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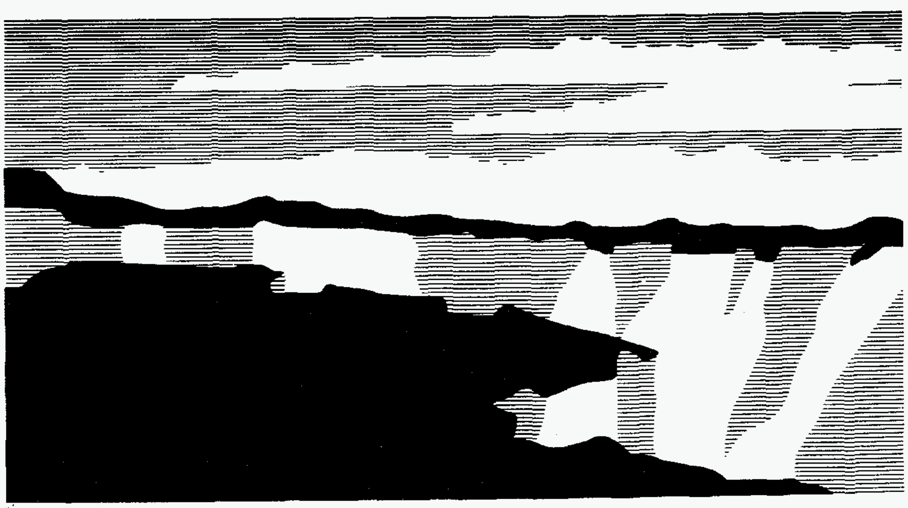

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HYDROGEOLOGIC ANALYSES IN SUPPORT OF THE CONCEPTUAL MODEL FOR THE LANL AREA G LLRW PERFORMANCE ASSESSMENT

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ABSTRACT

The Los Alamos National Laboratory (LANL) low level radioactive waste (LLRW) disposal facility at Area G is currently completing a draft of the site Performance Assessment (PA) as required per DOE orders. The site is located on a narrow mesa top of volcanic tuff where possible mechanisms of subsurface transport include vapor movement with vapor-liquid phase coupling, transport in fractures, and other as yet unresolved subsurface dynamics. The large depth to the water table (~250m) combined with uncertain hydrogeologic data below 100m and the complex stratigraphy of layered volcanic flows and ash provide for a challenging analysis. Results from previous field studies have estimated a range in recharge rate up to 1 cm/yr. Recent estimates of unsaturated hydraulic conductivity for each stratigraphic layer under a unit gradient assumption show a wide range in recharge rate of 10^{-4} to 1 cm/yr depending upon location. Numerical computations show that a single net infiltration rate at the mesa surface does not match the moisture profile in each stratigraphic layer simultaneously, suggesting local source or sink terms possibly due to surface connected porous regions. The best fit to field data at deeper stratigraphic layers occurs for a net infiltration of about 0.1 cm/yr. Surface moisture data and vertical moisture profiles suggest a wide range in infiltration at the near surface. Transients are hypothesized to play an important role in fracture infiltration and evaporation, but are seen in analyses to dampen rapidly within the mesa tuff matrix to a steady state condition.

A recent detailed analysis evaluated liquid phase vertical moisture flux, based on moisture profiles in several boreholes and van Genuchten fits to the hydraulic properties for each of the stratigraphic units. Results show a near surface infiltration region averages 8m deep, below which is a dry, low moisture content, and low flux region, where liquid phase recharge averages to zero. Analysis shows this low flux region is dominated by vapor movement. Field data from tritium diffusion studies, from pressure fluctuation attenuation studies, and from comparisons of in-situ and core sample permeabilities indicate that the vapor diffusion is enhanced above that expected in the matrix and is presumably due to enhanced flow through the fractures. Below this dry region within the mesa, near the interface of the vitrified and devitrified tuff units and also coincident with the elevation of the adjacent canyon floor, is a moisture spike which analyses show corresponds to a moisture source. This may indicate a narrow region with unique hydrologic properties, or horizontal moisture transport from the canyons. However, the likely physical explanation is seasonal transient infiltration through surface-connected fractures. This anomalous region is being investigated in current field studies, because it is critical in understanding the moisture flux which continues to deeper regions through the unsaturated zone.

