ISSUE RESOLUTION STATUS REPORT

KEY TECHNICAL ISSUE: UNSATURATED AND SATURATED FLOW UNDER ISOTHERMAL CONDITIONS

Division of Waste Management
Office of Nuclear Material
Safety & Safeguards
U.S. Nuclear Regulatory Commission

Revision 0

September 1997

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This report has been prepared jointly by staff from the NRC and the Center for Nuclear Waste Regulatory Analyses (CNWRA). Primary authors of the report are Neil Coleman (NRC), Stuart Stothoff (CNWRA), and William Murphy (CNWRA). The authors offer special thanks to Budhi Sagar (CNWRA), Gordon Wittmeyer (CNWRA), and David Brooks (NRC) for their excellent reviews. The report greatly benefitted from insights contributed by consultants David Groeneveld, Dani Or, and David Woolhiser.

QUALITY OF DATA, ANALYSES, AND CODE DEVELOPMENT

DATA: No NRC or CNWRA-generated original data are contained in this report. Sources for other data should be consulted for determining the level of quality of those data.

ANALYSES AND CODES: BREATH computational software was used to develop Figure B-2 (estimated net infiltration in the vicinity of the proposed repository footprint). BREATH is controlled under CNWRA Technical Operating Procedure-018, Development and Control of Scientific and Engineering Software. The calculations were checked as required by QAP-014, Documentation and Verification of Scientific and Engineering Calculation, and recorded in a scientific notebook.

1.0 INTRODUCTION

One of the primary objectives of the Nuclear Regulatory Commission's (NRC's) refocused prelicensing program is to focus all its activities on resolving the 10 key technical issues (KTIs) it considers to be most important to repository performance. This approach is summarized in Chapter 1 of the staff's annual progress reports (e.g., NUREG/CR-6513, Center for Nuclear Waste Regulatory Analyses, CNWRA, 1996). Other chapters address each of the 10 KTIs by describing the scope of the issue and subissues, path to resolution, and progress achieved during fiscal year (FY) 1996.

Consistent with 10 CFR Part 60 requirements and a 1992 agreement with the U.S. Department of Energy (DOE), staff-level issue resolution can be achieved during the prelicensing consultation period; however, such resolution at the staff level would not preclude the issue being raised and considered during the licensing proceedings. Issue resolution at the staff level during prelicensing is achieved when the staff has no further questions or comments (i.e., open items) at a point in time, regarding how the DOE program is addressing an issue. There may be some cases where resolution at the staff level may be limited to documenting a common understanding regarding differences in the NRC and the DOE points of view. Pertinent additional information could raise new questions or comments regarding a previously resolved issue.

An important step in the staff's approach to issue resolution is to provide DOE with feedback regarding issue resolution, before the viability assessment. Issue Resolution Status Reports (IRSRs) are the primary mechanism that the staff will use to provide DOE feedback on the subissues making up the KTIs. IRSRs comprise 1) acceptance criteria which will be used by the staff to review the DOE license application and prelicensing submittals, as well as indicating the basis for resolution of the subissue, and 2) the status of resolution including where the staff currently has no comments or questions as well as where it does. Feedback is also contained in the staff's annual progress report, which summarizes the significant technical work toward resolution of all KTIs during the preceding FY. Finally, open meetings and technical exchanges with DOE provide opportunities to discuss issue resolution, identify areas of agreement and disagreement, and develop plans to resolve such disagreements.

In addition to providing feedback, the IRSRs will be guidance for the staff's review of information in DOE's viability assessment. The staff also plans to use the IRSRs in the future to develop the Standard Review Plan (SRP) for the repository license application.

Each IRSR contains six sections, including this introduction in Section 1.0. Section 2.0 defines the KTI, all the related subissues, and the scope of the particular subissue that is the subject of the IRSR. Section 3.0 discusses the importance of the subissue to repository performance, including: 1) qualitative descriptions, 2) reference to a total system performance flowdown diagram, 3) results of available sensitivity analyses, and 4) relationship to DOE's Waste Containment and Isolation Strategy (i.e., the approach to its safety case). Section 4.0 provides the staff's review methods and acceptance criteria that will be used to evaluate DOE's prelicensing and licensing submittals. These acceptance criteria are guidance for the staff and indirectly for DOE as well. The staff's technical basis for its acceptance criteria will also be included to further document the rationale for the staff's decisions. Section 5.0 concludes the report with the status of resolution indicating those items resolved at the staff level or those items remaining open. These open items will be tracked by the staff and resolution will be documented in future IRSRs. Section 6.0 contains the references cited in the report.

2.0 ISSUE/SUBISSUE STATEMENT

The primary objective of this KTI is to assess all aspects of the ambient hydrogeologic regime at Yucca Mountain (YM) that have the potential to compromise the performance of the proposed repository. The secondary objective of this KTI is to develop review procedures and to conduct technical investigations to assess the adequacy of DOE's characterization of key site- and regional-scale hydrogeologic processes and features that may adversely affect performance Subissues deemed important to the resolution of this KTI have been identified, and are framed as questions:

(i) What is the likely range of future climates at YM?

(ii) What are the likely hydrologic effects of climate change?

(iii) What is the estimated amount and what is the spatial distribution of present-day shallow groundwater infiltration?

(iv) What is the estimated amount and what is the spatial distribution of present-day groundwater percolation through the proposed repository horizon?

(v) What is the estimated amount and what is the spatial distribution of groundwater percolation through the proposed repository horizon during the period of repository performance?

(vi) What are the ambient flow conditions in the saturated zone?

Subissues (i) and (ii) have already been addressed in an issue resolution status report dated June 30, 1997 (NRC, 1997). This revision of the IRSR addresses subissue (iii) above, which focuses on methods to estimate present-day shallow groundwater infiltration at YM. Subissues (iv), (v), and (vi) will be treated in future IRSRs by the staff.

Prevailing meteorological conditions, along with local geologic conditions and plant communities, control the rates of infiltration, deep percolation, and groundwater seepage through a geologic repository located in an unsaturated environment. Reasonable estimates of present-day infiltration, i.e., initial conditions, must be obtained so that projections can be made about future infiltration and deep percolation under conditions of climate change. This report summarizes the pertinent conclusions of numerous publications related to infiltration that are relevant to YM. Based on the extensive scientific literature, the NRC staff concludes that reasonable methods exist to bound the range of present-day shallow infiltration. Review methods and acceptance criteria are provided for reviewing DOE's evaluations of shallow infiltration, and how they will be used to assess the performance of a high-level waste (HLW) repository.

3.0 IMPORTANCE OF SUBISSUES TO REPOSITORY PERFORMANCE

3.1 What is the likely range of future climates at YM?

This information was provided in the pilot IRSR (see NRC, 1997). An EPA reference, Titus and Narayanan (1995), was omitted from the bibliography in NRC, 1997. Titus and Narayanan

(1995) is available via the internet (http://www.gcrio.org/EPA/sealevel/text.html).

- **NRC/CNWRA Sensitivity Studies**

The range of future climates at YM is not being assessed in our sensitivity studies. It is already well understood that repository performance can be significantly affected by climate change. NRC (1997) describes the acceptance criteria that the staff will use to review DOE's treatment of climate change in performance assessments.

3.2 What are the likely hydrologic effects of climate change?

This information was provided in the pilot IRSR (see NRC, 1997).

- **NRC/CNWRA Sensitivity Studies**

These studies are currently underway. The sensitivity of hypothetical dose to variations in shallow groundwater infiltration will be documented in a separate report in FY98.

3.3 What is the estimated amount and what is the spatial distribution of present-day shallow groundwater infiltration?

Present-day shallow infiltration is a key hydrologic factor in the isolation of HLW within a proposed geologic repository at YM. It must be reasonably understood to provide initial conditions for projecting future hydrologic changes, because the Earth's climate could change significantly during the time that wastes will remain hazardous. Climate controls the range of precipitation, which, in part, controls the rates of infiltration, deep percolation, and groundwater flux through a geologic repository located in an unsaturated environment. Water flow through a geologic repository and its environs depends on both surface processes (precipitation, evapotranspiration, overland flow, and infiltration) and subsurface processes (deep percolation, moisture recirculation, and lateral flow). Changes in infiltration will likely induce other changes, such as regional fluctuations in the elevation of the water table. Water-table rise would reduce the thickness of the unsaturated zone barrier. Therefore, future changes in climate could alter infiltration from present-day rates and significantly influence the ability of a repository to isolate waste.

The importance of groundwater flux as the key parameter for repository performance in an unsaturated zone is well known, and has been further emphasized by DOE's most recent report (DOE, 1995) on total system performance assessment (TSPA). On page ES-30 of that report it is stated that

> ...in the overall TSPA analyses, an over-arching theme comes back again and again as being the driving factor impacting the predicted results. Simply stated, it is the amount of water present in the natural and engineered systems and the magnitude of aqueous flux through these systems that controls the overall predicted performance.... Therefore, information on...[this topic]...remains the key need to enhance the representativeness of future iterations of TSPA.

Sensitivity studies clearly showed the predominance of percolation flux in estimating cumulative radionuclide releases and peak radiation doses over a 10-kyr (1 kyr=1000 years) period (see DOE, 1995, pp. 10-6 and 10-7).

DOE's "Waste Containment and Isolation Strategy" (DOE, 1996, p. 5) likewise states that "performance assessments have shown that seepage into the emplacement drifts is the most important determinant of the ability of the site to contain and isolate waste." The importance of infiltration as a hydrologic parameter was recognized by the staff in its Iterative Performance Assessment Phase 2. NRC (1995, p. 10-4) states that "Although the flux of liquid water through the repository depends on...infiltration, hydraulic conductivity, and porosity, performance correlates most strongly to infiltration." Finally, Figure 1 (CNWRA, 1994) shows that infiltration-related matters have been important factors in recent performance assessments.

	Response to Climate Change
U.S. Nuclear Regulatory Commission, Phase 1 (NRC, 1992)	• Increased Infiltration • Water-Table Rise
U.S. Nuclear Regulatory Commission, Phase 2 (NRC, 1995a)	• Increased Infiltration • Water-Table Rise
Sandia National Laboratories, TSPA 1991 (SNL, 1992)	• Increased Infiltration
Pacific Northwest Laboratory (PNL, 1993)	• Increased Infiltration
Electric Power Research Institute, Phase 1 (EPRI, 1990)	• Increased Infiltration
Electric Power Research Institute, Phase 2 (EPRI, 1992)	• Increased Infiltration - Current - Greenhouse - Micropluvials • Water-Table Rise

Figure 1. Comparison of implementations of infiltration scenarios for YM. (after CNWRA, 1994, p. 7-4)

The staff is developing a strategy for assessing the performance of a proposed repository at YM. As currently visualized by the staff, key elements of this strategy are defined by those elements needed to demonstrate repository performance. These elements are illustrated in draft Figure A-1 in Appendix A. Acceptance criteria for abstracting each of these elements into a demonstration of compliance are under development. Present-day shallow infiltration is an important factor in repository performance because it must be reasonably understood to provide initial conditions for projecting future changes in infiltration, deep percolation, near-field hydrology, and transport rates in the unsaturated zone. Therefore, the acceptance criteria for the treatment of infiltration are subsidiary to and designed to complement the broader-level acceptance criteria for the abstraction of the key elements.

For DOE to adequately demonstrate and quantify in its TSPA the effects that present-day infiltration might have on repository performance, it must consider how these effects interplay with the other factors within and between key elements in the engineered and natural subsystems of the repository. As highlighted in draft Figure A-1, present-day shallow infiltration is an important factor that needs to be abstracted into three of the key elements of the engineered and natural subsystems: (1) Quantity and Chemistry of Water Contacting Waste Forms (includes consideration of shallow infiltration and deep percolation); (2) Fracture vs. Matrix Flow (includes consideration of shallow infiltration); and (3) Spatial and Temporal Distribution of Flow (includes consideration of infiltration).

- **NRC/CNWRA Sensitivity Studies**

These studies are currently underway. The sensitivity of hypothetical dose to variations in shallow groundwater infiltration will be documented in a separate report in FY98.

3.4 What is the estimated amount and what is the spatial distribution of present-day groundwater percolation through the proposed repository horizon?

See Section 3.3.

- **NRC/CNWRA Sensitivity Studies**

These studies are currently underway. The sensitivity of hypothetical dose to variations in shallow infiltration, deep groundwater percolation, and unsaturated zone flow parameters will be documented in a separate report in FY98.

3.5 What is the estimated amount and what is the spatial distribution of groundwater percolation through the proposed repository horizon during the period of repository performance?

See Section 3.3.

- **NRC/CNWRA Sensitivity Studies**

These studies are currently underway. The sensitivity of hypothetical dose to variations in shallow infiltration, deep groundwater percolation, and unsaturated zone flow parameters will be documented in a separate report in FY98.

3.6 What are the ambient flow conditions in the saturated zone?

This subissue is important to repository performance because saturated zone characteristics will influence how future societies may use groundwater resources in the YM region. In brief, the ambient flow conditions in the saturated zone must be considered to: (1) estimate volumetric flow in well production zones; (2) estimate transport rates in the volcanic and alluvial aquifers; (3) estimate retardation of radionuclides in production zones and alluvium; (4) estimate dilution of radionuclides during well pumping; and (5) determine the location and lifestyle of a critical population group. These elements are shown in draft figure A-1 (see Appendix A).

- **NRC/CNWRA Sensitivity Studies**

These studies are currently underway. The sensitivity of hypothetical dose to variations in saturated zone flow parameters and groundwater pumping scenarios will be documented in a separate report in FY98.

4.0 REVIEW METHODS AND ACCEPTANCE CRITERIA

4.1 What is the likely range of future climates at YM?

Review methods, acceptance criteria, and technical bases were provided in a previous version of this IRSR (see NRC, 1997). One additional acceptance criterion should be added to Section 4.1, p. 6 of NRC, 1997, as follows:

- Data were collected and documented under acceptable quality assurance (QA) procedures. Analyses were developed and documented under acceptable QA procedures.

4.2 What are the likely hydrologic effects of climate change?

Review methods, acceptance criteria, and technical bases were provided in a previous version of this IRSR (see NRC, 1997). One additional acceptance criterion should be added to Section 4.2, p. 16 of NRC, 1997, as follows:

- Data were collected and documented under acceptable QA procedures. Analyses were developed and documented under acceptable QA procedures.

4.3 What is the estimated amount and what is the spatial distribution of present-day shallow groundwater infiltration?

The staff's technical review of DOE's treatment of present-day shallow infiltration will be based on an evaluation of the completeness and applicability of the data and evaluations presented by DOE. It is expected that DOE will summarize or document the results of all significant infiltration-related studies that have been conducted in the YM vicinity. The staff will determine whether DOE has reasonably complied with the Acceptance Criteria in section 4.3.1 below.

4.3.1 Acceptance Criteria

- DOE has estimated shallow infiltration for use in the performance assessment (PA) of YM using mathematical models that incorporate site-specific climatic, surface, and subsurface information. DOE has provided sufficient evidence that the mathematical models were reasonably verified with site data. These data would include measured infiltration data and indirect evidence such as geochemical and geothermal data. DOE may choose to use a vertical one-dimensional (1D) model to simulate infiltration. However, in that case. DOE must reasonably show that the fundamental effects of heterogeneities, time-varying boundary conditions, evapotranspiration, depth of soil cover, and surface-water runoff have been considered in ways that do not underestimate infiltration.

- DOE has (1) appropriately considered the spatial and temporal variability; (2) has analyzed infiltration at appropriate time and space scales; and (3) has tested the abstracted model against more detailed models to assure that it produces reasonable results for shallow infiltration under conditions of interest. Recent studies by NRC (Stothoff, et al., 1996) and the DOE (Flint, et al., 1994; Flint and Flint, 1995; Flint, et al., 1996a) suggest that shallow infiltration is relatively high in areas where rocks are covered with shallow soils or channels and relatively low in areas where soil cover is deep. In addition, infiltration takes place episodically in time with areas having a shallow soil cover contributing more frequently.

- DOE has characterized shallow infiltration in the form of either probability distributions or deterministic upper-bound values for PA. The DOE has provided sufficient data and analyses to justify the chosen probability distribution or bounding value. DOE's expert elicitation on unsaturated zone flow (DOE, 1997) resulted in various estimates of a related parameter, the groundwater percolation flux at the depth of the proposed repository (see Appendix C of this report, Table C-2). The estimated aggregate mean flux was approximately 10 mm/yr. The panelists estimated the 95th-percentile percolation flux over a range from 10 to 50 mm/yr, with an aggregate estimate of 30 mm/yr. An independent staff assessment of an upper bound for yearly shallow infiltration under present climatic conditions is about 25 mm, which is somewhat less than the aggregate 95th percentile flux estimated by the expert panel. Given the importance of infiltration in PA, and the degree to which estimates of this parameter have changed in recent years, the staff will continue to review infiltration at YM. If needed, we will provide updates in future revisions of the IRSR.

