April 30, 2003

Joseph D. Ziegler, Acting Director
Office of License Application and Strategy
U.S. Department of Energy
Office of Repository Development
P.O. Box 364629 M/S 523
North Las Vegas, NV 89036-8629

SUBJECT: REVIEW OF DOCUMENTS PERTAINING TO AGREEMENT TOTAL SYSTEM PERFORMANCE ASSESSMENT AND INTEGRATION (TSPAI).3.18 (STATUS: NEED ADDITIONAL INFORMATION)

Dear Mr. Ziegler:

In your letter dated January 21, 2003, the U.S. Department of Energy (DOE) enclosed a response to Agreements TSPAI.3.18, TSPAI.3.21, TSPAI.3.23, Thermal Effects on Flow (TEF).2.13, and General (GEN).1.01, Comments 18, 24, and 69. The enclosed report documented technical information and associated references, the physical relationship of the unsaturated flow system on barrier capabilities of the proposed repository, and sensitivity analyses for risk importance. The U.S. Nuclear Regulatory Commission (NRC) staff has reviewed this information, with respect to Agreement TSPAI.3.18, and the results of the staff's review are enclosed. Separate NRC review letters will be prepared for Agreements TSPAI.3.21, TSPAI.3.23 (including comments from GEN.1.01), and TEF.2.13.

Agreement TSPAI.3.18 states that DOE will provide a technical basis that the water-balance plug-flow model adequately represents the non-linear flow processes represented by Richards' equation. NRC staff identified several issues regarding data and the information used to constrain the net infiltration model results, including the use of a water-balance plug-flow submodel to estimate net infiltration rates. To address the concern that a water-balance plug-flow submodel may underpredict the net infiltration rate over the repository in comparison with a Richards' equation submodel, staff focused on evaluating whether DOE had provided an adequate technical basis for their water-balance plug-flow infiltration submodel, and whether their submodel captures the nonlinear flow processes described by Richards' equation. The technical basis reviewed has not shown that the non-linear flow processes represented by Richards' equation have been adequately incorporated in DOE's current model.

The DOE report also provided results from dose-based, sensitivity studies in order to demonstrate that the current understanding of net infiltration processes is adequate given that it has little significance to the calculation of the mean annual dose in the first 10,000 years following waste emplacement. The risk sensitivity studies provided are not sufficiently documented to have supported the completion of Agreement TSPAI.3.18 on the basis of low risk significance. Additional risk information is needed if DOE chooses to complete Agreement TSPAI.3.18 based upon risk assessments and sensitivity analyses. Guidance on the use of risk information to complete agreements was provided by NRC in its letter to DOE titled, "Use of Risk as a Basis for Closure of Key Technical Issue Agreements," dated January 27, 2003.

Additional information as described in the attachment is needed to complete the key technical issue Agreement TSPAI.3.18. DOE may choose to complete Agreement TSPAI.3.18 by either providing: 1) additional technical information as discussed in Section 4.1.3 of the attachment, or 2) additional risk information as discussed in Section 4.2 of the attachment. With regard to the latter option, the disposition of Agreement TSPAI.3.18 can be determined after DOE adequately addresses NRC's concerns with its approach to resolving agreements via risk assessments and sensitivity analyses as discussed in the January 27, 2003, risk letter.

The NRC's interest in the information requested in the agreements is to support a detailed review of the potential license application. The NRC will consider risk information provided by DOE in conjunction with other factors, when evaluating whether sufficient information exists for NRC to conduct a detailed review of a potential license application. Consequently, the NRC may need to continue to request the original information sought in an agreement if we are not satisfied that the risk-information provided is adequate.

The key technical issue Agreement TSPAI.3.18 has the status "need additional information." If there are any questions regarding this letter, please contact Bill Dam at 301-415-6710 or by e-mail at wld@nrc.gov.

Sincerely,

/RA/

Janet R. Schlueter, Chief
High-Level Waste Branch
Division of Waste Management
Office of Nuclear Material Safety
and Safeguards

Enclosure: NRC Review of DOE Documents
Pertaining to Key Technical Issue
Agreement TSPAI.3.18.

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Letter to J. Ziegler from J. Schlueter dated: April 30, 2003
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Additional information as described in the attachment is needed to complete the key technical issue Agreement TSPAI.3.18. DOE may choose to complete Agreement TSPAI.3.18 by either providing: 1) additional technical information as discussed in Section 4.1.3 of the attachment, or 2) additional risk information as discussed in Section 4.2 of the attachment. With regard to the latter option, the disposition of Agreement TSPAI.3.18 can be determined after DOE adequately addresses NRC's concerns with its approach to resolving agreements via risk assessments and sensitivity analyses as discussed in the January 27, 2003, risk letter.

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NRC Review of DOE Documents Pertaining to
Key Technical Issue Agreement TSPAI.3.18

The U.S. Nuclear Regulatory Commission (NRC) goal of issue resolution during the pre-licensing period is to assure that the U.S. Department of Energy (DOE) has assembled enough information on a given issue for NRC to accept a license application for review. Resolution by the NRC staff during pre-licensing does not prevent anyone from raising any issue for NRC consideration during review of a license application. Equally important to note is that resolution by the NRC staff during pre-licensing does not prejudge what the NRC staff evaluation of that issue will be after a licensing review. Issues are resolved by the NRC staff during pre-licensing when the staff has no further questions or comments about how DOE is addressing an issue. Pertinent new information could raise new questions or comments on a previously resolved issue.

This enclosure addresses Key Technical Issue (KTI) Agreement Total System Performance Assessment and Integration (TSPAI).3.18, which was reached between NRC and DOE during a technical exchange and management meeting.[1] This agreement pertains to the DOE approach for modeling the process of infiltration into the unsaturated zone at Yucca Mountain, and whether or not the DOE water-balance plug-flow approach adequately represents nonlinear processes that are generally described by the Richards' equation. This agreement was addressed by the DOE in a letter[2] and in the enclosed report (Rickertsen, 2003), which are the subject of this review.