INTRODUCTION

The Los Alamos National Laboratory (LANL) low-level radioactive waste (LLRW) disposal facility at Area G has completed a preliminary draft of the site Performance Assessment (PA)[1] as required per USDOE orders. The final draft PA becomes the technical basis for authorization and management of disposal operations at the active disposal site.

The Area G disposal facility is located on the top of a narrow finger-like mesa composed of volcanic tuff (Bandelier Tuff), deposited in stratigraphic layers of ash and solidified volcanic flows. Waste disposed at Area G is placed into pits excavated in the volcanic tuff, crushed in place, and backfilled with the native crushed tuff to about 30% waste package and 70% tuff by volume. These disposal operations are evolving to minimize future disposal volume, and to assure stability of emplaced waste.

The unresolved subsurface dynamics of the mesa top site location and the adjacent canyons with the large depth to the water table (~250m) provide for a challenging analysis. Uncertain hydrogeologic data below 100m have led to preliminary analyses focusing on the near surface hydrology in the mesa-canyon system. Preliminary review by the USDOE Peer Review Panel indicated that the proposed subsurface transport conceptual model[2] was not fully integrated with the numerical models[3] used to evaluate the site, especially in defining the transition from significant transient events to the steady state analysis and in defining the possible role of vapor transport. This report provides additional data review and analyses to address these issues.

DATA REVIEW

Area G site hydrology was summarized[4] as of 1987, based primarily on field studies by Bendix[5]. Several boreholes and core samples were used to characterize moisture verses depth and detailed hydrologic parameters. Moisture profiles by in-situ neutron probe measurements were seen to be independent of time below depths of about 2m. This was confirmed in recent measurements in a borehole into the crushed tuff backfill of an active Area G disposal unit[6]. These results suggest transients in moisture content play a negligible role at depth.

A recent review of the site geohydrologic data[7] including recent permeability work has been completed as part of the Area G PA work. The layered stratigraphy within and beneath the disposal site mesa is illustrated in Fig.1. Interpretation of the site geohydrologic data[2] identified several field observations which may be important in subsurface transport and postulated that transient infiltration into and long-term drying from fractures play a significant role.

In-situ air permeability measured by a borehole packer-isolation method was seen to be 4 to 20 times greater than the permeability of recovered core samples[4,5]. Similar results were obtained recently comparing core sample air permeability in borehole (G-5)[8] to in-situ permeability measured in the same borehole[9]. Attenuation with depth of atmospheric pressure oscillations[10] is consistent with permeabilities much larger than that measured on intact core samples. Subsurface diffusion of a tritium plume at Area G has been compared with numerical results to determine an in-situ diffusion coefficient.[11]

