1/18

REVIEW OF THE SATURATED ZONE FLOW AND TRANSPORT MODELS USED TO SUPPORT THE VIABILITY ASSESSMENT OF THE PROPOSED HIGH-LEVEL WASTE REPOSITORY AT YUCCA MOUNTAIN

Prepared for

Nuclear Regulatory Commission
Contract NRC-02-97-009

Prepared by

Amit Armstrong
David Farrell
Scott Painter
David Turner

Center for Nuclear Waste Regulatory Analyses
San Antonio, Texas

March 1999

2/18

ABSTRACT

In this report the Saturated Zone Flow and Transport Models used in the viability assessment (VA) of a repository at Yucca Mountain are reviewed. This review focuses on the applicability of these models, with the inherent assumptions, to the Total System Performance Assessment (TSPA) of the repository. It is acknowledged that the U.S. Department of Energy is continuously evolving new approaches for modeling. This report presents a review of work that is used for VA only. The areas of review covered under this report include regional saturated zone flow modeling, site-scale flow and transport modeling, and parameter uncertainty and sensitivity analyses. A brief discussion is also provided in each section to list technical concerns and ways to resolve them.

Many of the modeling studies reviewed in this report are either preliminary or are work in progress and are currently being refined. The regional groundwater flow model of the Death Valley area, as reviewed in this report, raised many technical concerns regarding lack of hydrogeologic field data, coarseness of the grid, and inadequate calibration. The effect of climate change on the regional flow is not reasonably bounded. The main technical concerns raised during the review of site-scale groundwater flow modeling studies include poor definition of boundary conditions, inadequate calibration, and large data gaps in hydrogeologic framework model. Review of TSPA-VA flow and transport simulations suggested that use of dilution factor approach is not supported by the rigorous analyses. The sensitivity analyses performed during TSPA-VA did not show any sensitivity to the saturated zone flow and transport parameters. Concerns are also raised about the lack of heterogeneities and numerical dispersion in the models. The current understanding of radionuclide sorption and retardation in alluvium is not sufficiently supported by field data. The uncertainty regarding degree of irreversible sorption onto natural colloids still exists.

CONTENTS

CONTENTS (cont'd)

4/18

TABLES

5/18

ACKNOWLEDGMENTS

This report was prepared to document work performed by the Center for Nuclear Waste Regulatory Analyses (CNWRA) for the Nuclear Regulatory Commission (NRC) under Contract No. NRC-02-97-009. The activities reported here were performed on behalf of the NRC Office of Nuclear Material Safety and Safeguards, Division of Waste Management. The report is an independent product of the CNWRA and does not necessarily reflect the views or regulatory position of the NRC.

The authors thank Mr. Neil Coleman of the Nuclear Regulatory Commission for providing a thorough technical review, Dr. Budhi Sagar for programmatic review, and Ms. Bonnie Caudle for format review; and the authors also wish to thank Ms. Barbara Long for editorial support and Ms. Roseanne Ard for providing secretarial support.

QUALITY OF DATA AND CODE DEVELOPMENT

DATA: There are no original CNWRA-generated data contained in this report. All Data used to support conclusions in this report are taken from documents published by U.S. Department of Energy (DOE) contractors and supporting organizations who operate under the quality assurance (QA) program developed for the Yucca Mountain Project. The reader should refer to data source documents, referenced throughout this report, to determine data QA status.

CODE: There are no computer codes used to prepare this report.

1 INTRODUCTION

The U.S. Department of Energy (DOE) issued the viability assessment (VA) of the repository at Yucca Mountain (YM) (U.S. Department of Energy, 1998) in December 1998. This multi-volume document includes a total system performance assessment (TSPA) of the proposed repository at YM, referred to hereafter as TSPA-VA. This report reviews the various saturated zone (SZ) flow and transport models used in the TSPA-VA and supporting technical basis for them. The various SZ reports reviewed here are individually listed in table 1-1.

The refinement of the regional flow model and the site-scale flow and transport models is currently ongoing and this review is limited only to the documents listed in table 1-1. The SZ flow/transport and biosphere workshops at Albuquerque, New Mexico (U.S. Department of Energy, 1999a) discussed new directions that DOE is likely to adopt in the future to resolve some of the areas of concern raised in this report.

The supporting documents for the TSPA-VA (U.S. Department of Energy, 1998) and the Technical Basis Document (Civilian Radioactive Waste Management System, Management & Operating Contractor, 1998) provide a complete and well-written description of modeling and analyses. This review will focus on critically examining the applicability and appropriateness of the key assumptions and parameters. Specific comments have also been developed with regard to the conceptual models. The continuing work by DOE will provide additional information to fill some data gaps, adequately modify the conceptual models, and provide site-specific data for some key parameters. The documents reviewed in this report cover a number of key technical issues (KTI). The SZ flow is reviewed predominantly under the Unsaturated and Saturated Flow Under Isothermal Conditions KTI, however, support from the Structural Deformation and Seismicity (SDS) KTI was solicited to address uncertainty in structural control on SZ flow and from the Radionuclide Transport (RT) KTI to address the uncertainties associated with RT parameters, including colloidal transport. The input provided by the RT and SDS KTIs is included to provide a complete and integrated review but detailed description of these issues may be found in the respective Issue Resolution Status Reports.

Table 1.1. List of documents reviewed

Review Topic	Key Supporting Documents
Regional Saturated Zone Flow Modeling	D'Agnese et al., 1997a,b; Civilian Radioactive Waste Management System, Management & Operating Contractor, 1998; U.S. Department of Energy, 1998
Site-Scale Flow and Transport Modeling	Czarnecki et al., 1997; Zyvoloski et al., 1997; Civilian Radioactive Waste Management System, Management & Operating Contractor, 1998; U.S. Department of Energy, 1998
Parameter Uncertainty and Sensitivity Analyses	Civilian Radioactive Waste Management System, Management & Operating Contractor, 1998; U.S. Department of Energy, 1998

7/18

2 REGIONAL SATURATED ZONE FLOW MODEL

2.1 U.S. GEOLOGICAL SURVEY REGIONAL SATURATED ZONE FLOW MODEL

A study of the regional groundwater flow for Death Valley was undertaken by the U.S. Geological Survey (USGS). The objectives of this study was to estimate aquifer parameters, provide boundary conditions for a site-scale model, and estimate the water budget. D'Agnese et al. (1997a) modeled an area of 100,000 km^2 using MODFLOWP (Hill, 1992), a three-dimensional (3D) finite difference mathematical model with nonlinear least square regression for parameter estimation. This regional model is based on a 3D hydrologic framework model, geologic maps and cross sections, and lithologic well logs. The hydrologic framework model provides a description of the geometry, composition, and hydraulic properties of the materials that control the regional groundwater flow system. Most surface recharge to the regional flow system occurs at high altitude where precipitation is much greater than at lower altitudes. Discharge from the groundwater system mainly occurs through evapotranspiration, spring discharges, and well pumping. The water budget for the regional system suggests that the outflow exceeds inflow. This can be attributed to the poor definition of the discharge volume, specifically pumping. D'Agnese et al. (1997a) also surmised the Death Valley system to be an open system and used interbasinal transfer of water in the deeper Paleozoic system to achieve a water balance during the modeling.