1 WORDING OF THE AGREEMENT

<u>TSPAI 3.18 states</u>: "Provide a technical basis that the water-balance plug-flow model adequately represents the non-linear flow processes represented by Richards' equation, particularly over the repository where there is thin soil (UZ1.2.1). DOE will provide a technical basis that the water-balance plug-flow model adequately represents the non-linear flow processes represented by Richards' equation, particularly over the repository where there is thin soil. The technical basis will be documented in an update to the Simulation of Net Infiltration for Modern and Potential Future Climates AMR (ANL-NBS-HS-000032). The AMR is expected to be available to NRC in FY 2003."

2 BACKGROUND

The shallow infiltration subissue of the Unsaturated and Saturated Flow Under Isothermal Conditions (USFIC) KTI was previously considered resolved at the NRC staff level following the publication by DOE of the total system performance assessment performed for the viability assessment (DOE, 1998; CRWMS M&O, 1998). The resolution of this subissue was based, in part, on staff's conclusion that the net infiltration rates for present and future climates considered in the DOE abstraction reasonably bounded the uncertainty in net infiltration at Yucca Mountain. DOE subsequently refined their net infiltration model, and estimates of net infiltration above the

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[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.

[2]Ziegler, J.D. "Transmittal of Report Addressing Key Technical Issue (KTI) Agreement Items Total-System Performance Assessment and Integration (TSPAI) 3.18, 3.21, 3.23, and Thermal Effects on Flow (TEF) 2.13." Letter (January 21, 2003) to J. Schlueter.

potential repository were revised to lower values. The revised net infiltration estimates prompted staff to reexamine the shallow infiltration subissue. In the Yucca Mountain Program, the term "shallow infiltration" has generally been replaced by the term "net infiltration," a usage that will be followed in the remainder of this document.

During the reexamination of the net infiltration model results, staff identified several issues regarding data and the information used to constrain the net infiltration model results, including the use of a water-balance plug- or piston-flow submodel to estimate net infiltration rates. The net infiltration process would be more accurately represented by a Richards' equation submodel. To address this concern, NRC staff focused on evaluating whether DOE had provided an adequate technical basis for their water-balance plug-flow infiltration submodel, and whether their submodel captures the nonlinear flow processes described by Richards' equation.

The redistribution of infiltrating liquid water in an unsaturated air and water system is typically modeled with Richards' equation, which assumes that the air phase is immobile so that the governing mass conservation equation may be simplified (Richards, 1931). This assumption is valid when the flow of air is essentially instantaneous in comparison with the flow of water in the subsurface. Unsaturated hydraulic conductivity at a given point in the subsurface can be expressed as a function of either the soil-water pressure head, effective water saturation, or water content. Because saturation-dependent hydraulic conductivity is not constant at a given location within the unsaturated zone (unless at steady-state), Richards' equation is nonlinear; thus, it can be computationally difficult to apply to large-scale transient flow problems. Water redistribution is calculated instantaneously at 24 hour intervals and is then averaged over the soil column within the DOE net infiltration rate water-balance plug-flow submodel (Flint, et al., 1996). Use of Richards' equation would allow the modeled distribution of water within the soil column to evolve more realistically with time. The foregoing considerations were the basis for the NRC staff's request that DOE evaluate the potential effects of neglecting nonlinearities when estimating net infiltration rates for the upper boundary condition to unsaturated zone flow models, as described in the wording of Agreement TSPAI.3.18.

3 NRC REVIEW

The Rickertsen (2003) report provides three areas of discussion to support the completion of KTI Agreement TSPAI.3.18. First, technical information and associated references are provided to support the DOE conclusion that the water-balance plug-flow submodel is an adequate representation for nonlinear flow processes within the DOE net infiltration submodel. Second, the physical relationship between the net infiltration rate and the barrier capabilities of the proposed repository is discussed. Third, analyses of sensitivity of total-system performance to bounding cases of net infiltration are provided.

3.1 Review of Technical Information and Associated References

The purpose of the DOE net infiltration submodel is to estimate the lateral distribution of net infiltration rate over the Yucca Mountain region under both present and future climate scenarios. These spatial infiltration rate distributions are input into the unsaturated zone flow model (CRWMS M&O, 2000a) as its upper boundary condition. The DOE net infiltration rate submodel uses the water-balance, plug-flow method, which assumes that lateral flow within the unsaturated zone is negligible. The DOE net infiltration rate submodel is a pseudo-threedimensional model, with infiltration and evapotranspiration occurring in the vertical dimension, and with two-dimensional routing of runoff at the surface. The plan-view area of individual grid cells for the site scale model is 30 × 30 m (98 × 98 ft), and the entire site-scale process model covers an area of 124 km^2 [48 mi^2 (CRWMS M&O, 2000b; USGS, 2001)]. Stream gauge-measured daily mean discharge rates [1994–1995 (CRWMS M&O, 2000b; USGS, 2001)] and volumetric water content data from neutron boreholes were used to calibrate the infiltration model for modern climate conditions (Flint, et al., 2000).

Measured or stochastically generated precipitation rates are input into this mass-balance model; evapotranspiration is simulated with a solar radiation submodel; storage changes are determined from soil-moisture conditions, soil depth, and bulk saturated hydraulic conductivity of the bedrock; if soil field capacity is exceeded by precipitation intensity or duration, runoff is routed from surface cell to surface cell until it infiltrates (Flint, et al., 2002). The net infiltration rate is then determined as the precipitation rate minus any storage changes, minus the evapotranspiration rate, minus runoff. Whenever saturated conditions exist immediately above the soil/bedrock interface, the net infiltration rate is calculated as the bulk saturated hydraulic conductivity of the bedrock under a unit gradient (Flint, et al., 2002).

