperatures for the fluid inclusions were estimated to be between 40–60 °C [104–140 °F] for the Exploration Studies Facility and Cross Drift, with the intensely fractured zone having homogenization temperatures of 40–50 °C [104–140 °F], and between 60–80 °C [140–176 °F] for the north and south ramps. No fluid inclusions were found with homogenization temperatures below 35 °C [95 °F]. Note that 35 °C [95 °F] temperature was cited as a cut-off temperature, in the sense that fluids trapped at or below 35 °C [95 °F] would be sufficiently metastable to effectively inhibit formation of vapor phase bubbles.

The University of Nevada, Las Vegas, study concluded that the fluid inclusion results do not support the upwelling fluid model and, that if upwelling occurred, there should be (i) extensive mineralization throughout Yucca Mountain, (ii) greater evidence for wall rock alteration usually associated with geothermal activity, and (iii) significantly higher homogenization temperatures.

At present, there is no consensus among the project scientists on the interpretation of the University of Nevada, Las Vegas, results. State of Nevada scientists, although accepting the fluid inclusion data as valid, assert that the data do not capture the most recent thermal history of the mountain, and question the conclusion that the thermal source ceased to affect Yucca Mountain between 2 and 4 million years ago. U.S. Geological Survey staff also appear to be divided on the interpretation of the fluid inclusions, with some staff suggesting the fluid inclusion data may yield misleading results because the inclusions were trapped in the vadose zone, whereas, other staff are attempting to incorporate the temperatures into a general thermal history model, in which Yucca Mountain cooled slowly after the eruption of the Timber Mountain Caldera approximately 11 million years ago. DOE agreed to evaluate the results of ongoing fluid inclusion studies in a future update to the saturated zone flow and transport process model report.[18]

The effect of future changes in water use patterns in Amargosa Valley is not considered in the current DOE saturated zone site-scale flow model. Nye County representatives suggested that water demands will increase in the future, with potentially all available groundwater being pumped for use by the community within the next 50 years.[19] Greater rates of groundwater pumping could potentially cause saturated zone flow patterns and radionuclide travel times to differ from those DOE abstracted in the total system performance assessment. The NRC staff considers it speculative whether Nye County will significantly increase use of groundwater resources in the near future. Current high-level waste regulations for Yucca Mountain do not require DOE to evaluate all the possible scenarios that could occur during the next 10,000 years with respect to biosphere characteristics.

In summary, the DOE approach for total-system performance assessment abstraction for flow paths in the saturated zone allows consideration of a range of alternative conceptual models.

---

[18]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Unsaturated and Saturated Flow Under Isothermal Conditions (October 31–November 2, 2000)." Letter (November 17) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

[19] Buqo, T. *Comments made to Nuclear Waste Technical Review Board meeting, January 31, 2001*. Amargosa Valley, Nevada. 2001.

To support the alternative conceptual models that are considered or excluded, however, DOE needs to provide additional information or scenario analyses regarding horizontal anisotropy in volcanic tuffs, flow across the Solitario Canyon fault, fluid inclusion studies in the unsaturated zone, and additional technical bases for flow paths in alluvium. As mentioned in the preceding discussion, DOE agreed to provide the additional data and analyses for NRC review.

3.3.8.4.5 Model Abstraction Output Is Supported by Objective Comparisons

Overall, the current information, along with agreements reached between DOE and NRC (Section 3.3.8.5), is sufficient to conclude that the necessary information will be available at the time of a potential license application to assess flow paths in the saturated zone with respect to model abstraction output being supported by objective comparisons.

Currently available data, including hydraulic head, groundwater chemistry, geophysics, stratigraphy, slip- and dilation-tendency analyses of faults, and analysis of horizontal anisotropy suggest that radionuclide arrival locations at the compliance boundary for groundwater flowing beneath Yucca Mountain can be constrained within the area between a point along the compliance boundary directly south of Yucca Mountain and the vicinity of Nye County Well NC–EWDP–5S, which is about 3 km [1.9 mi] northeast of the town of Amargosa Valley (Coleman, et al., 2000). The range of predicted flow paths from the basecase saturated zone site-scale flow model generally spans a large portion of this area (CRWMS M&O, 2000g, Figure 10).

DOE gained confidence in the results of its site-scale saturated zone flow model by comparing calculated to observed hydraulic heads, estimated to measured permeabilities and by comparing lateral flow rates calculated by the site-scale model to those calculated by the regional-scale flow model (CRWMS M&O, 2000a). In addition, predicted flow paths from the region of the proposed repository appear to be consistent with flow paths inferred from gradients of measured hydraulic heads and also from water chemistry data (CRWMS M&O, 2000k). There is a concern, however, that much of the data used for comparison to model results are the same data used in the calibration process. Hence, additional objective comparisons of model results to site data not used in the calibration process are needed to improve confidence in the saturated zone flow model. DOE agreed[20] to provide additional model support to be reported in a subsequent update to the Calibration of the Site-Scale Saturated Zone Flow Model analysis and model report.

In summary, the DOE approach for total-system performance assessment abstraction for flow paths in the saturated zone is consistent with and supported by available geologic, hydrologic, and geochemical data, but additional objective comparisons of model results with site data not used for model calibration are needed. As mentioned in the preceding discussion, DOE agreed to provide the additional data and analyses for NRC review.

---

[20]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Unsaturated and Saturated Flow Under Isothermal Conditions (October 31–November 2, 2000)." Letter (November 17) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

3.3.8.5 Status and Path Forward

Table 3.3.8-1 provides the status of all key technical issue subissues, referenced in Section 3.3.8.2, for the Flow Paths in the Saturated Zone Integrated Subissue. The table also provides the related DOE and NRC agreements pertaining to the Flow Paths in the Saturated Zone Integrated Subissue. The agreements listed in the table are associated with one or all five generic acceptance criteria discussed in Section 3.3.8.4. Note that the status and the detailed agreements (or path forward) pertaining to all the key technical issue subissues are provided in Table 1.1-3 and Appendix A.

The DOE-proposed approach, together with the DOE agreements to provide NRC with additional information (through specified testing, analyses, and the like), acceptably addresses the NRC questions so that no information beyond that provided, or agreed to, will likely be required at the time of a potential license application.

Table 3.3.8-1. Related Key Technical Issue Subissues and Agreements

Key Technical Issue	Subissue	Status	Related Agreements*
Unsaturated and Saturated Flow Under Isothermal Conditions	Subissue 2—Hydrologic Effects of Climate Change	Closed	None
	Subissue 5—Saturated Zone Flow and Dilution Processes	Closed-Pending	USFIC.5.01 through USFIC.5.14
	Subissue 6—Matrix Diffusion	Closed-Pending	USFIC.6.04
Structural Deformation and Seismicity	Subissue 1—Faulting	Closed-Pending	None
	Subissue 3—Fracturing	Closed-Pending	None
Total System Performance Assessment and Integration	Subissue 1—System Description and Demonstration of Multiple Barriers	Closed-Pending	None
	Subissue 2—Scenario Analysis and Event Probability	Closed-Pending	TSPAI.2.01 TSPAI.2.02 TSPAI.2.03
	Subissue 3—Model Abstraction	Closed-Pending	None
	Subissue 4—Demonstration of Compliance with the Postclosure Public Health and Environmental Standards	Closed-Pending	None

Table 3.3.8-1. Related Key Technical Issue Subissues and Agreements (continued)

Key Technical Issue	Subissue	Status	Related Agreements*
Radionuclide Transport	Subissue 1—Radionuclide Transport through Porous Rock	Closed-Pending	RT.1.05
	Subissue 2—Radionuclide Transport though Fractured Rock	Closed-Pending	RT.2.01 through RT.2.04 RT.2.08 RT.2.09 RT.2.11
	Subissue 3—Radionuclide Transport through Alluvium	Closed-Pending	RT.3.01 RT.3.03

*Related DOE and NRC agreements are associated with one or all five generic acceptance criteria.

Note: Key Technical Issue Agreement GEN.1.01 pertains to multiple integrated subissues, as well as some specific issues related to this integrated subissue.

3.3.8.6 References

Archambeau, C.B. and N.J. Price. "An Assessment of J.S. Szymanski's Conceptual Hydro-Tectonic Model and Its Relevance to Hydrologic and Geologic Processes at the Proposed Yucca Mountain Nuclear Waste Repository, Minority Report of the Special DOE Review Panel." Washington, DC: DOE. 1991.

Arnold, B.W. and G.E. Barr. "Numerical Modeling for Saturated-Zone Groundwater Travel Time Analysis at Yucca Mountain." High-Level Radioactive Waste Management: Proceedings of the Seventh Annual International Conference, Las Vegas, Nevada, April 29–May 3, 1996. La Grange Park, Illinois: American Nuclear Society. pp. 187–189. 1996.

Bedinger, M.S., W.H. Langer, and J.E. Reed. "Hydraulic Properties of Rocks in the Basin and Range Province. Studies of Geology and Hydrology in the Basin and Range Province, Southwestern United States, for Isolation of High-Level Radioactive Waste—Basis of Characterization and Evaluation." U.S. Geological Survey Professional Paper 1370–A. 1989.

Carrigan, C.R., G.C.P. King, G.E. Barr, and N.E. Bxleil. "Potential for Water-Table Excursions Induced by Seismic Events at Yucca Mountain, Nevada." *Geology.* Vol. 19, No. 12. pp. 1,157–1,160. 1991.

Coleman, N.M., J.R. Winterle, R.W. Fedors, A. Armstrong, D.A. Farrell, and D.L. Hughson. "Resolving Issues in Isothermal Hydrology at Yucca Mountain, Nevada—A Regulatory Perspective." Waste Management 2000 WM2K Proceedings: HLW, LLW, Mixed Wastes and Environmental Restoration—Working Toward a Cleaner Environment, University of Arizona, Tucson, Arizona, February 27–March 2, 2000. Tucson, Arizona: WM Symposia, Inc. No page numbers. Published on CD-ROM. 2000.

CRWMS M&O. "Saturated Zone Flow and Transport Expert Elicitation Project." SL5X4AM3. Las Vegas, Nevada: CRWMS M&O. 1998.

———. "Saturated Zone Flow and Transport Process Model Report." TDR–NBS–HS–000001. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000a.

———. "Repository Safety Strategy: Plan to Prepare the Safety Case to Support Yucca Mountain Site Recommendation and Licensing Considerations." TDR–WIS–RL–000001. Revision 04. Las Vegas, Nevada: CRWMS M&O. 2000b.

———. "Total System Performance Assessment for the Site Recommendation." TDR–WIS–PA–000001. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000c.

———. "Hydrogeologic Framework Model for the Saturated Zone Site-Scale Flow and Transport Model." ANL–NBS–HS–000033. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000d.

———. "Geologic Framework Model (GFM3.1)." MDL–NBS–GS–000002. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000e.

———. "Calibration of the Site-Scale Saturated Zone Flow Model." MDL–NBS–HS–000011. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000f.

———. "Input and Results of the Base-Case Saturated Zone Flow and Transport Model for TSPA." ANL–NBS–HS–000030. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000g.

———. "Unsaturated Zone Flow and Transport Model PMR." TDR–NBS–HS–000002. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000h.

———. "Water-Level Data Analysis for the Saturated Zone Site-Scale Flow and Transport Model." ANL–NBS–HS–000034. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000i.

———. "Uncertainty Distribution for Stochastic Parameters." ANL–NBS–MD–000011. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000j.

———. "Geochemical and Isotopic Constraints on Groundwater Flow Directions, Mixing, and Recharge at Yucca Mountain, Nevada." ANL–NBS–HS–000021. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000k.

———. "Features, Events, and Processes in Saturated Zone Flow and Transport." ANL–NBS–MD–000002. Revision 01. Las Vegas, Nevada: CRWMS M&O. 2001.

D'Agnese, F.A., C.C. Faunt, A.K. Turner, and M.C. Hill. "Hydrogeologic Evaluation and Numerical Simulation of the Death Valley Regional Ground-Water Flow System, Nevada and California." U.S. Geological Survey Water Resources Investigations Report 96-4300. 1997.

D'Agnese, F.A., G.M. O'Brien, C.C. Faunt, and C.A. San Juan. "Simulated Effects of Climate Change on the Death Valley Regional Ground-Water Flow System, Nevada and California." U.S. Geological Survey Water Resources Investigations Report 98-4041. 1999.

DOE. "Viability Assessment of a Repository at Yucca Mountain." Overview and all five volumes. DOE/RW–0508. Las Vegas, Nevada: DOE, Office of Civilian Radioactive Waste Management. 1998.

Dublyansky, Y., D. Ford, and V. Reutski. "Traces of Epigenetic Hydrothermal Activity at Yucca Mountain, Nevada: Preliminary Data on the Fluid Inclusion and Stable Isotope Evidence." *Chemical Geology*. Vol. 173. pp. 125–149. 2001.

Farrell, D.A., J. Winterle, W.A. Illman, and R.W. Fedors. "Review of Porosity Distributions in the Yucca Mountain Region." San Antonio, Texas: CNWRA. 2000.

Ferrill, D.A., J. Winterle, G. Wittmeyer, D. Sims, S. Colton, A. Armstrong, and A.P. Morris. "Stressed Rock Strains Groundwater at Yucca Mountain, Nevada." *GSA Today*. Vol. 9, No. 5. pp. 1–8. 1999.

Gauthier, J.H., M.L. Wilson, D.J. Borns, and B.W. Arnold. "Impact of Seismic Activity on Long-Term Repository Performance at Yucca Mountain." Proceedings of the Topical Meeting on Methods of Seismic Hazard Evaluation, FOCUS 95, Las Vegas, Nevada, September 17–21, 1995. La Grange Park, Illinois: American Nuclear Society. pp. 159–168. 1995.

Geldon, A.L. "Results and Interpretation of Preliminary Aquifer Tests in Boreholes UE–25c#1, UE–25c#2, and UE–25c#3, Yucca Mountain, Nevada." U.S. Geological Survey Water Resources Investigations Report 94-4177. 1996.

Graves, R.P., P. Tucci, and G.M. O'Brien. "Analysis of Water Level Data in the Yucca Mountain Area, Nevada, 1985–95." U.S. Geological Survey Water Resources Investigations Report 96-4256. 1997.

Luckey, R.R., P. Tucci, C.C. Faunt, E.M. Ervin, W.C. Steinkampf, F.A. D'Agnese, and G.L. Patterson. "Status of Understanding of the Saturated-Zone Ground-Water Flow System at Yucca Mountain, Nevada, As of 1995." U.S. Geological Survey Water Resources Investigations Report 96-4077. 1996.

NRC. "Issue Resolution Status Report, Key Technical Issue: Unsaturated and Saturated Flow Under Isothermal Conditions." Revision 2. Washington, DC: NRC. 1999.

———. "Issue Resolution Status Report, Key Technical Issue: Structural Deformation and Seismicity." Revision 3. Washington, DC: NRC. 2000a.

———. "Issue Resolution Status Report, Key Technical Issue: Total System Performance Assessment and Integration." Revision 3. Washington, DC: NRC. 2000b.

———. "Issue Resolution Status Report, Key Technical Issue: Radionuclide Transport." Revision 2. Washington, DC: NRC. 2000c.

———. NUREG–1804, "Yucca Mountain Review Plan—Draft Report for Comment." Revision 2. Washington, DC: NRC. March 2002.

Ressler, T.R. "Preliminary Characterization of the Valley-Fill Aquifer in Fortymile Wash, Southwestern Nevada." M.Sc. thesis. The University of Texas. Austin, Texas. 2001.