The regional system was modeled by using a 3D steady-state simulation using a finite difference grid consisting of 163 rows, 153 columns, and 3 layers. The grid cells were oriented north-south and of uniform size: 1,500 × 1,500 m. The three layers occurred at the following intervals below the water table: 0–500 m, 500–1,250 m, and 1,250–2,750 m. This simulation exercise supported the analyses of interactions between the relatively shallow local and subregional flow paths and the deeper regional flow paths controlled by the carbonate aquifer. A series of conceptual models was evaluated to test the validity of various interpretations about the flow system. The conceptual model providing the best fit during the calibration exercise was retained as the final optimized model. This final model showed water balance discrepancy (117,100 m^3/d) and high head residuals (up to 300 m).

The boundaries selected for the flow system were modified from Wadell et al. (1984), Harrill et al. (1988), and Bedinger et al. (1989). Most system boundaries were no-flow boundaries. However, inflows to the model may occur from Pahranagat Valley, Sand Springs Valley, Railroad Valley, Stone Cabin Valley, Ralston Valley, Fish Lake and Eureka Valley, Saline Valley, Panamint Valley, Pilot Knob Valley, and Soda Lake Valley. The flux estimate for Pahranagat Valley is 20,000 m^3/d (Winograd and Friedman, 1972). No estimate is available for the other inflows. The Death Valley regional system was modified and divided into three major subregional flow systems: Northern Death Valley, Central Death Valley, and Southern Death Valley. There is, however, evidence of groundwater flow across the subregional boundaries. In each subregion, the flow paths are grouped in groundwater basins containing various groundwater sections. The Northern Death Valley subregion was divided into four dominant groundwater sections: Lida-Stonewall, Sarcobatus Flats, Grapevine Canyon, and Oriental Wash. The Central Death Valley subregion was divided in three groundwater basins: Pahute Mesa-Oasis Valley, Ash Meadows, and Alkali Flat-Furnace Creek. The Southern Death Valley subregion was divided into four groundwater sections: Pahrump Valley, Shoshone-Tecopa, California Valley, and Ibex Hills.

During the study, numerous conceptual models were evaluated to test the validity of various flow system interpretations. These conceptual models were tested for (i) the location and type of flow system boundaries, (ii) the extent and location of recharge areas, and (iii) the configuration of the hydrogeologic framework model. The conceptual model changes that produced a significant improvement in flow model results were incorporated into the final model. Model calibration was performed by estimating 18 parameters. During calibration, however, some of the parameters were lumped together. After calibration, the model was evaluated by comparing the measured values with the simulated values. The comparison included hydraulic heads and spring flows; hydraulic conductivities, vertical anisotropy, and infiltration; and water budgets. The residuals for hydraulic heads showed a good match (~ 20 m) with observed heads in some areas of flat hydraulic gradient; however, a more moderate match (~ 20–60 m) dominated the flat hydraulic gradient area. Poor match (>60 m) to observed heads was simulated in the large hydraulic gradient areas. The simulated spring flows were generally lower than the observed flows. Evaluation of estimated parameters indicated that the values of hydraulic conductivity, vertical anisotropy, and recharge rates were all within expected range. The model simulation also indicated a reasonable water budget for the system. The model errors were attributed to coarse vertical discretization of the system and non-random distribution of weighted residuals of hydraulic head and spring flow. It was surmised that further calibration of the system will provide improved accuracy in model prediction. This model is currently being refined to incorporate a higher vertical resolution with 16 hydrostratigraphic layers and a better representation of structural features.

2.1.1 Climatic Effects on Regional Model

Another study (D'Agnese et al., 1997b) was undertaken to estimate the effects of future climates on the regional groundwater flow system. The effects of climate change on Death Valley groundwater flow system were simulated using the regional groundwater flow model (D'Agnese et al., 1997a). Climate change was implemented in the groundwater flow model by changing the distribution of recharge. Two simulations were performed to simulate the effects of full glacial conditions using climate conditions approximately 21,000 yr ago and global warming using climatic conditions in the future representing a doubling of atmospheric CO_2 concentration. The climate scenarios were simulated by the National Center for Atmospheric Research modeling approach, which is based on a nested global circulation model (GCM) and a regional climate model (RCM). The future climate scenario suggested that the atmospheric CO_2 concentration will double in the next 100 yr. The future climate scenario resulted in temperature increases of 2–3 °C.

In the past climate simulation, the water levels rose over the entire model domain due to increased recharge rates. The water levels rose significantly beneath areas of higher elevations due to a greater increase in recharge in these areas, and the large hydraulic gradients became more pronounced. The simulated recharge over the region increased five-fold relative to present-day recharge. The simulated water levels near YM were generally 60–150 m higher than the present-day levels. Simulated groundwater flux beneath YM increased by a factor of about 4 relative to present-day conditions. The most dramatic increase, on the order of about 500 m, occurred in the Timber and Shoshone Mountain areas. Even with these large changes in the water levels, the shape of the potentiometric surface did not change substantially. The potentiometric surface downgradient of YM was generally the same in past and present climate scenarios, suggesting that SZ flow paths will not change under full glacial conditions. No particle tracking simulations were performed to define the flow paths. The simulated water budget indicated that the model was close to being in balance, and the recharge accounted for 97 percent of water entering the system. The rest of the water entered the system as underflow via constant head cells on the northern boundary.

In the future climate scenario, the potentiometric surface rose less than 100 m in most of the model domain. Simulated water levels in parts of Amargosa Valley, Amargosa River Drainage, and Death Valley were equal to or lower than present-day conditions. At YM, the water levels rose less than 50 m in this scenario. Again, the largest increase in water levels was in the Timber and Shoshone Mountain areas. The potentiometric surface configuration was much similar to present-day conditions. Although no particle tracking simulations were performed, based on the potentiometric surface it appears that the flow paths will not change in the future climate scenario.

Due to inherent limitations imposed by modeling assumptions and the coarse grid of RCM and GCM, the simulated effects of climate change should be considered conceptual in nature.

2.2 TOTAL SYSTEM PERFORMANCE ASSESSMENT FOR THE VIABILITY ASSESSMENT APPROACH

The regional scale flow modeling results were used in the TSPA-VA (U.S. Department of Energy, 1998) and the Technical Basis Document (Civilian Radioactive Waste Management System, Management & Operating Contractor, 1998) to provide groundwater flux multipliers for the long-term average and super-pluvial climatic conditions. These groundwater flux multipliers were used to calculate the groundwater flux for each of climate states relative to present-day conditions.

2.3 TECHNICAL CONCERNS

The reviewers have the following technical concerns about the regional SZ flow model and its applicability to the TSPA-VA SZ flow model.

- The hydrogeologic framework model does not have sufficient information on the hydrogeology of the area downgradient of YM due to lack of borehole and geophysical information. This is an important data gap from the perspective of the repository program.

- The spatial resolution, both vertical and horizontal, of the regional flow model is not fine enough to incorporate the effects of structural features, flow channelization, and permeability contrast. The three-layer model was not sufficient to represent the various hydrostratigraphic layers identified in the YM vicinity.

- The regional flow model is not adequately calibrated as suggested by large hydraulic head residuals and a large range of estimated parameter values.

- The effects of climate change on the regional flow are not reasonably bounded. As the regional flow models assume the top layer as a confined layer to attain computational efficiency, the rise in water levels by 60–150 m does not produce any change in flow direction. If the water table is modeled as a phreatic surface, the rise in water levels will certainly cause the simulated water table to be in a different hydrostratigraphic layers and the property of these layers will affect the flow direction and magnitude.

Similar concerns about model calibration, definition of boundary conditions, and sparseness of data in the regional model were raised also by the SZ Expert Elicitation (SZEE) Panel (Geomatrix, 1998), U.S. Nuclear Waste Technical Review Board (1998), and the Performance Assessment Peer Review (PAPR) Panel (U.S. Department of Energy, 1999b).