The conceptual net infiltration model for Yucca Mountain, upon which the DOE numerical model is based, was developed from analysis of a volumetric water content data set that was compiled from multi-year neutron logging of shallow boreholes (Flint and Flint, 2000). Nearly full geographic and geomorphologic coverage of the volcanic ridge has been attained through detailed surface maps of the soils and bedrock at Yucca Mountain, and through 98 dry-drilled monitoring boreholes, which initially enabled continuous core sampling for water content, and which were subsequently neutron-logged monthly over many years to measure changes in the subsurface moisture environment (Flint and Flint, 2000; Flint, et al., 2002). Accessibility necessitated a bias in borehole locations: i.e., many boreholes are either located at the Yucca Mountain crest (thin or no soil cover) or in low areas (deep soil cover) that are not above the repository horizon.

Resulting net infiltration rates from the DOE net infiltration submodel can be summarized as follows: (i) temporally and spatially averaged net infiltration in the Yucca Mountain regional study area is 2.9 mm/yr (0.11 in/yr) for the current climate state; (ii) temporally and spatially averaged net infiltration above the potential repository horizon is 4.5 mm/yr (0.18 in/yr) for the current climate state; and (iii) local net infiltration within a given 30 × 30 m (98 × 98 ft) grid cell may range from 0 to 250 mm/yr (0 to 9.8 in/yr) for the current climate state, depending upon local elevation, precipitation/evaporation rates, soil depth, and bedrock permeability (Flint, et al., 2002).

Rickertsen (2003) maintains that the water-balance plug-flow submodel produces a wide range of bounding net infiltration rates for use in the total system performance assessment by incorporating both spatial variability and model/data uncertainty. Multiple lines of evidence from a variety of field measurements are presented by Rickertsen (2003) to show that the range of values produced by the submodel is appropriate, including results from Darcian methods. A summary of infiltration rate estimates determined for the Yucca Mountain region using a variety of methods is provided below.

Darcian approaches: Numerical models that solve the Darcy's law-based Richards' equation can be used to estimate infiltration rates on the site scale if realistic spatial distributions of saturation, water potential, and the saturation-dependent hydraulic conductivity are known. A unit hydraulic head gradient is frequently assumed if the actual gradient is unknown. The relationship between unsaturated hydraulic conductivity and water potential or saturation is an uncertain one at low saturations, because direct measurements are difficult. Another liability of Darcian methods is that they are less reliable in situations where non-Darcy, high-velocity fracture-flow is predominant.

The Rickertsen (2003) report does not provide net infiltration rate estimates obtained through use of a Richards' equation numerical submodel in response to this agreement (TSPAI.3.18). However, Kwicklis, et al. (1993) *have* used an analytical Darcian approach to determine the vertical distribution of infiltration rates within several Yucca Mountain boreholes; thus, the following estimates of infiltration flux are at the sub-borehole scale. Calculations performed for boreholes UZ #4 and UZ #5 provide net infiltration rates that range between a fraction of 1 mm/yr and 100 mm/yr (0.04 in/yr and 4 in/yr), dependent upon depth below the surface (Flint, et al., 2002). Other research estimates infiltration rate from two vertical boreholes that penetrate both the Paintbrush nonwelded tuff (PTn) and the Topopah Spring welded tuff (TSw). These boreholes have a lateral separation of 770 m (2500 ft), and are located just off the north ramp of the Exploratory Studies Facility (Flint, et al., 2002). Infiltration rate estimates within the PTn unit for these boreholes range between 8 and 15 mm/yr (0.3 and 0.59 in/yr), but decrease to approximately 1 mm/yr (0.04 in/yr) within the TSw (Flint, et al., 2002). Such a reduction in the *apparent* infiltration rate with increased degree of welding can be interpreted as a transition from matrix flow in the PTn to fracture flow in the TSw; hence, the measurement method fails to detect the fracture flow component of net infiltration within welded, fractured units [lateral flow reportedly amounted to less than 1 mm/yr (0.04 in/yr) in this case (Flint, et al., 2002)].

Flint, et al. (1996) reported early during the development of the DOE water-balance plug-flow submodel that a Richards' equation submodel was also in development. Net infiltration rate results were not available for inclusion in their report at that time, and subsequent publications by this group have been silent on the continued development of the alternative submodel. Staff believe that comparisons between a Richards' equation-based model and a water-balance plug-flow model over several small subareas of the repository horizon would provide valuable information.

Neutron moisture monitoring: Neutron-logging of 98 shallow boreholes in the Yucca Mountain region produced net infiltration rate estimates ranging between 0 and 80 mm/yr (0 and 3 in/yr; Flint and Flint, 2000), and the calculated average net infiltration rate over the greater Yucca Mountain region was 11.6 mm/yr (0.457 in/yr; Flint, et al., 2002). Over the repository horizon, however, infiltration estimates ranged between 10 and 30 mm/yr (0.4 and 1.2 in). This methodology finds its major usage within the DOE net infiltration rate submodel as a predictor of storage changes with time. Flint, et al. (2002) note that local net infiltration not incurring a storage change (e.g., fracture flow or deep steady-state flow) cannot be detected by this measurement method. Thus, neutron-logging provides a lower-bound estimate of net infiltration, because the method cannot detect fracture flow. This measurement method provides sub-borehole-scale estimates of net infiltration rate, but statistically correlated precipitation rates and soil thicknesses have been used to make inter-borehole estimates.