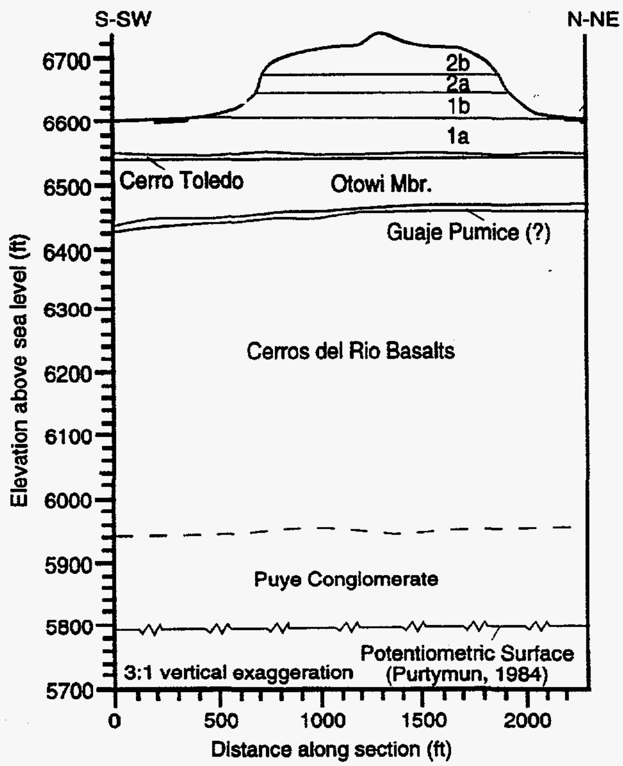

Fig.1 Stratigraphy beneath the Area G disposal facility, located on the top of a mesa (figure center). Disposal units are excavated to a depth of 70 feet or less into Unit 2b and can extend into Unit 2a.

Attributing the migration to vapor diffusion (liquid phase transport is negligible under the field conditions as will be discussed) gives a vapor diffusion coefficient which is more than one order of magnitude larger than that expected in the volcanic tuff matrix. These results indicate that fractures in the mesa top stratigraphic layers play a major role in determining the air permeability and effective vapor diffusion in the mesa.

ANALYSES

Unsaturated hydraulic conductivity and water characteristic curves were determined from van Genuchten fits[12] to matric potential data and from saturated conductivity data for several core samples in each of the near surface stratigraphic units at Area G disposal facility[13,14]. Detailed comparisons of unsaturated conductivities predicted in this manner with values measured by the unsaturated flow apparatus (UFA) centrifuge method[15] show good agreement in only about half the cases and indicate a large variability and uncertainty in the transport characterization[16,17].

The stratigraphic unit averages of van Genuchten fits were summarized for the Area G PA work[7] (Fig.2) over a range in moisture content up to 25% where the fits are accurately approximated by a straight line on a log scale. Assuming unit hydraulic gradients in the field, these curves correspond to recharge rates of 10^{-4} to 1. cm/yr in the