Robison, J.H. and R.W. Craig. "Geohydrology of Rocks Penetrated by Test Well USW H–5, Yucca Mountain, Nye County, Nevada." U.S. Geological Survey Water Resources Investigations Report 88-4168. 1991.

Savard, C.S. "Estimated Ground-Water Recharge from Streamflow in Fortymile Wash Near Yucca Mountain, Nevada." U.S. Geological Survey Water Resources Investigations Report 97-73. 1998.

Szymanski, J.S. "The Origin and History of Alteration and Carbonatization of the Yucca Mountain Ignimbrites." Two volumes. Las Vegas, Nevada: DOE. 1992.

Thomas, J.M. "Geochemical and Isotopic Interpretation of Groundwater Flow, Geochemical Processes, and Age Dating of Groundwater in the Carbonate-Rock Aquifers of the Southern Basin and Range." Ph.D. dissertation. University of Nevada. Reno, Nevada. 1996.

Thordarson, W., F.E. Rush, and S.J. Waddell. "Geohydrology of Test Well USW H–3, Yucca Mountain, Nye County, Nevada." U.S. Geological Survey Water Resources Investigations Report 84-4272. 1985.

Winograd, I.J., J.M. Landwehr, K.R. Ludwig, T.B. Coplen, and A.C. Riggs. "Duration and Structure of the Past Four Interglaciations." *Quaternary Research*. Vol. 48. pp. 141–154. 1997.

Winterle, J.R. and P.C. La Femina. "Review and Analyses of Hydraulic and Tracer Testing at the C-Holes Complex Near Yucca Mountain, Nevada." San Antonio, Texas: CNWRA. 1999.

3.3.9 Radionuclide Transport in the Saturated Zone

3.3.9.1 Description of Issue

The Radionuclide Transport in the Saturated Zone Integrated Subissue addresses features and processes that would affect movement of radionuclides in the saturated zone from the area beneath the proposed repository site at Yucca Mountain to the proposed 18-km [11-mi] compliance boundary. Figure 3.3.9-1 illustrates the relationship between the radionuclide transport in the saturated zone model abstraction and the flowpaths in the saturated zone model abstraction (see Section 3.3.8). The overall organization and identification of all the integrated subissues are depicted in Figure 1.1-2. The DOE description and technical basis for abstractions of radionuclide transport in the saturated zone are described in CRWMS M&O (2000a) and several supporting analysis and model reports. Implementation in Total System Performance Assessment–Site Recommendation is described in CRWMS M&O (2000b,c). This section provides a review of the abstractions DOE developed to incorporate these features and processes in its total system performance assessment.

3.3.9.2 Relationship to Key Technical Issue Subissues

This Radionuclide Transport in the Saturated Zone Integrated Subissue incorporates subject matter previously captured in the following key technical issue subissues:

- Radionuclide Transport: Subissue 1—Radionuclide Transport Through Porous Rock (NRC, 2000a)
- Radionuclide Transport: Subissue 2—Radionuclide Transport Through Alluvium (NRC, 2000a)
- Radionuclide Transport: Subissue 3—Radionuclide Transport Through Fractured Rock (NRC, 2000a)
- Radionuclide Transport: Subissue 4—Nuclear Criticality in the Far Field (NRC, 2000a)
- Unsaturated and Saturated Flow Under Isothermal Conditions: Subissue 5—Saturated Zone Ambient Flow Conditions and Dilution Processes (NRC, 1999a)
- Unsaturated and Saturated Flow Under Isothermal Conditions: Subissue 6—Matrix Diffusion (NRC, 1999b)
- Structural Deformation and Seismicity: Subissue 3—Fracturing and Structural Framework of the Geologic Setting (NRC, 2000b)
- Container Life and Source Term: Subissue 5—Effect of In-Package Criticality on Waste Package and Engineer Barrier System Performance (NRC, 2001a)

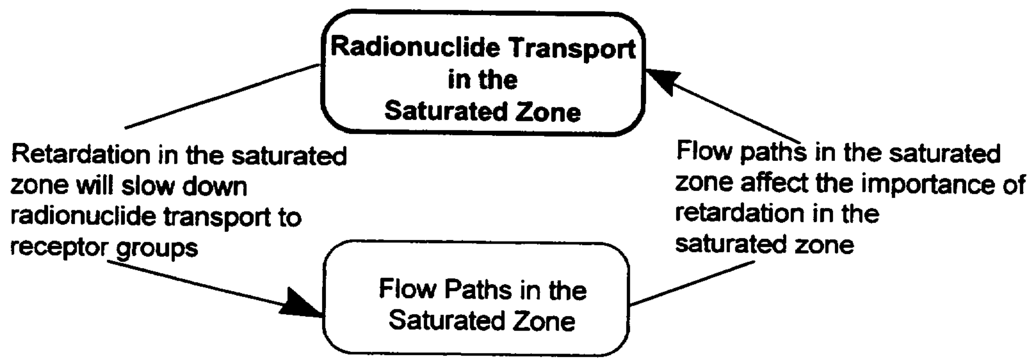

Figure 3.3.9-1. Diagram Illustrating the Relationship Between the Radionuclide Transport in the Saturated Zone and Flow Paths in the Saturated Zone Integrated Subissues

- Total System Performance Assessment and Integration: Subissue 1—System Description and Demonstration of Multiple Barriers (NRC, 2000c)
- Total System Performance Assessment and Integration: Subissue 2—Scenario Analysis and Event Probability (NRC, 2000c)
- Total System Performance Assessment and Integration: Subissue 3—Model Abstraction (NRC, 2000c)
- Total-System Performance Assessment and Integration: Subissue 4—Demonstration of Compliance with the Postclosure Public Health and Environmental Standards (NRC, 2000c)

The key technical issue subissues formed the bases for the previous versions of the issue resolution status reports and also were the bases for technical exchanges with DOE where agreements were reached on what additional information DOE needed to provide to resolve the subissue. The resolution status of this integrated subissue is based on the resolution status of each of the contributing key technical issue subissues. The subsequent sections incorporate applicable portions of these key technical issue subissues, however, no effort was made to explicitly identify each subissue.

3.3.9.3 Importance to Postclosure Performance

One aspect of risk informing the NRC review was to determine how this integrated subissue is related to the DOE repository safety strategy. DOE identifies radionuclide delay through the saturated zone at Yucca Mountain as a principal factor of the current postclosure safety case (CRWMS M&O, 2000d). The degree of radionuclide sorption on mineral surfaces within the rock matrix of the tuff aquifer system and in the alluvial aquifer system is the most important process affecting the ability of the saturated zone to act as a natural barrier by attenuating and delaying potentially released radionuclides. In the current DOE abstraction approach, sorption of radionuclides in the tuff aquifer system is assumed to occur only within the relatively stagnant rock matrix, whereas flow occurs primarily in fracture networks. Matrix diffusion, a process whereby aqueous radionuclides diffuse from actively flowing pore spaces into the relatively stagnant pore space within the rock matrix, is thus another important process to be considered because the majority of saturated pore volume in the saturated tuff aquifer system comprises relatively stagnant water within rock matrix.

DOE has investigated the importance of saturated zone transport through robustness and neutralization analyses (CRWMS M&O, 2000b,d). The degraded barrier analysis, in which 5th percentile values are used for parameters that positively promote delay of radionuclides in the saturated zone and 95th percentile values for parameters that positively promote transport in the saturated zone, suggests modest sensitivity (CRWMS M&O, 2000d) to the saturated zone transport barrier. The similarity of the degraded and basecases is attributed to the dominance in the basecase average dose of the high-dose realizations (CRWMS M&O, 2000b). A saturated zone transport barrier neutralization analysis, in which the unsaturated zone output is fed directly to the biosphere, yields a curve nearly identical to the robustness analysis (CRWMS M&O, 2000d). It is apparent that the modeled unsaturated zone barrier in the DOE total system performance assessment is the more important barrier; this may mask the potential importance of the saturated zone barrier. Nevertheless, the importance of the saturated zone is reflected in its status as a principal factor, chiefly as a component of defense in depth (CRWMS M&O, 2000d). Furthermore, an independent NRC performance assessment sensitivity analysis concluded that retardation in the saturated zone is important, based on much higher modeled doses that result from its removal from the analysis (NRC, 1999b). In particular, neptunium retardation has been shown to have a significant dose effect (NRC, 1999b, 2001b).

3.3.9.4 Technical Basis

NRC has developed a Yucca Mountain Review Plan (NRC, 2002) that is consistent with the acceptance criteria and review methods found in previous issue resolution status reports. A review of DOE approaches for including radionuclide transport in the saturated zone in total system performance assessment abstractions is provided in the following subsections. The review is organized according to the five acceptance criteria identified in Section 1.5: (i) System Description and Model Integration Are Adequate, (ii) Data Are Sufficient for Model Justification, (iii) Data Uncertainty Is Characterized and Propagated Through the Model Abstraction, (iv) Model Uncertainty Is Characterized and Propagated Through the Model Abstraction, and (v) Model Abstraction Output Is Supported by Objective Comparisons.

NRC previously reviewed the DOE abstraction approach for radionuclide transport in the saturated zone(1999b, 2000a,b,c) after DOE publication of the viability assessment (1998a). The DOE approach for the abstraction of saturated zone radionuclide transport has changed substantially since then, moving from a one-dimensional streamtube transport model to a three-dimensional particle-tracking model.

3.3.9.4.1 System Description and Model Integration Are Adequate

Overall, the current information, along with agreements reached between DOE and NRC (Section 3.3.9.5), is sufficient to conclude that the necessary information will be available at the time of a potential license application to assess radionuclide transport in the saturated zone with respect to system description and model integration.

The abstraction of radionuclide transport in the saturated zone for total system performance assessment analyses is developed by DOE using a site-scale, three-dimensional, single-continuum, particle-tracking transport model. Particle transport pathways are calculated based on spatially variable groundwater flux vectors (flow fields) derived from the site-scale saturated zone flow model (CRWMS M&O, 2000a). The influences of macro-scale dispersion, matrix diffusion, and adsorption of radionuclides to mineral surfaces (sorption) are incorporated through use of a residence-time transfer function that has been adapted to the finite element heat and mass transfer particle-tracking algorithm (Zyvoloski, et al., 1997). The residence-time transfer function describes a cumulative probability distribution function of particle residence times that is used to adjust travel times of particles through model cells to account for longitudinal dispersion and the delaying effects of sorption and matrix diffusion. The travel time of any given particle through a particular portion of its path is computed by generating a random number between 0 and 1 and determining the corresponding residence time from the residence-time transfer function. On average, if numerous particles travel through this portion of the model domain, the cumulative residence time distribution of particles will match the shape of the transfer function (CRWMS M&O, 2000e).

The residence-time transfer function used for the fractured tuff portion of the saturated zone flow paths is based on the Sudicky and Frind (1982) analytical solution, which takes into account advective transport in the fractures, molecular diffusion from the fracture to the porous matrix, radionuclide sorption on the fracture face, and adsorption within the matrix (CRWMS M&O, 2000f). Although the analytical solution provides for incorporating sorption on the fracture face, this option is not used in the model because of the lack of conclusive information on this process and the anticipated small impact of this option on the radionuclide transport simulations (CRWMS M&O, 2000a). It should also be noted that neglecting radionuclide sorption of fracture surfaces is a conservative approach.

The saturated zone radionuclide transport component of total system performance assessment is coupled to the unsaturated zone input and the output to the biosphere using the convolution integral method (CRWMS M&O, 2000a). In this method, a unit saturated-zone radionuclide mass breakthrough curve is computed for a step-function mass flux source; this breakthrough curve is then convoluted with the radionuclide mass flux history from the unsaturated zone to produce a radionuclide mass flux history curve that is output to the biosphere. The convolution integral method is computationally efficient and rests on the key assumptions of linear behavior and steady-state saturated zone flow conditions.

DOE relies on linear sorption isotherms and represents all noncolloidal retardation processes using the sorption coefficient (K_d) (CRWMS M&O, 2000a,g). Sorption coefficients for the radionuclides of interest are selected based on an initial informal expert elicitation conducted for Total System Performance Assessment–93, involving three experts (Wilson, et al., 1994).

Sorption parameter probability distribution functions were constrained assuming that water from the saturated volcanic tuff (Well J–13) and the Paleozoic aquifer (UE–25p#1) bound the chemistry of the groundwaters at Yucca Mountain. Total System Performance Assessment–93 only used geochemical information indirectly through expert elicitation to estimate probability distribution functions for K_d and did not explicitly incorporate geochemistry or geochemical modeling results. The approach has remained essentially unchanged since Total System Performance Assessment–93, although the specific constraints on the transport parameters have been modified, particularly for uranium, neptunium, and plutonium (Wilson, et al., 1994; CRWMS M&O, 2000g; Triay, et al., 1997). Sorption probability distribution functions are abstracted for four rock types: devitrified, vitric, and zeolitic tuff, and iron oxide. The iron oxide is intended to represent waste package corrosion products and is not used to simulate retardation by fracture-lining minerals. Radionuclide retardation is related to K_d, the sorption coefficient, by the equation

$$R_f = 1 + \frac{\rho_b}{n} K_d \qquad (3.3.9\text{-}1)$$

where R_f is the retardation factor, ρ_b is the bulk density, and n is the porosity. In fractured rocks, retardation by adsorption is assumed to occur only in the matrix, and the degree to which retardation contributes to overall repository performance depends on the nature of coupling between the matrix and fracture. In Total System Performance Assessment—Site Recommendation, K_ds are individually defined for the following radioelements assumed to not be affected by colloids: uranium, neptunium, iodine, technetium, and carbon (CRWMS M&O, 2000h). Radionuclides modeled to be reversibly attached to colloids (see later in this section) are given one of two K_d distributions in the following groups: americium, plutonium, protactinium, and thorium; and cesium and strontium (CRWMS M&O, 2000h).

The saturated zone transport simulation includes the effects of radioactive decay and ingrowth; radionuclide concentrations can increase or decrease according to decay constants. Decay of a transported radionuclide is applied directly to the convolution integral mass flux by decreasing the mass flux for the appropriate time interval using the decay equation. Decay and ingrowth during saturated zone transport for daughter radionuclides in the actinium, neptunium, thorium, and uranium decay series are treated under a one-dimensional transport model employed directly in total system performance assessment, rather than the offline three-dimensional model employed for radionuclides in general (CRWMS M&O, 2000a,i). The one-dimensional model simulates transport along pipe segments that use the average flow and transport characteristics of the corresponding flow path in the three-dimensional model. The only transport process not included in the one-dimensional model is transverse dispersion—the neglect of which is conservative (CRWMS M&O, 2000i).

Colloidal transport in the saturated zone is handled, as elsewhere in total system performance assessment, with two types of radionuclide attachment—reversible and irreversible (CRWMS M&O, 2000a,j). Colloids with irreversibly attached radionuclides are modeled as solutes, with a retardation factor applied specifically to the fractured tuff and alluvial aquifers; matrix diffusion of irreversible colloids in the saturated zone is conservatively neglected (CRWMS M&O, 2000c,j). Reversible colloidal transport is modeled using the K_c factor, representing equilibrium sorption of aqueous radionuclide onto colloids. One value for K_c, based on values representing sorption of americium to colloids at a fixed concentration in groundwater, is used for reversible attachment. Inclusion of reversible sorption to colloids lowers the effective diffusion coefficient D_e and the sorption coefficient K_d for the radionuclide (CRWMS M&O, 2000i), enhancing advective transport.