Borehole temperature profiles: Water consumes heat as the liquid flows from cool, shallow depths to deeper and warmer thermal regimes, thus producing an apparent heat flow deficit compared to a case where heat energy is transferred through conduction alone. Thus, the net infiltration rate may be estimated by comparing a modeled one-dimensional heat-conduction-only temperature profile with a borehole-measured temperature profile, and attributing differences to net infiltration. Following analyses of temperature profiles from boreholes UZ #4 and UZ #5, Kwicklis and Rousseau (1999) found that the percolation rate beneath Pagany Wash and in the vicinity of the PTn and TSw interface fell within the range of 10 to 20 mm/yr (0.4 to 0.8 in/yr) at these two locations. Using temperature-profile data from Sass, et al. (1988), Flint, et al. (2002) optimized the fit between measured and modeled temperature profiles at ten deep boreholes. They obtained percolation rates ranging from 0.5 to 20 mm/yr (0.02 to 0.8 in/yr) at these locations as a result of this exercise, and further constrained the rates between 5 and 12 mm/yr (0.2 and 0.47 in/yr) above the repository horizon (Flint, et al., 2002). Borehole temperature profiles in combination with inverse models provide a borehole scale estimate of the percolation rate, and deep percolation is often assumed equivalent to net infiltration.

Environmental tracer methods: Dependent upon the measurement location (pores, perched water zone, or groundwater), these methods produce results that range from point scale to watershed scale to basin scale estimates of net infiltration rate. The chloride mass balance method assumes that the chloride flux is constant. That is, the product of the net infiltration rate and the subsurface chloride concentration is assumed equal to the product of the precipitation rate and the chloride concentration in the precipitation. The chloride mass balance method assumes plug- or piston-flow allowing time for evaporation to occur and chloride concentrations to increase; thus, this method may not be applicable for fractured rock beneath shallow soils (Flint, et al., 2002) and net infiltration rate estimates will generally be on the low side. While attempting to minimize the bias discussed above, net infiltration rates obtained through the chloride mass balance method applied to pore water range between 0.1 and 10 mm/yr (0.004 and 0.4 in/yr; Flint, et al., 2002; see also CRWMS M&O, 2000c), contingent upon location-dependent geomorphology and soil thickness.

Applied to perched waters, the chloride mass balance method suffers less from the assumption of piston flow, and analyses from boreholes SD-7 and UZ #14 indicate infiltration rates in these areas are equal to 15 and 8.5 mm/yr (0.59 and 0.33 in/yr; Flint, et al., 2002). However, perched waters may be a mixture of Pleistocene and Holocene waters; when the Holocene portion from these borehole waters was considered alone, rates of 8.3 and 7.4 mm/yr (0.33 and 0.29 in/yr) resulted. Another environmental tracer, bomb-pulse ^{36}Cl, produced field data that are consistent with a net infiltration rate range between 1 and 10 mm/yr (0.04 and 0.4 in/yr; Fabryka-Martin, et al., 1997).

Calcite deposition method: Calcite age dating and abundance analysis in Yucca Mountain fractures indicate that the associated percolation flux ranges between 2 and 20 mm/yr (0.08 and 0.8 in/yr) (US DOE, 2002). Such estimates, which are determined from secondary mineral analyses, cannot be considered reliable for present and future climate conditions, because secondary mineral deposition at Yucca Mountain incorporates poorly understood processes that have occurred over millions of years.

Heat transport method: Yucca Mountain sits above a small portion of a regional heat sink of hydrologic origin (Sass, et al., 1988, 1995). Eighty to one-hundred percent of the heat sink is believed to be attributable to the deep saturated zone below Yucca Mountain. Rickertsen cites Sass, et al. (1988) when he suggests that a percolation flux between 2 and 5 mm/yr (0.008 and 0.2 in/yr) can explain the remainder of the heat sink. In reality, Sass, et al. (1988) plainly state that they believe there are two additional processes (vaporization and advective heat flow) that may collectively make up any remaining percentage of the heat flow deficiency. But, lest one think that negligible infiltration may be implied by this analysis, Sass, et al. (1988) also state that the available thermo-hydrologic data do not preclude locally heavy infiltration within the study area. As Sass, et al (1988; 1995) note, the heat transport analysis for Yucca Mountain relies on poorly constrained data and limited techniques. It is doubtful that this method can support completion of Agreement TSPAI.3.18.

Empirical methods: While Maxey and Eakin (1949) were concerned with estimating spatial recharge on the subbasin scale for Nevada basins containing thick alluvial fill, Hevesi and Flint (1998) developed a modified Maxey-Eakin method for estimating recharge on a regional scale; in particular, they were concerned with the Yucca Mountain region where upland areas are dominated by thin soils. With the modified Maxey-Eakin method, average annual precipitation [175 mm/yr (6.89 in/yr)] is used to subdivide a region into a number of recharge zones. The model is essentially an exponential fit to the original Maxey-Eakin series of step-functions; however, zero percent recharge is associated with precipitation amounting to less than 100 mm/yr (4 in/yr), as opposed to 203 mm/yr (8 in/yr) for the Maxey-Eakin method (Hevesi, et al., 2002; Flint, et al, 2000). For the Death Valley region as a whole, Hevesi and Flint (1998) estimated recharge to be 2.9 mm/yr (0.11 in/yr), and for Yucca Mountain in particular, they estimated recharge to range between 0.2 and 1.4 mm/yr (0.008 and 0.055 in/yr). Rickertsen (2003) also notes that estimated values of average recharge in the greater Yucca Mountain region have been computed with the original Maxey-Eakin method as: (i) 2.4 mm/yr (0.09 in/yr) at Pahute Mesa; (ii) 2.8 mm/yr (0.11 in/yr) at Buckboard Mesa; (iii) 1.5 mm/yr (0.59 in/yr) at Jackass Flats; (iv) 0.6 mm/yr (0.002 in/yr) at Crater Flat; and (v) 1.1 mm/yr (0.43 in/yr) at Oasis Valley (Rush, 1971). Empirical Maxey-Eakin methods do not account for local variations in soil depth or bedrock permeability, both of which are important to an adequate assessment of the spatial distribution of net infiltration rates.