2.4 PATHS TO RESOLUTION

The technical concerns can be addressed through the following paths.

- The hydrogeology framework model needs to be updated to fill the large data gaps south of YM. Also, the vertical resolution of the framework model needs refinement to include all identified hydrostratigraphic layers in the vicinity of YM.

- Both the horizontal and vertical resolution of the regional flow model should be refined. A variable grid spacing in the horizontal direction can incorporate the structural features (e.g., Solitario Canyon fault), focused recharge, and permeability contrasts. The number of layers should be increased to better differentiate between the aquifer and the confining units. Also, the model should incorporate horizontal and vertical anisotropy.

- Further calibration of the regional flow model should be performed to better watch the range of estimated parameters with observed values and reduce the hydraulic head residuals.

- For the climate change effects on regional flow, the top layer of the model should be treated as unconfined, and the water table should not be used as the top boundary. This can be achieved by performing simulations with a phreatic surface or by pseudo steady-state simulations. Additionally, the DOE can also show that the water table rise will be conservative due to an increase in alluvial flow path.

3 SITE-SCALE SATURATED ZONE FLOW AND TRANSPORT MODELING

3.1 SITE-SCALE SATURATED ZONE FLOW MODEL

The site-scale flow model was developed by USGS (Czarnecki et al., 1997). This steady-state numerical model covered an area approximately 1,350 km^2 (30 × 45 km) over a saturated thickness of about 1,500 m. The specific objectives of this model were (i) to estimate groundwater flow direction and magnitude from the repository to the accessible environment, (ii) to characterize the complex 3D behavior of flow through heterogeneous media, and (iii) to identify the potential role of faults in groundwater flow. The transport results from this modeling study (Czarnecki et al., 1997) were not directly used in the TSPA-VA for various reasons listed in the Technical Basis Document (Civilian Radioactive Waste Management System, Management & Operating Contractor, 1998).

The model grid was based on a digital hydrogeologic framework model and sampled at 1,500 × 1,500 m with variable thickness. The 3D model domain was discretized in a tetrahedral finite element mesh consisting of 9,279 nodes and 51,461 elements with 16 layers representing different hydrogeologic units. The faults were not incorporated as distinct hydrologic features. Only the top two layers were selected from the regional model. Flow simulations were performed using the Finite Element Heat Mass Nuclear (FEHMN) groundwater flow and transport code. Calibration of the flow model was performed with the Parameter ESTimation (PEST) code. The constant head boundary condition was derived from the regional model of D'Agnese et al. (1997a). The results from the flow simulations are presented by Czarnecki et al. (1997). Results from the transport simulations are presented by Zyvoloski et al. (1997). The transport simulations, are not reviewed here because they are not directly used in the TSPA-VA (U.S. Department of Energy, 1998).

The site-scale model assumed constant head along all four boundaries. The constant head values for the boundary were obtained from the regional flow model (D'Agnese et al., 1997a). No flow was assumed from the lower boundary of the model, whereas, the upper boundary of model, (i.e., the water table) received recharge along the upper reaches of Fortymile Wash. The large hydraulic gradient was simulated by incorporating a low permeability fault. The moderate hydraulic gradient was similarly simulated by incorporating a low permeability fault. Recharge due to infiltration was not applied in this model, and no pumpage was assumed in the model domain.

Model calibration was performed by an automated parameter estimation method to match the observed hydraulic heads at 94 locations by varying selected permeability values. During calibration, it was indicated that the available data were not sufficient to estimate all parameters individually. The hydrogeologic units with similar permeability values were lumped to minimize the number of estimated parameters. For various combinations of fixed and estimated parameters, 40 PEST runs were completed.

The simulation results suggest that the model performed optimally when the low permeability barriers were added corresponding to the Solitario Canyon fault and the downgradient side of the large hydraulic gradient, and also when the permeability of upper volcanic confining units was varied. The optimized model produced hydraulic head residuals in the range of −5 to +5 m. A greater disparity was noticed in flux across the model boundaries when compared with the regional model. Comparison between site-scale and regional models showed almost twice the amount discharging from the southern end of the site model and substantially different amounts for the north and east sides. It was suggested that the major flux difference between the two models at the northeast corner of the site model is due to recharge from the north that is diverted east and discharges in part because of the interaction of constant head boundaries and the low permeability east-west barrier representing the large hydraulic gradient.

Although the preliminary results provide a good fit with the measured head values, the permeability values used to attain this good fit show a large range for each aquifer, especially for the middle volcanic aquifer, where the value used to fit the model is three orders of magnitude smaller than the values reported for the C-Well complex. The authors attributed this to model error or to a local, large-permeability zone, which was not represented in the model, near the C-Well complex.

The major assumptions of the site-scale flow model include (i) bulk permeability is uniform within each hydrogeologic unit, (ii) the flow system is at steady state, (iii) the SZ can be represented as a single continuum, and (iv) the groundwater flow system is isothermal at 44 °C. Use of this model is limited to provide a large-scale description of the hydrogeologic framework of the SZ flow system, provide the flow field to perform preliminary transport simulations and estimate groundwater velocities, and provide initial estimates of permeability for the 16 hydrogeologic units and the recharge from Fortymile Wash. Due to inadequate calibration, the authors listed the following limitations for the model.

- Simulations are restricted to fully saturated conditions from the water table and below.
- The model does not account for the variations in temperature within the flow system.
- It is likely the flow model is nonunique.
- The large hydraulic gradient is poorly understood and greatly affects model calibration, simulated permeability values, and flux.
- Flux into the site model domain is poorly defined.
- Limited hydraulic test data exist for constraining permeability values used in the model.
- Definition of the hydrogeologic units within the model is limited by the sampling interval.

The authors suggested numerous ways to improve the model: (i) conduct sensitivity studies to identify the parameter having the greatest effect on the sum of the squared residuals for head; (ii) refine the hydrogeological framework model; (iii) use higher resolution sampling; (iv) use faults explicitly as surfaces; (v) use additional hydrochemical, flux, and isotopic data for model calibration; and (vi) include vertical flux through the bottom of the model.

3.2 TOTAL SYSTEM PERFORMANCE ASSESSMENT FOR THE VIABILITY ASSESSMENT APPROACH TO SATURATED ZONE FLOW AND TRANSPORT

The TSPA 3D SZ flow model was developed using FEHMN with a model domain of about 20 × 36 km to a depth of 950 m below the water table (Civilian Radioactive Waste Management System, Management & Operating Contractor, 1998). The model domain was discretized into a uniform orthogonal mesh with 500 × 500 × 50 m elements. The model was based on a refined hydrogeologic framework model used by D'Agnese et al. (1997a). A total of 16 hydrogeologic units were represented as homogeneous and isotropic. The large and moderate hydraulic gradients were represented by three linear vertical features with low permeability. The SZ flow was modeled as steady state. The focused recharge along Fortymile Wash was included as specified flux, and the specified pressure boundaries were applied to the lateral boundaries. The no-flow boundary was assigned to the bottom of the model domain. The model simulations were performed with isothermal conditions and uniform permeability for each hydrogeologic layer.

The trial and error calibration was performed to compare simulated hydraulic heads with observed hydraulic heads. In general, there was good agreement between simulated and observed heads and the head residual was about 2 m along the potential flowpaths down gradient of the repository. The simulated direction of groundwater flow was also consistent with the conceptual model of SZ as suggested by the regional and site-scale flow modeling. Solute transport simulations indicated an average simulated Darcy velocity of 0.61 m/yr along the flow path matching the 0.6 m/yr, as suggested by SZEE. A particle tracking simulation was used to estimate the flowpath lengths in the SZ through each of the hydrogeologic units downstream from the repository. The flow was mostly in the four hydrogeologic units: upper volcanic aquifer, middle volcanic aquifer, middle volcanic confining units, and alluvium/undifferentiated valley fill. The streamtubes generated by particle tracking simulations were used for the one-dimensional (1D) transport simulations.