- DOE's estimates of the probability distribution or upper bound for present-day shallow infiltration need not be refined further if the DOE demonstrates through TSPA and associated sensitivity analyses that such refinements will not significantly alter the estimate of total-system performance.

- If used, expert elicitations were conducted and documented using the guidance in the Branch Technical Position on Expert Elicitation (NRC, 1996), or other acceptable approaches.

- Data were collected and documented under acceptable QA procedures. Analyses were developed and documented under acceptable QA procedures.

4.3.2 Technical Basis for Review Methods and Acceptance Criteria

- **Implications of Net Infiltration Characterization for Repository Performance**

The behavior of deep percolation is of direct interest for characterizing repository performance, both for characterizing how liquid (the dominant vector of radionuclide release) contacts the waste packages and for characterizing how the released radionuclides migrate to the water table and to potential receptors. If flow is predominately within the matrix, the waste-emplacement drifts would tend to be protected through capillary-barrier effects and migration through the unsaturated zone would tend to be quite slow (e.g., assuming 1 mm/yr fluxes and 10 percent average moisture content, water travel times for 100 m would be 10^4 yr and sorption processes might further retard many radionuclides). As matrix flow in welded and nonwelded tuffs is strongly diffusive due to capillary forces, matrix flows would tend to be smoothly distributed in space and many drifts might be affected by matrix fluxes. On the other hand, if flow is predominantly through fractures, the drifts would be less well protected through capillary-barrier effects and travel times to the water table would be drastically reduced. Also, as permeabilities of the fractures are rather large, it is possible that relatively few fractures might carry the bulk of the water and only a few drifts would be contacted by a flowing fracture. Accordingly, it is important to characterize net infiltration in terms of the capacity for driving fracture flow at and below the repository horizon.

Net vertical infiltration from the ground surface is the predominant source of moisture for deep percolation with capillary rise from the water table and vapor redistribution due to the geothermal gradient both potentially contributing a small amount of water to deep percolation. Deep percolation patterns can be strongly dependent on the nature of infiltration due to the intermittent pattern of precipitation in arid and semiarid climates. For example, consider a homogeneous fractured welded tuff with a matrix saturated hydraulic conductivity K_{sat} of 10 mm/yr and a fracture K_{sat} of 10^4 mm/yr. If a source of water is applied at a steady rate of 5 mm/yr, then the fractures will not be active due to capillary effects. On the other hand, if the same total volume of water is due to an extreme precipitation event and applied over a short period, for example 1 month out of every 10 yr, the average flow during that month is 600 mm/yr and at best the matrix can carry 1.7 percent of the total flux, leaving the remainder to the fractures. Further, unless percolation-flux measurements are made at less than one-month intervals, the example episodic-flow event that dominates the hydraulic regime could be completely missed. High flux rates should not be unexpected, as a significant rainfall might be 1 cm over a period of a day (equivalent to 3,650 mm/yr under steady-state conditions). Accordingly, the episodicity of infiltration and the ability of the soil profile to attenuate the wetting pulses are issues that should be evaluated to appropriately characterize the behavior of deep percolation.

The spatial distribution of net shallow infiltration is a related issue with implications for deep percolation characterization. Consider the same homogeneous fractured welded tuff as before. If a steady 5 mm/yr source of water is applied uniformly over the surface of the tuff, the matrix should carry the entire flow and the fractures not participate. On the other hand, if the same steady total volume of water were concentrated in a small part of the area [i.e., channels in the study area considered by Flint, et al., 1996a], the local flux would be much larger and the fractures would carry most of the flow near the surface. Characterization of deep percolation behavior is dependent on the localization of shallow net infiltration.

The ability of shallow-infiltration characterization methods to predict shallow infiltration under climatic variation is a final issue that must be considered. This issue is not addressed explicitly in this report. Performance of the potential repository, however, must be assessed over periods of time long enough for climatic variation to be a factor. And, methods for characterizing shallow infiltration that are suitable for such long time periods are more useful for PA than methods that can only be applied for current climatic conditions. Thus, methods explicitly reliant on climatic information would be expected to be more useful than methods that do not consider it.

- **Measurements and Modeling Related to Net Infiltration at YM**

A wide variety of methods are used to estimate net infiltration and the components of a water-balance equation in semiarid environments. Good overviews of advantages and disadvantages of some of the more common methods are presented by Allison, et al. (1994) and Gee and Hillel (1988).

A number of background papers discuss issues related to infiltration in arid and semiarid environments (Barnes, et al., 1994; French, et al., 1996; Gee, et al., 1994; Stephens, 1994). In such environments, particularly in deep alluvial covers, recharge is highly intermittent due to the need for one or several large storms to overcome the soil-moisture deficit arising from an excess of potential evapotranspiration over average annual precipitation. Timing of the precipitation is important, as a moderate rainfall when evapotranspiration is low may be more significant to net infiltration than a much larger event when evapotranspiration is high. Distribution of extreme events is also important, as in some environments total precipitation over a month must be several times larger than the mean for that month for net infiltration to occur (Barnes, et al., 1994).

The literature generally does not discuss situations where shallow soils overlie fractured bedrock, common over much of the repository footprint. In such areas, there is relatively little storage volume to fill above fracture pathways that may conduct fluxes to depths below the evapotranspiration zone. One might expect that net infiltration in shallow soils may occur with smaller, more frequent storms than discussed in the literature.

Each of the methods discussed below has been used at YM or the Nevada Test Site (NTS) to estimate infiltration or a component of the water-balance equation. Advantages and disadvantages of each method, and relevant predictions using the method, are discussed in each section.

1. Empirical Correlations

a. Recharge

An empirical correlation between elevation and recharge for Nevada groundwater basins was developed by Maxey and Eakin in the late 1940s and early 1950s (Maxey and Eakin, 1949; Eakin, et al., 1951). The relationship was based on estimating discharges from a basin and correlating the discharge to the percentage of the basin within each of several broad elevation classes. Each elevation class has an associated precipitation and percent of precipitation that becomes recharge, both increasing with elevation. Watson, et al. (1976) investigated the relationship in 63 of the 212 basins in Nevada that were characterized at the time, concluding that the method is necessarily subjective, reasonably robust, but mainly useful as a first approximation.

Using the method, one can estimate recharge anywhere within Nevada; however, the method is most reasonable on a regional scale and larger and is highly questionable at scales as small as the YM site scale. The method is applicable to time scales comparable to the residence time within a basin. The method was developed under current climatic conditions and extending the method to consider climatic change is not straightforward. A variety of investigators have used the Maxey-Eakin method or a variant of the method at or near YM (Malmberg and Eakin, 1962; Rush, 1970; Czarnecki and Waddell, 1984; Czarnecki, 1985; Hevesi and Flint, 1996), primarily in the context of regional scale hydrology or regional-scale flow simulators. Rush (1970) estimates maximum recharge for Crater Flat and Jackass Flats to be 3 percent of infiltration. Czarnecki (1985) estimates areally distributed recharge for Crater Flat, Jackass Flats, and YM to be 0.5 mm/yr. In Czarnecki's model, Timber Mountain and the area northeast of YM were assigned a recharge value of 2 mm/yr; recharge along Fortymile Wash was estimated at 410 mm/yr (NRC, 1995a, p. I-10).

b. Potential Evapotranspiration

Evapotranspiration is a major component of the water balance equation commonly addressed through empirical relationships. Evapotranspiration is difficult to measure, particularly in areas with significant heterogeneity in vegetation or topography such as is common at YM. In arid and semiarid environments, areal evapotranspiration estimates can be obtained readily by simply using the measured or estimated values for precipitation, as net infiltration is typically a small percentage of precipitation. This procedure is useless for estimating net infiltration, however.

Potential evapotranspiration is the amount of evapotranspiration that would occur if soil moisture were not the limiting factor. An empirical relationship predicting potential evapotranspiration as a function of temperature and ground slope appropriate for Nevada was developed by Behnke and Maxey (1969). Shevenell (1996) provided a set of piecewise-linear regression relationships to approximate potential evapotranspiration in Nevada. Although potential annual evapotranspiration far exceeds annual precipitation at YM, potential evapotranspiration is quite low in the winter when most precipitation occurs.

2. Estimates of Net Infiltration Inferred from Indirect Evidence

a. Fluxes Inferred from Neutron-Probe Data

Neutron probes provide an estimate of the moisture content within a soil or rock mass, based on the percentage of neutrons reflected from the soil. The presence of water strongly mediates the return rate, thereby providing an estimate of the water content averaged over a volume with a radius somewhat larger than the borehole radius.

A total of 99 boreholes have been used to obtain neutron-probe data at YM (Flint and Flint, 1995) representative of different micro-environments. Yucca Crest, lower sideslopes, terraces, and channels are well represented, but no boreholes were drilled into upper or middle sideslopes due to the difficulty of drilling there. Flint, et al. (1994) discuss moisture contents from 34 of the boreholes. Every ridgetop and lower sideslope borehole is reported to have exhibited moisture-content responses in the bedrock, while only 4 of 20 terrace or channel boreholes had a response (each having a particularly shallow cover).

Hevesi and Flint (1993) used moisture contents from borehole N7 to calibrate a 1D numerical model. Borehole N7 is in the Pagany Wash channel and has 12.3 m of alluvium overlying welded Tiva Canyon (TCw) bedrock (Flint and Flint, 1995). During the model calibration process, a root zone was imposed to a depth of 7.1 m to account for observed changes in moisture content, while a root zone of 2 m was considered reasonable for site vegetation. Vapor flow is invoked as a possible explanation for the discrepancy. Hevesi, et al. (1994) use N7, N8, and N9 (closely spaced boreholes across the wash cross-section) with an additional year of data to further refine the model. The root zone was extended farther, to bedrock, to simulate observed changes in moisture content, again arguing that this must account for vapor or lateral flow.

Examining moisture content history from the complete set of closely spaced boreholes in Pagany Wash (N2 through N9 and N63), one can indeed see indications of flow spreading from the channel. Although the model may be calibrated for this location, the generality of the calibration is questionable, as the effects of plant uptake are not separated from the very special case of lateral spreading from the channel. In most other locations, it would be more appropriate to have the vegetation represented using physically appropriate parameters.

b. Fluxes Inferred From Hydraulic Properties

As discussed by Nimmo, et al. (1994), one can estimate fluxes in a small sample when one knows the *in situ* moisture content. By adjusting the flow through the minimally disturbed sample in the laboratory (e.g., using a centrifuge) until the moisture content is identical to the *in situ* moisture content, one can get a direct estimate of the flux passing through the sample in the field. If the *in situ* flux is steady state and vertical, an estimate of net infiltration is obtained. A less accurate way of estimating fluxes is to directly use Darcy's law with known *in situ* potentials and the unsaturated hydraulic conductivity appropriate for the potentials (Tyler, 1987).

Tyler (1987) and Tyler and Jacobson (1990) summarize several studies on the NTS where fluxes in deep alluvial soils were calculated using estimates of the hydraulic properties. The estimates range over 3 to 4 orders of magnitude, due to uncertainties in hydraulic gradient and hydraulic properties. The largest estimates from two deep-alluvium locations (Rock Valley and Frenchman Flat) are 0.12 and 2.6 mm/yr.

Several studies have attempted to estimate infiltration fluxes for YM bedrock while neglecting fractures. Waddell, et al. (1984) estimated the matrix flux to be 0.03 mm/yr in the welded Topopah Spring (TSw) unit, based on measurements in borehole UE-25a1, noting that either net infiltration is significantly less than in deep alluvium or fracture flow must be occurring. Montazer, et al. (1988) performed a similar study on the TSw unit based on observations from borehole UZ-1, estimating net infiltration of 0.1 to 0.5 mm/yr. Flint, et al. (1993) calculated the response of UZ-15 to paleoclimatic change using 1D simulations with time variation based on $\delta^{18}O$ records from ocean sediments, concluding that current conditions may actually reflect long-term drying. Gauthier (1993) used steady-state 1D Monte-Carlo simulations to estimate the most likely flux through H-1, neglecting fractures, and found that likely matrix fluxes are between 0 and 0.01 mm/yr. Fluxes of 0.1 and 0.5 mm/yr are rejected using statistical methods. Flint and Flint (1994) provided the first estimate of the spatial distribution of potential net infiltration by assuming saturated hydraulic conductivity of the matrix was the maximum infiltration flux with net infiltration rates ranging from 0.02 to 13.4 mm/yr and with an areal average of 1.4 mm/yr.

Brown, et al. (1993) attempted to predict moisture contents in boreholes N53, N54, and N55 assuming matrix-only fluxes. A range of fluxes between 0.01 to 0.1 mm/yr provided the best match to observed moisture contents, but the distribution of moisture contents with depth was not well matched. Considering fracture flow by using a dual-porosity model, Brown, et al. (1993) demonstrated that the distribution of predicted matrix moisture contents was much better matched using the dual-porosity model with fluxes between 1 and 10 mm/yr and found that predicted matrix moisture contents were relatively insensitive to flux when fracture flow was accommodated.

Kwicklis, et al. (1993) attempted to calculate vertical fluxes in boreholes UZ-4, UZ-5, UZ-7, and UZ-13 using estimated hydraulic properties and potential gradients. The calculations were hampered by the lack of a consistent set of both properties and potentials for any borehole. Estimates varied widely between boreholes, between layers within a borehole, and between results obtained using different assumptions for the same layer within a borehole. Locally, even the direction of flow may not have been consistent, suggesting that lateral flow may be occurring.

In general, it appears that the direct determination of infiltration fluxes from unsaturated hydraulic conductivity may be credible for some well-controlled situations, where fluxes are steady and vertical. A deep alluvial column may satisfy these requirements. Estimates obtained from fractured welded tuffs are not credible because flowing fractures cannot be sampled. The reliability of estimates from nonwelded units (typically having few fractures) cannot be rejected out of hand, but analyses assuming a unit hydraulic gradient in the matrix (without verification) are questionable, as significant variations of hydraulic properties may occur within a short vertical span so that capillary forces may cause significant flow.

c. Fluxes Inferred From Thermal Considerations

If the temperature and thermal conductivity profiles of a rock mass are known, one can calculate the energy flux due to conduction. If the actual energy flux through the rock mass differs from the conductive flux, it must be due to advection (i.e., energy transported through liquid or vapor fluxes). When a vertical column has smaller conductive fluxes than actual fluxes, it may be due to cool infiltrating water that warms while moving to depth or upward vapor transport with an associated large latent-heat transport. To estimate infiltration fluxes when moisture movement is predominantly vertical, one can use an analytic solution or a numerical simulator accounting for both conductive and advective fluxes, and adjust the infiltration flux until the measured temperature profile is obtained. Lachenbruch and Sass (1977) presented a relationship indicating that reduction in apparent heat flux is roughly proportional to volume of infiltrating water, thermal gradient, and distance considered. Typically it is assumed that vapor flux is negligible, although this assumption is not necessary if the vapor flux can be accounted for. Implicit in the approach is the assumption that liquid and rock remain in thermal equilibrium.

An advantage of the method is it is not necessary to know in detail how liquid moves within the rock. On the other hand, it is necessary to have an independent estimate for the thermal flux, which can be difficult to obtain. It is also essential to know thermal conductivities, but these are typically quite well constrained.

Estimates of thermal and liquid fluxes throughout the NTS are presented by Sass, et al. (1980) and Sass and Lachenbruch (1982), with results summarized by Sass, et al. (1988). Sass, et al. (1988) analyzed a set of boreholes in the YM area, with estimates of conductive and total heat fluxes from the saturated zone (SZ) into the unsaturated zone (UZ) of 40±9 and 49±8 mW/m^2 with an average heat flux in the UZ of about 41 mW/m^2. Sass, et al. (1988) contour conductive heat fluxes in the YM area (Figure 15 by Sass, et al., 1988), which indicates that conductive fluxes are 70 to 74 mW/m^2 southeast through southwest of YM; roughly 60 mW/m^2 in the southwest part of Midway Valley; roughly 50 mW/m^2 in and near Fortymile Wash, Dune Wash, Yucca Wash, and Solitario Canyon; and roughly 30 to 40 mW/m^2 over the repository footprint and north past Drillhole Wash. Sass, et al. (1988) suggest there may be an apparent reduction of heat flow from the SZ to the UZ of 5 to 10 mW/m^2 and calculate this apparent reduction of heat flow could be achieved by 2 to 5 mm/yr net infiltration. If 0.1 mm/yr of water were vaporized, about 8 mW/m^2 reduction would be achieved. Lateral flow in the shallow SZ is also considered a possible source of local anomalies. Sass, et al. (1988) also note (without further comment) that apparent heat flux is negatively correlated with elevation; one might infer that lateral diversion to lower topographic areas may be occurring, although the study by Rousseau, et al. (1996) discussed in another paragraph would suggest the opposite due to the insulating properties of alluvium.