The technical basis for selecting radionuclides for saturated zone transport modeling via reversible and irreversible colloid attachment is not transparent and traceable in all cases. CRWMS M&O (2000k) identifies radionuclides for the total system performance assessment model abstraction based on contribution to dose, inventory, and mobility considerations, but does not explicitly identify those radionuclides that will be transported as colloids. DOE agreed[1] to address this issue.

The basis for screening criticality from the postclosure performance assessment of the Yucca Mountain repository is contained in a DOE analysis and model report (CRWMS M&O, 2000l) that references CRWMS M&O (2000m), DOE addressed the potential for far-field criticality in the saturated zone (CRWMS M&O, 2000l) using two features, events, and processes: far-field criticality, precipitation in organic reducing zone in or near water table (2.2.14.02.00), and far-field criticality, precipitation caused by hydrothermal upwell or redox front in the saturated zone (2.2.14.04.00). Both features, events, and processes have been excluded from the total system performance assessment. The DOE screening argument for criticality relies heavily on the argument that the probability of a waste package failing within 10,000 years in absence of a volcanic intrusion is small. When there is no waste package failure, there is no release of fissile material; therefore, no fissile material can accumulate before 10,000 years in either unsaturated or saturated zones. More recent analyses documented in the Supplemental Science and Performance Analyses (Bechtel SAIC Company, LLC, 2001a,b), however, indicate that waste package failure can occur within the first 10,000 years following repository closure due to stress corrosion cracking of welds that have been improperly heat-treated. In light of the latest results, DOE agreed to reexamine the screening argument for postclosure criticality.[2]

DOE also developed a topical report that includes the description of a methodology to determine the probability and consequences of a nuclear criticality event within the saturated zone (DOE, 1998a). NRC staff accepted this topical report pending closure of 28 open items.[3] According to an agreement made during the DOE and NRC Technical Exchange on Criticality,[4] DOE provided the NRC with Revision 1 of this topical report, which should address 27 of the

---

[1]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Radionuclide Transport (December 5–7, 2000)." Letter (December 12) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

[2]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Range of Operating Temperature (September 18–19, 2001)." Letter (October 2) to S. Brocoum, DOE. Washington, DC: NRC. 2001.

[3]Ibid.

[4]Schlueter, J.R. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Criticality (October 23–24, 2000)." Letter (October 27) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

open items (DOE, 2000). The open items relevant to criticality in the saturated zone are concerned chiefly with methodology and validation for transport and redeposition models employed. If this new revision of the topical report is found to be acceptable, it will provide confidence that DOE will be able to address far-field criticality in the saturated zone in any potential license application even if it is unable to support its arguments for screening such criticality from the total system performance assessment.

DOE has used arguments based on low probability, low consequence, or both, to exclude various features, events, and processes from the radionuclide transport in the saturated zone Total System Performance Assessment–Site Recommendation abstraction. The screening arguments are outlined in CRWMS M&O (2001). The screening arguments for the following excluded features, events, and processes are insufficient:

- 1.2.06.00.00—Hydrothermal activity
- 1.3.07.01.00—Drought/water table decline
- 2.1.09.21.00—Suspension of particles larger than colloids
- 2.2.10.03.00—Natural geothermal effects
- 2.2.10.06.00—Thermo-chemical alteration (solubility, speciation, phase changes, precipitation/dissolution)
- 2.2.10.08.00—Thermo-chemical alteration of the saturated zone
- 2.2.10.13.00—Density-driven groundwater flow (thermal)
- 2.3.11.04.00—Groundwater discharge to surface

The comments on these features, events, and processes and possible pathways to resolution are discussed in more detail in Section 3.2 of this report. A general comment is that the analysis and model report (CRWMS M&O, 2001) neglects issues associated with transport in the alluvium. Several screening arguments focus on aspects other than those in the alluvium that might be influenced by those features, events, and processes (e.g., dissolution). DOE agreed[5] to address these concerns relating to the features, events, and processes.

In summary, system description and model integration for radionuclide transport in the saturated zone are not yet adequate, but DOE agreed to address these concerns in future documents.

[5]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Total System Performance Assessment and Integration (August 6–10, 2001)." Letter (August 23) to S. Brocoum, DOE. Washington, DC: NRC. 2001.

3.3.9.4.2 Data Are Sufficient for Model Justification

Overall, the current information, along with agreements reached between DOE and NRC (Section 3.3.9.5), is sufficient to conclude that the necessary information will be available at the time of a potential license application to assess radionuclide transport in the saturated zone with respect to data being sufficient for model justification.

Matrix Diffusion

The analytical solution of Sudicky and Frind (1982), which was used to develop the residence-time transfer function, requires estimation of several parameters, including fracture aperture, mean fracture spacing (flowing interval spacing), linear groundwater velocity within the fracture, porosity of the rock matrix, retardation factors in the rock matrix and in the fracture, and the effective matrix diffusion coefficient. Data to support estimates of these parameters and the conceptual model that matrix diffusion occurs in the saturated zone are obtained from laboratory and field testing and from the literature (CRWMS M&O, 2000h). Laboratory tests include measurements of rock matrix porosity (Flint, 1998) and diffusion-cell and rock-beaker experiments using tuffs from the saturated zone at Yucca Mountain (CRWMS M&O, 2000g). Field testing consisted of cross-hole tracer tests within the Prow Pass Tuff and Bullfrog Tuff intervals of the C-Wells Complex, which showed that tracers with differing diffusion coefficients were attenuated differently, with greater attenuation of the solute with a higher diffusion coefficient, as qualitatively predicted by the conceptual model (CRWMS M&O, 2000a; Reimus, et al., 1999).

Data obtained from flow-meter surveys of several wells in the Yucca Mountain area were used to estimate a statistical distribution of the spacing between flowing intervals in the saturated volcanic tuffs. As conceptualized for the analytical solution of Sudicky and Frind (1982), flowing interval spacing is the distance between equally spaced, parallel, planar-flowing fractures. As it applies to the volcanic tuffs beneath Yucca Mountain, this property can be thought to represent the surface area available for diffusion from flowing pore space into stagnant pore space. Smaller flowing interval spacing represents more flowing intervals and, hence, more surface area to accommodate matrix diffusion. The data to support flowing interval spacing have several limitations. For example, there was significant variability in the amount of water produced by the various features identified as flowing intervals: some features were associated with fracture zones, others were associated with permeable rock matrix—yet, the features were treated equally with regard to flowing interval spacing. Also, the flowing interval spacing parameter was used to support a conceptual model of flow through a series of parallel fractures, but there was considerable variability in the strike directions and dips of the identified flowing features. Finally, the spacing between flowing intervals was not correlated to particular hydrogeologic units of the volcanic tuffs. Thus, the estimated flowing interval spacings should be considered an effective property of the transport model that has considerable uncertainty. The combination of effective flowing interval spacing and of estimated flowing interval porosity (reviewed in Section 2.3) is used to infer the effective fracture (flowing interval) aperture used for the residence-time transfer function approach.

DOE described[6] a sensitivity analysis on the effect of flowing interval spacing on radionuclide breakthrough. As the spacing increases, the separation of the breakthrough curves decreases, such that the breakthrough curves for spacing of 50 m [160 ft] and 100 m [330 ft] are coincident. The DOE expected value of flowing interval spacing of 21 m [69 ft] results in a radionuclide breakthrough near the conservative limit of behavior.

In summary, the models DOE employed to simulate radionuclide transport in the saturated zone in performance assessment should be justified by reference to site-specific data, or data otherwise qualified for inclusion. Although there are uncertainties regarding the appropriate values for model parameters such as flowing interval spacing and diffusion coefficients, there are sufficient data to support conceptual and numerical models that include the process of matrix diffusion to predict radionuclide transport in volcanic tuffs. The DOE approach to treating uncertainty in these data is discussed in Section 3.3.9.3.3.

Sorption Coefficients

Although a significant amount of laboratory work and literature research is evident in the CRWMS M&O (2000g), the degree to which these data are used to support the total system performance assessment model abstraction of radionuclide transport in the saturated zone is not transparent and traceable. DOE refers to the expert elicitation (CRWMS M&O, 2000g, p. 42) conducted for Wilson, et al. (1994) as the original basis for K_d distributions for sorption modeling, and much of the text in a key document (Triay, et al., 1997) is virtually identical with the text in Wilson, et al. (1994). The Wilson, et al. (1994) values were based on one elicitation session conducted with three experts involved in the DOE Yucca Mountain program. The methods used to arrive at the K_d probability distribution functions are described in general terms in Barnard, et al. (1992), but the specific process implemented for the K_d elicitation is not described. Many of the methods normally used in expert elicitation (e.g., panel selection, training, mitigating bias, consensus building, incorporating dissenting opinions, aggregation of results, documentation) are not discussed. This information is needed to understand how K_d probability distribution functions were selected, what data were used, and how the experts arrived at their conclusions. For example, Wilson, et al. (1994) note that one of the experts believed that lead should be assigned a K_d of zero, but a consensus value of 0 to 500 [subsequently adjusted for Total System Performance Assessment—Viability Assessment (DOE, 1998b) to a consensus value of 100 to 500] was adopted. DOE agreed[7] to document how such differing opinions were reconciled.

Subsequent changes in both K_d ranges and distribution type have been made to the Wilson, et al. (1994) distributions without documentation. For example, protactinium is assumed to exhibit sorption characteristics similar to neptunium (Triay, et al., 1997), but the K_d distributions are different, and the upper limits are significantly higher {100 mL/g [173 in^3/oz] for protactinium versus 3 to 15 mL/g [5.2 to 25.9 in^3/oz] for neptunium}. In addition, niobium was assigned a

---

[6]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Radionuclide Transport (December 5–7, 2000)." Letter (December 12) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

[7]Ibid.

K_d = 0 for Total System Performance Assessment—Viability Assessment (DOE, 1998b, Chapter 7), but has since been assigned high K_d values similar to americium (CRWMS M&O, 2000g). DOE agreed[8] to supply technical bases for the sorption coefficients used in its performance assessments.

Despite the reference to bounding the groundwater characteristics using water from Wells J–13 and UE–25 p#1, the sorption data from the automatic technical data tracking system are limited in many instances only to experiments using J–13 water. Only uranium and plutonium appear to have significant numbers of analyses using UE–25 p#1 water. The number of experiments at different pH values is limited, and they are generally controlled by CO_2 overpressuring, making it difficult to identify other effects. The support for the K_d distributions is largely empirical. Although there is discussion of chemical effects on sorption, there is no process modeling to support assertions used in picking upper or lower bounds for K_d. Control of Eh is limited for much of the data. For example, in the dynamic column transport experiments, assertions are made regarding the predominance of Pu(V), without any description of how redox is controlled or how the dominant oxidation state is determined. Such description is especially critical for a redox sensitive element such as plutonium. In addition, there is no apparent correlation among the different radionuclides, and the link through geochemical effects is lost. There is also some uncertainty about the applicability of the effective K_d approach, given the potential for processes other than sorption (precipitation, colloid formation, etc.) and reaction kinetics to complicate data interpretation (NRC, 2000a). DOE agreed[9] to analyze column test data to determine whether plutonium sorption kinetics are important to performance. If found to be important, DOE will perform sensitivity analyses to evaluate the adequacy of uranium, plutonium, and protactinium sorption coefficients.

Documentation to determine how these types of geochemical uncertainties have been factored into the DOE assembly and selection of transport parameters for total system performance assessment is necessary. DOE agreed[10] to provide documentation of the technical basis for its expert elicitation of K_d values in accordance with NRC guidance in NUREG–1563 (1996). In addition, DOE will investigate the sensitivity of repository performance to K_d for uranium, protactinium, and plutonium to determine if available data are adequate.

Colloidal Transport

The data used to support transport parameters for colloid transport in the total system performance assessment are insufficient. The two categories of colloid transport parameters employed in Total System Performance Assessment—Site Recommendation are the irreversible colloid retardation factor R_c and the K_c parameter used to simulate reversible colloid attachment by lowering the radioelement K_d (see Section 3.3.9.3.1). The irreversible colloid

[8]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Radionuclide Transport (December 5–7, 2000)." Letter (December 12) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

[9]Ibid.

[10]Ibid.

retardation factor distribution for volcanic units is based on the poorly constrained results of a single microsphere tracer test, whereas the value for the alluvium uses no site-specific data (CRWMS M&O, 2000j). Applicability of the microsphere results rests on assumptions regarding size distributions of microspheres versus colloids. The K_c parameter is based on data for americium sorption to colloids and is applied to the K_d values for americium, plutonium, protactinium, thorium, cesium, and strontium (CRWMS M&O, 2000h). DOE has not used any data, site-specific or not, to demonstrate that the reversible colloid attachment parameter will bound the range of possible effects of this process. DOE agreed to address these issues by providing justification that microspheres can be used as analogs for colloids (e.g., equivalent ranges in size and charge) and providing constraints on colloid transport model parameters; this justification will accompany reports on C-Wells test results.[11] DOE also agreed[12] to use sensitivity analyses to constrain colloid transport parameters used in modeling reversible and irreversible attachment and the effects of colloid transport on the radionuclide transport in the saturated zone model abstraction.

Alluvium

The alluvial flow path is a source of great uncertainty in modeling radionuclide transport in the saturated zone (NRC, 2000a). DOE models of transport through alluvium depend to a large degree on nonsite-specific data (CRWMS M&O, 2000h,g), and NRC staff raised questions regarding the adequacy of the DOE plans for future data gathering. It is desirable for drill hole samples to be representative of the full range of lithologies and water chemistries present within the expected flow paths. For example, DOE may rely on drill cuttings to obtain alluvium samples, which may adversely affect its ability to accurately measure sorption coefficients, surface area, and effective porosity—all of which may vary considerably in alluvial strata. In cuttings, sample disruption during drilling could alter these critical transport properties. The number and placement of drill holes through the alluvium needs to be adequate for characterizing spatial variations in mineralogy and lithology. The Alluvium Testing Complex alone may not assure that DOE has adequately characterized the range of alluvium properties possible over the modeled flow path; available Alluvium Testing Complex planning documents, including those cited by DOE at the radionuclide transport technical exchange[13] do not provide a level of detail necessary to resolve this question. Questions still remain about the length of the flow path along the alluvial aquifer, which has quite different transport characteristics from the tuff aquifer; this issue is discussed in Section 3.3.8. In addition, DOE has not yet obtained sufficient information on colloid transport characteristics of the alluvium. In response to these concerns, DOE agreed to demonstrate that its site characterization plans, including work on Early Warning Drilling Program Wells, the Alluvium Testing Complex, and related laboratory studies, will ensure that data on transport properties of the alluvium are sufficient to support a

---

[11]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Radionuclide Transport (December 5–7, 2000)." Letter (December 12) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

[12]Ibid.

[13]Ibid.

license application.[14] These agreements included frequent updating of field and laboratory test plans as they develop. DOE will also consider supplementing laboratory K_d studies with data from analog sites or detailed process modeling to address issues of sample integrity and representativeness.

In summary, the models DOE employed to simulate radionuclide transport in the saturated zone for performance assessment should be justified by reference to site-specific data, or data otherwise qualified for inclusion. Revisions of the process model report and the supporting analysis model reports, along with DOE agreements described previously, will provide the needed information for addressing concerns related to data sufficiency and model justification.

3.3.9.4.3 Data Uncertainty Is Characterized and Propagated Through the Model Abstraction

Matrix Diffusion

Overall, the current information, along with agreements reached between DOE and NRC (Section 3.3.9.5), is sufficient to conclude that the necessary information will be available at the time of a potential license application to assess radionuclide transport in the saturated zone with respect to data uncertainty being characterized and propagated through the model abstraction.