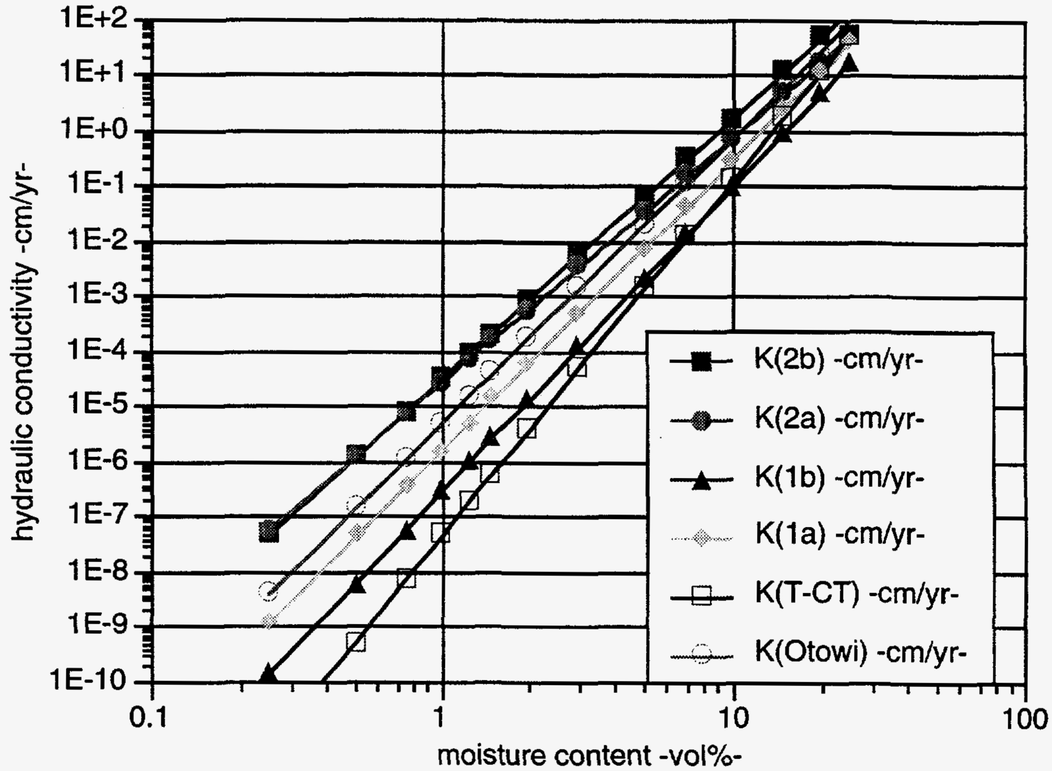

Fig. 2 Unsaturated hydraulic conductivity (van Genuchten fits) for the near surface stratigraphic units at Area G disposal facility. A preliminary estimate to the recharge rate is this function evaluated at the in-situ moisture content (in the range of 1-10%).

range of in-situ moisture content from about 1% to about 10%. If there are no local source or sink terms, then the recharge or flux through the strata must be constant, which would result in higher moisture contents in Units 1b and in the Cerro Toledo (see Fig.1, results labelled T-CT in Fig.2, and labelled C in Fig.3). This trend is consistent with field observations, but an accurate match of moisture content to field observations in each unit simultaneously is not possible as shown in the following.

This issue is examined in a comparison between numerical results and field data shown in Fig. 3. Steady state moisture contents are computed for several values of net infiltration at the mesa top, shown along a vertical line through the center of the mesa in a 2-D model with accurate stratigraphic cross-sections. The range of field data is shown as the darkened area. The canyon floors adjacent to the mesa coincide closely with the interface between Units 1b and 1a at Area G. The best agreement with field data occurs for downward vertical flux values of 0 to 0.001 cm/yr in the top two units, about 0.1 cm/yr through Units 1b and 1a, and as much as 1 cm/yr in the Otowi. Recent simulations show the higher moisture contents in the Otowi can be matched with lower flux values (≤ 0.1 cm/yr) when hydraulic properties of deeper strata (subject to large uncertainty) are included in the numerical model.

The steady saturation profile calculated for any single infiltration rate does not match all the in-situ saturation data gathered at the site. Saturations within the mesa top

(Units 2b and 2a) are extremely low in field data. Saturations below the base of the mesa (Unit 1b and below) are higher. Several factors which may contribute to this discrepancy include: 1) infiltration from canyons or from deep surface-connected fractures resulting in higher saturations below the base of the mesa, 2) evaporation from the mesa sides and from fractures resulting in very low saturations within the mesa top, 3) uncertainty and heterogeneity in the hydrologic transport parameters.

For preliminary PA modeling work through all of the stratigraphic units, a rate of 0.1 cm/yr was chosen as the best 'fit' because there is no detailed knowledge of local source or sink terms to supply to the numerical effort. However, the comparison summarized in Fig.3 suggests a complex situation with local (elevation dependent) source and sink terms to the recharge rate.