An implication of the analysis by Sass, et al. (1988) is that at least locally over the repository block and Drillhole Wash deficits in the apparent heat flux that occur in the UZ may be as much as 20 mW/m^2 [assuming that 10 mW/m^2 is roughly equivalent to 5 mm/yr infiltration, as calculated by Sass, et al. (1988)], so that locally about 10 mm/yr infiltration might be estimated. When estimating infiltration, it may be better to estimate the vertical heat flux from boreholes that are unlikely to have significant infiltration. Infiltration fluxes in deep alluvium and not close to channels are likely to be quite small, so that the boreholes in Midway Valley and south of YM in deep alluvium may be more representative of regional vertical heat flux. If so, vertical heat flux could be as much as 60 to 75 mW/m^2 and local deficits at YM could be as much as 45 mW/m^2, implying that locally more than 20 mm/yr infiltration could be inferred from the thermal data. Assuming that the UZ heat flux is 60 mW/m^2, heat-flux deficits on the order of 15 to 30 mW/m^2 in the area of the repository block and Drillhole Wash could be justified, implying that local infiltration rates may be 7 through 15 mm/yr in this area.

Montazer, et al. (1988) discuss the installation of devices for monitoring temperature, air pressure, matric potential, and water potential in borehole UZ-1 as well as analysis of some of the data. Using the temperature and air-pressure information, Montazer, et al. (1988) estimated the maximum upward vapor flux to be 0.025 to 0.05 mm/yr, which would account for 2 to 4 mW/m^2 of the heat-flux anomaly discussed by Sass, et al. (1988).

Both Montazer, et al. (1988) and Sass, et al. (1988) present a set of temperature profiles for boreholes in Drillhole Wash (UZ-1, UE-25a5, and UE-25a7) that show cooling suddenly (within weeks or months) at depths of 50 to 150 m, consistent with transient moisture redistribution such as might occur from infiltration events. Sass, et al. (1988) calculate heat fluxes for these boreholes of 32 to 33 mW/m^2, among the lowest reported, consistent with an interpretation of locally high infiltration. Rapid redistribution of moisture to depth is consistent with an interpretation of significant fault-related flow.

Fridrich, et al. (1994) provide an alternative interpretation of the Drillhole Wash heat-flux low and generally low temperatures at the water table under the repository footprint as indicative of lateral flow in the SZ associated with the large hydraulic gradient. If significant flow is moving down the large hydraulic gradient, the temperature anomaly south of Drillhole Wash would be partially explained. On the other hand, later information gathered from borehole G-2 suggests that the large hydraulic gradient may represent a perched zone (Czarnecki, et al., 1994; Czarnecki, et al., 1995), in which case flow may be predominantly vertical.

The regional-scale analysis presented by Sass, et al. (1988) provided the independent energy flux required for site-scale analyses by Bodvarsson, et al. (1996). Both conduction-only and coupled conduction/convection models were investigated. Using an average heat flux of 50 mW/m^2 and temperature data from UZ-7a, NRG-6, NRG-7, and SD-12, infiltration fluxes of 10 mm/yr were calculated for UZ-7a (WT-2 Wash) and SD-12 (Antler Wash) and 7 mm/yr for NRG-6 and NRG-7a (Drillhole Wash, outside the fault zone). Using an average heat flux of 40 mW/m^2, the infiltration rates dropped to 6 and 2 mm/yr. The infiltration rates would increase to about 15 and 11 mm/yr if the heat flux is assumed to be about 60 mW/m^2.

Rousseau, et al. (1996) estimate net infiltration from thermal fluxes in Pagany Wash (UZ-4 and UZ-5). One- and two-dimensional (2D) combined conduction/convection simulations were used to estimate infiltration based on a heat flux of 36.5 mW/m^2 applied at the water table. It was found that significant 2D heat-flow variation may result due to the insulating properties of the alluvium in the wash; a 2D conduction-only simulation had a heat flux from the wash surface of about 2/3 of the flux at the water table, and a heat flux from the sideslope surface of about 5/3 of the flux at the water table. Based on 1D simulations of the temperature profiles in the boreholes, estimates of net infiltration were roughly 18 mm/yr in UZ-4 (channel) and 5 mm/yr UZ-5 (sideslope), although the 2D heat flow effects were interpreted as causing the UZ-4 estimate to be too high and the UZ-5 estimate to be too low. Note that the thermal flux used by Rousseau, et al. (1996) is quite low relative to estimates by Sass, et al. (1988); calculated infiltration fluxes with a thermal flux of 50 mW/m^2 would be larger by more than 5 mm/yr.

Not only are the estimates of infiltration based on heat-flux calculations insensitive to the precise manner in which water percolates in the fractured medium, but the estimates are on a particularly useful scale, considerably larger than the borehole, as heat conduction tends to quickly damp out temperature perturbations. Additional studies using site-scale simulations, such as the one by Finsterle, et al. (1996) should help delineate the impacts of coupled heat and moisture transport.

One significant advantage of the heat-flux method is that it can yield upper-bound estimates for infiltration rates. Assuming that the regional heat flux is 85 mW/m^2, neglecting all other sources of reduction in apparent heat flux such as lateral flow in the SZ and vapor fluxes, using a value of 35 mW/m^2 as the average apparent heat flux over the repository block and using the rule-of-thumb that 10 mW/m^2 reduction in apparent flux is equivalent to 5 mm/yr infiltration, one finds the maximum average infiltration over the repository block is about 25 mm/yr.

d. Fluxes Inferred From Natural and Anthropogenic Tracers

Both naturally occurring and anthropogenic (e.g., bomb-pulse related) tracers can be used to estimate infiltration, and methods based on tracers are considered particularly robust in arid environments (Gee and Hillel, 1988; Allison, et al., 1994). Tracer methods average flux over long periods of time, a significant advantage in environments with highly sporadic infiltration events.

Assuming that flows are perfectly vertical, that tracers do not mix (water moves as piston flow and dispersive processes are negligible), water-rock interaction is negligible, and that the age of a tracer can be accurately determined, one is able to directly infer the travel time as a function of depth within a borehole. The time required for the tracer to reach a depth may be calculated by integrating the tracer mass to that depth (e.g., the chloride mass balance method); calculating the ratio of a radioactive isotope to the stable isotope (e.g., the ratio of ^{36}Cl to Cl or ^{14}C to C); relating the variation with depth of stable-water-isotope compositions to known climatic variation; or calculating the ratio of daughter product to the parent radioactive isotope (e.g., ^{230}Th to ^{234}U). Further assumptions regarding moisture content are required to convert travel time into velocity, and velocity into flux.

There are several areas of uncertainty involved with tracer methods. The inability to unambiguously achieve tracer mass balance is a primary uncertainty. The time history of the tracer input must be known, which can be difficult to determine, particularly over geologic time scales. For example, the cosmogenic production of ^{36}Cl is estimated to have increased by a factor of 2 over the last 500 ka (Fabryka-Martin, et al., 1996a). Deposition rates of bomb-pulse constituents (i.e., ^{36}Cl, ^{14}C, tritium) varied in both time and space, due to the influence of particular testing events and were not measured at YM. Due to this uncertainty, tracer mass balance is uncertain and one may be unable to determine if fast pathways bypass sampled locations. On the other hand, if inputs are variable in time but known, one may be able to correlate the variability of the tracer with depth in terms of source variability, thus improving estimates of velocities.

Another cause of uncertainty arises from the various transport pathways that the tracers follow. Each tracer may be transported somewhat differently causing uncertainties in interpretation. Tritium is subject to vapor transport. Carbon-14 is partitioned into the gas phase as carbon dioxide. Chloride may move up to 20 percent faster than ambient water, perhaps because of anion exclusion in the soil (Gee and Hillel, 1988). A suite of tracers is often used to provide corroboratory interpretations.

A further confounding uncertainty arises when waters of different ages or different chemistries mix, thereby yielding a composite age perhaps not representative of either pathway. Once two waters have mixed, one cannot extract the age of the input waters from the apparent age of the mixture, although one may constrain the ages somewhat. This uncertainty arises whenever more than one flow pathway exists (e.g., both matrix and fracture pathways) or when dispersive fluxes are significant and can make flux interpretations very difficult at depth in fractured rocks such as exist at YM. In each of the cases discussed by Phillips (1994) (all with soil or alluvium profiles), he asserts that piston flow appears to be closely approximated except at the shallowest soil depths with the implication that mixing may be minimal in many desert soils.

Even when the actual age of waters can be accurately calculated with depth, the actual flux history may not be uniquely determined; at best, a velocity history may be calculated under the assumption that fluxes are constant with depth even though varying in time. The flux history is less certain than the velocity history, due to the uncertainties associated with moisture content over time. Often however, the uncertainties associated with moisture content are small relative to other uncertainties.

Phillips (1994) presents a comparison of data from tracer studies across the American Southwest (including two boreholes from the NTS) using ^{36}Cl, tritium, and chloride tracers and discusses various interpretations of the profiles. Phillips (1994) suggests that the 12 profiles he considered, from west Nevada to west Texas, consistently support a 20-fold drop in net infiltration over the period of 16 to 13 ka, and further suggests that this drop is due partly to changing climatic conditions and perhaps partly due to a change in vegetation from mesic to xeric species.

Tyler (1987) and Tyler and Jacobson (1990) review soil-moisture flux studies at the NTS, including those that examined bomb-pulse tritium. Velocities are estimated between 30 to 80 mm/yr, and as much as 200 mm/yr (with a calculated flux of 38 mm/yr) in the Yucca Flat playa where occasional ponding occurs. As discussed by Tyler and Walker (1994), net infiltration from bomb-pulse tracers may be seriously overpredicted if changing water velocities with depth in the root zone, due to plant uptake of soil water, is not accounted for. Tyler and Walker (1994) report discrepancies of tritium dating relative to the chloride mass balance approach that result in net-infiltration overpredictions of as much as 3 orders of magnitude. The influence of the root zone on predicted travel times is negligible once the tracers have migrated deep into the profile, so that the infiltration estimates most affected by the root zone may be those using bomb-pulse tracers.

Tyler, et al. (1995) discuss dating of waters from three deep-alluvium boreholes in Frenchman Flat using ^{36}Cl, stable chloride, and stable isotopes. Tyler, et al. (1995) interpret the results as likely showing the effects of the last two glacial periods with one borehole receiving focussed runoff recharging to the water table in the last glacial period and the other two recording wetting pulses in the last two glacial periods that did not reach the water table. No evidence of wetting pulses from even earlier glacial stages was detected. Removal of tracers due to a higher water table is considered and dismissed by both Conrad (1993) and Tyler, et al. (1995) based on arguments by Jones (1982) and Winograd and Doty (1980). Conrad (1993) estimates average net infiltration for another Frenchman Flat deep-alluvium borehole of about 0.04 mm/yr using the chloride mass balance technique.

Using shallow bomb-pulse tritium profiles, Kwicklis, et al. (1993) estimate net infiltration to be 35.1 mm/yr at UZ-4 (the channel of Pagany Wash) and 23.6 mm/yr at UZ-7 (the channel of Wren Wash). Using ^{14}C profiles, Kwicklis, et al. (1993) estimate net infiltration to be 20 mm/yr at UZ-4 and 4 mm/yr at UZ-5 (the sideslope of Pagany Wash, near UZ-4). Analyses based on heat-flux considerations suggest that net infiltration is less than 18 mm/yr at UZ-4 and more than 5 mm/yr at UZ-5 (Rousseau, et al., 1996), corroborating the estimates from near-surface tracer calculations. Estimates however, of percolation fluxes at depth in the UZ are significantly smaller. Using pore waters from the nonwelded Paintbrush tuff (PTn) unit obtained from UZ-4 and UZ-5, chloride mass balance calculations yield estimates of net infiltration of 1.1 and 1.5 to 2.5 mm/yr (Fabryka-Martin, et al., 1996b) apparently by assuming that precipitation, net infiltration, and chloride deposition rates have been constant for sufficient time to reach a steady state and further assuming that matrix and fracture waters have fully mixed.

The chloride mass balance technique, as applied by Fabryka-Martin, et al. (1996b), assumes that average Cl^- concentration multiplied by total flux is conserved. Knowing (1) the average precipitation rate, (2) Cl^- concentration corresponding to the average Cl^- deposition rate, and (3) Cl^- concentration in a well-mixed reservoir at depth, the percolation flux at depth can be determined. Yang, et al. (1996) report Cl^- concentrations in perched water of 4.1 to 15.5 mg/L, with 15 of the 17 reported values being no greater than 8.3 mg/L and a Cl^- concentration of 7 mg/L at NRG-7a (the nearest borehole to UZ-4 and UZ-5 with a reported perched-water sample). Using the same precipitation rate (170 mm/yr) and Cl^- concentration (0.62 mg/L) as Fabryka-Martin, et al. (1996b) and assuming that the perched water is well mixed with the matrix waters, calculated net infiltration is 25.7, 12.7, and 6.8 mm/yr for concentrations of 4.1, 8.3, and 15.5 mg/L, respectively. An infiltration value of about 26 mm/yr would represent an upper bound based on the perched-water chloride data; if the matrix waters do not mix completely with the perched water, infiltration values may be lower. The estimated infiltration values are more consistent with the shallow infiltration estimates than the estimates from the PTn, however, suggesting that a considerable portion of the infiltrating water may bypass the PTn matrix.

Fabryka-Martin, et al. (1996b) use the chloride mass balance approach to estimate net infiltration from alluvium profiles in the YM area, with estimates below the root zone generally less than 1 mm/yr and with some estimates as low as 0.015 mm/yr. Norris, et al. (1987) estimate infiltration in Yucca Wash (apparently not in the channel) using the ratio of ^{36}Cl to Cl, arriving at a value of 1.8 mm/yr; however, the peak in $^{36}Cl/Cl$ is within the root zone and coincides with a change in soil properties.

Paces, et al. (1996) provide a preliminary estimate of the percolation fluxes required to deposit calcite and opal in the form of fracture fillings and lithophysae coatings at YM. Assuming that the fracture characteristics and filling patterns observed in the Exploratory Studies Facility (ESF) are representative of the entire UZ, all cations are deposited within the UZ, and infiltrating water has the composition observed under current conditions, the average infiltration flux rate required to match the observed patterns is calculated to be 2.1 mm/yr for calcite and 0.3 mm/yr for opal. As noted by Paces, et al. (1996), these are minimum estimates, as almost certainly not all calcium and silica is deposited.

One can test conceptual models for shallow infiltration by observing the degree of compatibility with unambiguous bomb-pulse signatures. Fabryka-Martin, et al. (1996b) present ^{36}Cl data obtained from 23 boreholes. Areas with minimal soil depths (ridges, sideslopes) generally had unambiguous bomb-pulse signatures at depths tens of meters and more into the underlying TCw bedrock and locally into the underlying PTn, suggesting that wetting pulses in the last 50 yr have penetrated well below the zone of evapotranspiration. These deep bomb-pulse signatures are consistent with an interpretation of relatively high infiltration rates in areas with shallow soils. Areas with deeper soils tended not to have bomb-pulse signatures in the bedrock, consistent with relatively low infiltration rates. Recent modeling work that may aid in assessing consistency of conceptual models of deep percolation with ^{36}Cl data, thereby enabling estimates of net infiltration, are discussed by Wolfsberg, et al. (1996), Fabryka-Martin, et al. (1996a), Fairley and Sonnenthal (1996), and Robinson, et al. (1996).

Fabryka-Martin, et al. (1996b) describe studies of $^{36}Cl/Cl$ ratios in precipitation, subsurface waters, and packrat middens at YM. The work also included many rock samples from the ESF at YM, including samples from the proposed repository horizon in the Topopah Spring tuff. Fabryka-Martin, et al. (1996b, p. 33) conclude that "the initial $^{36}Cl/Cl$ ratio in infiltrating water could have been more than twice as high as its present ratio of 500 x 10^{-15} during the past several hundred thousand years...." Also,

> ...ratios significantly higher than a threshold of 1500 x 10^{-15} are interpreted as being clearly elevated above meteoric background and most likely contain a component of bomb-pulse ^{36}Cl. Samples with ratios ≤ 1500 x 10^{-15} may contain a component of bomb-pulse ^{36}Cl but may also contain Cl from old water recharged when the input ratio was higher....

Murphy (1997, p. 4), in a commentary on the ^{36}Cl studies in the ESF, concludes that "samples containing ^{36}Cl/Cl ratios greater than 900 x 10^{-15} to 1000 x 10^{-15} contain some bomb pulse ^{36}Cl..." and that "...fast pathways for water flow from the surface to the ESF are fairly common. Statistical analyses interpreting the data as the mixture of two normally distributed samples indicate that 20 to 25 percent of samples reported for the ESF show signs of bomb pulse contamination." Although the ^{36}Cl data provide unequivocal evidence of relatively fast flow paths from the surface down to the ESF, the corresponding magnitude of infiltration flux is unclear. Simulation of ^{36}Cl transport to the ESF by Fabryka-Martin, et al. (1996b) suggests that average recharge rates probably exceed 1 mm/yr.