Uncertainty in data used to support the inclusion of matrix diffusion in the transport model is treated in the total system performance assessment abstraction of saturated zone radionuclide transport by stochastically sampling two parameters: the effective diffusion coefficient and the effective flowing interval spacing. Uncertainty in the effective diffusion coefficient is a function of the uncertainty and variability in the radionuclide size, temperature, heterogeneity of rock properties, and geochemical conditions along the transport pathway. DOE analyses (CRWMS M&O, 2000h, Section 6.8.4) show that most of the uncertainty in this parameter can be attributed to variability in the tortuosity of the connected pore space in the rock matrix. Based on its analyses, DOE estimated a range of possible values for effective diffusion coefficients in volcanic tuffs from 10^{-9} to 10^{-6} cm^2/s [10^{-10} to 10^{-7} in^2/s]. To ensure the effective diffusion coefficient is not overestimated, the upper bound of this range is set to below the smallest observed molecular diffusion coefficient. A log-uniform distribution is assumed for this range because it is considered unbiased with respect to the order of magnitude of the sampled parameter value and skewed toward lower values. This approach reasonably encompasses the uncertainty of this parameter.

Another important uncertainty is that of flowing interval spacing. Smaller values for effective flowing interval spacing would result in predictions of more rapid matrix diffusion. Analyses were performed to estimate a lognormally distributed range of flowing interval spacing with a mean $\log_{10}$ value of 1.29 and a standard deviation of 0.43 (CRWMS M&O, 2000p). This

[14]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Radionuclide Transport (December 5–7, 2000)." Letter (December 12) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

estimate results in a range of approximately 2–200 m [7–700 ft] with a median flowing interval spacing of approximately 20 m [70 ft]. This wide range of values reasonably encompasses the uncertainty of flowing interval spacing and, given the highly fractured nature of the volcanic tuffs beneath Yucca Mountain, does not seem overly optimistic. It should be noted that the effective flowing interval spacing is used only as a transport parameter that affects the rate of matrix diffusion; it does not affect modeled groundwater fluxes or flow velocities.

Sorption Coefficients

Although a significant amount of laboratory work and literature research is evident in the DOE process model report (CRWMS M&O, 2000a) and supporting analysis and model reports (CRWMS M&O, 2000h,g), the process used in conducting the expert elicitation (or expert judgment) for transport parameter distributions, particularly K_d values, is not described in sufficient detail. Many of the methods normally used in expert elicitation (e.g., panel selection, training, bias, consensus building, dissenting opinions, aggregation, and documentation) are not discussed. In addition, the information used by the expert panel is not described in a way that demonstrates how the strengths and weaknesses of different data sets were evaluated and considered to derive the K_d probability distribution functions. Also, subsequent changes from the initial elicitation are not documented in a transparent manner. This type of information is important to allow a reviewer to trace the process used to develop parameter distributions from the original data and assumptions to the results and conclusions (NRC, 1996). Although the parameter distributions used may be appropriate, without the underlying basis for the expert judgments, the radionuclide transport in the saturated zone model abstraction does not provide a sufficient treatment of data uncertainty. DOE agreed[15] to provide the underlying basis for the expert judgments concerning sorption coefficient distributions.

In discussions of geochemical effects on saturated zone transport outlined in CRWMS M&O (2001), DOE states that the specific effects are included because uncertainty distributions of sorption coefficients are broad enough to encompass them. In each case, staff conclude that DOE has not provided sufficient technical basis that the uncertainty distributions account for the effects. Specific comments on the included features, events, and processes follow.

2.2.08.01.00—Groundwater Chemistry/Composition in Unsaturated and Saturated Zone: This feature, event, and process is included for the saturated zone on the basis that K_d uncertainty ranges bound possible variations because of chemistry variations (CRWMS M&O, 2001). The discussion of total system performance assessment disposition, however, does not address the potential for correlation among radioelement K_ds and possible performance effects. Furthermore, CRWMS M&O (2000g) states that K_d values derived from experiments are not considered to be influenced by microbial and precipitation/dissolution processes—the effects of which are asserted to be included.

[15]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Radionuclide Transport (December 5–7, 2000)." Letter (December 12) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

2.2.08.02.00—Radionuclide Transport in a Carrier Plume: This feature, event, and process is included in the saturated zone, based on the assertion that no credit is taken for chemical changes within the plume that would decrease the transport rate (CRWMS M&O, 2001, p. 56). However, the feature, event, and process discussion does not state how potentially adverse plume effects are accounted for; it is apparent that DOE is relying on K_d distributions. This argument appears to ignore the aspects of retardation that suggest sorption is dominated by solution chemistry rather than rock type. Because DOE does not explicitly model evolving water chemistry in the migrating carrier plume, including transport effects, DOE should provide a technical basis that states that ignoring this process is conservative or has negligible consequences.

2.2.08.03.00—Geochemical Interactions in the Geosphere: This feature, event, and process, which addresses processes such as dissolution and precipitation, is included (CRWMS M&O, 2001). There is an inconsistency in that, while DOE claims its K_d uncertainty distributions account for variations from possible interactions along the transport path, it is not clear that these processes were considered in deriving the distributions (CRWMS M&O, 2000g).

2.2.08.06.00—Complexation in the Geosphere: This feature, event, and process is stated to be included because the effects of complexation agents in the existing groundwater system are included implicitly in the distribution for the K_d value for each element (CRWMS M&O, 2001, p. 59). Parameter distributions and current DOE process models do not appear to address adequately the effects of organic complexation on transport parameters (CRWMS M&O, 2000g).

2.2.09.01.00—Microbial Activity in Geosphere: This feature, event, and process is said to be included (CRWMS M&O, 2001) based on the argument that K_d uncertainty ranges account for effects of microbial activity. The analysis and model report (CRWMS M&O, 2000g), however, states that K_d values derived from experiments are not considered to be influenced by microbial processes.

The issue common to these five included features, events, and processes is the same as that addressed in the preceding paragraphs—DOE has not adequately demonstrated that uncertainty distributions include all the possible variations in K_d in the saturated zone below Yucca Mountain. DOE can address these issues within the bounds of the existing agreement (see following paragraph) on expert judgment and transport parameter distributions.[16] Resolution of two open issues—on excluded FEP 1.2.06.00.00 and FEP 2.2.10.06.00—to be discussed in Section 3.2.1 of this report, could be addressed in the same way.

Documentation is necessary to determine how DOE developed the total system performance assessment transport parameter distributions and the type of information used to support the

[16]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Radionuclide Transport (December 5–7, 2000)." Letter (December 12) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

expert elicitation. DOE agreed to provide documentation of the technical basis for its expert elicitation[17] in accordance with NRC guidance in NUREG–1563 (1996).

In summary, DOE needs to provide experimental and field information to constrain data uncertainty for all transport parameters. Where it is not practical to obtain these data, DOE needs to document the expert elicitations used to provide uncertainty estimates in accordance with NRC guidance in NUREG–1563 (1996) and its own quality assurance program. Sensitivity analyses and bounding calculations are important means of providing a risk-informed, performance-based context for the DOE data uncertainty and for evaluating the need for additional data.

DOE agreed[18] to justify the sorption coefficient distributions used in total system performance assessment.

Fault Zones

Faults can provide fast pathways for radionuclide transport in the saturated zone. Furthermore, the flow and transport characteristics of fault zone pathways can differ widely from those elsewhere in the tuff aquifer. It is not clear that DOE has adequately accounted for the possible effects of these differences in formulating transport parameter distributions (CRWMS M&O, 2000h,g). DOE agreed[19] to provide a technical basis for the importance to performance of transport through fault zones below the repository and to provide the technical basis for the parameters and distributions if such transport is found to be important to performance.

Colloidal Transport

DOE has improved its capability to model saturated zone colloid transport in recent total system performance assessment efforts (CRWMS M&O, 2000a,b), but many of the parameters (e.g., the colloid partitioning coefficient, K_c) used in the models are not supported by site characterization or laboratory data. DOE addressed this problem, to some extent, by using bounding analyses and sensitivity analyses, but there are insufficient radioelement specific data to determine whether the uncertainty in colloid transport has been constrained in the radionuclide transport in the saturated zone model abstraction. As discussed in Section 3.3.9.3.2, the two key parameters that affect saturated zone colloid transport are colloid partition coefficient K_c and colloid retardation factor R_c; colloid matrix diffusion is neglected (CRWMS M&O, 2000c). In the saturated zone, R_c is defined for the tuff aquifer on the basis of one field test, and no site-specific data are available for the alluvial aquifer (CRWMS M&O, 2000h,j). The microspheres used in the tests had diameters between 280 nm [1.1×10^{-5} in] and 640 nm [2.5×10^{-5} in] (CRWMS M&O, 2000j); this value is large compared with a typical

[17]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Radionuclide Transport (December 5–7, 2000)." Letter (December 12) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

[18]Ibid.

[19]Ibid.

size range in colloids from 1 nm to 450 nm [4×10^{-8} in to 2×10^{-5} in]. Smaller colloids will have a much higher specific surface area and perhaps be greater contributors to the potential colloid load. Conversely, these smaller colloids may be small enough to diffuse into the matrix and be physically filtered, reducing their impact on repository performance. DOE discusses these limitations in Section 6.1.5 of CRWMS M&O (2000j), but does not provide sensitivity analyses to test their effects on repository performance. Finally, in calculating R_c from the field data, assigning equal weight to results from the lower Prow Pass Tuff and the lower Bullfrog Tuff may not be conservative because the lower Bullfrog Tuff is the most transmissive interval at the C-Wells (CRWMS M&O, 2000a, p. 3-29). DOE agreed[20] to provide additional justification for the use of microspheres as analogs for colloids.

The K_c parameter, used to simulate reversible colloid attachment by lowering the radioelement K_d, is based on data for americium sorption to colloids and is applied to the K_d values for all reversibly attached radionuclides (CRWMS M&O, 2000h). Calculation of K_c also involves a term for colloid concentration in the water. The colloid concentration adopted is 0.03 mg/L [0.03 ppm]. This value is claimed to be conservative because it corresponds to the highest observed or expected colloid concentration (CRWMS M&O, 2000c). This concentration, however, is well below the maximum values used in release models for waste form 5 mg/L [5 ppm] and iron (hydr)oxide 1 mg/L [1 ppm] colloids derived from the engineered barrier system (CRWMS M&O, 2000o). DOE has not used any data, site-specific or not, to demonstrate that the reversible colloid attachment parameter will bound the range of possible effects of this process, nor have sensitivity analyses been employed to investigate the effects of parameter uncertainty on modeled repository performance. DOE agreed to perform such sensitivity analyses.[21,22]

Alluvium

As discussed in Section 3.3.9.3.2, characterization of the alluvial transport path is incomplete and uncertain. It is, therefore, important that parameter distributions used in total system performance assessment reflect those uncertainties. As acknowledged in CRWMS M&O (2000g), Total System Performance Assessment—Site Recommendation K_d distributions for alluvium are based on a limited number of site-specific tests that do not allow strong conclusions to be drawn (CRWMS M&O, 2000g, p. 92). Furthermore, DOE states in the discussion of assumptions in CRWMS M&O (2000g, p. 36) that it has not confirmed that sorption data are adequate for the alluvium. Parameter uncertainty could be particularly important for relatively poorly sorbing radioelements such as neptunium, iodine, and technetium. The distribution for alluvial effective porosity (CRWMS M&O, 2000h) uses no

---

[20]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Radionuclide Transport (December 5–7, 2000)." Letter (December 12) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

[21]Ibid.

[22]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Evolution of the Near-Field Environment (January 9–12, 2001)." Letter (January 26) to S. Brocoum, DOE. Washington, DC: NRC. 2001.

site-specific data and rests on unconfirmed assumptions. The alluvial aquifer is subject to possibly large spatial and stratigraphic variations in transport parameters (NRC, 2000a), which DOE has not demonstrated that uncertainty distributions accommodate. DOE agreed[23] to accomplish further alluvium characterization that should better define parameter variability (see also Section 3.3.9.3.2).

In summary, DOE has not yet assembled the information relating to methods used to characterize and propagate data uncertainty through the radionuclide transport in the saturated zone model abstraction, but has agreed to do so before submitting any license application. Key areas of data uncertainty to be addressed are K_d distributions, colloid transport parameters, and parameters specific to fault zone and alluvial transport paths.

3.3.9.4.4 Model Uncertainty Is Characterized and Propagated Through the Model Abstraction

Overall, the current information, along with agreements reached between DOE and NRC (Section 3.3.9.5), is sufficient to conclude that the necessary information will be available at the time of a potential license application to assess radionuclide transport in the saturated zone with respect to model uncertainty being characterized and propagated through the model abstraction.

DOE does not have an alternative conceptual model for matrix diffusion in the saturated zone for total system performance assessment analyses. A sensitivity analysis would presumably provide a comparison to an alternative conceptual model with no matrix diffusion, which would provide a better understanding of the relative importance of matrix diffusion in the saturated zone. DOE agreed to provide a sensitivity analysis for matrix diffusion in the saturated zone.[24]

DOE has neglected radionuclide sorption in fractures and applied a linear sorption model to simulate radionuclide transport through the matrix and in unfractured rocks in the saturated zone in total system performance assessment (Wilson, et al., 1994; DOE, 1998b; CRWMS M&O, 2000b). Parameter variability caused by model uncertainty is believed to be contained within the probability distribution functions defined for the retardation parameters. The potential for processes such as precipitation and colloid formation to contribute to the results from batch sorption experiments is also believed to be conservatively bounded by the K_d approach (CRWMS M&O, 2000g). The acceptability of this approach to model uncertainty will depend to a large extent on the documentation of the processes and information used in the expert judgments for sorption coefficient probability distribution functions as discussed in Sections 3.3.9.3.2 and 3.3.9.3.3.

---

[23]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Radionuclide Transport (December 5–7, 2000)." Letter (December 12) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

[24]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Unsaturated and Saturated Flow Under Isothermal Conditions (October 31–November 2, 2000)." Letter (November 17) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

For saturated zone colloid transport modeling, DOE addresses model uncertainty chiefly by adopting each of two distinct attachment modes—reversible and irreversible (CRWMS M&O, 2000o). DOE has not provided sufficient evidence that its selection of colloid transport parameters bounds model uncertainties, so that the radionuclide transport in the saturated zone model abstraction realistically or conservatively bounds the possible effects of colloids. Total System Performance Assessment–Site Recommendation sensitivity analyses do not provide a clear indication of the relative importance to performance of colloid transport, and more general sensitivity analyses allow adjustment of transport parameters only within the established distribution ranges (CRWMS M&O, 2000b). Such analyses do not address the adequacy of the model itself. DOE needs to show, for example, that neglect of kinetic adsorption and desorption effects will not result in an underestimate of the effects on performance of reversible attachment. In addition, the R_c model for retardation of irreversible colloids rests on interpretation of field test results that are highly model-dependent. Breakthrough curves of microspheres at the C-Wells Complex formed a bimodal distribution that would not readily fit a simple retardation model; for example, it was necessary to assume five separate subpathways of undefined physical significance for microsphere transport (CRWMS M&O, 2000j). The irreversible colloid retardation factor distribution for the alluvial aquifer is based on a theoretical analysis (CRWMS M&O, 2000j). No site data can presently be used to confirm if the retardation model is an appropriate approach to colloidal transport in the alluvium. DOE agreed to obtain such data in the future.[25] More generally, DOE agreed to perform sensitivity analyses on the importance of colloidal transport that will address, in part, the adequacy of parameter uncertainty ranges to account for model uncertainty.[26]

In summary, DOE has not adequately assembled the information relating to methods used to characterize and propagate model uncertainty through the radionuclide transport in the saturated zone model abstraction. DOE agreed[27] to address staff concerns. These issues will be addressed chiefly through sensitivity analyses and as a result of continued data acquisition.