3.2 Review of the Physical Relationship of the Unsaturated Flow System on Barrier Capabilities of the Proposed Repository

Rickertsen (2003) provides a discussion in response to Agreement TSPAI.3.18 regarding the physical relationship between the net infiltration rate and barrier capabilities. In the event of a waste package failure, local areas of elevated precipitation and net infiltration may lead to local areas of increased seepage, which may cause more water to contact waste, and may also increase the transport velocity in the drift invert and in the unsaturated zone below the repository. Both of these latter effects (i.e., more water contacting waste and faster transport velocity) would be expected to have some effect on total-system repository performance. While the discussion by Rickertsen (2003) provides some useful insights, it does not provide a basis for closure of Agreement TSPAI.3.18. Rickertsen (2003) provides dose-based sensitivity analyses to provide insight on the significance to risk of increased net infiltration rates, seepage rates, and contaminant transport rates.

As conceptualized in the DOE performance assessment model, increased seepage would likely result in a larger fraction of drip shields in an aqueous environment, rather than just a humid environment, for more of the time. Rickertsen (2003) speculates that increased seepage would make the environment for drip shield corrosion more benign because of dilution and the presence of corrosion inhibiting ions, such as nitrate, in seepage water. In the event of drip shield failure, increased seepage would also cause a larger fraction of waste packages to be in an aqueous environment. Rickertsen points out, however, that DOE studies show that corrosion rates for Alloy 22 are similar for aqueous and humid air environments, implying that higher seepage would not substantially affect waste package lifetimes. The evaluation of the complex processes that might affect the chemistry of seepage water and the resulting effects on corrosion rates for drip shields and waste packages are part of the key technical issue Agreements ENFE.2.06 and ENFE.2.09. Additional confidence will be provided for conclusions stating that increased seepage would have either minimal or beneficial effects on corrosion rates upon the successful completion of such agreements which increase the understanding of the potential range of local chemical conditions that may occur on drip shield and waste package surfaces.

3.3 Review of Sensitivity Analyses for Risk Importance

Rickertsen (2003) provides dose-based sensitivity analyses to provide insight on the significance to risk of increased infiltration and seepage, and faster contaminant transport rates. The total-system sensitivity study described by Rickertsen (2003) includes three types of analyses: (i) a comparison of mean dose estimates between a case where the base-case net infiltration rate is used and a bounding case where the net infiltration rate is approximately equal to the present-day mean annual precipitation; (ii) a comparison of mean dose estimates between an expected seepage case with an average seepage rate of less than 0.1 m^3/yr (3.5 ft^3/yr) over approximately half the packages, and a bounding case where the seepage rate is set to 1.0 m^3/yr (35 ft^3/yr) over all waste packages; (iii) a comparison of dose estimates between the expected case and cases where flow and transport parameters are computationally neutralized (i.e., radionuclides are assumed to be released directly into wells in Amargosa Valley). The three types of sensitivity analyses are made for each of two scenarios: a nominal scenario for otherwise expected conditions, and an igneous activity groundwater release scenario in which magma is assumed to damage waste packages and drip shields in a portion of the repository.

For both the bounding net infiltration rate and seepage rate sensitivity analyses, the results of the nominal scenario analyses suggest mean annual dose estimates are dominated by highly soluble radionuclides and, because the inventory of these radionuclides can be exhausted by relatively small amounts of water, the results are not very sensitive to an increase in the net infiltration rate.

For the igneous activity groundwater release scenarios of bounding infiltration rate and seepage rate, dose estimates are also influenced by some less soluble radionuclides, and therefore the amount of water contacting the waste is shown to have a more significant effect on dose than for the nominal case. The increase in mean annual dose estimates for the bounding cases was generally less than an order of magnitude above the expected case dose estimates, however, and was generally less than about 1×10^{-3} mSv (0.1 mrem) during the 10,000 yr compliance period, which is substantially below the 0.15 mSv (15 mrem) regulatory limit.

For the sensitivity analyses of complete neutralization of flow and transport, mean doses for both the nominal scenario and igneous activity groundwater release scenario were modeled to arrive much earlier, as would be expected. Although the mean dose rates modeled for these scenarios were two to three orders of magnitude greater than the base-case dose estimates, the peak doses remained significantly below the 0.15 mSv (15 mrem) regulatory limit during the 10,000 yr compliance period.

4 NRC COMMENTS AND CONCLUSIONS

Rickertsen (2003) provided originally requested information to address the topic of the TSPAI.3.18 agreement, and the results of total system performance assessment simulations that illustrate the lack of sensitivity of dose to estimates of the net infiltration rate.

4.1 Comments and Conclusions on the Technical Information and Associated References

4.1.1 Water-Balance Plug-Flow Submodel as a Substitute for a Richards' Equation Submodel

The water-balance plug-flow submodel lacks realism because it redistributes liquid by instantaneously averaging it over the soil profile once every 24 hours. For shallow soils, this inaccuracy is probably acceptable during extreme El Nino-like precipitation events, and may be negligible during low precipitation periods (Flint, et al., 1996). Had the DOE used a Richards' equation submodel, it would have yielded higher evapotranspiration rates for soils with elevated moisture contents near the top of the soil profile, compared to the rates estimated by the water-balance plug-flow submodel with its uniform distribution of soil moisture, particularly in areas with moderately deep to deep soils [i.e., greater than 0.5 m (2 ft)]; however, it should be stated that deep soils are not prevalent above the repository horizon. Offsetting to this process would have been capillarity, which, when modeled by Richards' equation, would have allowed water to infiltrate into the bedrock earlier than what is possible with use of the water-balance plug-flow submodel because it requires that the entire soil profile be saturated before any water can infiltrate into the bedrock below.