The use of tracers to robustly estimate infiltration rates in the YM area would appear to be limited to deep alluvium profiles where lateral flow processes are not significant. Difficulties with estimating the impacts of vegetation, lateral flow, and multiple pathways would appear to limit their use over most of the repository footprint, where shallow soils overlie fractured bedrock. Nevertheless, unambiguous bomb-pulse signatures observed at depth in the ESF, which are interpreted as occurring where high infiltration occurs over a zone having a fault that provides a fast pathway through the PTn unit (Levy, et al., 1997) were instrumental in demonstrating that fast pathways exist and, by implication, that at least locally there are areas where infiltration might be much higher than previously thought.

Despite the limitations of tracer methods, the chloride mass balance technique does provide a means of estimating an upper bound for net infiltration. The upper-bound value obtained by chloride mass balance on perched water, 26 mm/yr, is remarkably consistent with the upper-bound value obtained by geothermal heat-flux calculations.

3. Estimates of Net Infiltration from Water Balance Calculations

Direct estimates of net infiltration are considered more robust than estimating infiltration from water balance considerations (Gee and Hillel, 1988; Allison, et al., 1994), as the magnitude of uncertainties in precipitation, runoff, and evapotranspiration may be considerably larger than the magnitude of net infiltration. Nevertheless, simulation methods based on water-balance calculations are likely to provide the basis for predictions of net infiltration used in PA. In order to quantify net infiltration under potential future climatic changes, it is necessary to be able to understand and predict the response of net infiltration under current conditions.

a. Precipitation Data

Precipitation is perhaps the best characterized of all components of the water balance, although the record is still too short to estimate frequencies of extreme events. There are numerous stations where precipitation records have been obtained across southern Nevada and into California. Available data and interpretations are discussed by French (1983), Quiring (1983), French (1986), Nichols (1987), Hevesi, et al. (1992a), Hevesi, et al. (1992b) Hevesi, et al. (1994), Ambos, et al. (1995), Hevesi and Flint (1996), and Flint, et al. (1996a).

b. Evapotranspiration Data

Although evapotranspiration is the second-largest component of the hydrologic balance in the YM area, behind only precipitation, far less attention has been focussed on measuring evapotranspiration. Nichols (1987) discusses evaporation studies relevant to the low-level Beatty facility, and Czarnecki (1990) considers evapotranspiration at Franklin Lake playa (approximately 60 km downgradient of YM), but little attention has been paid to evaporation at YM in particular. Measurements of evaporation at YM over several years, using a class A pan, are found to exceed calculated potential evaporation by about a factor of 2 (Flint, et al., 1996a). Flint, et al. (1996b) reports that the most success in estimating evapotranspiration at YM has been using inverse modeling based on neutron-probe data, with numerous limitations.

Information is available on the types and distributions of vegetation on the NTS (Wallace and Romney 1972; Beatley 1974; Beatley 1976; O'Farrell and Emery 1976; O'Farrell and Collins 1983; EG&G 1991; and Hessing, et al., 1996). Most information, however, emphasizes vegetation description and habitat, rather than plant uptake patterns.

Leary (1990) directly measured plant water use, soil moisture evaporation, and soil moisture flux in 3 study plots (a wash, an alluvial fan, and a sideslope) 13 km northwest of the ESF north portal. The work emphasized measurement-technique evaluation, however rather than quantifying uptake patterns. Preliminary estimates of rooting depths, active months, and minimum xylem potential for some species common to YM are presented by Flint, et al. (1996a).

The relative lack of YM-specific attention is unfortunate, due to the impact of desert vegetation uptake patterns, responses to precipitation, and life cycles on net infiltration. In particular, information on the impact of a fractured bedrock with shallow soil cover on plant uptake patterns has received very little attention, despite the ubiquity of shallow soils over the repository footprint.

c. Lateral-Moisture-Flow Data

According to Flint, et al. (1996a) episodic runoff has been observed at YM during the period from 1984 to 1995. Data quantifying some of the events are reported by Pabst, et al. (1993), Osterkamp, et al. (1994), and Savard (1994, 1995). Flint, et al. (1996a) discusses several overland-flow episodes in the period of 1984 to 1995, indicating that both short, intense convective events and extended winter storms can cause overland flow events. The largest runoff events occurred in the winter of 1994–95; unfortunately, neutron-probe data collection had already been discontinued, so that subsequent redistribution could not be monitored.

Little or no data has been collected quantifying shallow lateral flow. Anecdotal and suggestive evidence does exist, however. Flint, et al. (1996a) state that lateral flow has been observed to occur along the soil-bedrock interface. Norris, et al. (1987) suggest that lateral flow is probably the reason that ^{36}Cl and chloride profiles from a soil profile near the ESF North Portal showed complex layering and that only 7 percent of estimated chloride deposition was found in the profile.

d. Hydraulic-Property Data

A large database of bedrock hydraulic properties has been collected, correlated to lithologic structure, and analyzed for spatial trends, using core samples collected from outcrops and from boreholes, (Peters, et al., 1984; Klavetter and Peters, 1986; Flint and Flint, 1990; Rautman and Flint, 1992; Flint and Flint, 1994; Istok, et al., 1994; McKenna and Rautman, 1995; Rautman, et al., 1995; Schenker, et al., 1995; Flint, 1996; Flint, et al., 1996b; Moyer, et al., 1996; Rousseau, et al., 1996).

Hydraulic properties of soils are less well characterized, with estimated or measured properties reported by Nichols, 1987; Schmidt, 1989; Guertal, et al., 1994; Flint, et al., 1996a; and Stothoff and Winterle, 1997. A general agreement exists that the hydraulic properties of the soils are quite spatially uniform; *in situ* saturated hydraulic conductivities over the repository footprint measured by Stothoff and Winterle (1997) (using a ponded-head permeameter) are on the order of 10 to 18 cm/hr, while estimated values for soils in similar locations, based on textural characteristics, are about 2 cm/hr (Schmidt, 1989; Flint, et al., 1996a), suggesting that textural analysis may underpredict *in situ* values by up to an order of magnitude.

Surficial-cover classification is mapped by Lundstrom, et al. (1994, 1995, 1996) and Taylor (1995). Soil depths are qualitatively described by Flint, et al. (1996a). Quantitative soil-depth estimates are primarily available at boreholes and trenches. A modeling approach for estimating soil thickness is presented by Stothoff, et al. (1996) and Bagtzoglou, et al. (1996).

Hydraulic properties of bedrock fractures are poorly characterized. General descriptions of fracture hydraulic properties are presented by Flint, et al. (1994); approximate distributions of fracture apertures and percentage of filled fractures appropriate for each lithostratigraphic layer, for modeling purposes, are presented by Flint, et al. (1996a). Despite the relative lack of characterization, unpublished 1D simulations by Stothoff (1997) examining the impact of soil and fracture properties on net infiltration suggest that it is important to know if fractures are filled or not, but fracture densities are sufficiently high in many areas that net infiltration may be controlled by other factors, such as soil hydraulic properties and soil depths.

e. Predictive Modeling of Net Infiltration

A number of studies have attempted to estimate net infiltration using numerical simulations. By far the most common approach is to perform vertical 1D or quasi-1D (e.g., bucket, local 2D) water-balance simulations [Electric Power Research Institute (1990, 1992, 1996); Lane and Osterkamp, 1991; Hevesi and Flint, 1993; Long and Childs, 1993; Hevesi, et al., 1994; Hudson, et al., 1994; Fairley and Sonnenthal, 1996; Flint el al., 1996a; Stothoff, 1997]. The models treat processes such as moisture redistribution, energy, hydraulic properties, and evapotranspiration using differing approximations, but fundamentally all of the models consider vertical processes and neglect lateral redistribution (aside from allowing surface runoff to occur). Generally the 1D models agree that infiltration increases as soils become shallower, as precipitation increases (particularly in winter), and as temperatures decrease.

The appropriateness of a 1D simulation requires that net lateral flow is negligible, so that areas with active lateral flow (e.g., channels) are poorly approximated by 1D approaches. Nevertheless, 1D simulations do provide estimates of the relative importance of various processes and features, and 1D simulations are much faster than 2D or 3D (three-dimensional) simulations.

Stothoff (1997) analyzed the calculated response of net infiltration to hydraulic properties and climatic inputs, by performing a series of simulations that systematically varied one property or climatic input per simulation. Stothoff (1997) found that in cases where soil overlies a fractured bedrock with an impermeable matrix and unfilled fractures, net infiltration is much less when soil covers are deeper than a few tens of centimeters, due to the infrequent wetting pulses that breach the capillary barrier represented by an open fracture. Net infiltration was found to be somewhat sensitive to soil properties but insensitive to fracture properties.

Subsequent unpublished simulations suggest that net infiltration is somewhat different when carbonate-filled fractures are considered. The sensitivity of net infiltration to soil depth is muted for filled fractures. An order-of-magnitude change in bubbling pressure or saturated hydraulic conductivity for the fracture filling changes net infiltration by factors of about 3 and 2, respectively, in contrast to the open-fracture simulations. There are no published data on the bubbling pressure of the fillings found at YM, and only minimal information on saturated hydraulic conductivity is available (i.e., Flint, et al. (1996a).

Several researchers have made estimates of the spatial distribution of net infiltration based on independent 1D simulations, either on a pixel-by-pixel basis (Flint, et al., 1996a) or as a basis for abstraction (Stothoff, et al., 1996; Bagtzoglou, et al., 1996). Qualitatively the resulting maps are quite similar, and bear a remarkable qualitative similarity both to the map of vertical heat flux presented by Sass, et al. (1988) and to the maps of net infiltration based on regressions of neutron-probe data as presented by Hudson and Flint (1996). Estimated average infiltration fluxes over the repository block using the 1D simulations are generally within a factor of less than half an order of magnitude, remarkably in agreement considering the different physical processes considered in the simulations. Even the simulations presented by Electric Power Research Institute (1992, 1996) would provide qualitatively similar maps, although the calculated infiltration magnitudes would be somewhat lower than predicted by Flint, et al. (1996a) and Stothoff, et al. (1996).

4.4 What is the estimated amount and what is the spatial distribution of present-day groundwater percolation through the proposed repository horizon?

Review methods, acceptance criteria, and technical bases will be provided in Revision 1 of this IRSR in FY98.

4.5 What is the estimated amount and what is the spatial distribution of groundwater percolation through the proposed repository horizon during the period of repository performance?

Review methods, acceptance criteria, and technical bases will be provided in Revision 1 of this IRSR in FY98.

4.6 What are the ambient flow conditions in the saturated zone?

Review methods, acceptance criteria, and technical bases will be provided in Revision 1 of this IRSR in FY98.

5.0 STATUS OF OPEN ITEMS AT THE STAFF LEVEL

The staff has identified numerous SCA (Site Characterization Analysis; NRC, 1989), study plan, and other open items related to this KTI. As discussed below, a number of these open items can be resolved at the staff level. Others will be addressed in future updates of this KTI IRSR. No new open items have been raised in this IRSR

Appendix D contains a list of open items related to this KTI. It is not yet clear whether these may be resolved at the staff level. However, they will be further reviewed in future updates of this IRSR.

5.1 What is the likely range of future climates at YM?

The staff has identified no open items solely related to climate change. Accordingly, the staff has no further questions at this time on methods to estimate future climate variability (see NRC, 1997).

5.2 What are the likely hydrologic effects of climate change?

The staff has identified no open items solely related to hydrologic effects related to climate change. Accordingly, the staff has no further questions at this time on methods to estimate the hydrologic effects of climate change (see NRC, 1997).

5.3 What is the estimated amount and what is the spatial distribution of present-day shallow groundwater infiltration?

The staff has identified a number of open items related to present-day shallow infiltration. As discussed below, some of these open items can be resolved at the staff level. Others will be addressed in future updates of this KTI IRSR. No new open items have been raised in this IRSR on the topic of present-day shallow infiltration

5.3.1 Items Resolved at the Staff Level

The staff has reviewed the status of open items described in NRC, 1995b, many of which were first described in the staff's SCA for YM (NRC, 1989). Recent events in the DOE program provide a sufficient basis to resolve a number of open items at the staff level. The construction of the ESF has produced a wealth of subsurface data that reflects on hydrologic properties, such as evidence from Cl-36 for localized paths of groundwater flow and detailed information about faults and fracture systems. The planned east-west drift will add even further to that information base. DOE is also planning to drill additional wells at the site. For example, WT-24 has already begun and is located in an area favorable for analyzing the source of the so-called large hydraulic gradient. Most importantly, DOE has developed a Waste Containment and Isolation Strategy (WCIS) that identifies key site issues related to site performance (DOE, 1996). Since development of the WCIS. DOE has conducted a series of performance assessment abstraction workshops, on topics such as unsaturated zone flow and saturated zone flow and transport. Subsequent expert elicitations have been held on the topics of unsaturated zone flow and saturated zone flow and transport. Finally, the NRC staff has refocused its review program into a series of key technical issues that concentrate on issues most pertinent to performance. The staff have reviewed DOE's most recent total system performance assessment and participated in an NRC/DOE workshop on performance assessment. In summary, the staff believes that DOE now has in place a program that is effectively identifying and obtaining the information needed to support a license application.

SCA (NRC, 1995b) comments 1, 10, and 18 address the need for a systematic, iterative approach to identify the information needed to support a license application. They are summarized below. Based on the rationale given in the previous paragraph, they are considered resolved at the staff level.

SCA Comment 1: Although the SCP commits to a systematic, iterative approach to identifying the information needed to support a license application (the Issue Resolution Strategy), the documentation in the SCP does not demonstrate that such a program is in place. While this comment includes several concerns not raised elsewhere, it also collects and summarizes concerns expressed in other comments, which collectively point to the absence of such a program.

SCA Comment 10: No technical basis was provided for assessments of significance of hydrogeologic features, events and processes to design and performance measures and parameters.

SCA Comment 18: DOE has given only partial consideration of all features, events or processes that may be essential for a valid mathematical representation of the hydrogeologic system for use in performance assessment analyses. As a consequence, planned activities are insufficient to provide technical justification for initial modeling strategies.

5.4 What is the estimated amount and what is the spatial distribution of present-day groundwater percolation through the proposed repository horizon?

Under this topic, information on open items will be provided in a 1998 update of this IRSR.

5.5 What is the estimated amount and what is the spatial distribution of groundwater percolation through the proposed repository horizon during the period of repository performance?

Under this topic, information on open items will be provided in a 1998 update of this IRSR.

5.6 What are the ambient flow conditions in the saturated zone?

Under this topic, one open item can be resolved. Information on other open items will be provided in a 1998 update of this IRSR.

5.6.1 Item Resolved at the Staff Level

The following open item (study plan Question 4) can be resolved at the staff level. It was developed during the staff review of DOE's study plan on Site Saturated-Zone Hydrologic System Synthesis and Modeling (DOE, 1993). The question is no longer relevant because it is a clarifying question about unclear language in a study plan that DOE has cancelled. Therefore, question 4 is resolved at the staff level.

SP 831233 Question 4 - What is meant by "actual results should be bounded in a statistical sense by predicted results?"

5.7 Other Technical Issues in Isothermal Hydrology.

5.7.1 Items Resolved at the Staff Level

The following four open items were developed during the staff review of DOE's study plan on Characterization of the Yucca Mountain Regional Surface-Water Runoff and Streamflow (DOE, 1990). They are resolved at the staff level because we agree with the rationale presented in DOE's most recent progress report (DOE, 1997). On page A-8 of that report, it is stated that

> ...the data are not needed for the regional ground-water-flow model. Regional ground-water modeling .. did not require runoff data for model calibration because data describing a direct relationship between precipitation and ground-water recharge was used... Because flooding and fluvial-debris transport were shown ... to pose little or no threat to the ESF, the potential repository, or surface facilities at Yucca Mountain, studies to document transport of debris by severe runoff were terminated before being fully implemented.

The staff agrees that flooding is primarily a pre-closure concern, and we have determined that no open items exist with respect to flooding so long as portals to the ESF are sited above the probable maximum flood (PMF), as discussed by Coleman, et al., 1996. Previous DOE studies (Blanton, 1992; Bullard, 1992; Glancy, 1994) address flooding at Yucca Mountain and indicate that portals to the ESF are adequately sited above the PMF. DOE must also provide assurance in a possible license application that any facilities where HLW could temporarily be stored at a hypothetical repository would be sited above the PMF, or otherwise provide adequate justification that storage facilities are designed to safely withstand the effects of a PMF.

SP 831212 Comment 2 - The NRC staff recommended that regionalization methods be included in analyses of the probabilities of runoff magnitudes.

SP 831212 Question 1 - Have the field-tests of the surface runoff measurement devices, systems, and proposed techniques been completed? And if not, when will they be completed?

SP 831212 Question 2 - Has DOE considered any other instrumentation for measuring in-situ flow depth and velocity, especially for large ephemeral flows, such as sonar, pressure transducers, and induction probes?

SP 831212 Question 3 - Are there plans for taking sediment samples at the gaging stations?