3.3.9.4.5 Model Abstraction Output Is Supported by Objective Comparisons

Overall, the current information, along with agreements reached between DOE and NRC (Section 3.3.9.5), is sufficient to conclude that the necessary information will be available at the time of a potential license application to assess radionuclide transport in the saturated zone with respect to model abstraction output being supported by objective comparisons.

The available C-Wells Complex tracer test results provide convincing evidence that matrix diffusion occurs in the saturated volcanic tuffs along flow paths from Yucca Mountain (CRWMS M&O, 2000a). Not all results from the C-Wells Complex testing have been published, however. Thus, DOE agreed to provide documentation for the C-Wells Complex testing and to

---

[25]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Radionuclide Transport (December 5–7, 2000)." Letter (December 12) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

[26]Ibid.

[27]Ibid.

use the field-test data to provide justification that the data from the laboratory tests used for parameter estimations are consistent with the data from the field tests.[28]

The residence-time transfer function method for coupling matrix diffusion to the particle-tracking transport was compared with predictions from analytical solutions and other numerical models (CRWMS M&O, 2000f,q). For cases where many particles are used, predictions made using the residence-time transfer function particle-tracking approach compare well with one-dimensional analytical solutions (CRWMS M&O, 2000f, Section 6.3). A comparison of the residence-time transfer function approach to the results of a three-dimensional unsaturated zone simulation using an alternative Lagrangian-approach numerical model showed that, of the two models, the residence-time transfer function approach predicts much faster solute breakthrough times (CRWMS M&O, 2000p, Section 6.2.5). Although this verification exercise was performed using the unsaturated zone model and may not be strictly applicable for the model parameters estimated for the saturated zone transport model, the result suggests the residence-time transfer function predictions are not overly optimistic.

Verification of the ability of the particle-tracking approach to simulate advective transport of sorbing solute was also reported in CRWMS M&O (2000f). For the Total System Performance Assessment–Site Recommendation, correct implementation of the saturated zone radionuclide transport abstraction was addressed by checking that model inputs were correctly selected, that parameter functions were calculated properly, that the relationships between unsaturated zone and saturated zone outputs correctly reflected intended saturated zone behavior (e.g., more sorbing radionuclides were delayed relative to less sorbing radionuclides), and that ingrowth of radioactive daughters was simulated (CRWMS M&O, 2000c, Figures 6-176 to 6-181). The verification exercises checked both the one-dimensional and three-dimensional transport models (see Section 3.3.9.3.1), and included colloidal species. Another DOE report (CRWMS M&O, 2000i) compared one- and three-dimensional saturated zone model results for carbon and neptunium. Breakthrough curves for the two models were not identical; fractional discrepancies were largest at the 5-km [3.1-mi] points. This discrepancy is not relevant to proposed regulations concerning Yucca Mountain. At 20 and 30 km [12.4 mi and 18.6 mi], differences in breakthrough times for the two models were less than a factor of two. Although it is true that these results are, as the report says, generally comparable (CRWMS M&O, 2000i, p. 63), the differences should not be ignored in interpreting transport. Effectively, this exercise was a comparison between a detailed process-level model (three-dimensional) and a total system performance assessment implementation (one-dimensional). More such comparisons using other radionuclides and including colloidal transport may prove useful to further verify the total system performance assessment abstraction.

DOE has not provided sufficient evidence, either through field tests or natural analogs, that results from laboratory sorption/transport experiments can be extended or used to bound transport over larger distances and longer times. For example, if credit is to be taken for radionuclide attenuation, DOE should demonstrate that nonradioactive tracers used in field

[28]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Unsaturated and Saturated Flow Under Isothermal Conditions (October 31–November 2, 2000)." Letter (November 17) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

tests (e.g., C-Wells) are appropriate homologues for radioelements. DOE agreed to provide the technical basis for the reconciliation of field and laboratory data in a future report on the C-Wells tests.[29]

The DOE discussion of model validation for the saturated zone flow and transport process model focuses on flow issues (CRWMS M&O, 2000a, Section 3.4). For transport, DOE claims that independent, quantitative comparisons are not possible because of differences between the Yucca Mountain environment and those at natural and anthropogenic analog sites. Therefore, DOE appears to be relying on site-specific tests, such as at the C-Wells Complex, for validation of data obtained in other ways such as laboratory tests. The explicit application of such exercises to model validation, however, is not apparent in available reports (e.g., CRWMS M&O, 2000a, Section 3.2.4.1.1; 2000f); an exception is the observation of matrix diffusion at the C-Wells (Section 3.3.9.3.2). DOE should clarify how field tests are used for validation of laboratory results and model abstractions (see previous paragraph). In contrast, DOE is using the C-Wells and Alluvial Testing Complex results for parameter development for colloid transport (CRWMS M&O, 2000o). At this point, no objective comparisons have been made for validating the colloidal transport parameters or abstraction. DOE needs to develop such comparisons or test colloid models by sensitivity studies and more quantitative comparisons to analogs (see Section 3.3.9.3.2). DOE agreed to perform sensitivity studies as the basis for consideration of the importance of colloid transport parameters and models to performance for the saturated zone and will document the results in updates to appropriate analyses and model reports in fiscal year 2003.

In summary, DOE has not yet adequately assembled the information relating to methods used to support model abstractions of the radionuclide transport in the saturated zone. DOE has agreed to address staff concerns chiefly through sensitivity analyses and as a result of continued data acquisition.

3.3.9.5 Status and Path Forward

Table 3.3.9-1 provides the status of all key technical issue subissues, referenced in Section 3.3.9.2, for the Radionuclide Transport in the Saturated Zone Integrated Subissue. The table also provides the related DOE and NRC agreements pertaining to the Radionuclide Transport in the Saturated Zone Integrated Subissue. The agreements listed in the table are associated with one or all five generic acceptance criteria discussed in Section 3.3.9.4. Note that the status and the detailed agreements (or path forward) pertaining to all the key technical issue subissues are provided in Table 1.1-3 and Appendix A.

The DOE-proposed approach, together with the DOE agreements to provide NRC with additional information (through specified testing, analyses, and the like), acceptably addresses the NRC questions so that no information beyond that provided, or agreed to, will likely be required at the time of a potential license application.

---

[29]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Radionuclide Transport (December 5–7, 2000)." Letter (December 12) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

Table 3.3.9-1. Related Key Technical Issue Subissues and Agreements

Key Technical Issue	Subissue	Status	Related Agreement*
Radionuclide Transport	Subissue 1—Radionuclide Transport Through Porous Rock	Closed-Pending	RT.1.02 through RT.1.05
	Subissue 2—Radionuclide Transport Alluvium	Closed-Pending	RT.2.01 through RT.2.07 RT.2.10
	Subissue 3—Radionuclide Transport Through Fractured Rock	Closed-Pending	RT.3.07 RT.3.08 RT.3.09
	Subissue 4—Nuclear Criticality in the Far Field	Closed-Pending	RT.4.01 RT.4.03
Unsaturated and Saturated Flow Under Isothermal Conditions	Subissue 5—Saturated Zone Ambient Flow Conditions and Dilution Processes	Closed-Pending	USFIC.5.03
	Subissue 6—Matrix Diffusion	Closed-Pending	USFIC.6.04
Structural Deformation and Seismicity	Subissue 3—Fracturing and Structural Framework of the Geologic Setting	Closed-Pending	None
Container Life and Source Term	Subissue 5—Effect of In-Package Criticality on Waste Package and Engineered Barrier System Performance	Closed-Pending	CLST.5.04
Total System Performance Assessment Integration	Subissue—1 System Description and Demonstration of Multiple Barriers	Closed Pending	None
	Subissue 2—Scenario Analysis and Event Probability	Closed Pending	TSPAI.2.01 TSPAI.2.02 TSPAI.2.03
	Subissue 3—Model Abstraction	Closed Pending	TSPAI.3.30 TSPAI.3.31 TSPAI.3.32
	Subissue 4—Demonstration of Compliance with the Postclosure Public Health and Environmental Standards	Closed Pending	None

*Related DOE and NRC agreements are associated with one or all five generic acceptance criteria.

Note: Key Technical Issue Agreement GEN.1.01 pertains to multiple integrated subissues, as well as some specific issues related to this integrated subissue.

3.3.9.6 References

Barnard, R.W., M.L. Wilson, H.A. Dockery, J.H. Gauthier, P.G. Kaplan, R.R. Eaton, F.W. Bingham, and T.H. Robey. "TSPA 1991: An Initial Total-System Performance Assessment for Yucca Mountain." SAND91–2795. Albuquerque, New Mexico: Sandia National Laboratories. 1992.

Bechtel SAIC Company, LLC. "FY01 Supplemental Science and Performance Analyses." Vol. 1: Scientific Bases and Analyses. TDR–MGR–MD–000007. Revision 00 ICN 01. Las Vegas, Nevada: Bechtel SAIC Company, LLC. 2001a.

Bechtel SAIC Company, LLC. "FY01 Supplemental Science and Performance Analyses." Vol. 2: Performance and Analyses. TDR–MGR–PA–000001. Revision 00. Las Vegas, Nevada: Bechtel SAIC Company, LLC. 2001b.

CRWMS M&O. "Saturated Zone Flow and Transport Process Model Report." TDR–NBS–HS–000001. Revision 00 ICN 02. Las Vegas, Nevada: CRWMS M&O. 2000a.

———. "Total System Performance Assessment for the Site Recommendation." TDR–WIS–PA–000001. Revision 00 ICN 01. Las Vegas, Nevada: CRWMS M&O. 2000b.

———. "Total System Performance Assessment (TSPA) Model for Site Recommendation." MDL–WIS–PA–000002. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000c.

———. "Repository Safety Strategy: Plan to Prepare the Safety Case to Support Yucca Mountain Site Recommendation and Licensing Considerations." TDR–WIS–RL–000001. Revision 04. Las Vegas, Nevada: CRWMS M&O. 2000d.

———. "Particle Tracking Model and Abstraction of Transport Processes." ANL–NBS–HS–000026. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000e.

———. "Saturated Zone Transport Methodology and Transport Component Integration." ANL–NBS–HS–000010. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000f.

———. "Unsaturated Zone and Saturated Zone Transport Properties." ANL–NBS–HS–000019. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000g.

———. "Uncertainty Distribution for Stochastic Parameters." ANL–NBS–MD–000011. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000h.

———. "Input and Results of the Base Case Saturated Zone Flow and Transport Model for TSPA." ANL–NBS–HS–000030. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000i.

———. "Saturated Zone Colloid-Facilitated Transport." ANL–NBS–HS–000031. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000j.

———. "Inventory Abstraction." ANL–WIS–MD–000006. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000k.

———. "Features, Events, and Processes—System Level and Criticality." ANL–WIS–MD–000019. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000l.

———. "Probability of Criticality Before 10,000 Years." CAL–EBS–NU–000014. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000m.

———. "Probability Distribution for Flowing Interval Spacing." ANL–NBS–MD–000003. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000n.

———. "Waste Form Colloid-Associated Concentration Limits: Abstraction and Summary." ANL–WIS–MD–000012. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000o.

———. "Analysis of the Base-Case Particle Tracking Results of the Base-Case Flow Fields." ANL–NBS–HS–000024. Revision 00. Las Vegas, Nevada: CRWMS M&O. 2000p.

———. "Features, Events, and Processes in SZ Flow and Transport." ANL–NBS–MD–000002. Revision 01. Las Vegas, Nevada: CRWMS M&O. 2001.

DOE. "Disposal Criticality Analysis Methodology Topical Report." YMP/TR–004Q. Revision 00. Las Vegas, Nevada: DOE, Office of Civilian Radioactive Waste Management. 1998a.

———. "Viability Assessment of a Repository at Yucca Mountain." Overview and all five volumes. DOE/RW–0508. Las Vegas, Nevada: DOE, Office of Civilian Radioactive Waste Management. 1998b.

———. "Disposal Criticality Analysis Methodology Topical Report." YMP/TR–004Q. Revision 01. Las Vegas, Nevada: DOE, Office of Civilian Radioactive Waste Management. 2000.

Flint, L.E. "Characterization of Hydrogeologic Units Using Matrix Properties, Yucca Mountain, Nevada." U.S. Geological Survey Water Resources Investigations Report 97-4243. 1998.

NRC. NUREG–1563, "Branch Technical Position on the Use of Expert Elicitation in the High-Level Radioactive Waste Program." Washington, DC: NRC. November 1996.

———. "Issue Resolution Status Report, Key Technical Issue: Unsaturated and Saturated Flow Under Isothermal Conditions." Revision 2. Washington, DC: NRC. 1999a.

———. NUREG–1668, "NRC Sensitivity and Uncertainty Analyses for a Proposed HLW Repository at Yucca Mountain, Nevada, Using TPA 3.1." Washington, DC: NRC. March 1999b.

———. "Issue Resolution Status Report Key Technical Issue: Radionuclide Transport." Revision 2. Washington, DC: NRC. 2000a.

———. "Issue Resolution Status Report, Key Technical Issue: Structural Deformation and Seismicity." Revision 3. Washington, DC: NRC. 2000b.

———. "Issue Resolution Status Report, Key Technical Issue: Total System Performance Assessment and Integration." Revision 3. Washington, DC: NRC. 2000c.

———. NUREG–1746, "System-Level Repository Sensitivity Analyses Using TPA Version 3.2 Code." Washington, DC: NRC. August 2001a.

———. "Issue Resolution Status Report, Key Technical Issue: Container Life and Source Term." Revision 3. Washington, DC: NRC. 2001b.

———. NUREG–1804, "Yucca Mountain Review Plan—Draft Report for Comment." Revision 2. Washington, DC: NRC. March 2002.

Reimus, P.W., A. Adams, M.J. Haga, A. Humphrey, T. Callahan, I. Anghel, and D. Counce. "Results and Interpretation of Hydraulic and Tracer Testing in the Prow Pass Tuff at the C-Holes." Yucca Mountain Project Milestone SP32E7M4. Los Alamos, New Mexico: Los Alamos National Laboratory. 1999.

Sudicky, E.A. and E.O. Frind. "Contaminant Transport in Fractured Porous Media: Analytical Solutions for a System of Parallel Fractures." *Water Resources Research*. Vol. 18, No. 6. pp. 1,634–1,642. 1982.

Triay, I.R., A. Meijer, J.L. Conca, K.S. Kung, R.S. Rundberg, and E.A. Strietelmeier. "Summary and Synthesis Report on Radionuclide Retardation for the Yucca Mountain Site Characterization Project, Milestone 3784M." LA–13262–MS. Los Alamos, New Mexico: Los Alamos National Laboratory, Chemical Science and Technology Division. 1997.

Wilson, M.L., J.G. Gauthier, R.W. Barnard, G.E. Barr, H.A. Dockery, E. Dunn, R.R. Eaton, D.C. Guerin, N. Lu, M.J. Martinez, R. Nilson, C.A. Rautman, T.H. Robey, B. Ross, E.E. Ryder, A.R. Schenker, S.A. Shannon, L.H. Skinner, W.G. Halsey, J.D. Gansemer, L.C. Lewis, A.D. Lamont, I.R. Triay, A. Meijer, and D.E. Morris. "Total-System Performance Assessment for Yucca Mountain—SNL Second Iteration (TSPA–1993)." SAND93–2675. Albuquerque, New Mexico: Sandia National Laboratories. 1994.