The TSPA 1D transport model was developed to generate the radionuclide concentration breakthrough curves for the TSPA-VA analyses using FEHMN. The 1D approach eliminated the transverse dispersion inherent in the 3D approach due to coarse gridding. The longitudinal and transverse dispersion was included in the model as a postprocessing step in the form of a dilution factor. Flow and transport occurred in the six 20-km-long streamtubes, which are about 3,000 m in width and 10–20 m in depth. The volumetric flow rate of each streamtube was determined at the water table from the unsaturated zone (UZ) site-scale model (Bodvarsson et al., 1997). The Darcy velocity into each streamtube was 0.6 m/yr under current climatic conditions. The cross-sectional area of each streamtube was proportional to the volumetric groundwater flow rate. The transport simulations were performed with a 5-m grid spacing in the streamtubes and a steady, unit radionuclide mass source at the upstream end of the streamtube. Nine radionuclides were simulated separately.

A convolution integral method, assuming linear system behavior and steady-state flow system, was used to determine the concentration of each of the radionuclides in the SZ at the receptor locations. This method provides an approximation of the transient radionuclide concentration at a specific point down gradient in the SZ in response to the transient radionuclide mass flux from transport in the UZ (Civilian Radioactive Waste Management System, Management & Operating Contractor, 1998). This computationally efficient method makes full use of a single detailed transport realization for all subsequent TSPA-VA realizations. The input to the convolution integral approach includes a unit concentration breakthrough curve in response to a step-function mass flux source as simulated by the SZ flow and transport model and the radionuclide mass flux history as simulated by the UZ transport model (Civilian Radioactive Waste Management System, Management & Operating Contractor, 1998). The effects of varying climatic conditions on RT were incorporated in the convolution integral simulations by varying the magnitude of groundwater flux and assuming there is an instantaneous change from one steady state to another due to climate change scenarios. The multiclimate convolution code was verified against a 3D SZ transport simulation using FEMHN, and the results compared well.

3.3 ALTERNATIVE CONCEPTUAL MODELS

There are no alternative conceptual models for the site-scale SZ flow model, however, the NRC Total-System Performance Assessment (TPA) Version 3.2 code uses the saturated zone flow and transport (SZFT) module to perform SZ flow and transport modeling. A brief discussion of this module is provided here and a complete description is provided in the NRC report (1998). The SZFT module describes RT in the SZ from the location where radionuclides enter the water table beneath the repository to a receptor location. The SZ transport model consists of an array of 1D streamtubes originating at the water table below the repository and terminating at a receptor location. RT in the SZFT module is simulated using the NEFTRAN II code (Olague et al., 1991), which calculates the radionuclide release rate (Ci/yr) at the down-gradient receptor location. In the SZFT module, there are a number of SZ streamtubes each connecting to one or more UZ streamtubes.

The steady-state velocity field used in the SZFT module for the SZ region from below the repository to the receptor location is abstracted from a detailed two-dimensional (2D) model (Baca et al., 1996). The abstraction is made by constructing four streamtubes that emanate from the vertical projection of the repository lateral boundary onto the water table and terminate at the appropriate receptor location. Differences in the mean travel time along each of the four streamtubes arise from differences in streamtube length and the sampled values of effective porosity for the tuff and alluvium units.

The boundaries of the detailed 2D model from which the four streamtubes were abstracted are based in part on information from the 2D, subregional flow model developed by Czarnecki and Waddell (1984). The eastern and western boundaries of the flow domain are coincident with a pair of streamlines from this subregional model that extend from just upgradient of the proposed YM repository southward to the major groundwater withdrawal area of Amargosa Farms (Czarnecki and Waddell, 1984, plate 1). The northwestern and southern boundaries, which were selected to be roughly coincident with head contours 800 m and 675 m, were treated as Dirichlet boundaries in the detailed model. Because the western and eastern edges of the flow domain are coincident with the streamlines, these boundaries were treated as no-flow boundaries in the detailed model.

To match measured head data, the domain of the detailed flow model was divided into seven zones in which the hydraulic conductivity was assumed uniform. The boundaries of these seven zones were determined from available hydrostratigraphic cross sections and from inspection of head contours. Initial estimates of hydraulic conductivity were obtained by manually calibrating the MAGNUM 2D-based detailed flow model. These estimates were refined using an automatic calibration routine to fit heads predicted from the detailed model to measured head data (Baca et al., 1996). Because the detailed model uses two Dirichlet and two no-flow boundary conditions, the values of hydraulic conductivity in the seven zones are not uniquely identifiable in the absence of prior estimates of areal flux or hydraulic conductivity (Carrera and Neuman, 1986). Inasmuch as areal recharge within this region is minimal, fixing one hydraulic conductivity value is the best option. Zone 7, located at the southern end of the detailed model, was assigned a fixed hydraulic conductivity value of 1.7×10^{-5} m/s (Czarnecki, 1985).

The four streamtubes abstracted from the 2D detailed flow model describe the trajectories of the dissolved radionuclides. Mean Darcy velocities along the centerline trajectory of each streamtube are also extracted from the detailed flow model. The widths of the streamtubes vary from the repository to the receptor location. Because of the variation in streamtube width, mean centerline Darcy velocities vary from 0.25 to 1.3 m/yr. Mean transport velocities along the centerline trajectories are determined by dividing the Darcy velocity by the sampled effective or kinematic porosities. The effective porosity varies from 0.001 to 0.01 for the portion of the streamtube that transits fractured tuff and from 0.10 to 0.15 for the portion transiting the alluvium. Based on these ranges for effective porosity, linear transport velocities range from 40 to 1,300 m/yr in the fractured tuff and from 1.7 to 4 m/yr in the alluvium.

Other sampled transport parameters whose probability distribution or sampling range is defined in the input file include the longitudinal dispersivity (α_L), retardation coefficients for each radionuclide, and parameters used to effect matrix diffusion in the fractured tuff unit. Inasmuch as the longitudinal macrodispersivity is generally assumed to increase with the scale of the contaminant plume until an asymptotic upper bound is attained (Gelhar, 1993), it is incorrect to assign a separate dispersivity value to each NEFTRAN II transport leg. Consequently, a single value is sampled that depends on the distance to the critical group location. The retardation coefficients set in the input file depend on the dominant mineralogy of the medium in the transport leg as well as the particular radionuclide transported.

3.4 TECHNICAL CONCERNS

The reviewers have the following technical concerns regarding the site-scale flow and transport model and the TSPA-VA approach to SZ flow and transport.

- The boundary conditions for the site-scale flow model, both flux and specified head, are not reasonably bounded because the regional flow model is not sufficiently calibrated. No vertical leakage was simulated from the lower aquifers because the no-flow boundary was imposed for the bottom of the model.

- The site-scale model was not sufficiently calibrated because the paucity of data prevented estimation of all parameters. The large data gap in the hydrogeologic framework model south of YM still exists.

- The horizontal spatial resolution is not sufficiently fine to include permeability contrasts.

- The TSPA-VA flow and transport simulations, performed using a 3D flow model and a 1D transport model, assume the system as isotropic and homogeneous at large scale. There is ample evidence this is not the case.