The following open item (Question 3) was developed during staff review of DOE, 1992. This item is resolved at the staff level because we agree with the rationale provided by DOE in the most recent progress report (DOE, 1997). On page A-48 of that report, it is noted that "...precipitation-runoff models of modern surface-water conditions and basin characteristics were terminated because runoff occurs so infrequently that collecting data sets sufficient to calibrate the models was not feasible." We recognize that the calibration and validation of regional surface water models for an ephemeral surface drainage like Fortymile Wash is not attainable with existing data. Much more data are available for the Amargosa River, but that drainage has regional significance only and will not contribute to an understanding of repository performance at YM. Nonetheless, it is expected that DOE will estimate groundwater recharge along Fortymile Wash during the period of repository performance. This estimate should be based on available hydrologic information and reasonable climatic assumptions (see NRC, 1997).

SP 831522 Question 3 - How will surface water models for regional hydrology studies be calibrated and validated?

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APPENDIX A

DRAFT FIGURE ILLUSTRATING ELEMENTS OF THE NRC STAFF'S TOTAL SYSTEM PERFORMANCE ASSESSMENT

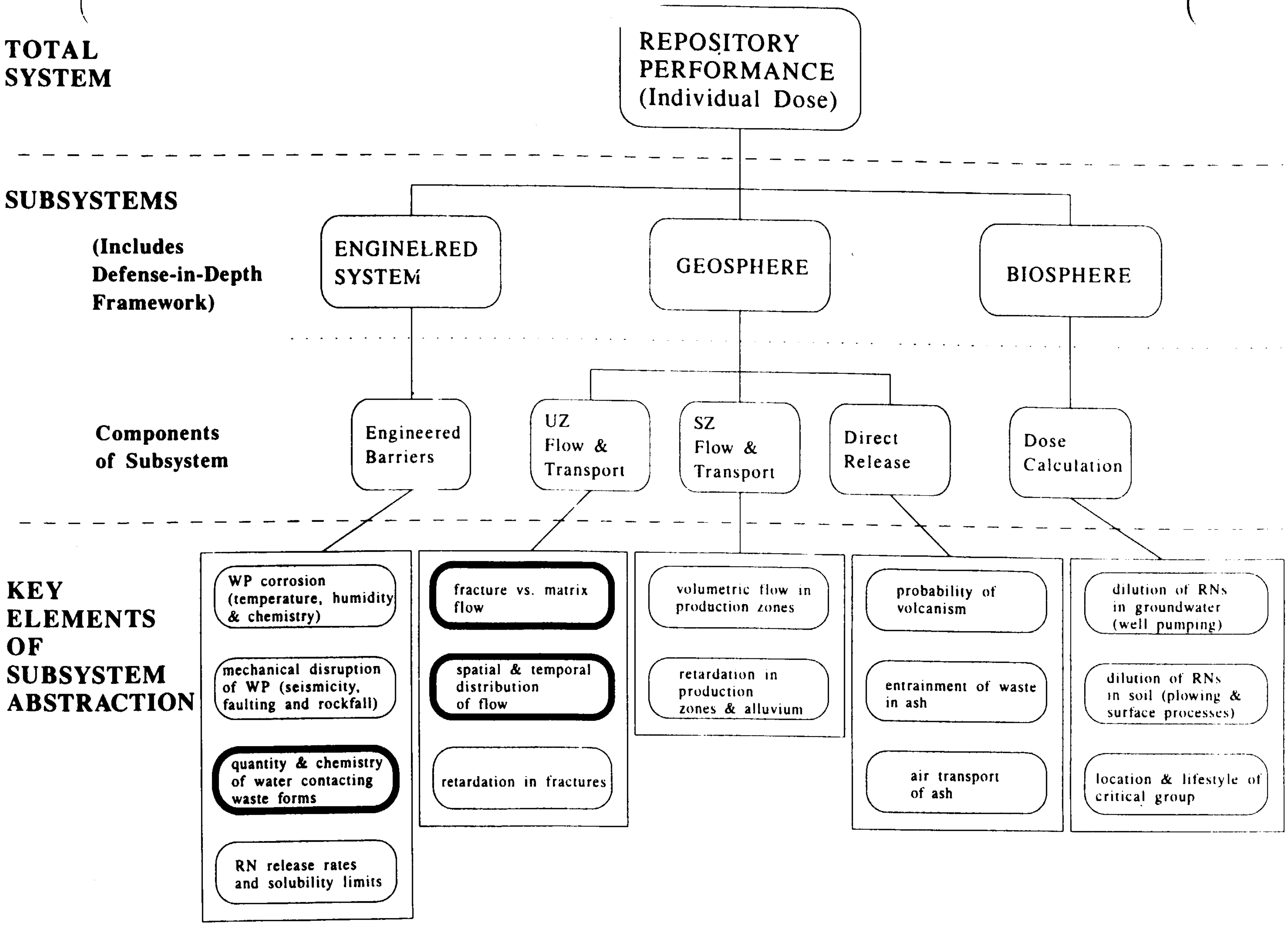

Figure A-1. Flowdown diagram for total system performance assessment. The subissue of "Present-Day Infiltration" provides input to the highlighted key elements.

APPENDIX B

CONCEPTUAL MODEL OF INFILTRATION AT YUCCA MOUNTAIN

CONTROLLING INFLUENCES ON NET INFILTRATION

Net infiltration is one component of a general water-balance equation that is usefully written for a control volume that extends from the ground surface to a depth below the rooting zone. Descriptions of the water-balance equation and example applications are provided by any soil-science textbook [e.g.. Jury, et al. (1991) and Hillel (1980)]; Flint, et al. (1996) provides a description that is specific to Yucca Mountain (YM). The water balance for the control volume over a specified period of time can be written

$$P + A - I_{net} + O_{net} + L_{net} + R_{net} - E_{net} - T = \Delta S_a + \Delta S_b + \Delta S_p$$

where

- P - net precipitation (including rain, snow, dew, and frost)
- A - applied moisture (human induced)
- I_{net} - net infiltration (liquid and vapor flow across the bottom of the control volume)
- O_{net} - net overland flow (runon and runoff)
- L_{net} - net lateral subsurface flow (liquid and vapor)
- R_{net} - net lateral subsurface root flow
- E_{net} - net vapor transport out of the top of the system (excluding transpiration)
- T - transpiration
- ΔS_a - change in above-ground storage
- ΔS_b - change in below-ground storage
- ΔS_p - change in plant-biomass storage

A schematic diagram of the components of the water balance equation is shown in figure B-1.

Depending on the time period of interest and the location of the control volume, some of the components may be negligible (i.e., changes in storage; human-induced moisture). Over long time periods (decades to centuries), net infiltration is typically only a small component of the water balance [e.g., a few percent or less (Maxey and Eakin, 1949; Montazer and Wilson, 1984; Watson, et al., 1976; Winograd and Thordarson, 1975)], particularly in arid and semiarid environments such as occur at YM. Factors to consider when evaluating components of the water-balance equation are discussed in the following subsections.

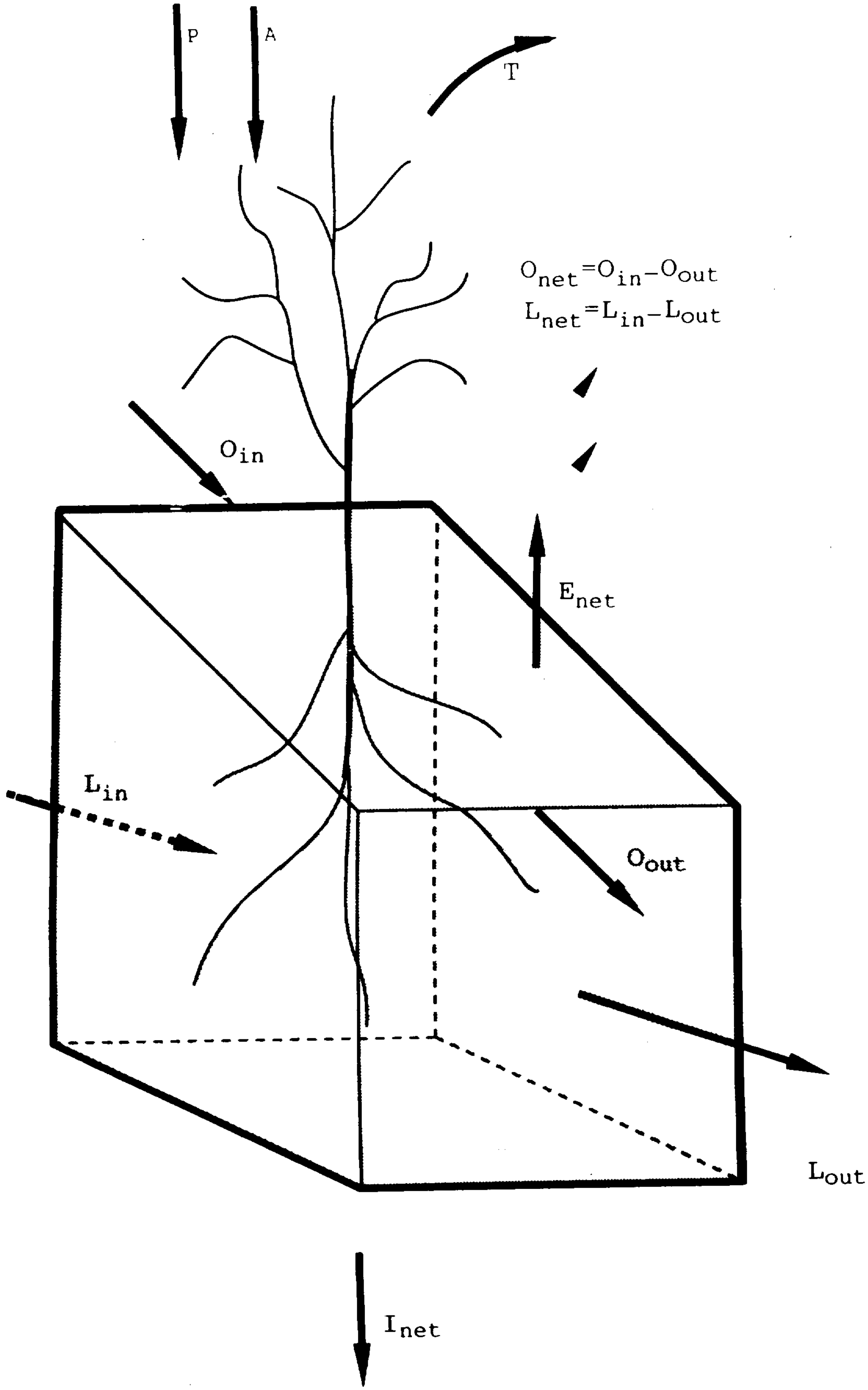

Figure B-1. Schematic diagram of the components of the water balance equation.

PRECIPITATION

Precipitation is one of the most significant factors in determining net shallow infiltration, as precipitation is the source of infiltrating water. Flint, et al. (1996) provide a good qualitative description of precipitation processes active at YM. Historical precipitation records are available for a number of locations in the YM area, including Beatty, Lathrop Wells, Mercury, and locations within the Nevada Test Site. Mean annual precipitation generally increases with elevation and is affected by the rain shadow of the Sierra Nevada and other mountain ranges. Mean annual precipitation data in the YM region is summarized by Hevesi, et al. (1992) and references therein. At YM, mean annual precipitation under current climatic conditions is generally reported to be in the range of 150 to 170 mm/yr.

Precipitation at YM is seasonal, with winter precipitation consisting predominantly of frontal storms that cover large areas, while summer precipitation consists predominantly of convective storms that may be quite local. Winter storms are controlled by storm tracks that are set up by the position of the jet stream, and may be strongly influenced by global circulation patterns that are in turn influenced by the El Niño Southern Oscillation. As shown by Hessing, et al. (1996), annual precipitation at United States Geological Survey (USGS) weather station 4JA, near YM, is highly cyclic over the 35-yr period of record from water year 1961 through 1995, supporting assertions that oscillations such as the El Niño events drive precipitation. The record also suggests that wet years are getting wetter.

Flint, et al. (1994) notes that summer storms can produce runoff in one wash while the next wash receives no rainfall; summer storms are generally less than 10 km in radius and have total precipitations of tens of mm to as much as 100 mm (Flint, et al., 1996). Regression equations presented by French (1986) suggest that precipitation is about 2.5 times more strongly affected by elevation in the summers than in the winters, which may be explained by the phenomenon of virga (evaporation of rain while falling).

Under current climatic conditions, snow occurs at the higher elevations and can remain on the ground for several weeks (Flint, et al., 1994). Under cooler conditions, snow might accumulate to greater depths and for longer periods of time, perhaps serving as an efficient source of infiltrating water (Gee and Hillel, 1988).

In arid and semiarid areas, it is commonly accepted that recharge may not occur every year. Instead, an occasional exceptionally large precipitation event or series of events allows moisture to move below the evapotranspiration trap (Barnes, et al., 1994; French, et al., 1996; Gee and Hillel, 1988; Gee, et al., 1994; Lane and Osterkamp, 1991; Phillips, 1994), particularly when the precipitation occurs when evapotranspiration demands are low. Precipitation is known to be highly variable in the YM area; for example, at Beatty annual precipitation ranged from 1.8 to 26.3 cm in the period of 1949 to 1979, and at Lathrop Wells recorded precipitation ranged from 2.4 to 13.4 cm in the same period (Nichols, 1987). As a corollary, it may be most important to properly characterize the return period and magnitude of these anomalous types of events, rather than magnitudes and frequencies of small and isolated medium-size events.

The historical record does not extend more than 50 yr in the vicinity of YM, so it is difficult or impossible to defensibly characterize events with long return periods. Most of the historical record consists of daily precipitation totals, while most events occur on time scales of minutes to hours. For winter storms, with low evapotranspiration demands and longer-duration events, daily records are more representative than for the typically much shorter and more intense summer storms.

EVAPOTRANSPIRATION

Evaporation is the process of vapor transfer from the soil surface to the atmosphere, while transpiration is the process of vapor transfer from plants to the atmosphere. Evaporation and transpiration are commonly lumped into a single term for convenience. It is physically possible for vapor to transfer from the atmosphere to the soil surface (e.g., dew, frost); however, it is difficult to conceive of a situation at YM where any net infiltration will occur due to this reversed vapor transfer.

Evaporation occurs under two conditions: (i) climate limited, where sufficient moisture exists at the ground surface to evaporate as fast as the atmosphere will accept it; and (ii) soil limited, where the ability of the soil to deliver moisture to the ground surface is the rate-limiting factor. Evaporation typically occurs in the top few centimeters of the ground.

Potential evapotranspiration is the amount of water that could be evaporated under climate-limited conditions, reported as 876 mm/yr by Flint, et al. (1996) and estimated by Shevenell (1996) to be approximately 1,200 to 1,500 mm/yr. Nichols (1987) reports that pan evaporation at the low-level waste site near Beatty probably exceeds 2,500 mm/yr and measured pan evaporation at Boulder City, NV, is 2,800 mm/yr. If all precipitation was subject to evaporation at the potential rate, clearly no net infiltration could occur at YM.

Climatic controls on evaporation include temperature, net solar radiation, net longwave radiation, atmospheric vapor density, and windspeed. Evaporation flux is from higher to lower vapor density. Relative humidity is the ratio of the actual vapor density to the maximum possible vapor density for the same gas temperature. Typically the relative humidity of the soil is almost 100 percent unless the soil is quite dry, while the relative humidity of the atmosphere is significantly less than 100 percent. The larger the gradient, the faster that evaporation can take place. The relative humidity of the atmosphere is largest during winter months and smallest during the summer months. Therefore, evaporative demand is least in the winter and greatest in the summer.

The rate at which evaporation takes place is also controlled by the vapor conductance. The vapor diffusion conductance increases as atmospheric turbulence in the surface boundary layer increases, which in turn increases as the windspeed increases. Also, the less stable the atmosphere is, the larger the conductance. Atmospheric instability is fostered by a hot ground surface relative to the atmosphere, so that the vapor conductance is larger in regions where relatively more net radiation is available to heat the ground. Accordingly, south-facing slopes with their increased solar load have an increased evaporative demand over north-facing slopes and would be expected to have a smaller net infiltration. The difference in evaporation from north-facing and south-facing slopes may only be a few percent; however, the difference between 98 percent and 99 percent removal of precipitation through evaporation translates into a factor of 2 change in net infiltration.

Coarse materials at the ground surface can limit evaporation by providing shelter from winds. For example, studies presented by Kemper, et al. (1994) comparing evaporative losses from bare soil and soil covered by sand or gravel mulches indicate that while bare soil had about 81 percent of applied moisture evaporated, only 15 to 19 percent evaporated when the same type of soil was covered with 5 cm of gravel. Scree slopes at YM may be local areas where significant net infiltration could occur unless adjacent vegetation is able to take advantage of the moisture. Desert vegetation does not grow within scree piles because desert vegetation is typically adapted to growing with sunlight almost immediately available upon germination and does not have the energy reserves to reach sunlight from deep within a scree pile[1].