It is difficult to determine whether and during what scenarios the water-balance plug-flow submodel or a Richards' equation-based submodel would yield more conservative net infiltration values. The system is complex and factors that might cause a divergence of infiltration estimates between a Richards' equation-based and a water-balance plug-flow submodel include:

- Submodel grid resolution
- Prediction capability of a submodel that is calibrated to present-day conditions
- Future climate states
- Storm type (e.g., initial conditions, intensity, and duration)
- Soil thickness
- Bedrock properties
- Localized non-Darcy flow conditions (e.g., rapid flow in open fractures)

Darcian methods are commonly used to estimate deep percolation flux and eventual recharge to the saturated zone; however, the lack of Richards' equation-based numerical models for simulating net infiltration at Yucca Mountain indicates that there is a general belief among DOE staff that this type of numerical model is not computationally efficient for use in the large-scale transient Yucca Mountain net infiltration model; thus, are not suitable for the determination of net infiltration rates. Staff maintain, however, that smaller Richards' equation-based numerical models for portions of the large-scale domain could provide valuable information and a truly viable method for drawing a direct comparison between the DOE's numerical water-balance plug-flow net infiltration submodel and a numerical Richards' equation-based submodel.

4.1.2 Multiple Lines of Evidence

While the multiple lines of evidence called upon by Rickertsen (2003) indicate that local point estimates of the net infiltration rate at Yucca Mountain are as high as 80 to 100 mm/yr (3 to 4 in/yr) in some locations, the DOE water-balance plug-flow submodel provides local 30 × 30 m (98 × 98 ft) grid cell estimates of the net infiltration rate that range between 0 and 250 mm/yr (0 and 9.8 in/yr; Flint, et al., 2002) for the present-day climate state. Some of the independent analysis methods provide estimates for a constrained range of net infiltration rates above the repository horizon {e.g., neutron-logging [10–30 mm/yr (0.4–1.2 in/yr)] and borehole temperature profiles [5–12 mm/yr (0.2–0.47 in/yr)]; Flint, et al., 2002}. Likewise, the DOE water-balance plug-flow submodel provides an estimate of the spatially and temporally averaged net infiltration rate above the potential repository horizon equal to 4.5 mm/yr (0.18 in/yr) for the current climate state. Finally, the modified Maxey-Eakin method is suitable for estimating average net infiltration in the greater Yucca Mountain regional study area, and has produced values ranging between 0.6 and 2.9 mm/yr (0.002 and 0.11 in/yr), while the DOE water-balance plug-flow submodel provides an estimate for the spatially and temporally averaged net infiltration rate in the Yucca Mountain regional study area of 2.9 mm/yr (0.11 in/yr) for the current climate state.

In the above comparison between field-derived and numerically derived estimates of net infiltration, one might find fault with the water-balance plug-flow submodel estimate of the average net infiltration rate above the repository horizon [4.5 mm/yr (0.18 in/yr)], because it appears too low compared to the independent analyses that led to higher estimates by a factor of between one and six. One must consider, however, the measurement or estimation scale used to determine the average net infiltration rate. For example, neutron logging has a sub-borehole measurement scale. Similarly, borehole temperature profile analysis has a borehole measurement scale. The water-balance plug-flow submodel, on the other hand, provides an estimate on the numerical grid cell scale of 30 × 30 m (98 × 98 ft), which is then spatially *and* temporally averaged.

While the local results from field estimates were spatially averaged to obtain a net infiltration rate range over the repository horizon, no attempt was made to obtain a combined spatial *and* long-term temporal average of the net infiltration rate that would be comparable to the long-term averages reflected in the infiltration model results. In fact, it is a much more simple matter to construct a long-term temporal average with a site scale numerical model, than it is to do so with the results from short-term physical measurement methods. From this situation alone, it can be surmised that a direct comparison between field-derived and numerically derived estimates provides limited insight into the accuracy of numerical estimates of net infiltration.

Furthermore, the scale represented by a conventional 51 mm (2 in) diameter borehole is at least five orders of magnitude smaller than the volume of porous material represented by the 30 × 30 m (98 × 98 ft) grid cell scale. Fast flow paths through fractures may be considered akin to some number of sub-borehole scale features within a single numerical grid cell. Thus, elevated infiltration rates through some number of sub-borehole scale fractures in a grid cell would be expected to be moderated by lower infiltration rates through the rest of the porous medium within the same grid cell. If there has been any bias in choosing borehole locations above the repository horizon, such as locating them at the most physically interesting sites (e.g., in this case, sites expected to experience larger amounts of infiltration), this fact would certainly affect the resulting spatial average, likely causing it to be elevated. Given all of these considerations, the factor of between one and six difference in the range of net infiltration rate estimates above the repository horizon is relatively small and is almost within the range of uncertainty considered in the DOE abstraction of net infiltration for performance assessment. Staff note that the net infiltration rate estimates are *almost* within the range of uncertainty considered by DOE because some of the multiple lines of evidence cited by Rickertsen (2003) suggest estimates that range between 10 and 30 mm/yr (0.4 and 1.2 in/yr) above the repository horizon. Meanwhile, the upper bound estimate that is considered in the DOE performance assessment for the present-day climate is only 11.1 mm/yr (0.437 in/yr) (CRWMS M&O, 2000a). Thus, it is not clear that either the mean or upper bound infiltration scenarios used in the total system performance assessment for site recommendation (CRWMS M&O, 2000b) adequately capture the range of net infiltration uncertainty.