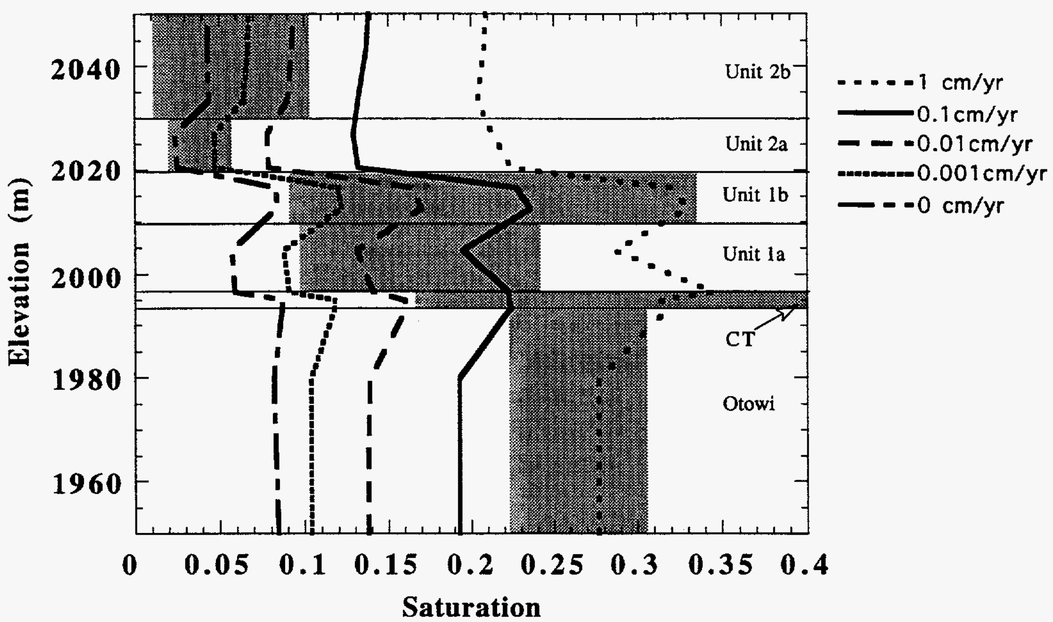

Fig.3 Numerical model prediction of saturation values verses depth at several net infiltration rates (from Ref.3). These are shown in comparison to field observations (the range in data within each stratigraphic unit is shown as a shaded area).

The source and sink terms in the underlying strata were examined in detail in a recent study[18]. The vertical flux and the vertical component of its divergence, interpreted as a local source or sink term, were evaluated directly from vertical moisture profiles using the stratigraphic unit-averaged van Genuchten fits to determine the hydraulic transport parameters for matric potential and for unsaturated hydraulic conductivity, and thus the vertical flux as a function of local moisture content. Results are discussed in detail for data from a dozen boreholes at Area G[18], for example, as shown for one 'typical' hole in Fig. 4.

Fig. 4A(top) shows the moisture profile in a borehole located near the center of the mesa top disposal facility. The inferred vertical flux and an effective source term to the local recharge rate labelled 'source' in figure 4B (middle), evaluated as the difference in vertical flux between adjacent points, show nearly zero flux or source throughout the range in depth from 7m to 25m. Near the surface there is a net downward flux (negative value of flux) of about 1 cm/yr, but there is also a net sink (negative source term) in this region, presumably corresponding to an evaporative loss to the surface or surface-connected fractures. At ~30m depth there is an apparent source of moisture with vertical moisture movement and evaporation (net sink) away from that source location. Similar results are seen in all the boreholes at this depth, however, quantitatively, there is a large variability with location[18].

The near surface infiltration region also has a large variability with location dependent upon the local disposal operations[18]. Modeling of deep percolation from the disposal pits is sensitive to assumed rooting depths, leaf area index, and other parameters which govern the detailed surface water balance[19]. The large variability in surface flux is consistent with the broad range measured in surface soil moisture content[20].

The source term indicated by the vertical difference in moisture flux can also be normalized per unit depth which allows the source to be expressed as an inverse time scale. This time scale can be interpreted as a characteristic time over which the moisture flux (labelled St-inv in Fig. 4C) is changing locally due to liquid phase movement, or, the time scale over which the moisture content (labelled St-inv*vol%) is changing if the entire vertical component of the divergence of flux is interpreted as a time dependent effect.