Barometric pumping, thermosyphons, and windpumping are other ways vapor can be exchanged with the atmosphere. Barometric pumping refers to short-term gas-flow cycles induced by barometric-pressure variation in the atmosphere, and can occur in both soil and fractured-rock outcrops. A thermosyphon refers to a circulation pattern in the soil due to temperature-induced pressure differences between atmospheric and rock gases, where dry atmospheric air enters at one end of the syphon and moist rock air exits at the other end, and requires a significant difference in elevation. Windpumping occurs due to the airfoil effect of wind being forced to move around a barrier. Both thermosyphons and windpumping are expected to occur primarily on Yucca Crest and ridges east of Yucca Crest. Measurements and simulations assessing the magnitude of gas flow through these mechanisms are discussed by Patterson, et al. (1996). The calculated net exchange of moisture through these effects is on the order of 0.02 mm/yr (E. Weeks, presentation at the U.S. Department of Energy's (DOE's) Unsaturated Zone Expert Elicitation Workshop, February 4, 1997). All of these mechanisms exchange gas between the atmosphere and the soil, thus may be effectively removing vapor from below the root zone

Transpiration is a significant process for removing soil moisture. Desert shrubs can be extremely efficient at removing water stored in a soil column, as demonstrated by lysimeter studies at Beatty, Nevada, and at the Hanford site (Gee, et al., 1994). The effectiveness of desert vegetation at removing water from shallow soils over fractured bedrock has not been established to date, due to the difficulty in performing measurements.

The vegetation at YM is transitional between Mojave and Great Basin associations (Flint, et al., 1996), with Mojave species (bursage and range rhatany) dominating on the warmer south-facing slopes and Great Basin species (yellow rabbitbrush, green ephedra, big sagebrush, and burrobrush) dominating on the cooler north-facing slopes. As soils change from deep, loose, and sandy to rockier but still relatively flat to steep and shallow, the vegetation associations change from the *larrea-ambrosia* association (creosote bush and bursage) to the *larrea-lycium-grayia* association (creosote bush, desert thorn, and spiny hopsage) to the *lycium-grayia* association. The Great Basin *coleogyne* association (blackbrush) dominates in cooler and flatter areas, particularly where lateral flow provides additional moisture. The pinyon-juniper association is not found in the immediate repository area but can be found at higher elevations, on Shoshone Mountain about 18 km northeast the proposed repository, and might be expected to move south in cooler climatic conditions. An isolated population of junipers currently exists on the Prow just north of the repository site. The general description of vegetation distributions is adapted from that presented by Flint, et al. (1996) based on a cursory confirmatory field survey.

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[1] D. Groeneveld, oral communication, 1997.

Characterization of transpiration patterns due to desert vegetation is currently somewhat poorly constrained. Little site-specific measurement of transpiration has been attempted, with most efforts concentrating on describing plant dynamics rather than water-uptake dynamics. Available information on rooting depths is typically obtained under conditions where the roots are not constrained by bedrock, while the presence of bedrock and bedrock fissures is strongly constraining on ridgetops and sideslopes. There is a strong seasonality component to desert vegetation, with the growing season synchronized within the autumn-winter-spring period. Annuals can respond within weeks to significant soil moisture. An invading alien species, cheatgrass, tends to be most active in the winter.

Mathematical relationships describing transpiration are most fully developed for areas with deep soil and are most poorly characterized in areas with shallow, rocky soil, particularly with bedrock constraints on roots. For comparison, estimates of bare-soil net infiltration tend to be relatively small in deep soils and relatively high in shallow soils (Stothoff, 1997).

Relationships between precipitation, plant biomass, edaphic constraints, phenologic constraints, seasonality, soil moisture distributions, and transpiration are more qualitative in nature than quantitative, although some phenologic events have predictable outcomes. For example, a significant rainfall (greater than 25 mm) in late September through early December is a good predictor of seasonal activity through the spring, while lack of such a rainfall causes perennial plants to remain dormant from March through May and annual plants to be absent (Beatley, 1974). Drought periods can dramatically change the percent cover of the species as well (Flint, et al., 1996) with the implication that the first rainy period subsequent to a drought has reduced vegetation available for transpiration.

MOISTURE REDISTRIBUTION

Moisture redistribution can be conveniently partitioned into vertical and lateral redistribution. Vertical redistribution is the component of flow that contributes to net shallow infiltration. Lateral redistribution can be defined as any nonvertical flow [above the representative elementary volume (REV) scale]. Lateral redistribution can occur as overland flow, where water is moving across the ground surface, or it can occur in the soil matrix. Lateral redistribution can be a concentrating mechanism, increasing effective precipitation in local areas (e.g., wash channels, local depressions, fractures), or it can be a dissipating mechanism, decreasing effective precipitation (e.g., ridgetops). Barring capillary effects, the more permeable that a medium is, the less lateral redistribution occurs.

When considering wetting-front penetration during a rainfall event, important factors include K_{sat} (governing how fast water can infiltrate relative to rainfall rate); porosity (governing how deep a wetting pulse can move); and depth to a restricting layer (governing the total volume of water that can infiltrate before runoff occurs). The last two factors are often multiplied to yield storage capacity. Low-permeability rocks within a soil matrix effectively reduce the porosity and thus the storage capacity. At the time scales of infiltration events (minutes to days), the matrix of a fractured low-permeability bedrock has minimal effect on flow and the fractured medium can be considered to have very low porosity and thus low storage capacity.

For small to medium storms, soils with a high storage capacity tend to return the infiltrated water to the atmosphere through evapotranspiration while soils with a low storage capacity above a fractured bedrock may have some water enter the fractures and escape downward as net infiltration. On the other hand, if the fractures in the low storage-capacity area have restricted K_{sat} and flow concentration occurs in the high storage-capacity area (i.e., wash channels), large events may cause water to penetrate below the evapotranspiration zone in the areas with large storage capacity and yield more net infiltration than in the low storage-capacity areas for the same event.

The primary cause of overland flow is when the ground cannot accept water at the rate of precipitation, and the excess water either locally concentrates or flows downhill. After an equilibration period where capillary effects are dominant, a porous medium accepts water due to gravity, with a maximum rate of K_{sat}. An intense storm might have intensities of over 100 mm/hr for 5 minutes, but only infrequently will average precipitation over an hour be more than 25 mm [based on depth-duration frequency curves presented by French (1983)].

Welded tuff typically has very low K_{sat} on the order of 10^{-6} to 10^{-1} mm/hr (Flint, 1996) so that overland flow is expected wherever unfractured welded tuffs crop out. Nonwelded tuff typically has higher K_{sat} on the order of 10^{-1} to 10 mm/hr (Flint, 1996) so that overland flow is also expected for at least some precipitation events wherever nonwelded tuffs crop out.

Flint, et al. (1996) asserts that 2.5, 25, and 250 μm fractures have K_{sat} values of about 20, 650, and 3.1×10^5 mm/hr, respectively, while fracture-fill materials are reported to have K_{sat} values that average about 1.8 mm/hr. Open fractures of an appreciable size should limit overland flow if the fractures intercept a rivulet, while a filled fracture would not appreciably limit overland flow. The upper washes east of Yucca Crest and the west flank of YM are likely candidates for exposed fractures.

Soils at YM have similar compositions for all environments (Schmidt, 1989). YM soils tend to have higher K_{sat} than tuffs or fracture-fill materials, with estimated values based on texture analysis of about 20 mm/hr (Schmidt, 1989) or on the order of 20 to 140 mm/hr (Flint, et al., 1996) with measured values of as much as 500 mm/hr (Guertal, et al., 1994), and with wash channels having as much as 2,500 mm/hr (trip report by S. Stothoff and J. Winterle, 1997), so runoff would only occur for intense storms or for cases where the soils become saturated due to contact with bedrock or other impeding layers such as carbonate deposits (caliche). Note that considerable volumes of water can be imbibed into wash channel soils when the wash is flowing.

Another source of overland flow is when lateral subsurface flow moves from topographic highs to topographic lows and emerges as a permanent or intermittent spring, then moves off downhill. At YM, no permanent springs exist and intermittent springs would be most likely to occur at the base of sideslopes.

Lateral subsurface flow tends to occur whenever there is

- a focused source of water (e.g., washes);
- heterogeneity and layering;
- and a soil-rock interface, particularly when the interface is tilted.

Even in apparently homogeneous media, there can be lateral movement of water (McCord and Stephens, 1987) due to microtextural effects; however, other factors should be far more significant for lateral subsurface flow at YM.

A significant focused source of water at YM occurs when water is flowing in wash channels due to overland flow. Where soils are shallow or nonexistent, fractured bedrock is exposed to flowing water and any open fractures would be expected to flow at full capacity. Where soils exist, water would be expected to imbibe radially at early times, due to capillary forces, and relatively quickly (due to the relatively coarse materials in wash channels) convert to predominantly vertical flow. If sufficient water imbibes that a wetting pulse contacts the soil-bedrock interface, lateral flow along the interface would be expected to take place. According to Flint, et al. (1996) channels cover about 2 percent of the surface area, so that lateral flow due to a channel source should be a relatively local phenomenon.

Another focused source of water occurs when water runs off of exposed bedrock into a local depression (e.g., a pocket of soil or a fracture). The local wetting front is then deeper than would otherwise have been the case and water is likelier to drain below the evapotranspiration zone. Significant focusing through this mechanism should be most likely along Yucca Crest and on the west flank of YM.

Due to the relatively large K_{sat} values for soils at YM and the relatively shallow soils everywhere but in washes, soil heterogeneity and soil layering are not expected to strongly impact moisture redistribution except, perhaps, in deep alluvium. Calcium carbonate (caliche) layers, however, have the potential to strongly impact redistribution. Well-developed caliche is observed at YM in earth flow and colluvial deposits on steep slopes in low positions (Schmidt, 1989). In soils, caliche layers tend to form in the root zone from calcium in eolian dust (Schlesinger, 1985) and were more likely to have formed during a wetter Pleistocene with cooler winters than under current climatic conditions (Marion, et al., 1985). Depth of caliche-layer formation is strongly affected by the depth of wetting pulses from extreme precipitation events (Marion, et al., 1985). Reported values for caliche K_{sat} are generally on the order of 40 to 120 mm/hr (Baumhardt and Lascano, 1993), so that no runoff can be expected for most precipitation events; however, strong capillary barriers to flow may form (Hennessy, et al., 1983), which would tend to hold water in the evapotranspiration zone and lower net infiltration.

At YM, carbonate contents are generally less than 5 percent of the fine fraction (<2 mm) of soils deposited since the late Holocene and are associated with thin coats on clast undersides, while late Pleistocene soils are more cemented with a maximum carbonate content of less than 10 percent of the fine fraction and with cementation occurring at depths greater than 30 cm (Lundstrom, et al., 1995). Little information is available on the spatial distribution of caliche at YM, but it would be reasonable to assume that caliche would not be present in soils anywhere but in alluvium that is greater than 30 cm in depth. On the other hand, the soil-bedrock interface can form a barrier to flow that fosters evaporation and thus carbonate deposition, so that it would not be unexpected to have caliche deposits on top of the bedrock covered by shallow soils (e.g., sideslopes and ridgetops) at YM.

An excellent candidate for substantial lateral subsurface flow within the soil exists wherever there is a sloping soil-bedrock interface at a sufficiently shallow depth that a wetting pulse could contact the interface. Particularly good candidates exist on the sideslopes in washes east of Yucca Crest, where the soil is sufficiently permeable to allow most or all of the precipitation to imbibe during precipitation events and the soil-bedrock interface is steeply tilted. Vegetation tends to be relatively sparse at the top of the slopes and locally heavier where the slope breaks. Neutron probes provide evidence of lateral flow when moistures increase at depth without increasing closer to the surface, although it cannot be determined whether the lateral flow is due to a fast vertical pathway just outside the range of the probe or due to lateral flow at depth. At Abandoned Wash, in the spring of 1993, neutron-probe evidence suggestive of lateral flow along the sideslopes was documented in the form of increased moisture at about 7 m of depth in N58 (located in a terrace adjacent to a sideslope), appearing well below a wetting front from the surface.

ENVIRONMENTS TO CONSIDER AT YM

The conceptual model laid out by Flint and Flint (1995) and Flint, et al. (1994, 1996) proposes four hydrologic environments [ridgetop, sideslope (north-facing and south-facing), terrace, and channel] covering 14, 62, 22, and 2 percent of the site-scale model. The conceptual model laid out by Long and Childs (1993) is similar, with three hydrologic environments [shallow (soil depth <0.35 m), slopes (soil depth 0.35 to 2 m), and basins (deep soils)] covering 18, 70, and 12 percent of the repository footprint.

The NRC staff agrees that these broad divisions are reasonable, particularly east of Yucca Crest, although the categories may be somewhat too generic. The ridgetop category may have two different infiltration behaviors depending on whether crystal-rich (Tpcr) or crystal-poor (Tpcp) bedrock is exposed, due to significantly different bedrock-fracturing patterns. As generally described, the sideslope category is representative of the washes east of Yucca Crest but may inadequately account for the west flank of Yucca Crest.

1. Ridgetop

The ridgetop environment is generally flat to gently sloping, characterized by shallow (roughly 30 to 40 cm, with deeper pockets in scattered locations) to no surficial deposits. The soils have a significant fine eolian component. Flint, et al. (1996) classify the soils as lithic haplocambids with a K_{sat} of 24 mm/hr (based on texture analysis), porosity of 0.33, and rock fragments of 15.2 percent. From personal observation, both the number of rock fragments and their size increase with depth, and permeameter measurements suggest that a representative K_{sat} may be as much as 150 to 175 mm/hr (Stothoff and Winterle, 1997). In general, K_{sat} for the ridgetop soils is large enough to accept most or all rainfall and overland-flow runoff should be minimal until the soil storage capacity is reached. Assuming that representative and maximum soil depths are 20 and 60 cm, representative and maximum soil capacities are about 5.5 to 17 cm^3/cm^2.

Two general classes of bedrock are present along ridgetops and the hydrologic behavior of the two classes may be significantly different.

a. Crystal-Rich Tiva Canyon Bedrock (Tpcr)

The first bedrock class is crystal-rich Tiva Canyon Tpcr [cuc using the notation of Scott and Bonk, 1984)] overlying Yucca Crest and extending somewhat to the east along some ridges. This bedrock is somewhat permeable with K_{sat} on the order of 0.1 mm/hr (Flint, 1996) and weathers into monolithic boulders. The vegetation is typically crack loving and can form linear features aligned with fissures in the bedrock even in soils as deep as 40 cm (Stothoff and Winterle, 1997). Based on cursory field checking, bedrock fissures can be 5 to more than 10 cm in aperture; are typically filled with soil to at least some depth, although fissures may be cemented at depth; there is no evidence of significant carbonate layering above the bedrock; and there are relatively few rock fragments in the soil.

The hydrologic regime of the first bedrock class is expected to be primarily vertical, with lateral flow locally focussing runoff from outcrops into soil and from soil into fissures. For soil-filled fissures, there is no capillary or permeability barrier to prevent water from escaping to depth quickly. If the fissure has carbonate fillings at depth, permeability and capillary barriers may retard wetting pulses. In general, it is expected that water may quickly escape to depth. Although vegetation rooting is strongly preferential to the fissures, it is not yet clear what proportion of a precipitation event can be intercepted through vegetation.

Bomb-pulse ^{36}Cl was located to depths of at least 17 m in seven of the eight ridgetop neutron-probe boreholes discussed by Fabryka-Martin, et al. (1996) with no trace in the other borehole. All eight ridgetop boreholes were completed in Tpcr. Moisture-content records in the boreholes (Flint and Flint, 1995) appear consistent with the bomb-pulse ^{36}Cl data. One borehole had bomb-pulse ^{36}Cl to a depth of 62 m, although this may be due to lateral flow. One-dimensional simulations by Flint, et al. (1996) and Stothoff, et al. (1996) suggest that infiltration should be quite significant in this environment.

b. Crystal-Poor Tiva Canyon Bedrock (Tpcp)

The second bedrock class is crystal-poor Tiva Canyon, or Tpcp. This bedrock class is exposed at lower elevations where the overlying Tpcr has eroded away. Few data are available to quantify infiltration in this environment. The Tpcp bedrock is somewhat less permeable with K_{sat} on the order of 0.04 mm/hr (Flint, 1996) and is densely fractured. Overlying soils are also classified as lithic haplocambids by Flint, et al. (1996) but may be somewhat shallower than for the Tpcr unit. Fractures typically have much smaller apertures and are generally filled with carbonate materials with K_{sat} on the order of 1.8 mm/hr (Flint, et al., 1996). Carbonate materials should have a strong capillary attraction for water relative to the soils so that considerably increased sorption rates would be anticipated at early times in a precipitation event.

For large precipitation events, the hydrologic regime of the second bedrock class is expected to have a larger lateral-flow component than for the Tpcr unit, due to somewhat smaller soil storage capacity, greater slopes, and restricted capacity for infiltration into the bedrock. The hydrologic regime however, may allow a greater amount of net infiltration for small events, due to small soil storage capacity and capillary attraction of fracture-fill materials. Vegetation is relatively sparse in this environment. It does not appear that vegetation rooting is able to significantly penetrate the carbonate-filled fractures.