4.1.3 Agreement Completion Based on Technical Merit

The technical content and references in the report by Rickertsen (2003), combined with other analyses of net infiltration rates at and near Yucca Mountain (e.g., Flint, et al., 2002), do provide the staff with a sufficient understanding of the DOE water-balance plug-flow submodel and the resulting estimates of net infiltration. It is not clear to staff, however, that the DOE total system performance assessment analyses adequately account for nonlinear flow processes in the estimates of net infiltration, and therefore does not underpredict infiltration. Nor has the technical basis presented shown that the non-linear flow processes represented by Richards' equation have been adequately represented in DOE's current model. Additional technical information is needed to complete Agreement TSPAI.3.18 based upon technical merit. Required is either a technical basis showing that the non-linear flow processes represented by Richards' equation have been adequately represented in DOE's current model, or a technical basis demonstrating that a water-balance plug-flow submodel is not underpredicting the net infiltration rate over the repository in comparison with a Richards' equation submodel.

4.2 Comments and Conclusions on the Sensitivity Analyses for Risk Importance

The sensitivity analyses outlined by Rickertsen (2003) provide useful insight into the risk importance of the net infiltration rate in a total system performance assessment context and, combined with existing site data, may ultimately provide a sufficient basis for resolution of the USFIC KTI subissue shallow infiltration. However, the risk sensitivity study provided is not sufficiently documented to support the completion of Agreement TSPAI.3.18 on the basis of low risk significance. In a recent letter,[3] NRC staff have previously relayed to DOE that additional information is needed when using risk as a basis to complete key technical issue agreements. First, an analysis of combined uncertainty for all of the key technical issue agreements that are to be addressed using the low risk significance argument is required. Second, DOE should provide an adequate description of the sensitivity analyses completed. Third, some measure of how the variability of results changes between the different modeled cases is needed, because

[3]Schlueter, J.R. "Use of Risk as a Basis for Closure of Key Technical Issue Agreements." Letter (January 27, 2003) to J.D. Ziegler, DOE.

only the mean results of the stochastic performance assessment simulations have been presented to date. For example, presentation of the 5th and 95th percentiles of annual dose estimates, in addition to the mean dose estimates, would be a satisfactory way of conveying the variability and uncertainty of performance assessment estimates. These information needs apply to the DOE sensitivity analyses provided in the response to Agreement TSPAI.3.18. The three areas of information missing from these sensitivity analyses are described in more detail below.

1. The combined effect of uncertainties (for all agreements addressed with a risk argument) needs to be evaluated before the individual uncertainties can be dropped from further consideration. Otherwise, one could have the situation where moderate increases in risk are considered insignificant but, if numerous uncertainties are addressed in this manner, the combined effect could be significant even when using a risk-based performance metric.

   If agreements in other areas (e.g., waste package corrosion, spent nuclear fuel dissolution) that influence total-system performance assessment model results were not to be resolved via the use of risk-information in lieu of the originally agreed upon information, then there would be no need to evaluate the combined effects of uncertainties. However, it is the NRC's understanding that this is not the case. For example, the letter report for Agreement TSPAI.3.03 analyzed the sensitivity of the drip shield by means of neutralization, while the analyses for Agreement TSPAI.3.22 showed the sensitivity results of neutralizing natural barrier flow parameters and natural barrier flow and transport parameters. An adequate combined effects uncertainty analyses is needed as discussed in the January 27, 2003, letter from Schlueter (NRC) to Ziegler (DOE).

2. To further support the analysis results, DOE should provide an adequate description of the analysis (e.g., changes to the models, discussion of results) completed to evaluate the sensitivity cases. It is the NRC's understanding that the record package developed for the analysis contains an adequate description of the changes to the base case TSPA model.

   An adequate description is needed of the changes made to the model for the analyses. Some examples of questions, for which staff currently do not have adequate answers, are given below.

   - The Rickertsen (2003) report states that the model for the igneous activity groundwater release scenario assumes that magma "damages" a number of waste packages and drip shields. The number is a probability distribution that average 300. What is the level of damage represented within this number?

   - Section 2.3 of the Rickertsen (2003) report states that the bounding infiltration case analysis includes the far field effect of increased infiltration but does not include near-field effects such as increased seepage into emplacement drifts. Does the spatial and temporal variability of seepage in the bounding infiltration case change in any way compared to the base case?

- The DOE needs to update their total-system sensitivity analyses with regards to the groundwater protection standards (nominal scenario only) to support their claim that Agreement TSPAI.3.18 will not play a significant role in determining whether the groundwater protection standards will be met. The last such analyses were done before December 2000 (CRWMS M&O, 2000b).

3. To convey uncertainty in the analyses, DOE should provide information on the variability of simulation results for the sensitivity cases and base cases, by plotting, for example, the 5^{th} and 95^{th} percentiles of dose estimates along with the mean dose estimates.

   Uncertainty and variability in the output of the analysis was not presented, but it is NRC's understanding that this information is readily available.

In conclusion, additional risk information is needed to complete Agreement TSPAI.3.18 based upon risk assessments and sensitivity analyses. When the DOE's risk sensitivity study is sufficiently documented to support the completion of Agreement TSPAI.3.18, staff will consider this agreement to be complete on the basis of low risk significance.

5 STATUS OF AGREEMENT

The status of the KTI Agreement TSPAI.3.18 is "need additional information." Additional technical information is needed if DOE chooses to complete Agreement TSPAI.3.18 based upon technical merit (see Section 4.1.3). Additional risk information is needed if DOE chooses to complete Agreement TSPAI.3.18 based upon risk assessments and sensitivity analyses (see Section 4.2).

6 REFERENCES

CRWMS M&O. "Total System Performance Assessment–Viability Assessment (TSPA-VA) Analyses Technical Basis Document." Chapter 2: Unsaturated Zone Hydrology Model. B00000000–01717–4301–00002. Revision 00. Las Vegas, Nevada: CRWMS M&O. 1998.

CRWMS M&O. "Unsaturated Zone Flow and Transport Model Process Model Report." TDR–NBS–HS–000002. Revision 00. ICN 02. Las Vegas, Nevada: CRWMS M&O. 2000a.