- The applicability of the dilution factor approach to sufficiently incorporate the effects of transverse dispersivity is not clearly supported by analyses. However, it is our understanding that the proposed methodology by the DOE for the TSPA for License Application (LA) will not incorporate the dilution factor approach.

- The sensitivity analyses performed in the TSPA-VA did not show any sensitivity of the SZ flow and transport parameters. NRC staff TPA analyses, however, show the radionuclide dose at the receptor locations is quite sensitive to the properties of the alluvium.

Similar concerns about sufficient calibration, definition of boundary conditions, sparseness of site-specific data for the alluvial aquifer, and adequate incorporation of heterogeneity and anisotropy in the site-scale model were also raised by the SZEE Panel (Geomatrix, 1998), the U.S. Nuclear Waste Technical Review Board (1998), and the PAPR Panel (U.S. Department of Energy, 1999b).

3.5 PATHS TO RESOLUTION

The technical concerns can be addressed through the following paths.

- The regional flow model should be refined for better estimate of boundary conditions for the site-scale flow model. The vertical flow from the deeper aquifer also should be incorporated in the site-scale flow model. A better estimate of boundary fluxes and vertical fluxes will provide a better water balance for the site-scale model. With well-defined boundary conditions, the aquifer parameters can be estimated during calibration with a greater degree of confidence. Well data from p #1, H-1, and H-3 shows the potential for upward flow from the deeper aquifer. Additionally, the well data from Nye County is expected to provide upward potential for flow in alluvium.

- The hydrogeologic framework model used for the site-scale flow and transport model should be modified to incorporate more site-specific information south of YM. Additional field investigations and characterization are needed to address the transition of the water table from the tuff aquifer to the alluvial aquifer.

- The spatial horizontal resolution of the site-scale flow model should be refined to better represent the heterogeneity in the system.

- The TSPA-VA transport simulations should be performed with an anisotropic and heterogeneous representation of the SZ.

- The model abstraction for SZ flow and transport should be refined to respond to various SZ flow and transport parameters during sensitivity and uncertainty analyses.

4 PARAMETER UNCERTAINTY AND SENSITIVITY ANALYSES

4.1 HETEROGENEITY AND FLOW CHANNELIZATION

4.1.1 Total System Performance Assessment for the Viability Assessment Approach

The base case considered in the DOE analyses of transport in the saturated aquifer underlying YM treated the hydraulic properties of the individual hydrostratigraphic units as uniform. Faults were considered as offsets in the hydrostratigraphic framework, but potential permeability enhancements near faults were not considered. These simplifications of the complex geological system neglect potential connected high-permeability pathways and flow channeling induced by small-scale permeability heterogeneities that could significantly affect repository performance. The sensitivity of repository performance to these simplifications was addressed in the Technical Basis Document (Civilian Radioactive Waste Management System, Management & Operating Contractor, 1998). Given the well-understood sensitivity of transport to permeability heterogeneities, introduction of permeability heterogeneity is a significant advance over the base case scenario. However, these sensitivity studies are based on limited heterogeneity characterization and contain unjustified assumptions and potential numerical artifacts that may be masking the underlying effects.

Of greatest concern is numerical dispersion in the coarsely gridded solution to the advection-dispersion equation. Although the base case scenario used a streamtube approach to avoid the issue of numerical dispersion, the heterogeneity studies used a conventional 3D finite element solution with $500 \times 500 \times 50$ m elements. The reviewers concerns with this model have been expressed previously in this report. Numerical dispersion in this coarsely gridded model is unacceptably large and probably masks any differences between the heterogeneous and base case models. The simulations do not address in a credible manner the topic of heterogeneity-induced flow channeling.

The DOE study of sensitivity to flow channeling and fast flow paths employed geostatistical simulation methods to create realizations of permeability. The average bulk permeability in each unit was constrained to match the permeability obtained by calibrating to hydraulic head measurements. In one set of simulations, permeability enhancements associated with major mapped faults were also added to the heterogeneous property distributions. In both situations, the resulting hydraulic heads matched measured values as least as well as the base case with uniform properties, indicating that the existence of high-permeability pathways cannot be ruled out solely on the basis of the measured heads.

The heterogeneity model employed for the fractured units is poorly constrained by heterogeneity data and is nonconservative. The study used the geostatistical technique sequential Gaussian simulation (SGS) to create realizations of the permeability in the fractured volcanic units. The correlation range used in the model was not estimated from permeability data directly due to sparseness of data. It was estimated instead from matrix porosity data presumed correlated with the degree of welding, and thus, the permeability of the fracture system. The standard deviation in the logarithm of permeability, another important parameter in the SGS algorithm, was reduced by a factor of one-half from the available well-derived permeability measurements to account for the different scales of the simulated and measured permeabilities.

The mathematical model underlying the SGS algorithm, the multi-Gaussian model, is known to be nonconservative for contaminant transport. That is, it is possible to construct alternative models with more flow channeling and the same two-point correlation structure and univariate statistics (Rubin and Journel, 1991). The multi-Gaussian model tends to produce isolated values of high permeability distributed more or less uniformly throughout the simulation domain, whereas geological systems may have more connected regions of high permeability leading to more flow channeling. Given this bias in the SGS algorithm and the limited characterization of the fractured units, the topic of potential flow channeling in the fractured units is not addressed adequately. At the least, the consequences of assuming the multi-Gaussian model for heterogeneity need to be assessed.

Permeability characterization of the alluvium is even more limited than the fractured units. Here DOE relied on more geologically based methods. Categorical (indicator) methods were used for the simulation. Two classes were used in the simulation, a low-permeability class corresponding to fine-grained paleosols and debris flow deposits and a higher-permeability class corresponding to coarse-grained sands deposited during flood events. Qualitative information obtained from similar alluvium deposits in nearby Frenchman's Flat were used to constrain the model parameters. In general terms, this approach may be more defensible than the SGS approach used for the fractured units, despite the lack of direct characterization of the alluvium. Indicator simulation does not suffer the same limitations as the SGS method. In particular, it is able to better reproduce connected regions of high permeability. Nevertheless, the characterization requirements are greater for the alluvium compared to the volcanic aquifer because repository performance is known from sensitivity studies to be more sensitive to the hydraulic properties of the alluvium. The DOE heterogeneity models would be more defensible if based on direct measurements of hydraulic properties in the alluvium.

Permeability enhancements associated with major faults could potentially provide radionuclides with fast pathways through the SZ. DOE addressed the sensitivity of transport to these potential features by enhancing permeability in grid blocks crossed by major faults. Each of these grid blocks was assigned a permeability value of 1×10^{-11} m^2, consistent with values inferred from multiwell testing of the faulted interval in the C-Wells. Potential anisotropies in the permeability were not considered. Depending on the details of the flow geometry, such permeability anisotropies may act to channel flow more efficiently than the isotropic permeability model employed by DOE.

DOE and NRC have both recognized the potential significant controls structures exert on groundwater flow and resulting potential radionuclide migration pathways at YM (Civilian Radioactive Waste Management System, Management and Operating System, 1998). Lehman and Brown (1996) suggested that the failure to account for structural controls of groundwater flow and transport could adversely affect estimates of potential radionuclide exposure to members of the critical group. However, the sensitivity analyses by NRC/CNWRA suggest that the radionuclide dose is more sensitive to the alluvium properties than the tuff properties.

4.1.2 Technical Concerns

The reviewers have the following concerns about the DOE approach to handling heterogeneity and flow channelization in the SZ.

- Numerical dispersion caused by the coarse resolution of the flow and transport model may be masking effects of heterogeneities and flow channelization.