Zyvoloski, G.A., B.A. Robinson, Z.V. Dash, and L.L. Trease. "Summary of Models and Methods for the FEHM Application—A Finite Element Heat—and Mass-Transfer Code." LA–13307–MS. Los Alamos, New Mexico: Los Alamos National Laboratory. 1997.

3.3.10 Volcanic Disruption of Waste Packages

3.3.10.1 Description of Issue

The Volcanic Disruption of Waste Packages Integrated Subissue evaluates the interaction of ascending basaltic magma with subsurface repository systems and the establishment of flow paths to the surface as part of a possible volcanic eruption. Key processes associated with this integrated subissue are (i) ascent of basaltic magma in the Yucca Mountain region, (ii) interaction of the ascending magma with rock in the modified stress regime around repository drifts, (iii) initial interactions between ascending magma and repository drifts, (iv) interactions between magma in drifts and engineered barriers, (v) establishment of magma flow paths to the surface, and (vi) effect of sustained magma flow on engineered barrier performance and possible waste package and high-level waste disaggregation. The transition to the Airborne Transport of Radionuclides Integrated Subissue occurs when high-level waste is incorporated into the flowing basaltic magma that is erupting subaerially. Interactions between basaltic magma and waste packages not located along a subvolcanic conduit to the surface are evaluated in the Mechanical Disruption of Engineered Barriers Integrated Subissue. The relationship of this integrated subissue to other integrated subissues is depicted in Figure 3.3.10-1. The overall organization and identification of all the integrated subissues are depicted in Figure 1.1-2.

This section provides a review of the abstractions of volcanic disruption of waste packages by DOE in the Total System Performance Assessment–Site Recommendation (CRWMS M&O, 2000a). The DOE description and technical basis for its analyses of volcanic disruption of waste packages are documented in CRWMS M&O (2000b) and three supporting analysis and model reports (CRWMS M&O, 2000c,d,e). Calculation documents (CRWMS M&O, 2000f,g) and the analysis and model report (CRWMS M&O, 2000h) also provide information relevant to this integrated subissue.

3.3.10.2 Relationship to Key Technical Issue Subissues

The Volcanic Disruption of Waste Packages Integrated Subissue incorporates subject matter previously captured in the following key technical issue subissues:

- Igneous Activity: Subissue 1—Probability of Igneous Activity (NRC, 1999)
- Igneous Activity: Subissue 2—Consequences of Igneous Activity (NRC, 1999)
- Container Life and Source Term: Subissue 2—Mechanical Disruption of Waste Packages (NRC, 1999)

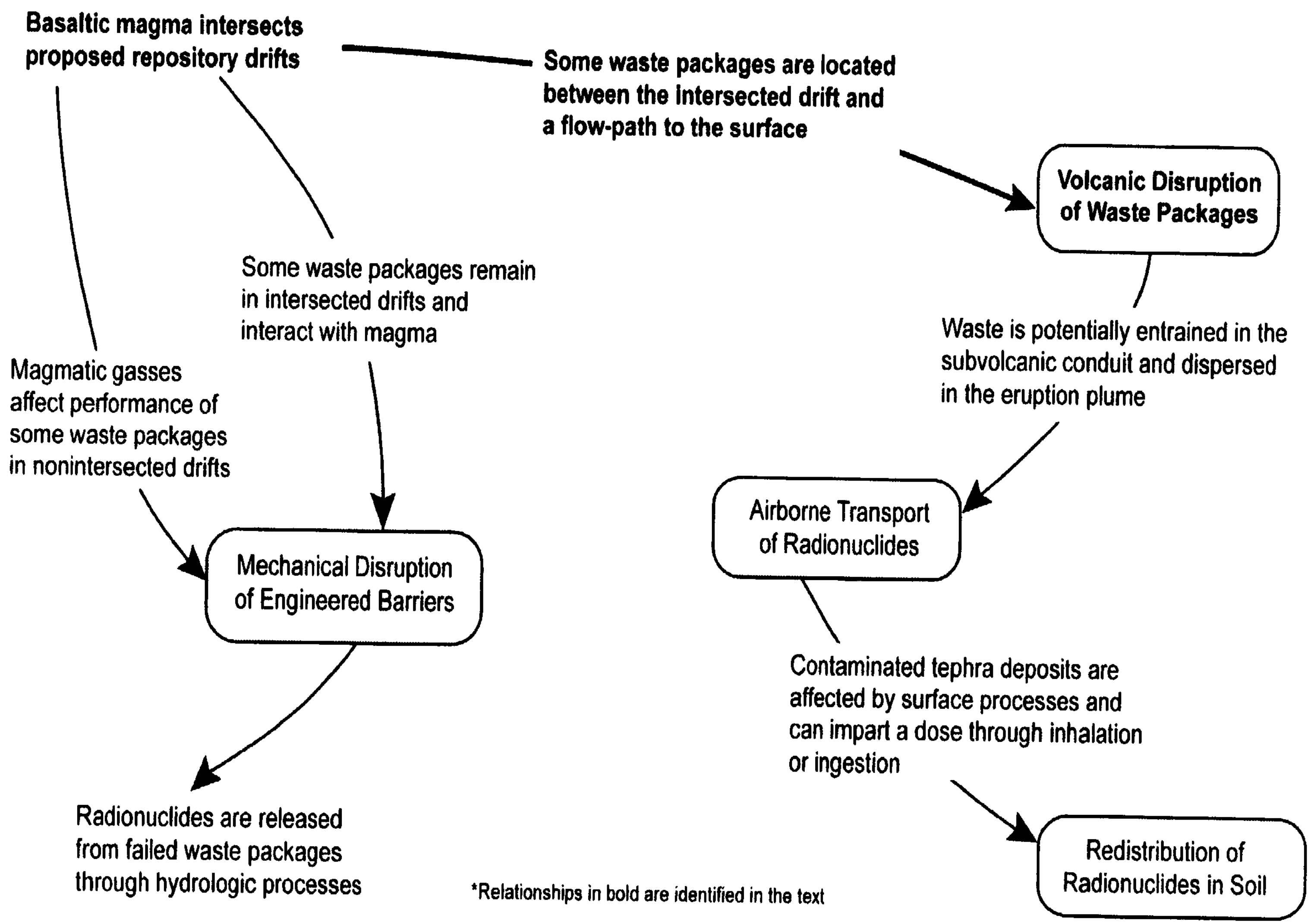

Figure 3.3.10-1. Diagram Illustrating the Relationship Between Volcanic Disruption of Waste Packages and Other Integrated Subissues

- Total System Performance Assessment and Integration: Subissue 1—System Description and Demonstration of Multiple Barriers (NRC, 2000)

- Total System Performance Assessment and Integration: Subissue 2—Scenario Analysis and Event Probability (NRC, 2000)

- Total System Performance Assessment and Integration: Subissue 3—Model Abstraction (NRC, 2000)

- Total System Performance Assessment and Integration: Subissue 4—Demonstration of Compliance with the Postclosure Public Health and Environmental Standards (NRC, 2000)

The key technical issue subissues formed the basis for the previous versions of the issue resolution status reports and also were the basis for technical exchanges with DOE where agreements were reached on the additional information DOE needed to provide to resolve the subissue. The resolution status of this integrated subissue is based on the resolution status of each of the contributing key technical issue subissues. The subsequent sections incorporate applicable portions of these key technical issue subissues, however, no effort has been made to explicitly identify each subissue.

3.3.10.3 Importance to Postclosure Performance

One aspect of risk-informing the NRC review was to determine how this integrated subissue is related to the DOE repository safety strategy. The Total System Performance Assessment–Site Recommendation reports no radiological risk in 10,000 years from the basecase repository (CRWMS M&O, 2000a). Postclosure volcanism has a maximum probability weighted risk of approximately 0.1 μSv/yr [0.01 mrem/yr], however, DOE has not classified it as a principal factor. Based on DOE analyses, intrusive igneous activity has a probability weighted risk of approximately 1 μSv/yr [0.1 mrem/yr], and DOE has classified it as a principal factor (CRWMS M&O, 2000i). Both these risk values increase by approximately one order of magnitude when probability values acceptable for prelicensing issue resolution are used (CRWMS M&O, 2000a).[1] Volcanism risks increase to approximately 1 μSv/yr [0.1 mrem/yr] in supplemental analyses presented in Bechtel SAIC Company, LLC (2001a). In contrast, risks from intrusive igneous activity decrease by approximately an order of magnitude to 0.1 μSv/yr [0.01 mrem/yr] in Bechtel SAIC Company, LLC (2001a). These levels of igneous risk clearly exceed calculated risks from other postclosure features, events, and processes in CRWMS M&O (2000a) or Bechtel SAIC Company, LLC (2001a,b).

Concerns have been raised with the technical bases DOE has used to evaluate both extrusive and intrusive igneous activity in the Total System Performance Assessment–Site

[1]Schlueter, J.R. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Igneous Activity (August 29–31, 2000)." Letter (October 23) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

Recommendation[2,3] (Hill and Connor, 2000). Analyses presented in, for example, NRC (1999) also demonstrate that probability-weighted risk from postclosure volcanism may be on the order of 10 μSv/yr [1 mrem/yr], with significant uncertainties associated with this value. DOE will need to continue resolving technical concerns with igneous processes, including those associated with postclosure volcanism, due to significant uncertainties with igneous risk calculations and the absence of other processes that lead to similar levels of risk in postclosure total system performance (i.e., CRWMS M&O, 2000a).

Processes of magma-repository interaction, which form the primary emphasis of the Volcanic Disruption of Waste Packages Integrated Subissue, affect the amount of radionuclides potentially released by both volcanic and groundwater pathways. Evaluation of the risks associated with these release pathways is predicated on a well-supported understanding of the magnitude of ascending basaltic magma that can interact with subsurface repository systems and of the possible rates of interaction. This interaction directly controls the amount and character of high-level waste potentially available for subsequent volcanic and hydrologic transports.

3.3.10.4 Technical Basis

As outlined in NRC (1999) and Hill and Connor (2000), previous DOE total system performance assessments have evaluated a limited range of effects from volcanic disruption of the proposed repository. In the Total System Performance Assessment–Viability Assessment, DOE relied on several critical assumptions to support the conclusion that there is no risk from volcanic disruption during a 10,000-year performance period (DOE, 1998). As discussed in Section 4.2 of Hill and Connor (2000), these assumptions were based on levels of information not adequate to substantiate waste package and waste form resiliences during igneous events.

Significant changes were made to DOE igneous activity models subsequent to the Total System Performance Assessment–Viability Assessment, as discussed in Section 4.2 of Hill and Connor (2000). These changes have addressed many technical concerns with key modeling assumptions previously made by DOE. Most importantly, DOE currently assumes waste packages fail on intersection by an erupting subvolcanic conduit and that all contained high-level waste is available for entrainment (CRWMS M&O, 2000d). In addition, the models now include a significant reduction in high-level waste particle size during volcanic disruption, and all eruptions have violent strombolian dispersal characteristics (CRWMS M&O, 2000e). The Total System Performance Assessment–Viability Assessment also assumed passive flow of magma from a dike segment that intersected subsurface drifts (DOE, 1998). Scoping calculations by Woods and Sparks (1998) indicated flow of magma would likely be more rapid and energetic than previously modeled. These calculations led to significant revisions of the

---

[2]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Igneous Activity (June 21–22, 2001)." Letter (June 27) to S. Brocoum, DOE. Washington, DC: NRC. 2001.

[3]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Igneous Activity (September 5, 2001)." Letter (September 12) to S. Brocoum, DOE. Washington, DC: NRC. 2001.

DOE model abstraction (e.g., CRWMS M&O, 2000c). DOE also agreed to provide additional modeling support for magma-repository interactions, including evolution of potential magma flow paths through the duration of an igneous event. The Volcanic Disruption of Waste Packages Integrated Subissue currently is closed-pending, after agreements reached at the September 5, 2001, Technical Exchange on Igneous Activity.[4]

NRC developed a Yucca Mountain Review Plan (2002) that is consistent with the acceptance criteria and review methods found in previous issue resolution status reports. A review of DOE approaches for including volcanic disruption of waste packages in total system performance assessment abstractions is provided in the following subsections. The review is organized according to the five acceptance criteria identified in Section 1.5 as follows: (i) System Description and Model Integration Are Adequate, (ii) Data Are Sufficient for Model Justification, (iii) Data Uncertainty Is Characterized and Propagated Through the Model Abstraction, (iv) Model Uncertainty is Characterized and Propagated Through the Model Abstraction, and (v) Model Abstraction Output Is Supported by Objective Comparisons.

3.3.10.4.1 System Description and Model Integration Are Adequate

Overall, the current information, along with agreements reached between DOE and NRC (Section 3.3.10.5), is sufficient to conclude that the necessary information will be available at the time of a potential license application to assess volcanic disruption of waste packages with respect to system description and model integration.

The DOE approach to evaluating volcanic disruption of waste packages involves several conceptual models.

- Ascending basaltic magma interacts with the subsurface rock surrounding the repository drifts. Based on calculations for an older high thermal-load repository design, CRWMS M&O (2000c) indicates that ascending magma may be deflected from repository drifts during the first 2,000 years of postclosure. This deflection is attributed to the rotation of rock-stress directions in response to heating of the rock by emplaced waste. The Total System Performance Assessment–Site Recommendation, however, apparently does not take credit for this magma deflection in current analyses (CRWMS M&O, 2000a).

- Ascending magma intersects the repository drifts. Because the magma is thought to be under lithostatic pressure {i.e., about 7.5 MPa [1,088 psi]}, volatiles in the magma expand upon entering the drift, and magma flows rapidly into the drift (CRWMS M&O, 2000c). The shock associated with this initial entry may be sufficient to wholly damage three waste packages on either side of the intersecting dike (CRWMS M&O, 2000c,d,f).

[4]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Igneous Activity (September 5, 2001)." Letter (September 12) to S. Brocoum, DOE. Washington, DC: NRC. 2001.

- Magma continues to flow into a nonbackfilled drift at a rate sufficient to block the ends of drifts with an accumulation of drip shields, debris, and quenched magma fragments (CRWMS M&O, 2000c,d). For a backfilled repository, the extent of this flow is much more limited, with drifts thought to be wholly plugged within 15 m [49 ft] on either side of the intersecting dike (CRWMS M&O, 2000c).

- Magma fills the plugged drift until the pressure in the magma exceeds the force needed to hydraulically fracture the drift roof and propagate magma to the surface (CRWMS M&O, 2000c).

- A subvolcanic conduit forms 77 percent of the time at the point of dike intersection in the drift. The remaining 23 percent of the time, the conduit forms in the pillars, and no high-level waste is released through volcanism (CRWMS M&O, 2000c,d,g).

- All waste packages intersected by the conduit are assumed to fail from the adverse physical, thermal, and chemical conditions in the erupting conduit (CRWMS M&O, 2000d,f).