In Fig. 4C (bottom) the source term time scale for the moisture content (St-inv*vol%) is seen to be at least one year at all locations, and 100-1000 years over most of the 'low flux region' identified from Fig. 4B. In the near surface infiltration region, the observed characteristic time scale of 6-10 years implies deep penetration only once every several years, consistent with predictions by detailed surface water balance modeling studies[19]. Interestingly, the apparent source at the ~30m horizon has the minimum characteristic source time scale of about 1-3 years, consistent with significant infiltration once every few years. The short times near depth 30m may be an artifact of the unresolved stratigraphic hydrologic properties near the 1b-1a interface or may indicate a significant local source. Field studies are currently underway to resolve the matric properties within this region, which should allow a determination as to whether the apparent source term is real.

If the apparent source of moisture proves to be real, it may indicate moisture influx by horizontal transport from the adjacent canyons or from another fast flow path. A possible explanation is that this elevation is the bottom of a network of surface-connected fractures which allow transient infiltration during intense and infrequent storm events. The magnitude of the source term as a characteristic time scale of about 1-3 years is consistent with significant recharge once every few years.

DISCUSSION

Transients

Field studies [4,5] and analyses[18] indicate that transients in moisture content within the Bandelier Tuff matrix are dampened over short distances of 1-2m. Transients are