- The heterogeneity model used in the geostatistical study is poorly constrained. Little direct characterization of the alluvial aquifer exists. Use of the multi-Gaussian model for the fractured units without supporting empirical evidence is nonconservative, as this model is known to underpredict the degree of flow channeling (relative to other models) for random heterogeneities.

4.1.3 Paths to Resolution

The technical concerns can be addressed through the following paths.

- DOE should continue with studies of sensitivities to potential fast pathways and flow channeling. However, these topics cannot be resolved with the DOE current approach because numerical dispersion caused by the coarse resolution of the flow and transport model probably is masking any sensitivity. An alternative transport model or a more finely gridded solution should be employed.

- DOE should continue with geostatistical simulations of the alluvial aquifer. Supporting measurements of hydraulic properties would make these more defensible. If the heterogeneity model is not better constrained by data on the aquifer properties, the sensitivity to the choice of heterogeneity model needs to be addressed.

- If ongoing studies of performance sensitivities reveal an important role for the volcanic units, geostatistical simulations of the volcanic units should be revisited. In particular, alternatives to SGS should be explored.

- The TSPA-VA transport simulations should be performed with an anisotropic and heterogeneous representation of the SZ.

- If the heterogeneity models are not better constrained by data on the aquifer properties, the sensitivity to the choice of heterogeneity model needs to addressed. The SGS approach used for the fractured aquifer is of particular concern, as this is known to underpredict the degree of flow channeling (relative to other models) for random heterogeneities.

4.2 DILUTION AT PUMPING WELLS

4.2.1 Introduction

The radionuclide dose to which users of the groundwater system, the critical group, may be exposed is controlled by several factors. Some of the more widely discussed factors include the engineered barrier systems at the location of the repository and the natural processes operating in the travel path such as dispersion, radionuclide decay and retardation processes. One factor that is not often discussed but which may be of importance in reducing radionuclide concentrations reaching the biosphere is dilution at receptor locations due to pumping. Dilution of this nature results from the mixing of contaminated and uncontaminated waters within well bores, thereby, reducing concentration. This process should not be confused with dilution along the flow path that is a consequence of dispersion processes operating within the aquifer.

DOE and NRC both recognize the potential importance of well bore dilution for achieving compliance at receptor locations as is discussed in the VA (U.S. Department of Energy, 1998) and the TPA

Version 3.2 code. Indeed, failure to account for this process increases the potential radionuclide exposure to members of the critical group, and thus, may be viewed as a conservative estimate.

A standardized approach for defining dilution at pumping wells is lacking. Current approaches for modeling dilution at pumping wells are based on volumetric flux relationships or concentration relationships. However, despite the approach used, well bore dilution appears influenced by the following factors: pumping or extraction rate, well design parameters (e.g., the depth and length of the well screen), aquifer heterogeneity, plume release rate, dimensions and concentration distribution, and groundwater flow rates. Due to the number of parameters that influence well bore dilution, abstraction of this process into performance assessment (PA) methodologies is complicated.

4.2.2 Total System Performance Assessment For The Viability Assessment Approach

In the VA (U.S. Department of Energy, 1998), DOE currently is not taking credit for dilution due to pumping. This position is stated in the following two excerpts:

> (vol. 3, chap. 5, sec. 5.8.2)
> "There is no dilution during withdrawal of water from the aquifer; that is, there is no mixing of contaminated water and uncontaminated water when water is pumped from the ground or when water is stored in a tank."

and

> (vol. 3, chap. 6, sec. 6.4.17)
> "No credit is taken for the pumping dilution in the base case analyses of the reference design."

As a result of its position, the DOE has not proposed any models for this phenomenon.

4.2.3 Review of Alternative Conceptual Models

Standardized approaches for modeling and quantifying well bore dilution for abstraction into PA methodologies are currently lacking. Two approaches have been proposed in literature: volumetric flux-based methods and dispersive-transport-based methods. A summary of these methods is presented in the following paragraphs.

Volumetric flux-based dilution estimates are determined by comparing the dimensions of the migrating contaminant plume and the pumping well capture zone. With this approach, concentration variations along the flow path are not taken into account. Instead, the mass released into the system is considered the transported property. Using this approach, dilution may be quantified based on the ratio of the cross-sectional area of the capture zone to the cross-sectional area of the plume that intersects the capture area in the plane perpendicular to the principal direction of flow (Fedors and Wittmeyer, 1998). This approach allows for the quantification of dilution through dilution factors, which may be expressed as functions of the applied pumping rate. Because the method is based on purely volumetric relationships, no credit is given to the concentration distribution within the plume.

NRC TPA Version 3.2 code utilizes a volumetric approach to calculate radionuclide concentrations at a pumping well receptor location. This approach allows the explicit calculation of dilution factors at the well bore such as described by Fedors and Wittmeyer (1998). In the NRC TPA Version 3.2 code approach, the volumetric relationship of interest, used to calculate the mass of radionuclides reaching the receptor, is based on the fraction of the plume volume captured (Vc); for high-capacity pumping rates such as those associated with irrigation wells, it is assumed the entire plume volume is captured (Vc = 1), whereas for low-pumping rates such as those associated with residential wells, it is assumed only a fraction of the plume volume is captured (Vc<1).

Dispersive-transport models may also be used to estimate dilution at extraction well bores. With this approach, concentration variations along the transport path are explicitly taken into account. One such approach has been described by staff at Sandia National Laboratories (SNL) in CRWMS M&O (1997). In this study, well bore dilution factors were defined that related the concentration in the well bore to the maximum concentration adjacent to the well bore. Fedors and Wittmeyer (1998) also proposed an approach for quantifying dilution at extraction wells for the dispersive-transport scenario. Under this approach, dilution factors at the well bore were determined based on the ratio between the integrated concentration distribution across the portion of the plume captured and the source concentration. Dilution factors defined in this manner may also be expressed as applied pumping rate.

Despite the approach used to quantify dilution at the well bore, a common finding is that the estimate is sensitive to the following factors (i) extraction rate at the well, (ii) hydraulic properties of the medium, (iii) well design characteristics, and (iv) plume geometry.

4.2.4 Technical Concerns

Because the DOE currently is not accounting for dilution due to pumping in the TSPA-VA (U.S. Department of Energy, 1998), the reviewers have no concerns.

4.2.5 Paths to Resolution

Should the DOE revise its position and decide to take credit for dilution at pumping wells, the NRC provided the following acceptance criteria in the Issue Resolution Status Report (Nuclear Regulatory Commission, 1998):

> "It will be required to demonstrate that reasonable assumptions have been made about well design, aquifer characteristics, plume geometry, withdrawal rates, and capture zone analysis for the receptor location."

4.3 RETARDATION

4.3.1 Total System Performance Assessment for the Viability Assessment Approach

Chapter 8 of the Technical Basis Document (Civilian Radioactive Waste Management System, Management & Operating Contractor, 1998) assumes that radionuclide sorption and retardation occurs in the alluvium during SZ transport. Radionuclide retardation is a complex coupling of different processes all strongly affected by the physical and chemical conditions of the system of interest. Also in chapter 8 (sec. 8.4.2, 8–54), the basis for the values used for alluvium sorption parameters for a reduced suite of radionuclides (nine) is the compilation of linear sorption coefficients (K_D) by Thibault et al. (1990). For application of these parameters in the vicinity of YM, distributions were derived by assuming the presence of oxidizing conditions and the presence of at least 5 percent calcite.