These models rely on several key assumptions that are not consistent with physical processes generally associated with igneous events. Most significant of these assumptions is that the pressure in an ascending basaltic magma at 300-m [984-ft] depth is equivalent to a 7.5-MPa [1,088-psi] lithostatic confining pressure (CRWMS M&O, 2000c). Magma likely ascends in the shallow crust by propagating a fracture that extends vertically for some distance above the dike tip (e.g., Delaney, et al., 1986; Rubin, 1993). Differences in horizontal deviatoric stress are relatively small in the Yucca Mountain region (e.g., Morris, et al., 1996). Thus, a hydraulic pressure greater than lithostatic is necessary to dilate a 300-m [984-ft]-deep fracture from approximately 0.1 cm [0.04 in] to typical dike widths of approximately 100 cm [39 in] (e.g., Rubin, 1993). Many authors calculate this pressure to be 1–10 MPa [145–1,450 psi] greater than lithostatic pressure for shallow dikes (Delaney, et al., 1986; Rogers and Bird, 1987; Baer and Reches, 1991; Rubin, 1993; Woods and Sparks, 1998). This amount of magmatic overpressure is important because it directly affects the potential rate of magma flow into the drift, which, in turn, determines the volume of ascending magma that can be captured by the intersected drift (e.g., Bokhove and Woods, 2000; Woods, et al., 2001). In addition, as the drift fills with magma and pressure reequilibrates with the pressure in the intersecting dike, the amount of magmatic overpressure affects when and where basaltic magma can break out of the drift roof and propagate to the surface (CRWMS M&O, 2000c; Woods, et al., 2001). In the Igneous Activity Key Technical Issue agreement 2.18, DOE agrees to evaluate how the presence of repository structures may affect magma ascent processes. This evaluation will use a range of physical conditions appropriate for the duration of igneous events.[5]

The pressure in the magma system likely affects the extent of magma flow into the subsurface drift system. The DOE volcanic disruption of waste packages model relies on debris plugs to

[5]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Igneous Activity (September 5, 2001)." Letter (September 12) to S. Brocoum, DOE. Washington, DC: NRC. 2001.

form at the ends of the intersected drift (CRWMS M&O, 2000c,d). These plugs prevent magma from flowing into the drift network and from potentially damaging additional waste packages. In addition, these debris plugs must be stronger than the fracture strength of the roof rock along the drift to direct the repressurized magma vertically for the duration of the igneous event. Models to date have not demonstrated that these debris plugs will have a mechanical strength sufficient to withstand a 3–7 MPa [435–1,015 psi] repressurization of the magma-filled drift, throughout the duration of an igneous event. Although access drifts will likely be completely backfilled (Bechtel SAIC Company, LLC, 2001b), the absence of backfill could allow magma to break through the debris plugs and flow into drifts not directly intersected by a dike (Hill and Connor, 2000; Woods, et al., 2001). DOE agreed to evaluate the mechanical strength and durability of natural or engineered barriers that could restrict magma flow within intersected drifts, using an appropriate range of repository design options.[6]

DOE models for the deviation of ascending dikes caused by thermally altered stresses around proposed repository drifts have examined a limited range of processes and geologic couplings. Although these analyses are not currently used to reduce volcanism risk (CRWMS M&O, 2000a,d), the model implies that dike intersection with repository drifts may be unlikely during the first 2,000 years of postclosure when heat released from the waste packages may be greatest. Models that evaluate potential changes in rock stress because of thermal effects from the emplacement of waste will need to use consistent and appropriate design characteristics in the analyses; CRWMS M&O (2000c) uses wall-rock temperatures that are significantly higher than currently proposed repository designs. Stress models also will need to consider how stress induced through thermal expansion can be accommodated through strains along existing structures or through the propagation of new strain structures such as fractures. Topographic variations above the proposed repository horizon also can affect the maximum amount of stress that can accumulate from thermal expansion before a displacement strain occurs. Models also will need to evaluate the effects of differential thermal expansion because proposed waste-package loadings in drifts will not result in a uniform heat source (e.g., Bechtel SAIC Company, LLC, 2001b). Models for potential deviation of ascending magma away from proposed repository drifts will need to account for complex couplings between heterogeneous thermal stress and multiple strain accommodation processes. DOE agreed to evaluate the potential effects of topography and stress and the likely strain responses on existing or new geologic structures resulting from thermal loading of high-level waste, in future models of dike ascent.[7]

The processes that control the initial development of a subvolcanic conduit are poorly known. A common observation at basaltic cinder cone volcanoes is that a roughly 1-km [3,280-ft]-long fissure forms during the first 24 hours of an eruption, which supports a fire-fountain eruption. A central vent then localizes along the fissure, with the eruption becoming more energetic and forming a dispersive cinder cone volcano (e.g., Thorarinsson, et al., 1973; Fedotov, et al., 1984). One explanation for this process is that a preferred vertical-flow pathway develops in

---

[6]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Igneous Activity (September 5, 2001)." Letter (September 12,) to S. Brocoum, DOE. Washington, DC: NRC. 2001.

[7]Ibid.

the dike-fed fissure as a result of irregularities in dike width or fracture roughness. Magma in a typical shallow dike that is ascending slowly can solidify in several hours (Delaney and Pollard, 1982; Huppert and Sparks, 1985; Bruce and Huppert, 1989, 1990). Thus, any feature that favors vertical magma ascent should favor the localization of a subvolcanic conduit, because the conduit will not form in stagnated, solidifying basalt. Repository drifts represent one possible low-resistance flow path for vertically ascending magma, especially as calculations indicate magma will accelerate into the intersected drifts because of decompression effects (e.g., Woods and Sparks, 1998; Bokhove and Woods, 2000; CRWMS M&O, 2000c; Woods, et al., 2001). Streamlines for magma in the intersecting dike should focus on the drifts, with lower ascent velocities or possibly stagnation occurring in the areas between the drifts. The effect of focusing the vertical ascent of magma toward drifts may localize subsequent conduit formation in the drift. The potential effects of flow focusing on conduit formation, however, has not been evaluated. CRWMS M&O (2000h) asserts that the presence of repository drifts causes conduits to localize there only 50 percent of the time, and that conduits will form randomly in a drift an additional 27 percent of the time. No technical basis is supplied in CRWMS M&O (2000a–h), however, that evaluates potential magma flow processes in the presence of repository drifts. Such a technical basis is required to reduce resulting dose calculations by 23 percent (CRWMS M&O, 2000a,d), which is the credit taken for a conduit forming outside a repository drift. DOE agrees to evaluate how the presence of repository structures may affect conduit localization and evolution of the conduit system. This evaluation will include a range of physical conditions appropriate for the duration of basaltic igneous events.[8]

Current DOE total system performance assessment models (CRWMS M&O, 2000a,d,g) calculate the amount of high-level waste available for volcanic disruption by determining the number of waste packages that fall within the diameter of a circle centered on the point of dike-drift intersection. This modeling approach does not consider how the presence of repository structures may potentially affect igneous processes. Models presented in CRWMS M&O (2000c) conclude that magma may not ascend above the level of the drift until the drift is filled with magma at equilibrium pressure with the dike. There is no basis presented in CRWMS M&O (2000a–h), however, that demonstrates why magma should resume propagating vertically at the initial point of dike intersection rather than at some other location where the overlying lithostatic load is lower (e.g., Woods and Sparks, 1998; NRC, 1999; Woods, et al., 2001). Bedrock thicknesses overlying the proposed repository range from 200 to 300 m [656 to 984 ft]. Assuming that the overlying rock has an average density of 2,400 kg m^{-3} [150 lb/ft^3], results in a lithostatic load that ranges from approximately 4.7 MPa [682 psi] on the east to approximately 7.1 MPa [1,030 psi] beneath Yucca Crest. Subvertical breakout toward Solitario Canyon also may represent a potential pathway with lower lithostatic load than pathways to the east. Assuming a vertical fracture, the amount of horizontal force needed to dilate the fracture to 1 m [3.3 ft] is then controlled by the thickness of overlying rock, because other parameters essentially are equivalent along the drift length. Thus, a dike intersecting the western part of a drift has sufficient overpressure to dilate rock with a 7.1-MPa [1,030-psi]

---

[8]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Igneous Activity (September 5, 2001)." Letter (September 12) to S. Brocoum, DOE. Washington, DC: NRC. 2001.

lithostatic load during ascent. If the drift fills with magma and begins to repressurize, hydrofracturing and breakout through the drift roof are more likely to occur on the eastern part of the drift, or perhaps subvertically toward Solitario Canyon where the overlying rock is thinnest, and less fluid pressure is needed to dilate a fracture (e.g., CRWMS M&O, 2000c). In this situation, magma could flow horizontally through the drift between the initial intersection point and the final breakout point. Waste packages in this flow path would most likely fail because of the high thermal, physical, and chemical loads in the erupting volcanic conduit (CRWMS M&O, 2000d,f). Because the length of this horizontal flow path could readily exceed 150 m [492 ft] (i.e., the maximum diameter of the DOE subvolcanic conduit), more waste packages could be disrupted and entrained than currently calculated (CRWMS M&O, 2000a,d). DOE agreed to evaluate how magma flow paths may develop through time as a result of interactions with subsurface repository structures and the surrounding rock.[9]

Basaltic igneous events, like those that occurred in the geologic past in the Yucca Mountain region, can sustain weeks to years, and perhaps decades, of periodic activity. Subvolcanic conduits clearly evolve throughout the course of an eruption, because variations in mass flow result in wall-rock entrainment and conduit widening (Macedonio, et al., 1994; Valentine and Groves, 1996; Doubik and Hill, 1999). Models will need to evaluate the effects of sustained igneous activity on (i) changes in conduit geometry that could affect additional waste packages, (ii) strength of barriers restricting magma flow in drifts, and (iii) effects of sustained flow on waste package damage and waste entrainment (e.g., Woods, et al., 2001). In addition to the evolution of flow paths, DOE agreed to evaluate waste package response to a range of flow conditions that include pathways that may develop through drifts.[10]

The following is a summary evaluation for system description and model integration for the volcanic disruption of waste packages abstraction. The Disruptive Events Process Model Report and associated analysis and model reports (i.e., CRWMS M&O, 2000b–h) do not adequately consider the range of physical processes generally associated with igneous events. Ascending basaltic magmas must have a fluid pressure greater than lithostatic to dilate fractures significantly. DOE models that restrict magma flow to within a drift will need to evaluate the effects of this overpressure on structures or debris assumed to block drift ends. DOE models that propose stress reorientation and resulting dike deflection away from thermally loaded drifts will need to examine an appropriate range of stress-strain relationships rather than unbounded strain accumulation effects. The models presented to date do not adequately consider how the presence of subsurface repository structures may affect typical igneous processes. Repository drifts may localize magma flow significantly during the initial stages of a potential igneous event. This localization may force conduit development into drift areas and greatly restrict the ability of a conduit to form in the pillars. In addition, the continued path of magma ascent is poorly constrained and could range from the DOE model (e.g., CRWMS M&O, 2000h) to a model where magma is diverted down a number of drifts before resuming ascent (e.g., Woods and Sparks, 1998; Woods, et al., 2001). Magma

---

[9]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Igneous Activity (September 5, 2001)." Letter (September 12) to S. Brocoum, DOE. Washington, DC: NRC. 2001.

[10]Ibid.

diversion could disrupt a larger number of waste packages than currently modeled. The initial flow of magma into a drift likely will be rapid (i.e., Woods and Sparks, 1998; CRWMS M&O, 2000c). Modeling initial and sustained flow of magma through repository systems is complex but appears necessary to support DOE risk assessments. Based on agreements reached at the September 5, 2001, Technical Exchange on Igneous Activity, DOE has a reasonable path forward to address staff questions and uncertainties regarding the system description and model integration for volcanic disruption of waste package processes. With the exceptions already described, DOE models appear generally consistent with the types of igneous activity likely to occur in possible future Yucca Mountain region basaltic igneous events. Model assumptions are generally consistent with available data, but interrelationships between important processes need to be better described and justified in agreed-on investigations by DOE. For example, conduit development is a dynamic process that occurs throughout an igneous event (e.g., Woods, et al., 2001). Current models only evaluate the initial stages of conduit development and do not consider how magma flow paths may change during the course of a basaltic eruption in response to flow within the intersected drift system. These comments are supported by previous reviews and analyses conducted for the Igneous Activity Key Technical Issue (e.g., NRC, 1999).

3.3.10.4.2 Data Are Sufficient for Model Justification

Overall, the current information, along with agreements reached between DOE and NRC (Section 3.3.10.5), is sufficient to conclude that the necessary information will be available at the time of a potential license application to assess volcanic disruption of waste packages with respect to data being sufficient for model justification.

There are, however, few data used directly in the analysis of volcanic disruption of waste packages. Data for the physical and chemical characteristics of basaltic magmas used in CRWMS M&O (2000c,e) appear reasonable for evaluating volcanic disruption of waste package processes. The range and distribution of subvolcanic conduit dimensions in CRWMS M&O (2000e) also appear reasonable for basaltic cinder cone volcanoes. The number of conduits for each igneous event is derived from a generally reasonable interpretation of Yucca Mountain region volcano characteristics in CRWMS M&O (1996).

DOE has assembled sufficient information to support conclusions (CRWMS M&O, 2000d) that all waste package components fail when exposed to magma flowing in the subvolcanic conduit. Data are not available on the responses of proposed waste-package components to the physical and thermal conditions of an igneous event representative of the Yucca Mountain region. Internal pressurization analyses in CRWMS M&O (2000f) are combined with reasonable assumptions regarding dynamic stresses to conclude all waste packages in the subvolcanic conduit will fail (CRWMS M&O, 2000d). Scoping analyses presented in NRC (1999) also conclude that waste package failure is a reasonable assumption for the thermal, physical, and chemical conditions likely to occur in an erupting subvolcanic conduit. This assumption will not underestimate risk to public health and safety, and there are no alternative interpretations to available data that would indicate a greater level of risk. Staff recognize that a detailed engineering analysis has not been conducted for waste package performance during basaltic volcanic events. If the assumption of waste package failure during basaltic volcanic events is not used in future DOE models, DOE agreed to explicitly evaluate waste package response to stresses from thermal and mechanical effects associated with exposure to basaltic magma along relevant flow pathways.[11]

3.3.10.4.3 Data Uncertainty Is Characterized and Propagated Through the Model Abstraction

Overall, the current information, along with agreements reached between DOE and NRC (Section 3.3.10.5), is sufficient to conclude that the necessary information will be available at the time of a potential license application to assess volcanic disruption of waste packages with respect to data uncertainty being characterized and propagated through abstraction.

The number of waste packages directly intersected by a basaltic subvolcanic is calculated using a range of conduit characteristics summarized in CRWMS M&O (2000e,h). Current total system performance assessment models sample a range of conduit diameters and the number of conduits per igneous event. These parameter ranges appear reasonably consistent with the underlying technical basis (CRWMS M&O, 1996, 2000e). Using simple geometric relationships, models then calculate the number of waste packages intersected by each sampled conduit. The range sampled (CRWMS M&O, 2000a) for the number of waste packages entrained in the erupting conduit is the simple product of the number of waste packages intersected per conduit diameter and the number of conduits that form in each sampled event.

DOE performed only one sensitivity calculation in the Total System Performance Assessment–Site Recommendation relative to volcanic disruption of waste packages (CRWMS M&O, 2000a). Variations in the number of waste packages entrained in the erupting subvolcanic conduit (i.e., 6 at 5th percentile, 16 at 95th percentile) had a factor of 1.5 variation in probability-weighted dose. Based on this sensitivity, one order of magnitude increase in dose appears likely for one order of magnitude increase in the number of waste packages entrained in the eruptive subvolcanic conduit. Thus, the physical dimensions of the subvolcanic conduit in the presence of repository drifts are a critical parameter in postclosure performance.

3.3.10.4.4 Model Uncertainty Is Characterized and Propagated Through the Model Abstraction

Overall, the current information, along with agreements reached between DOE and NRC (Section 3.3.10.5), is sufficient to conclude that the necessary information will be available at the time of a potential license application to assess volcanic disruption of waste packages with respect to model uncertainty.