2. Sideslopes

The sideslope category covers the largest portion of the area over the potential repository footprint. Over the footprint to the east of Yucca Crest, the sideslope category represents the sides of washes incised into Tpcp subunits. To the west of Yucca Crest, the sideslope category represents the east flank of Solitario Canyon and exposures of all units from Tpcr through Tptpll (TCw, PTn, and TSw through the lower lithophysal unit).

Scree formation is a common characteristic of all sideslopes. Based on about two dozen observations in washes east of Yucca Crest[2], scree is generally not present on slopes less than about 30 percent slope, linearly increases with slope above 30 percent, and completely covers areas with about 60 percent slope, with a coefficient of determination of 0.67 (i.e., a substantial correlation exists between slope and the presence of scree). This relationship may overpredict scree cover on fault-controlled sideslopes such as the west flank of YM.

a. Sideslopes East of Yucca Crest

The sideslopes of washes east of Yucca Crest fit the common conceptualization of the sideslope category. Ground slopes are as much as 35 degrees. Soil depth is 0 to roughly 1 to 2 m, typically less than 0.5 m, with fragments of rock increasing in size and plentitude as bedrock is approached. Over the repository footprint, bedrock is exclusively Tpcp with characteristics described in section 1.b. (Crystal-Poor Tiva Canyon Bedrock).

The general east-west trend of the washes results in north-facing and south-facing slopes with significantly increased solar loading for the south-facing slopes. Mojave vegetation typically dominates on south-facing slopes, and plant activity is likely to be strongly seasonal. Great Basin vegetation dominates north-facing slopes and plant activity may be less seasonal. The soil-bedrock interface is irregular in locations while the soil surface is much smoother, so vegetation may locally take advantage of pockets of deeper soil for moisture requirements.

Lateral subsurface flow is more likely on sideslopes than on ridgetops based on the steep slopes, low soil storage capacity, and bedrock permeability (in common with the Tpcp ridgetops). The sparsity of vegetation at the top of slopes and relative abundance of vegetation at the foot of slopes is indirect evidence for lateral flow. Overland flow undoubtedly occurs on sideslopes in upper washes based on lack of soil cover and smooth rock surfaces in such areas. Overland flow is probably minimal elsewhere on the sideslopes, due to the lack of evidence for gully formation and the rather high soil permeabilities.

Three neutron-probe boreholes in lower sideslopes were sampled for bomb-pulse ^{36}Cl as discussed by Fabryka-Martin, et al. (1996). Two boreholes in WT-2 Wash (N53 and N55, each with soil covers of about 0.7 m) had bomb-pulse ^{36}Cl to depths of 58 and 79 m. Both had bomb-pulse ^{36}Cl throughout the TCw and into the PTn with the deeper borehole also showing bomb-pulse ^{36}Cl in the TSw unit. On the other hand, no bomb-pulse ^{36}Cl was found in N61 (with soil cover of 3.1 m) in Abandoned Wash. In borehole N54, in the channel of WT-2 Wash between N53 and N55, all bomb-pulse ^{36}Cl was found in alluvium at depths less than 4.6 m and

[2]D. Groeneveld, written communication, 1997.

the infiltration rate for N54 calculated using chloride mass balance is 0.06 to 0.29 mm/yr (Fabryka-Martin, et al., 1996). Sideslopes with shallow soil cover can be far more effective at providing net infiltration than channels in deep alluvium. As bomb-pulse ^{36}Cl is found deeper in N53 and N55 than in typical ridgetop environments, lateral flow may supply additional water downslope to both N53 and N55.

In Pagany Wash, there are contradictory interpretations of infiltration at UZ-4 (terrace with 12 m of alluvium) and UZ-5 (sideslope with little or no soil cover). Percolation fluxes calculated using pore-water chloride mass balance in the PTn are 1.1 and 1.5 to 2.5 mm/yr for UZ-4 and UZ-5 (Fabryka-Martin, et al., 1996). Using tritium and ^{14}C data yields 35.1 and 20 mm/yr for UZ-4, and ^{14}C data yields 4 mm/yr for UZ-5 (Kwicklis, et al., 1993). Thermal-flux calculations using 1995 data suggest that infiltration fluxes are 18 and 5 mm/yr at UZ-4 and UZ-5 (Rousseau, et al., 1996), although the authors expect the methodology to yield fluxes too high for UZ-4 and too low for UZ-5. As discussed by Tyler and Walker (1994), the use of bomb-pulse tracers can overestimate recharge by an order of magnitude or greater when the impact of transpiration on the flow velocities is neglected. Tyler and Walker (1994) consider chloride balance to be far more reliable. The thermal-flux calculations may have been influenced by nonrepresentative wet years to some extent. It may also be that channel infiltration dominates sideslope infiltration, at least occasionally, in Pagany Wash. Moisture-content data from a set of neutron probes in Pagany Wash (N2 through N9 and N63) are indicative of lateral flow from the channel; lateral flow from the sideslopes in the TCw bedrock cannot be precluded, either. Nevertheless, it appears that flow may be predominantly vertical.

Approaches considering flow to be essentially vertical have been used to model infiltration on YM sideslopes (Flint, et al., 1996; Stothoff, et al., 1996). Despite the apparent contradiction of perhaps significant lateral flow, the approach may not be unreasonable for the washes east of Yucca Crest as long as the modeling approach assumes that any water not infiltrating runs off to be accounted for separately. Salvucci and Entekhabi (1995) present a modeling study examining hillslope controls on equilibrium shallow-water-table profiles that demonstrated that hills with long slopes relative to the soil thickness have an extended domain with equilibrium profiles essentially parallel to the bedrock surface. If this characteristic is reproduced for the highly intermittent conditions at YM, lateral inflow would be almost balanced by lateral outflow for most of the hillslope and the one-dimensional (1D) approach would be appropriate except at ridgetops (drier than predicted) and at the base of the slope (wetter than predicted).

Approaches considering flow to be 2D (two-dimensional) or 3D (three-dimensional) have not been considered for YM sideslopes. If the 1D approach is used for sideslopes, it is critical to consider lateral flow to and from channels separately.

b. Sideslopes West of Yucca Crest

Although the bulk of the potential repository footprint lies below and to the east of Yucca Crest, the west flank of YM is of interest as it may be possible for infiltration to enter the TSw below the PTn and move laterally into the repository horizon without being buffered by the PTn.

The sideslope environment along the west flank of YM is more heterogenous than in the washes east of Yucca Crest, due to the wider range of bedrock exposures and gullying due to the steeper slopes. Slopes are greater than 30 degrees. Vegetation is dominated by crack-loving species. Solar loading is far more spatially uniform than on the east of Yucca Crest, due to the western exposure.

Above the PTn exposure, scree is dominant, channels expose bedrock, and where scree is not present, soils only exist in pockets and cracks. In the PTn exposure, slopes flatten with shallow soils developing in places, although bedrock is exposed in channels and local patches. Below the PTn exposure, slopes are generally less than 15 degrees and soils begin to develop although gullies expose bedrock even near the bottom of Solitario Canyon.

As with the washes east of Yucca Crest, the predominant modeling approach has been vertical and 1D. The steep slopes and presence of gullies suggest that overland flow is significant. It is anticipated that overland flow is relatively short so that although the fractured bedrock exposed in the channels might accept water rapidly, total volume entering the bedrock may be limited. Due to shallow to nonexistent soils, the 1D approach may once again be appropriate, as long as overland flow is explicitly accounted. Overland flow to provide infiltration into channels will likely be the predominant source of net infiltration on the west face of YM.

3. Wash Bottoms

All wash bottoms have a channel that exposes bedrock in upper reaches and lies within alluvial fill in lower reaches. In addition, lower reaches have alluvial terraces that the channel may be incised within. Total depth of alluvial fill may be as much as 10 m over the repository footprint and Solitario Canyon and hundreds of meters in Jackass Flats. In the relatively narrow washes between Yucca Crest and the Exploratory Studies Facility (ESF), wash terraces are shallow to nonexistent.

a. Wash Terraces

Lower washes have a terrace of alluvial fill, at least 1 m in depth to as much as 10 m, in which a channel may be incised. Terraces were formed in climates with runoff events larger than observed historically (Lundstrom, et al., 1995). Terraces have shallow slopes and are characterized by deep-rooted vegetation such as creosotebush. As with the ridgetop and sideslope soils, terrace soils have a significant eolian component near the ground surface (Lundstrom, et al., 1995).

Net infiltration is expected to be small to nonexistent in wash terraces unless there is significant lateral flow from sideslopes. The storage capacity of the terraces is large relative to precipitation events so that vegetation should be efficient in transpiring soil moisture before it can escape to depth. Wash terraces are analogous to the deep alluvium cases commonly studied in the literature. Recharge is typically found to be small in deep alluvium unless concentrating mechanisms exist (e.g., active channels, depressions).

Heterogeneity is probably significant in terrace soils based on complex ^{36}Cl signatures (Fabryka-Martin, et al., 1993), making calibration of 1D simulations difficult. Flow fields in terraces are likely to be inherently 2D or 3D due to lateral redistribution from sideslopes and channels.

b. Wash Channels

All washes in the YM area are ephemeral. Bedrock is exposed in upper washes while in lower washes the channel may be incised into alluvial fill. Soils in lower-wash channels are coarser and more permeable than in adjacent terraces. Vegetation is sparse in active channels, due to scouring from occasional runoff events, although roots typically should extend under the channel from adjacent terraces.

Net infiltration may be large in the channels, due to concentration of flow from large areas and high permeability of channel bottoms. As discussed in section 2.a. (Sideslopes East of Yucca Crest), evidence based on heat-flux arguments is available suggesting that net infiltration from the Pagany Wash channel may be on the order of 20 mm/yr (Rousseau, et al., 1996), although it is not clear over what area this infiltration rate applies. In 1983, about 15 months after the previous reading, temperature perturbations were also observed in UE-25 a#7 following a major storm. Borehole UE-25 a#7 lies on or near the Drillhole Wash fault zone. The perturbations developed to a depth of 150 m, which Sass, et al. (1988) assessed as possibly attributable to borehole-annulus fluxes. If annulus fluxes were significant, the temperature anomalies are meaningless. Since the temperature anomaly persisted for at least 1 year and was not atypical of previous conditions, the anomaly may represent an infiltration event moving through the fault. If so, the moisture penetrated 47 m of alluvium, 4 m of TCw, 42 m of PTn, and 58 m of TSw in as little as 1 week to as much as 15 months.

To date channel flow over the potential repository footprint has not been rigorously considered in modeling efforts. Recharge from channels is considered to be 3 percent of precipitation by Flint, et al. (1996) based on regressions from neutron-probe measurements.

CALCULATED DISTRIBUTION OF INFILTRATION AT YM

A map of estimated spatial distribution of net infiltration was presented by Bagtzoglou, et al. (1996) based on abstractions of 1D simulations considering the impact of soil properties, soil depths, bedrock-fracture properties, elevation, and solar loading on net infiltration. The simulations are based on the assumptions that (i) where unfilled fractures exist, they dominate the hydrologic response of the bedrock; and (ii) a few unfilled fractures exist everywhere. Using the same assumptions as Bagtzoglou, et al. (1996), a map of estimated net infiltration in the area of the proposed repository footprint is presented in figure B-2.

Figure B-2 is in qualitative agreement with the conceptual model of distributed net infiltration being dominated by areas with shallow soil depths (i.e., higher infiltration along ridgetops and sideslopes). The distribution of infiltration in figure B-2 does not explicitly account for lateral flow or localized infiltration under scree and only qualitatively addresses infiltration in areas where PTn crops out. Further, the impact of vegetation is not considered, which is anticipated to significantly decrease net infiltration in areas with deep soils. Infiltration resulting from channel flow is indirectly accounted for by occasional shallow soil depths within active wash channels and distributed recharge in areas with deep soils that also have drainage channels.

Net infiltration values predicted by the 1D simulations were found to be insensitive to the hydraulic properties of unfilled fractures as long as some fractures existed (i.e., nonzero fracture porosity), but the net infiltration was found to be very sensitive to soil depth (Stothoff, 1997).

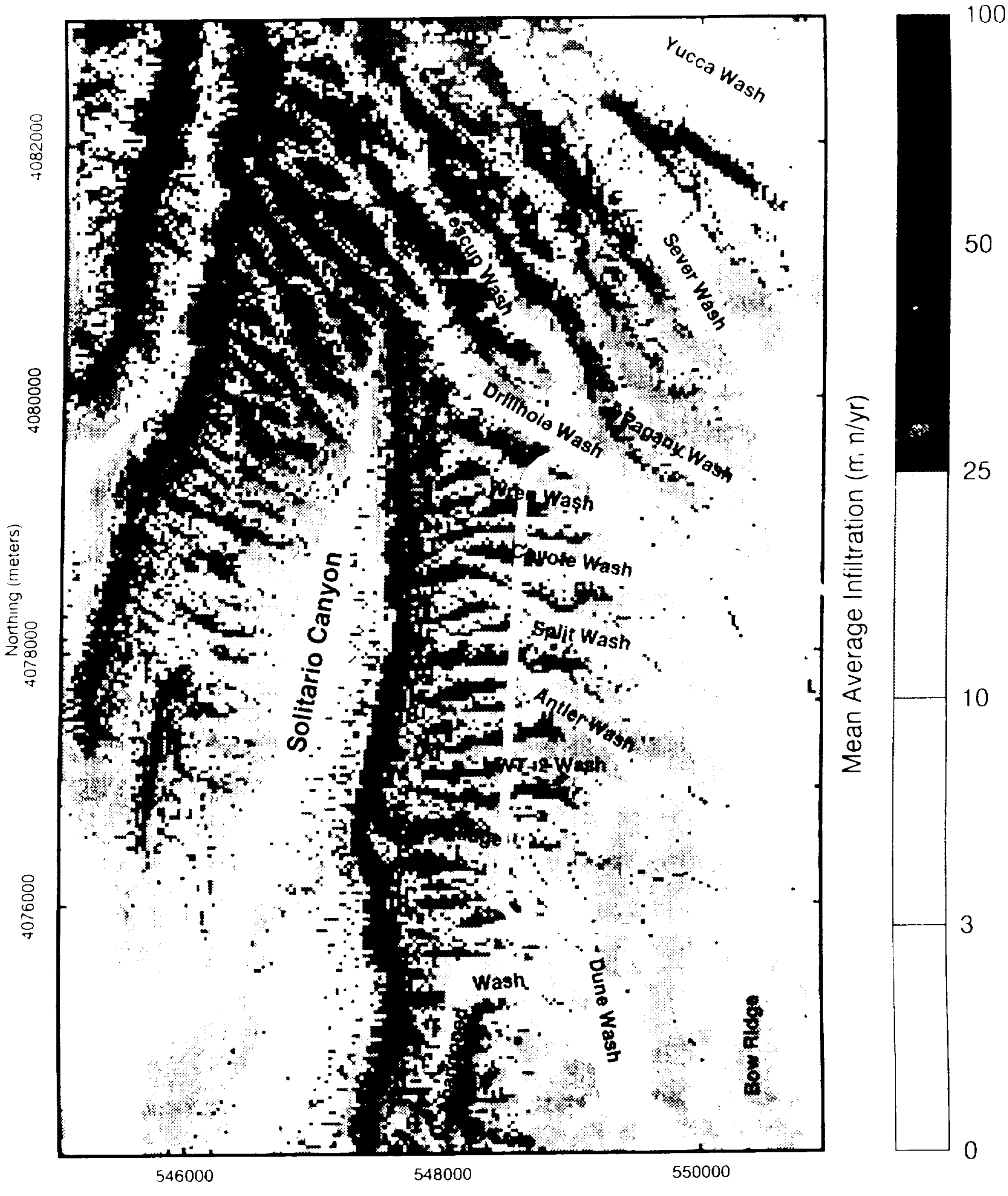

Figure B-2. Estimated net infiltration in the vicinity of the proposed repository footprint.

Subsequent unpublished simulations assumed that the bedrock was impermeable, aside from filled fractures having saturated hydraulic conductivities similar to those reported by Flint, et al. (1996). It was suggested that in cases where all fractures are filled with carbonates, net infiltration is comparatively less sensitive to soil depth. In contrast to cases with unfilled fractures, net infiltration in carbonate-filled fractures is quite sensitive to the hydraulic properties of the fillings, particularly bubbling pressure and saturated hydraulic conductivity. As with unfilled fractures, the (nonzero) porosity assigned to the fractures does not appear to have a significant influence on net infiltration implying that as long as a few fractures exist, it is not important to characterize the number of fractures or their apertures.

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APPENDIX C

DOE'S UNSATURATED ZONE FLOW MODEL EXPERT ELICITATION PROJECT

From the Fall of 1996 through the Spring of 1997, the U.S. Department of Energy (DOE) performed an expert elicitation assessing issues related to modeling the Yucca Mountain unsaturated zone at the site scale (DOE, 1997). In section 1.1 of DOE's report, the objectives of the elicitation are spelled out (DOE, 1997, p. 1-1).