These assumptions are not based on field evidence specific to the alluvium south of YM, and their applicability to the mineralogy and water chemistry conditions at YM is not demonstrated in either volume 4 of the VA (U.S. Department of Energy, 1998) or chapter 8 of the Technical Basis Document (Civilian Radioactive Waste Management System, Management & Operating Contractor, 1998). Without specific data on alluvium properties at YM, there is little technical basis for accepting these data as representative.

The DOE has performed sensitivity analyses to investigate the effects of uncertainty in sorption parameters on performance. These analyses focused on the length of the alluvium path (0–6 km), considered a parameter of interest because of "...a larger sorption capacity for neptunium and selenium..." as indicated in the Technical Basis Document (Civilian Radioactive Waste Management System, Management & Operating Contractor, 1998, chap. 8, sec. 8.4.2, 8–51). Sensitivity analyses were not conducted to investigate the effects of uncertainty in alluvium sorption coefficients on performance. The effects of uncertainty in sorption of neptunium in the SZ volcanics were investigated using a sensitivity analysis, but the K_D for neptunium sorption in the alluvium was held constant at 10 mL/g.

4.3.2 Technical Concerns

The reviewers have the following technical concerns about the DOE approach to radionuclide sorption and retardation in the alluvium.

- DOE has limited information to adequately support its estimates for the effects of alluvium on repository performance or otherwise adequately constrain the transport of radionuclides through water production zones and alluvium.

- The inherent assumptions used in deriving the alluvium sorption coefficient are not based on field evidence specific to the alluvium south of YM, and their applicability to the mineralogy and water chemistry conditions at YM is not demonstrated.

- DOE financed the drilling of monitoring wells by Nye County, Nevada, but has no apparent additional plans to complete characterization of the SZ flow path. Data from the Nye County wells are unlikely to address all the uncertainties in SZ flow and transport; it is not certain what types of samples will be collected, what laboratory experiments will be performed, what radionuclides will be investigated, or what types of water chemistries will be used in any experiments. The lack of DOE plans for characterization of the alluvium and the current drilling schedule for the Nye County wells make it unlikely that much new information will be available in time for inclusion in the LA (U.S. Department of Energy, 1998, vol.4, sec. 3.1.3, 3-16).

4.3.3 Paths to Resolution

The technical concerns can be addressed through the following paths.

- The DOE recognized the need to continue characterization of the SZ to constrain transport through water-production zones and alluvium. DOE should be able to collect sufficient data to develop an adequate licensing basis for radionuclide retardation in the SZ. The activities outlined in DOE LA plan (U.S. Department of Energy, 1998) are believed to be appropriate steps to provide a better basis for the alluvium transport parameters, but activities related to sorption and transport parameters will not be available until after the cutoff date for TSPA models.

- Sensitivity analyses should be conducted for varying sorption coefficients in the alluvium. Information from natural analogs and mechanistic sorption models applied for site-specific water chemistry data should be used to provide constraints on sorption are more appropriate to the YM environment.

- Characterization of the transport properties of alluvium will increase the robustness of LA and may decrease the need to perform more difficult investigations of transport through fractured tuff. The potential importance of characterizing the SZ at distances up to 20 km has also increased with the possibility that compliance may be based on exposures to the average member of the critical group, where the critical group may be located 20 km from the repository.

4.4 COLLOID TRANSPORT

4.4.1 Total System Performance Assessment for the Viability Assessment Approach

The DOE recognizes that colloids may be important to performance because they could increase the transport velocity of radionuclides through the alluvium. The transport velocity of radionuclides attached to colloids may be faster than that of dissolved radionuclides because colloids may travel in the faster parts of the flow paths, and colloids may sorb to host rock less than dissolved radionuclides. For example, DOE notes that one of the more significant findings in the TSPA-VA is that, under certain conditions, colloid-facilitated transport is moderately important to repository performance in the time period from 10,000 to 100,000 yr (U.S. Department of Energy, 1998).

A number of radionuclides were eliminated from consideration in the DOE PA analyses on the basis the radionuclides are strongly sorbing and would have low probability of reaching the accessible environment as dissolved species. An exception was made for plutonium, a strongly sorbing radioelement, because of its potential transport in colloidal form. However, no other strongly sorbing radionuclide was included in the colloid transport analysis. Plutonium is believed by DOE to be the radionuclide most likely affected by colloidal transport because it is a major part of the waste inventory, has low solubility, and is assumed to have high sorption onto host rock. Field evidence at the Nevada Test Site also supports the rapid migration of plutonium with a colloid phase (Kersting et al., 1999). But the colloid transport was associated with a 1.3 MT nuclear test detonated beneath the water table. Additional data related to colloid formation and transport of other radionuclides are required to ensure adequate information to evaluate the LA.

In the initial analysis and discussion of colloid transport in the near field (Civilian Radioactive Waste Management System, Management & Operating Contractor, 1998), the DOE focused only on plutonium while recognizing that other radionuclides also have the potential for colloidal transport. The models assume both reversible and irreversible sorption of colloids onto a colloidal phase. The proposed repository will have high inventories of plutonium isotopes with half-lives short enough to pose a dose danger but also long enough to allow transport over significant distances. Other radionuclides with low solubility and high sorption include americium and thorium. DOE concluded, however, that their inventories and half-lives make them less likely than plutonium to affect repository performance. This is not demonstrated in CRWMS M&O (1998) through simulation of colloidal transport of other radionuclides. DOE noted that as more data are obtained, colloidal transport of additional radionuclides will be investigated.

4.4.2 Technical Concerns

The reviewers have the following concerns about the DOE approach to radionuclide sorption.

- DOE has focused its analyses of colloid transport only on plutonium; other radionuclides that have a potential for colloidal transport through the alluvium are neglected. These include high sorbing radioelements such as americium and thorium and elements the DOE described as chemical analogues to these (e.g., actinium, niobium, samarium, and zirconium).

- There is still significant uncertainty regarding the extent to which radionuclides are irreversibly sorbed onto natural colloids. This may be an even greater uncertainty considering that other radionuclides may be transported with a colloidal phase.

4.4.3 Paths to Resolution

The technical concerns can be addressed through the following paths.

- Models presented for colloid transport in the engineered barrier system, the UZ, and the SZ for the TSPA-VA all assume that radionuclides experience reversible sorption on groundwater colloids. If irreversible sorption processes are dominant or if waste-form colloids survive without dissolution during transport, the DOE models could underpredict RT and lead to overoptimistic estimates of repository performance. The limitation of the DOE models for colloid transport was discussed in an earlier DOE/NRC interaction. Also, this information gap has been raised previously. This comment was acknowledged and agreed to by DOE in the VA (U.S. Department of Energy, 1998). DOE should continue to study the irreversible attachment of radionuclides to colloidal particles.

- The DOE states in its VA (U.S. Department of Energy, 1998) that the initial colloid analysis focused on plutonium, but that as more data are obtained, colloidal transport of additional radionuclides will be investigated. This should be followed through by conducting sensitivity analyses to colloidal transport of other low-solubility, high-sorption radionuclides. The DOE has included studies related to the transport of radionuclide-bearing colloids in its ongoing technical work at the C-Wells complex. As stated in volume 4 of the VA (U.S. Department of Energy, 1998), laboratory studies are planned to address uncertainties about the formation and stability of colloids and their interactions with radionuclides, particularly plutonium. The principal factor for colloid formation and transport is assigned a relatively high priority for the LA.