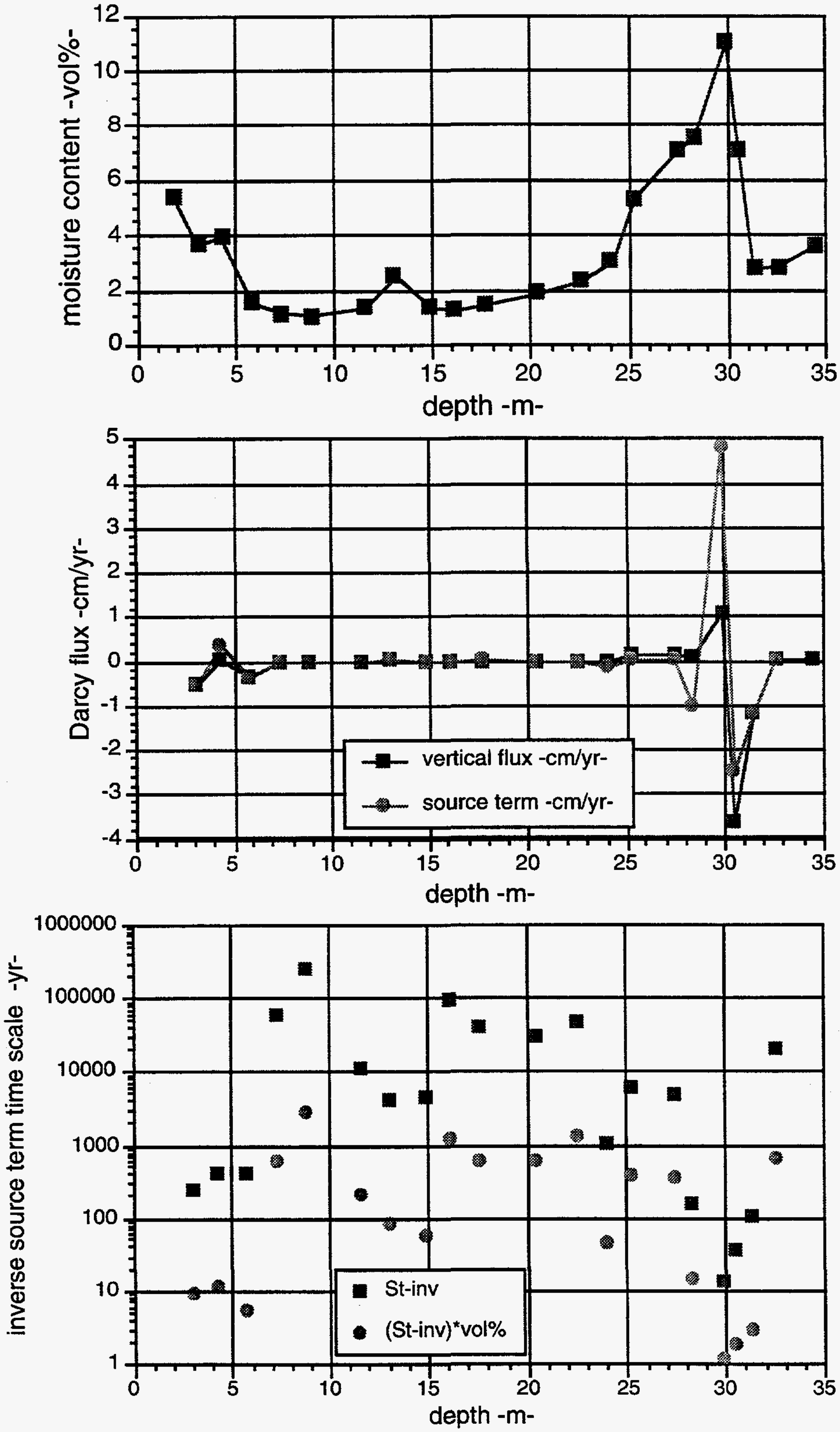

Fig. 4 Vertical profiles for hole **LGM-85-06** showing: A. volumetric moisture content, B. vertical flux and the source term expressed as a flux, and C. source terms expressed as a characteristic response time (from Ref .18).

expected to play a negligible role in moisture flux through the mesa tuff matrix compared to steady state flux. Transients can be significant if fast paths exist, e.g., near elements of surface-connected macro-porosity which can include surface-connected fractures, horizontal strata of high permeability (as proposed may occur at the surge beds between Units 2a and 2b) or other possible 'macro-pores'. An example of this may be the moist horizon observed near the vitrified-devitrified interface at ~30m depth. These transients average to an effective steady state moisture flux and moisture source term for long time scale numerical simulations.

Vapor Phase Flow

Vapor phase movement may be enhanced by diffusion due to barometric pumping or temperature fluctuations especially in strata of high permeability, however, the net convective movement of air through the tuff matrix is negligible. Evidence suggests convective movement through surface-connected features is significant and may influence the matrix flow. As such, diffusion of vapor phase contaminants is related to empirically determined effective diffusion coefficients which include possible barometric pumping effects.

Moisture profiles are expected to be driven by vapor diffusive movement when the moisture content falls below a specific value, which is about 2-5% for the hydrologic properties of the Bandelier Tuff under Area G. Here, in the low flux, dry region of the mesa interior, vapor phase loss through evaporation to surface connected fractures may contribute as a local sink term to drying regions below the moisture content expected to support liquid phase movement. It may be possible to model this as a sink term in the liquid phase matrix transport equations. To model transient dynamics between the fractures and the matrix, more sophisticated source/sink terms need to be considered such as that afforded by a dual porosity, dual permeability numerical model which can account for rapid fracture flow following infiltration events and evaporation along fractures during dry periods.

Upward and Horizontal Migration

Analysis of upward vertical moisture or contaminant flux from the disposal units to the surface is on-going. Preliminary results suggest near surface moisture profiles relax rapidly enough that long-term upward contaminant transport is negligible, leading to less surface contamination than the small amount attributed to translocation by biotic species as analyzed previously[1].

A preliminary parametric evaluation of horizontal moisture flux from the disposal unit to the mesa edges shows small contaminant concentrations can reach the mesa edge on the time scale of a thousand years. Numerical simulations currently in progress in accurate 2-D mesa geometry yield similar results and show radionuclide concentrations in the adjacent canyons comparable to that eventually reaching the ground water compliance point. Contamination at the mesa edge is assumed to be carried to the adjacent canyon floor by run-off and will be input to the off-site receptor dosimetry model and to a surface contamination source term for subsequent unsaturated transport to the deep aquifer under the saturation conditions existing beneath the canyon. The net contribution to canyon receptor dose and to deep ground water contamination via this canyon contamination route is expected to be demonstrated to be small compared to the direct path beneath the mesa site.