> This report presents results of the Unsaturated Zone Flow Model Expert Elicitation (UZFMEE) project at Yucca Mountain, Nevada. This project was sponsored by the U.S. Department of Energy (DOE) and managed by Geomatrix Consultants, Inc. (Geomatrix), for TRW Environmental Safety Systems, Inc. The objective of this project was to identify and assess the uncertainties associated with certain key components of the unsaturated zone flow system at Yucca Mountain. This assessment reviewed the data inputs, modeling approaches, and results of the unsaturated zone flow model (termed the "UZ site-scale model") being developed by Lawrence Berkeley National Laboratory (LBNL) and the United States Geological Survey (USGS). In addition to data input and modeling issues, the assessment focused on percolation flux (volumetric flow rate per unit cross-sectional area) at the potential repository horizon. An understanding of unsaturated zone processes is critical to evaluating the performance of the potential high-level nuclear waste repository at Yucca Mountain.
>
> A major goal of the project was to capture the uncertainties involved in assessing the unsaturated flow processes, including uncertainty in both the *models* used to represent physical controls on unsaturated zone flow and the *parameter values* used in the models. To ensure that the analysis included a wide range of perspectives, multiple individual judgments were elicited from members of an expert panel. The panel members, who were experts from within and outside the Yucca Mountain project, represented a range of experience and expertise. A deliberate process was followed in facilitating interactions among the experts, in training them to express their uncertainties, and in eliciting their interpretations. The resulting assessments and probability distributions, therefore, provide a reasonable aggregate representation of the knowledge and uncertainties about key issues regarding the unsaturated zone at the Yucca Mountain site.

Table 3-1 of the expert elicitation (DOE, 1997) summarizes key issues discussed with the experts and the responses of the experts to the issues. Portions of that table relevant to shallow infiltration are reproduced here as Table C-1 Table 3-2 of the expert elicitation (DOE, 1997) presents a summary of the estimates of percolation flux provided by the experts; this table is reproduced as Table C-2. Six of the seven experts thought that the statistical distributions for net shallow infiltration and deep percolation fluxes were identical; the remaining expert (G. Campbell) thought that slightly higher values would occur for net shallow infiltration than for deep percolation flux. Median percolation flux estimated by the experts is 7.2 mm/yr; mean percolation flux estimated by the experts is 10.3 mm/yr.

The NRC staff cautions that the tables reproduced here from DOE (1997) are provided as a summary for the convenience of the reader. The information should not be interpreted without full consideration of the text within DOE's (1997) expert elicitation report, and especially the elicitation interview summaries for each of the seven expert panelists.

The NRC staff is not bound by the conclusions of an elicitation *a priori* solely based on adherence to guidance provided by the staff. As noted in NUREG-1563 (NRC, 1996, p. 8), "...the use of a formal elicitation process, even when conducted in a manner consistent with guidance provided in this BTP [NRC, 1996], [does not] guarantee that specific technical conclusions will be accepted and adopted by the staff, a Licensing Board, the Commission itself, or any other party to a potential HLW licensing proceeding."

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	Gaylon Campbell	Glendon Gee	James Mercer	Shlomo Neuman	Karsten Pruess	Daniel Stephens	Edwin Weeks
Net Infiltration: Temporal Issues	+ Major storm events with intervals of ~10 yrs + Essentially no infiltration between these events	+ Major storm events with intervals of about 1 yr + Essentially no infiltration between these events	+ Episodic storm events with average intervals of about 5 yrs give rise to most (~80% of infiltration)	+ Major storm events lead to infiltration, recurrence interval tied to precipitation record	+ Infiltration occurs from few isolated storm events, 1-2 per yr + Infiltration near zero or negative between these events	+ Infiltration occurs during short bursts of severe storm events that have recurrence intervals of 20 yrs + Between these events, infiltration occurs, but in low amounts	+ Storm event or sequence every few yrs leads to infiltration event ; intervening time essentially no net infiltration + More severe events with longer recurrence intervals
Net Infiltration: Spatial Issues	+ Agree with basic Flint map and relative importance of various factors + Horse-tailing faults important	+ Flint map generally OK, but expect more infiltration at upper reaches of washes + Funneling of water into faults and fractures (< 5% of surface area) is important process	+ At lower net infiltration values, Flint map is OK + At higher values, would expect higher values in washes and lower values on ridge-tops + Lateral flow within alluvium into fractures is important	+ Expected to be heterogeneous, but Flint map is counter-intuitive, highs expected in washes, lows on ridge tops + Lateral flow at bedrock alluvium contact into fractures/faults/high-permeability paths	+ May be nonlinear relationship between amount of infiltration and spatial distribution	+ Flint infiltration map is generally OK, but would expect moderate infiltration amounts on ridgetops and high rates in washes + Underflow at alluvium-bedrock surface is important process	+ Net infiltration map would be smoother than Flint's, with lower highs on the ridges and higher rates in the washes + Flow at alluvium bedrock contact into open fractures is important
Net Infiltration: Temporal and Spatial Average (Note: mean values are calculated)	Mean: 7.4 mm/yr Median: 7 mm/yr 5th: 1 mm/yr 95th: 15 mm/yr Averaged over 50-1,000 yr	Mean: 12.7 mm/yr Median: 12.7 mm/yr 5th: 7 mm/yr 95th: 18 mm/yr Average over ~100 yr	Mean: 8.4 mm/yr Median: 7.5 mm/yr 5th: 2 mm/yr 95th: 20 mm/yr Average over ~100 yr	Assessed percolation flux, and thus net infiltration, on the basis of deeper subsurface data	Mean: 11.3 mm/yr Median: 7 mm/yr 5th: 0.5 mm/yr 95th: 40 mm/yr Averaged over several major storm events	Mean: 3.9 mm/yr Median: 3.1 mm/yr 5th: 0.7 mm/yr 95th: 10 mm/yr Averaged over 100 yr	Assessed percolation flux, and thus net infiltration, on the basis of deeper subsurface data
Temporal Behavior of UZ flow System	+ Episodic infiltration events; dampening of pulsed flow at PTn; essentially steady-state below PTn (except fast-flow component, which is transient)	+ Episodic infiltration events lead to pulse of water that can reach depth quickly, as evidenced by ^{36}Cl	+ Transient pulse related to infiltration is significantly dampened as it moves through system; fast-flow component remains transient	+ Transient pulse related to episodic infiltration events dampened in PTn + Fast flow component is transient and slightly dampened	+ Episodic pulses can flow through system + Pulses dampened as they pass through PTn and other layers with different hydraulic properties + System may not be steady state	+ Fast-flow component is yrs to tens of yrs; fracture component travel times are ~ thousands of yrs; matrix component ~ hundreds of thousands of yrs	+ Transient pulse related to infiltration events moves through system with little matrix interaction + At high percolation fluxes a significant fraction may occur in fractures as pulses following extreme precipitation events

Table C-1. Summary of key issues (reproduced in part from Table 3-1, pp. 3-27 to 3-30, DOE, 1997)
(page 1 of 3)

	Gaylon Campbell	Glendon Gee	James Mercer	Shlomo Neuman	Karsten Pruess	Daniel Stephens	Edwin Weeks
Method(s) Used to Estimate Percolation Flux at Repository Horizon	Relative weights: Net infiltration/surface water balance (0.3) ^{36}Cl (0.3) Flux through PTn (0.2) Concentration heat flux (0.05) Radiocarbon decay (0.05) Mineral coating (0.05) Perched water (0.05)	+ Net infiltration, checked with water potentials and isotopic evidence	+ Net infiltration, checked with chloride mass balance, temperature gradients, and perched water	+ Saturations and water potentials within PTn, supplemented by isotopic evidence and ESF moisture balance	+ Net infiltration	+ Net infiltration	+ Temperature gradients + Radiocarbon gas + Perched Water
Percolation Flux Estimate: Temporal and Spatial Average (Note: mean values are calculated)	Mean: 5.3 mm/yr Median: 4 mm/yr 5th: 1 mm/yr 95th: 14 mm/yr Based on net infiltration, ^{36}Cl, and flux through PTn	+ Same spatial and temporal average as net infiltration	+ Same spatial and temporal average as net infiltration	Mean: 21.1 mm/y Median 17 mm/y 5th 6 mm/y 95th: 50 mm/y	+ Same spatial and temporal average as net infiltration	+ Same spatial and temporal average as net infiltration + Lateral input from Solitario Canyon to TSw is probably minor	Mean 7.4 mm/yr Median 6 mm/yr 5th 1 mm/yr 95th 22 mm/yr
Percolation Flux: Spatial Issues	+ Generally same as net infiltration map, but smoother + As predicted by LBNL model results	+ Generally same as net infiltration map	+ More uniform distribution than infiltration, because of diffusion into TSw fracture network (which contains ubiquitous fractures)	+ Should generally correlate with infiltration map, but local lateral flow, medium heterogeneities and fast-flow channels will modify	+ Not known; may be similar to net infiltration map; or heterogeneities may develop new variability	+ Generally same as infiltration map (highs and lows generally the same locations) + Superimposed are local highs at faults and fractures	+ Map expected to be subdued replica of net infiltration map
Modeling Issues	+ 1-d finite difference model for net infiltration is OK	1-d infiltration modeling doesn't adequately address runoff + Need mass balance model for infiltration + Neutron probe data do not capture episodic nature of storm events	+ Dual-K above PTn, ECM probably OK below, as long as fast-flow component included	+ 1-d modeling is not capable of incorporating lateral flow at bedrock alluvium contact + Uncertainty and error analyses of heat flux estimates and measured temperature profiles should be conducted	+ A WEEPS-type model embedded in .. more complex model may be way to portray fast-flow component + Continuum description of flow assumes volume-averaging and may miss much of localized flow volume + Role of faults is not understood; may not be needed in PTn + Spatial stability of flow paths through time is uncertain	+ No confidence in Bucket model for infiltration Maxey-Eakin not satisfactory for points within a watershed + Perched water balance and overall water balance including water table fluctuations should be modeled + TOUGH2 modeling should predict key observations such as the wet spot if ESF at station 75+00	+ Transient pulse through PTn and deeper in section with little matrix interaction + Episodic pulse, not steady state + Predictability of which fractures in TSw will carry flow should be modeled as random

Table C-1 (cont.). (page 2 of 3)

	Gaylon Campbell	Glendon Gee	James Mercer	Shlomo Neuman	Karsten Pruess	Daniel Stephens	Edwin Weeks
Additional Data Collection/Future Work to Reduce Uncertainties	+Water potential, water content, hydraulic properties measurements in situ in ESF +Unsaturated conductivity measurements should be high priority +Surface water balance info; plant uptake, rock cover on slopes, snow, washes, rock-alluvium contact	+Mass balance using drip line source above ESF and pan +Inject water above sealed-off room of ESF to test for seepage +Perform non-linear fit to temperature data to see if profiles show curvature	+Run UZ model to examine the effect of higher infiltrations +Evaluate effect of more infiltration in washes	+Develop a detailed database of saturations, pressure, hydraulic conductivities at ambient saturations, and PTn thicknesses to obtain vertical and lateral resolution of percolation flux in PTn	+Monitoring and data collection related to net infiltration should continue	+Thoroughly study and instrument small drainage basin above repository, including rain gauges, mapping of fractures, nets of piezometers, observation of bedrock-alluvium contact, buried pan lysimeters, and TDR probes +More unsaturated hydraulic conductivity measurements +More accurate measurements of water potentials in PTn using tensiometers and heat-dissipation probes +Infiltration study of Solitario Canyon and development of hydrographs of perched water	+Obtain temperature logs with measurements at close intervals

Table C-1 (cont.). (page 3 of 3)

Percolation Flux (mm/yr)						
Expert	Mean	5th	15th	50th	85th	95th
G. Campbell	5.3	1.1	2.0	3.8	9.4	13.6
G. Gee	13.2	3.0	5.5	**12**	21.7	27.5
J. Mercer	8.4	**2**	4.4	7.5	10.8	**20**
S. Neuman	21.1	**6**	9.0	17.3	34.2	**50**
K. Pruess	11.3	0.5	1.8	7.0	25.0	40.0
D. Stephens	3.9	0.7	1.3	3.1	6.3	**10**
E. Weeks	7.4	1.0	2.3	6.1	11.7	21.7
Aggregate	10.3	1.0	2.3	7.2	19.3	30.0
Numbers in bold were assessed directly by the experts. The other numbers were interpolated from their assessed distributions						

Table C-2. Summary of estimates of percolation flux (from Table 3-2 of DOE, 1997)

APPENDIX D

OPEN KTI ITEMS UNRESOLVED AT THE STAFF LEVEL

TSPA95	Area of Concern (USFIC) - Infiltration and deep percolation calculations presented in Chapter 7 of TSPA-95 lack defensibility.
TSPA95	Area of Concern (USFIC) - Dilution factor calculations presented in Chapter 7 of TSPA-95 lack defensibility.
TSPA95	Statement of Concern (USFIC) - The lower limit chosen for the "satiated matrix saturation" remains unrealistically high and not adequately conservative.
SCA	Comment 15 - Solitario Canyon horizontal borehole activity inadequate to address impact of faults on fluid flow.
SCA	Comment 19 - Activities for the saturated zone flow system are inadequate to characterize boundaries, flow directions, magnitudes, and paths.
SCA	Comment 20 - Current and proposed well locations inadequate for defining the potentiometric surface in the controlled area.
SCA	Comment 21 - No consideration of I-129 and Tc-99 in characterization of saturated zone hydrochemistry.
SCA	Comment 22 - Inadequate saturated zone hydrology sample collection methods.
SCA	Question 55 - No analysis of potential test interference from water storage facilities.
SP 831212	Comment 1 - The NRC staff considers that specific attention should be given to the study of surface runoff flows from the west face of YM and in Solitario Canyon.
SP 831214	Comment 1 - The study needs to identify what minimum information and documentation about pre-existing wells will be acceptable to support the use of those wells in calibrating regional models.
SP 831214	Comment 2 - The study needs to be updated with respect to available literature on the alternate conceptual models for the regional ground water system. The study plan does not adequately describe the approach for modifying existing conceptual models based on new hydrogeologic data.

SP 831214 Comment 3 - Data may be insufficient to adequately construct and calibrate subregional or regional groundwater models.

SP 831214 Question 1 - What approaches will be used to evaluate evapotranspiration and recharge on a regional basis?

SP 831228 Question 1 - How will laboratory-scale models and data be used to estimate model parameters in the corresponding site-scale models?

SP 831228 Question 2 - Why have particular modeling strategies been assigned to address particular technical issues?

SP 831228 Question 3 - Is the method used by Cacas, et al. (1990) for the determination of fracture network hydraulic aperture distributions applicable for unsaturated flow?

SP 831228 Question 4 - How can one build confidence in conceptual models if every time a conceptual model is refuted by experimental data, the experiment is redesigned as inappropriate or not sensitive enough to capture the essence of the model?

SP 831228 Question 5 - What modeling strategies will be used to address technical issues for fluid flow studies?

SP 831229 Comment 1 - Solitario Canyon fault as a water infiltration pathway.

SP 831229 Question 1 - Evaluation of wetting front instabilities for modeling the Yucca Mountain hydrologic regime.

SP 831229 Question 2 - Obtaining hydrologic parameters for fractures.

SP 831229 Question 3 - Measurement of local water gradients in fractures to infer net moisture flux rates.

SP 831229 Question 4 - Calibration of hydrologic sub-models using experimental perturbations.

SP 831229 Question 5 - Evaluation of modeling the non-Darcian flow regime in specific fault zones.

SP 831233 Comment 1 - Hydrochemical data should be used to support conceptual and numerical groundwater models for the saturated zone.

SP 831233 Question 1 - Which hydrologic codes may be used to model complex heterogeneities in the saturated zone?

SP 831233 Question 2 - What methods will be used to incorporate "soft" information in analyses of hydrologic parameters?

SP 831233	Question 3 - How will site saturated-zone hydrologic modeling be integrated with other site characterization activities?
SP 831233	Question 5 - How will upper and lower boundary conditions be selected for a three-dimensional groundwater model at the scale of the controlled area?
SP 831233	Question 6 - If additional multiple-well sites are not constructed, how will DOE demonstrate that fracture-network models represent the saturated groundwater system in portions of the controlled area beyond the vicinity of the C-well complex?
SP 831521	Comment 2 - Planned thermal scanner flight data may not provide sufficient areal coverage to characterize regional properties.
SP 831521	Question 6 - Will tracer isotopic compositions be determined for analog deposits and compared to those in Trench 14?
SP 831522	Comment 1 - There appears to be a gap in the documentation of groundwater modeling work under this study.
SP 831522	Question 1 - How will the work in regional surface water and saturated zone modeling be integrated with the site unsaturated zone modeling?
SP 831522	Question 2 - How will infiltration be simulated under the surface water modeling activity?