- Current DOE TSPA-VA models do not include colloid filtration. In this respect, they may be considered conservative to the extent that colloid transport is not retarded or reduced through interaction with the minerals of the SZ aquifers. In developing more realistic colloid models, the DOE should incorporate those aspects of colloid filtration likely under geochemical and hydrological conditions existing in the vicinity of YM. Support for these realistic models should be based on laboratory and field observations. DOE included the effects of filtration on colloid transport in developing preliminary reactive colloid transport models (Civilian Radioactive Waste Management System, Management & Operating Contractor, 1998), although there is still uncertainty in model parameters. DOE has acknowledged the preliminary nature of the model results and used sensitivity analyses to identify areas of greatest parameter uncertainty. The DOE has also included field studies related to colloid transport through volcanic aquifers in the ongoing work at the C-Wells complex.

5 REFERENCES

Baca, R.G., G.W. Wittmeyer, and R.W. Rice, *Analysis of Contaminant Dilution in Groundwater. Scoping Calculations for Revisions to the EPA Standard,* NUREG-1538. Washington, DC: Nuclear Regulatory Commission, 1996.

Bedinger, M.S., K.A. Sargent, W.H. Langer, F.B. Sherman, J.E. Reed, and B.T. Brady. 1989. 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. USGS Professional Paper 1370–A. Denver, CO: U.S. Geological Survey.

Bodvarsson, G.S., T.M. Bandurraga, and Y.S. Wu, eds. 1997. *The Site-Scale Unsaturated Zone Model of Yucca Mountain, Nevada for the Viability Assessment.* LBNL–40376. Berkeley, CA: Lawrence Berkeley National Laboratory.

Carrera, J., and S.P. Neuman. 1986. Estimation of aquifer parameters under transient and steady state conditions: 2. Uniqueness, stability, and solution algorithms. *Water Resources Research.* 22(2): 211–227.

Civilian Radioactive Waste Management System. Management and Operation. 1997. *Biosphere Abstraction/Testing Workshop Results.* B00000000–01717–2200–0192. Las Vegas, NV: TRW Environmental Safety Systems, Inc.

Civilian Radioactive Waste Management System, Management & Operating Contractor. 1998.*Total System Performance Assessment—Viability Assessment (TSPA-VA) Analyses Technical Basis Document.* B00000000–01717–4301. Revision 01. Las Vegas, NV: Civilian Radioactive Waste Management System, Management & Operating Contractor.

Czarnecki, J.B. 1985. *Simulated Effects of Increased Recharge on the Ground-Water Flow System of Yucca Mountain and Vicinity, Nevada-California.* USGS Water Resources Investigations Report 84-4344. Denver, CO: U.S. Geological Survey.

Czarnecki, J.B., and R.K. Waddell. 1984. *Finite-Element Simulation of Ground-water Flow in the Vicinity of Yucca Mountain, Nevada-California.* USGS Water Resources Investigations Report WRI–84–4349. Denver, CO: U.S. Geological Survey.

Czarnecki, J.B., C.C. Faunt, C.W. Gable, and G.A. Zyvoloski. 1997. *Hydrogeology and Preliminary Three-Dimensional Finite-Element Ground-Water Flow Model of the Site-Saturated Zone, Yucca Mountain, Nevada.* SP23NM3. Denver, CO: U.S. Geological Survey.

D'Agnese, F.A., C.C. Faunt, A.K. Turner, and M.C. Hill. 1997a. *Hydrogeologic Evaluation and Numerical Simulation of the Death Valley Regional Ground-water Flow System, Nevada and California.* USGS Water-Resources Investigations Report 96-4300. Denver, CO: U. S. Geological Survey.

D'Agnese, F.A., G.M. O'Brien, C.C. Faunt, and C.A. San Juan. 1997b. *Simulated Effects of Climate Change on the Death Valley Regional Ground-water Flow System, Nevada and California.* SP23OM3. Denver, CO: U.S. Geological Survey.

Fedors, R.W., and G.W. Wittmeyer. 1998. *Initial Assessment of dilution Effects Induced by Water Well Pumping in the Amargosa Farms Area.* San Antonio, TX: Center for Nuclear Waste Regulatory Analyses.

Gelhar, L.W. 1993. *Stochastic Subsurface Hydrology.* Englewood Cliffs, NJ: Prentice-Hall.

Geomatrix Consultants, Inc. and TRW. 1998. *Saturated Zone Flow and Transport Expert Elicitation Project.* WBW 1.2.5.7. San Francisco, CA: U.S. Department of Energy.

Harrill, J.R., J.S. Gates, and J.M. Thomas. 1988. *Major Ground-Water Flow Systems in the Great Basin Region of Nevada, Utah, and Adjacent States.* USGS Hydrologic Investigations Atlas HA-694-C. Denver, CO: U.S. Geological Survey.

Hill, M.C. 1992. *A Computer Program (MODFLOWP) for Estimating Parameters of a Transient Three-dimensional, Ground-water Flow Model Using Nonlinear Regression.* USGS Open-File Report 91-484. Denver, CO: U.S. Geological Survey.

Kersting, A.B., D.W. Efurd, D.L. Finnegan, D.J. Rokop, D.K. Smith, and J.L. Thompson. 1999. Migration of plutonium in groundwater at the Nevada Test Site. *Nature* 397: 56–59.

Lehman, L.L., and T.P. Brown. 1996. Summary of State of Nevada—Funded Studies of the Saturated Zone at Yucca Mountain, Nevada: Performed by L. Lehman and Associates, Inc. Las Vegas, NV: L. Lehman & Associates, Inc.

Nuclear Regulatory Commission. 1998. *Issue Resolution Status Report Key Technical Issue: Unsaturated and Saturated Flow Under Isothermal Conditions.* Revision 1. Washington, DC: Nuclear Regulatory Commission.

Olague, N.E., D.E. Longsine, J.E. Campbell, and C.D. Leigh. 1991. *User's Manual for the NEFTRAN II Computer Code.* NUREG/CR–5618. Washington, DC: Nuclear Regulatory Commission.

Rubin, Y. and A.G. Journel. 1991. Simulation of non-Gaussian space random functions for modeling transport in groundwater. *Water Resources Research* 27(7): 1,711–1,721.

Thibault, D.H., M.I. Sheppard, and P.A. Smith. 1990. *A Critical Compilation and Review of Default Soil Solid/Liquid Partition Coefficients, K_d, for Use in Environmental Assessments.* AECL–10125. Pinawa, Manitoba, Canada: Whiteshell Nuclear Research Establishment, Atomic Energy of Canada Limited.

U.S. Department of Energy. 1998. *Viability Assessment of a Repository at Yucca Mountain.* 5 Volumes. DOE/RW–0508. Las Vegas, NV: U.S. Department of Energy, Office of Civilian Radioactive Waste Management.

U.S. Department of Energy. 1999a. *Proceeding of the Saturated Zone Flow/Transport and Biosphere Workshop, Albuquerque, NM, February 17–19, 1999.* Yucca Mountain Performance Assessment Operations. Albuquerque, NM: Sandia National Laboratories.

U.S. Department of Energy. 1999b. Final Report: Total Performance Assessment Peer Review Panel. Washington, DC: U.S. Department of Energy.

U.S. Nuclear Waste Technical Review Board. 1998. *Report to the US Congress and the US Secretary of Energy.* Arlington, VA: U.S. Nuclear Waste Technical Review Board.

Waddell, R.K., J.H. Robison, and R.K. Blankennagel. 1984. *Hydrology of Yucca Mountain and Vicinity, Nevada-California: Investigative Results Through Mid-1983.* USGS Water Resources Investigations Report 84-4267. Reston, VA: U.S. Geological Survey: 72.

Winograd, I.J. and I. Friedman. 1972. Deuterium as a tracer of regional groundwater flow, Southern Great Basin, Nevada, California. *Geological Society of America Bulletin* 83 (12).