Canyon Recharge

Recharge under the canyons adjacent to the mesa top disposal facility is likely to be much larger that that predicted within the mesa. Borehole data at nearby canyon locations shows volumetric moisture content values greater than 10% and profiles which do not vary greatly with depth in the Otowi layer. Assuming unit gradient conditions, valid under the reasonable assumptions that $\partial\theta/\partial z \sim 0$, and $\partial h_m/\partial z \sim 0$ (where θ is volumetric water content and h_m is matric potential expressed as a head) then the recharge rate is evaluated from the K_{unsat} curve (Fig.2) and corresponds with (1 to ~30) cm/yr over the observed moisture range in the Otowi from 10% to 22%. This large recharge rate may mix with the low recharge rate under the mesa at some depth, dependent upon the complex 3-D stratigraphy and stratigraphic properties. This is the subject of on-going investigation.

Toward a Conceptual Model

In this iteration of continuing analyses, the conceptual model which emerges considers first the unperturbed system and then the result of disposal operations. Transient events and vapor-liquid phase coupling can be modeled using local sources (increased local infiltration) and sinks (net evaporation from fractures or surge beds) or using more sophisticated dual porosity, dual permeability models.

Vertical contaminant flux through the unsaturated zone may be complicated by moisture source and sink terms for elevations equal to and above the adjacent canyon floors. The physical nature of these terms is uncertain, however, a picture consistent with data in the upper most strata assumes that infiltration and drying from the fractures in the mesa contribute to near surface (0-10m) moisture profiles and deeper (10-25m) drying relative to that expected for a constant vertical moisture flux. At the elevation of the adjacent canyons there is evidence of a moisture source which implies moisture migration from canyon alluvial aquifers with possible 2-D and 3-D effects, or deep infiltration through open fractures. The evidence is ambiguous and intended to be resolved in on-going field studies.

Disposal operations have been projected to increase the net moisture flux to the aquifer by over 200% of the unperturbed flux[1,3], through effectively increasing the moisture content and thus the hydraulic conductivity of the region beneath the disposal units and thus beneath the mesa as a whole. This perturbation is very sensitive to the assumed ground cover and rooting depth on the disposal unit post-closure covers[19]. The effect of disposal operations on moisture flux and therefore contaminant migration from the site is therefore likely to be significant, emphasizing that operations should be conducted to minimize the perturbations to a geologic system which is naturally well suited to minimize contaminant migration and maximize waste isolation.

Unsaturated transport from the disposal site through each of the strata to the main aquifer is being approximated using conservative estimates for the unknown transport properties in the deeper strata. The net result in concentrations and transit time to the aquifer is being revised from that determined in the original steady state analysis[1,3] to include transport through the deeper basalt layers and 3-D geometry effects.

CONCLUSIONS

As more data and analyses accumulate, the best estimate of the mean recharge rate in the upper stratigraphic layers within the mesa decreases while the variation between locations remains large. Our present best estimate is that the mesa interior is dominated by vapor phase movement and supports negligible liquid phase movement at least down to an elevation near the adjacent canyon floors. This holds under undisturbed conditions but is uncertain under the disturbance of disposal operations. A moisture source is apparent in analyses of the moisture profile peak observed near the depth of the interface between the vitrified and the devitrified tuff, also near the elevation of the adjacent canyon floors. Surface connected fractures to this depth could explain this source although the analysis method is inconclusive, subject to data uncertainties requiring additional field work for verification. At greater depths below the mesa the recharge rate is less well determined but results are consistent with a downward flux of 1 mm/yr or less directly beneath the mesa. Beneath the adjacent canyons the recharge rate is higher and remains to be quantified in near future studies. Preliminary results showed little mixing of infiltration originating beneath the canyon and mesa in the case of horizontal stratigraphy. Recent model results show different behaviour with mixing sensitive to the imposed dip of some units. The extent of mixing between canyon and mesa infiltration in more realistic 3-D geometry is currently under evaluation. The implications for PA modeling is the subject of on-going work.

ACKNOWLEDGMENT

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