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

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

Fabryka-Martin, J.T., A.L. Flint, D.S. Sweetkind, A.V. Wolfsberg, S.S. Levy, G.J.C. Roemer, J.L.Roach, L.W. Wolfsberg, and M.C. Duff. "Evaluation of flow and transport models of Yucca Mountain, based on chlorine-36 studies for FY97". YMP Milestone Report SP2224M3. Los Alamos, New Mexico: Los Alamos National Laboratory. 1997.

Flint, A.L., J.A. Hevesi, and L.E. Flint. “Conceptual and Numerical Model of Infiltration for the Yucca Mountain Area, Nevada.” Milestone 3GUI623M. Denver, Colorado: U.S. Geological Survey. 1996.

Flint, A.L. and L.E. Flint. “Near Surface Infiltration Monitoring Using Neutron Moisture Logging, Yucca Mountain, Nevada.” *Vadose Zone, Science and Technology Solutions*. B.B. Looney and R.W. Falta, eds. Battelle Press. 2000.

Flint, A.L., L.E. Flint, J.A. Hevesi, F. D’Agnese, and C. Faunt. “Estimation of Regional Recharge and Travel Time Through the Unsaturated Zone in Arid Climates.” *Dynamics of Fluids in Fractured Rock*. B. Faybishenko, P.A. Witherspoon, and S.M. Benson, eds. AGU. 2000.

Flint, A.L., L.E. Flint, E.M. Kwicklis, J.T. Fabryka-Martin, and G.S. Bodvarsson. “Estimating Recharge at Yucca Mountain, Nevada, USA: Comparison of Methods.” *Hydrogeology Journal*. Vol. 10, No. 1. pp. 180–240. 2002.

Hevesi, J.A. and A.L. Flint. “Geostatistical Estimates of Future Recharge for the Death Valley Region.” Proceedings of the Eighth International Conference on High-Level Radioactive Waste Management, Las Vegas, Nevada, May 11-15, 1998. LeGrange Park, Illinois: American Nuclear Society. pp. 173–177. 1998.

Hevesi, J.A., A.L. Flint, and L.E. Flint. “Preliminary Estimates of Spatially Distributed Net Infiltration and Recharge for the Death Valley Region, Nevada–California.” USGS Water-Resources Investigations Report 02-4010. Sacramento, California: U.S. Geological Survey. 2002.

Kwicklis, E.M., A.L. Flint, and R.W. Healy. “Estimation of Unsaturated Zone Liquid Water Flux at Borehole UZ #4, UZ #5, UZ #7, and UZ #13, Yucca Mountain, Nevada, From Saturation and Water Potential Profiles.” Proceedings of the Topical Meeting on Site Characterization and Model Validation, Focus, 93, Las Vegas, Nevada, September 26–29, 1993. LaGrange Park, Illinois: American Nuclear Society. pp. 39–57. 1993.

Kwicklis, E.M. and J.P. Rousseau. “Analysis of Percolation Flux Based on Heat Flow Estimated in Boreholes.” *Hydrogeology of the Unsaturated Zone, North Ramp Area of the Exploratory Studies Facility, Yucca Mountain, Nevada.* J.P. Rousseau, E.M. Kwicklis, and D.C. Gillies, eds. USGS Water-Resources Investigations Report 98-4050. Denver, Colorado: U.S. Geological Survey. pp. 184–208. 1999.

Maxey, G.B. and Eakin, T.E. “Ground Water in White River Valley, White Pine, Nye, and Lincoln Counties, Nevada” Water Resources Bulletin No. 8. Carson City, Nevada: State of Nevada, Department of Conservation and Natural Resources. 1949.

Richards, L.A. “Capillary conduction of liquids in porous mediums.” *Physics*. Vol. 1. pp. 318–333. 1931.

Rickertsen, L.D. “KTI Letter Report: Response to TSPAI 3.18, 3.21, 3.23, and TEF 2.13." REG-WIS-PA-000001. Revision 02. Las Vegas, Nevada: Bechtel SAIC Company. 2003.

Rush, F.E. “Regional Ground-Water Systems in the Nevada Test Site Area, Nye, Lincoln, and Clark Counties, Nevada.” Water Resources–Reconnaissance Series Report 54. Carson City, Nevada: State of Nevada, Department of Conservation and Natural Resources. 1971.

Sass, J.H., A.H. Lachenbruch, W.W., Dudley, Jr., S.S. Priest, and R.J. Munroe. “Temperature, Thermal Conductivity, and Heat Flow Near Yucca Mountain, Nevada: Some Tectonic and Hydrologic Implications.” Open-File Report 87-649. Denver, Colorado: U.S. Geological Survey. 1988.

Sass, J.H., W.W. Dudley, Jr., and A.H. Lachenbruch. “Regional Thermal Setting.” *Major Results of Geophysical Investigations at Yucca Mountain and Vicinity, Southern Nevada*. H.W. Oliver, D.A. Ponce, and W.C. Hunter, eds. Open-File Report 95-74. Menlo Park, California: U.S. Geological Survey. 1995.

U.S. Department of Energy. "Viability Assessment of a Repository at Yucca Mountain: Introduction and Site Characteristics." DOE/RW–0508. Vol. 1. Washington, DC: U.S. Department of Energy. 1998.

U.S. Department of Energy. “Yucca Mountain Science and Engineering Report.” DOE/RW–0539. Revision 01. Washington, DC: U.S. Department of Energy, OCRWM. 2002.

U.S. Geological Survey. “Simulation of Net Infiltration for Modern and Potential Future Climates Analysis Model Report.” ANL-NBS-HS-000032. Revision 00, ICN 02. Denver, Colorado: U.S. Geological Survey. 2001.

Watson, P., P. Sinclair, and R. Waggoner. “Quantitative Evaluation of a Method for Estimating Recharge to the Desert Basins of Nevada.” *Journal of Hydrogeology*. Vol. 31, No. 3/4. pp. 335–357. 1976.