CRWMS M&O (2000c) presents a single conceptual model for the initial interaction between ascending magma and thermally loaded repository drifts. This model does not discuss how significant variations in repository design, including currently proposed design alternatives, can potentially affect the distribution of rock stress around repository drifts. Also not evaluated are

---

[11]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Igneous Activity (September 5, 2001)." Letter (September 12) to S. Brocoum, DOE. Washington, DC: NRC. 2001.

potentially significant variations in thermal loads from different waste-package inventories, which may produce significant differences in thermal expansion in affected subsurface rock. In addition, this model does not address uncertainties on how stress induced through differential thermal expansion may be accommodated through resulting strain on existing geologic structures or the formation of new strain accommodation structures. Each of these processes can affect how ascending magma interacts with the potentially disturbed zone of rock around repository drifts. CRWMS M&O (2000a) apparently does not take credit for dike deflection during the first 2000 years of postclosure (i.e., CRWMS M&O, 2000c). Acceptance of this model in future total system performance assessments requires DOE to address these significant model uncertainties. Agreed-on investigations by DOE should address these concerns with model uncertainties.[12]

CRWMS M&O (2000c) presents several alternative conceptual models for magma flow into open or backfilled drifts. The performance implications of these alternative models, however, are not discussed. For example, CRWMS M&O (2000c) discusses multiple flow modes that pyroclastic flows or liquid magma could follow, which result in different rates and extents of magma interactions within and between proposed repository drifts (i.e., Woods, et al., 2001). Only one of those models is evaluated within the Total System Performance Assessment–Site Recommendation: flow into and repressurization within each discretely intersected drift (CRWMS M&O, 2000a). A critical assumption for these flow models is that the ends of repository drifts are plugged by debris, which allows magmatic pressures to reestablish in the drifts (CRWMS M&O, 2000c). No technical basis is provided to demonstrate that debris plugs can withstand magmatic pressures of 3–7 MPa [435–1,015 psi] at representative magmatic temperatures, and alternatives to plugged drifts are not evaluated in CRWMS M&O (2000a,c,d). Although drifts may be plugged by debris immediately following initial flow of magma into a drift, debris plugs are not certain to form at the ends of drifts. In addition, the mechanical strength of anticipated debris plugs will need to be evaluated for the range of physical conditions associated with the duration of an igneous event. A reasonable alternative interpretation is that if debris plugs form, they may fail during repressurization of the magma-drift system in response to heating of the debris and the 3–7 MPa [435–1,015 psi] pressures within the magma system. Magma could then flow beyond directly intersected drifts, create additional locations where conduit formation may be favored, and affect a larger number of waste packages than are currently evaluated in CRWMS M&O (2000a,c,d,g). Agreed-on investigations by DOE, however, should resolve these concerns regarding alternative flow paths during potential igneous events.[13]

CRWMS M&O (2000c) concludes that debris-plugged drifts will fill with magma and reequilibrate with the pressure in the underlying magmatic system. Although some flow modes are thought to favor repropagation of the dike near the initial dike-drift intersection, other flow modes could establish vertical propagation anywhere along the drift roof where pressure in the magma system exceeds the pressure needed to fracture the roof rock (CRWMS M&O, 2000c;

---

[12]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Igneous Activity (September 5, 2001)." Letter (September 12) to S. Brocoum, DOE. Washington, DC: NRC. 2001.

[13]Ibid.

Woods, et al., 2001). This process could create a magma ascent path initially horizontal along some distance in the drift. Horizontal flow paths could be significantly longer than 150 m [492 ft], which is the maximum diameter of subvolcanic conduits, and thus entrain more waste packages than currently modeled in CRWMS M&O (2000a,c,d). Analyses presented in NRC (1999), Hill and Connor (2000), and Woods, et al. (2001) demonstrate that magma could ascend away from the point of initial dike-drift intersection. Although alternative flow-path models are presented in CRWMS M&O (2000c), the performance implications of these models have not been evaluated by DOE (CRWMS M&O, 2000a,d).

In summary, alternative conceptual models that are consistent with available information are not evaluated within the context of total system performance. Uncertainties with existing conceptual models are not quantified nor discussed, and the potential effects of these uncertainties are not evaluated in the Total System Performance Assessment–Site Recommendation. The staff anticipate that these alternative models will be evaluated as part of agreed-on investigations by DOE.

3.3.10.4.5 Model Abstraction Output Is Supported by Objective Comparisons

Overall, the current information, along with agreements reached between DOE and NRC (Section 3.3.10.5), is sufficient to conclude that the necessary information will be available at the time of a potential license application to assess volcanic disruption of waste packages with respect to model abstraction output being supported by objective comparisons.

Models relevant to volcanic disruption of waste packages in CRWMS M&O (2000a–h) have not been compared with detailed process-level models, appropriate laboratory or field tests, or natural analogs. Models for the flow of magma into repository drifts (CRWMS M&O, 2000c) are critically dependent on sustaining a debris plug at the end of each intersected drift. The abstracted models used to calculate pressures in the magma-drift system will need to be supported acceptably, in conjunction with an analysis of debris-plug strength, before magma flow can be modeled as wholly restricted to within an intersected drift. Models that presume the location and geometry of subvolcanic conduits are not significantly influenced by the presence of repository drifts (CRWMS M&O, 2000c,h) also will need support through detailed process-level models. Potential inconsistencies between the abstracted models and comparative data need to be explained and quantified, and the resulting uncertainties will need to be included in total system performance assessment model results.

3.3.10.5 Status and Path Forward

The Igneous Activity Key Technical Issue Consequences Subissue relating to Volcanic Disruption of Waste Packages is considered closed-pending at the staff level. Status of subissue closure is provided in Table 1.1-3. A consolidated list of all DOE and NRC agreements relevant to the Volcanic Disruption of Waste Packages Integrated Subissue is given in Table 3.3.10-1 and Appendix A. In summary, alternative interpretations of available data have potentially significant effects on postclosure risk calculations, and current DOE risk calculations (CRWMS M&O, 2000a; Bechtel SAIC Company, LLC, 2001a) likely underestimate the risk from volcanic igneous activity. Reports revised after the August 2000 Technical Exchange on Igneous Activity (CRWMS M&O, 2000c,d,g; Bechtel SAIC Company, LLC, 2001b) have not addressed staff concerns related to the processes of magma-repository interactions. Agreements reached at the September 2001 Technical Exchange on Igneous Activity present a reasonable path forward for DOE to obtain needed data and to conduct additional analyses that would meet current acceptance criteria prior to any potential license application. The Volcanic Disruption of Waste Packages Integrated Subissue thus is considered closed-pending.

The staff have discussed the technical basis for their concerns with DOE at an Appendix 7 meeting in Las Vegas, Nevada, on May 18, 2001, and at formal technical exchanges on June 21–22, 2001, and September 5, 2001. Movement of this issue from closed-pending to closed status will require completion of the agreed-on investigations by DOE and successful review of these investigations by NRC staff. DOE may also chose to address these agreements by using consistent, reasonably conservative assumptions in deterministic analyses for volcanic disruption of waste packages.

Table 3.3.10-1. Related Key Technical Issue Subissues and Agreements

Key Technical Issue	Subissue	Status	Related Agreements*
Igneous Activity	Subissue 1—Probability of Igneous Activity	Closed-pending	IA.1.01 IA.1.02
	Subissue 2—Consequences of Igneous Activity	Closed-pending	IA.2.05 IA.2.10 IA.2.18 IA.2.19 IA.2.20
Container Life and Source Term	Subissue 2—Mechanical Disruption of Waste Packages	Closed-pending	CLST.2.10 CLST.2.19
Total System Performance Assessment and Integration	Subissue 1—System Description and Demonstration of Multiple Barriers	Closed-pending	None
	Subissue 2—Scenario Analysis and Event Probability	Closed-pending	None
	Subissue 3—Model Abstraction	Closed-pending	TSPAI.2.02
	Subissue 4—Demonstration of Compliance with the Postclosure Public Health and Environmental Standards	Closed-pending	None

*Related DOE and NRC agreements are associated with one or all five generic acceptance criteria.

NOTE: Key Technical Issue Agreement GEN. 1.01 pertains to multiple integrated subissues, as well as some specific issues related to this integrated subissue

3.3.10.6 References

Baer, G. and Z. Reches. "Mechanics of Emplacement and Tectonic Implications of the Ramon Dike Systems, Israel." *Journal of Geophysical Research*. Vol. 96. No. B7. pp. 11,895–11,910. 1991.

Bechtel SAIC Company, LLC. "FY01 Supplemental Science and Performance Analyses." Vol. 2: Performance Analyses. TDR–MGR–PA–000001. Revision 00. Las Vegas, Nevada: Bechtel SAIC Company, LLC. 2001a.

———. "FY01 Supplemental Science and Performance Analyses." Vol. 1: Scientific Bases and Analyses. TDR–MGR–MD–000007. Revision 00 ICN 01. Las Vegas, Nevada: Bechtel SAIC Company, LLC. 2001b.

Bokhove, O. and A.W. Woods. "Explosive Magma-Air Interactions by Volatile-Rich Basaltic Melts in a Dike-Drift Geometry." San Antonio, Texas: CNWRA. 2000.

Bruce, P.M. and H.E. Huppert. "Thermal Control of Basaltic Fissure Eruptions." *Nature*. Vol. 342. pp. 665–667. 1989.

———. "Solidification and Melting Along Dykes by the Laminar Flow of Basaltic Magma." *Magma Transport and Storage*. M.P. Ryan, ed. Chichester, England: John Wiley & Sons. pp. 87–101. 1990.

CRWMS M&O. "Probabilistic Volcanic Hazards Analysis for Yucca Mountain, Nevada." BA0000000–1717–2200–00082. Revision 00. North Las Vegas, Nevada: DOE, Yucca Mountain Site Characterization Office. 1996.

———. "Total System Performance Assessment for the Site Recommendation." TDR–WIS–PA–000001. Revision 00 ICN 01. North Las Vegas, Nevada: DOE, Yucca Mountain Site Characterization Office. 2000a.

———. "Disruptive Events Process Model Report." TDR–NBS–MD–000002. Revision 00 ICN 01. North Las Vegas, Nevada: DOE, Yucca Mountain Site Characterization Office. 2000b.

———. "Dike Propagation Near Drifts." ANL–WIS–MD–000015. Revision 00 ICN 01. North Las Vegas, Nevada: DOE, Yucca Mountain Site Characterization Office. 2000c.

———. "Igneous Consequence Modeling for the Total System Performance Assessment–Site Recommendation." ANL–WIS–MD–000017. Revision 00 ICN 01. North Las Vegas, Nevada: DOE, Yucca Mountain Site Characterization Office. 2000d.

———. "Characterize Eruptive Processes at Yucca Mountain, Nevada." ANL–MGR–GS–000002. Revision 00. North Las Vegas, Nevada: DOE, Yucca Mountain Site Characterization Office. 2000e.

———. "Waste Package Behavior in Magma." CAL–EBS–ME–000002. Revision 00. North Las Vegas, Nevada: DOE, Yucca Mountain Site Characterization Office. 2000f.

———. "Number of Waste Packages Hit by Igneous Intrusion." CAL–WIS–PA–000001. Revision 01. North Las Vegas, Nevada: DOE, Yucca Mountain Site Characterization Office. 2000g.

———. "Characterize Framework for Igneous Activity at Yucca Mountain, Nevada." ANL–MGR–GS–000001. Revision 00 ICN 01. North Las Vegas, Nevada: DOE, Yucca Mountain Site Characterization Office. 2000h.

———. "Repository Safety Strategy: Plan to Prepare the Safety Case to Support Yucca Mountain Site Recommendation and Licensing Considerations." TDRL–WIS–RL–000001. Revision 04. Las Vegas, Nevada: CRWMS M&O. 2000i.

Delaney, P.T. and D.D. Pollard. "Solidification of Basaltic Magma During Flow in a Dike." *American Journal of Science*. Vol. 282. pp. 856–885. 1982.

Delaney, P.T., D.D. Pollard, J.I. Ziony, and E.H. McKee. "Field Relations Between Dikes and Joints: Emplacement Processes and Paleostress Analysis." *Journal of Geophysical Research*. Vol. 91. No. B5. pp. 4,920–4,938. 1986.

DOE. "Viability Assessment of a Repository at Yucca Mountain." Overview and all five volumes. DOE/RW–0508. Las Vegas, Nevada: DOE, Office of Civilian Radioactive Waste Management. 1998.

Doubik, P. and B.E. Hill. "Magmatic and Hydromagmatic Conduit Development During the 1975 Tolbachik Eruption, Kamchatka, with Implications for Hazards Assessment at Yucca Mountain, Nevada." *Journal of Volcanology and Geothermal Research*. Vol. 91. pp. 43–64. 1999.

Fedotov, S.A., A.M. Chirkov, and A.A. Razina. "Northern Breakout." *Large Tolbachik Fissure Eruption, Kamchatka 1975–1976*. S.A. Fedotov, ed. Moscow, Russia: Science. pp. 11–74. 1984.

Hill, B.E. and C.B. Connor. "Technical Basis for Resolution of the Igneous Activity Key Technical Issue." San Antonio, Texas: CNWRA. 2000.

Huppert, H.E. and R.S.J. Sparks. "Cooling and Contamination of Mafic and Ultramafic Magmas During Ascent Through Continental Crust." *Earth and Planetary Science Letters*. Vol. 74. pp. 371–386. 1985.

Macedonio, G., F. Dobran, and A. Neri. "Erosion Processes in Volcanic Conduits and Application to the AD 79 Eruption of Vesuvius." *Earth and Planetary Science Letters*. Vol. 121. pp. 137–152. 1994.

Morris, A., D.A. Ferrill, and D.B. Henderson. "Slip-Tendency Analysis and Fault Reactivation." *Geology*. Vol. 24. No. 3. pp. 275–278. 1996.

NRC. "Issue Resolution Status Report, Key Technical Issue: Igneous Activity." Revision 2. Washington, DC: NRC. 1999.

———. "Issue Resolution Status Report, Key Technical Issue: Total System Performance Assessment and Integration." Revision 3. Washington, DC: NRC. 2000.

———. NUREG–1804, "Yucca Mountain Review Plan—Draft Report for Comment." Revision 2. Washington, DC: NRC. March 2002.

Rogers, R.D. and D.K. Bird. "Fracture Propagation Associated with Dike Emplacement at the Skaergaard Intrusion, East Greenland." *Journal of Structural Geology*. Vol. 9. No. 1. pp. 71–86. 1987.

Rubin, A.M. "Tensile Fracture of Rock at High Confining Pressure: Implication for Dike Propagation." *Journal of Geophysical Research*. Vol. 98. pp. 15,919–15,935. 1993.

Thorarinsson, S., S. Steinthórsson, Th. Einarsson, H. Kristmannsdóttir, and N. Oskarsson. "The Eruption on Heimaey, Iceland." *Nature*. Vol. 241. pp. 372–375. 1973.

Valentine, G.A. and K.R. Groves. "Entrainment of Country Rock During Basaltic Eruptions of the Lucero Volcanic Field, New Mexico." *Journal of Geology*. Vol. 104. pp. 71–90. 1996.

Woods, A.W. and R.S.J. Sparks. "Report on Scoping Calculations for Magma-Repository Interaction at Yucca Mountain, Nevada." San Antonio, Texas: CNWRA. 1998.

Woods, A.W., S. Sparks, O. Bokhove, A-M. LeJeune, C.B. Connor, and B.E. Hill. "Modeling the Explosive Eruption of Basaltic Magma into the Proposed High-Level Radioactive Waste Repository at Yucca Mountain, Nevada, U.S.A." San Antonio, Texas: CNWRA. 2001.