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March 17, 2004

To: Nuclear waste Technical Review Board
Arlington, VA

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Re: Feedback on Natural Systems Panel meeting
March 10-11, 2004, Las Vegas, Nevada

Introduction

The purpose of this memo is to provide feedback about the above meeting of the Panel on Natural Systems. The meeting focused on fluid flow and radionuclide transport processes in the unsaturated zone (UZ) and the saturated zone (SZ) of Yucca Mountain, NV. As requested, most of my comments will relate to UZ presentations during the first day.

The presentations, without exception, were very useful in terms of providing a general overview of ongoing work at Yucca Mountain (YM). They generally did not provide a lot of detail of the current status of fundamental and applied flow and transport research dealing with YM. As such I will provide only limited feedback on individual papers or projects, but rather give overall impressions of ongoing research. These impressions are based on the presentations, the handouts, and perusal of several documents and papers focusing on YM, including especially review papers by Flint et al. (2001) and Eddebbarh et al. (2003), and several papers in a special JCH issue on YM edited by Bodvarsson et al. (2003). References are given at the end of this memo.

Overall impression

The level and breath of research dealing with YM is impressive. I previously (in 1991) served on a Yucca Mountain Peer Review Team that focused on UZ and SZ flow processes at YM. Much of the discussions at that time dealt with such issues as the possible existence of preferential (fast flow) paths through the mountain, the mechanisms of preferential flow generation, the overall significance of flow, if present, through fractures at various depths, the hydraulic properties of unsaturated fractured rock, matrix-fracture interactions, and the potential role of the Paintbrush Nonwelded Unit (PTn) in mediating flow through the unsaturated zone. Clearly, much has been accomplished since then in understanding prevailing flow and transport processes at YM. An excellent and very comprehensive treatise of what is known (and not known) about YM is given by Bodvarsson et al. (2003). While tremendous advances have been made since that 1991, the shear complexity of the site is such that many of the earlier questions are still not fully answered. The issues of fast flow paths through UZ fractures, their importance relative to matrix flow, the degree of matrix-fracture interactions, and how the repository will affect the flow regime still remain largely unresolved, or are subject to great uncertainty. I will briefly discuss several of these issues and related topics.

1. Fast flow paths through fractures in the unsaturated zone

Direct and anecdotal evidence exist that at least some fast flow paths currently exist at UM. While the total volume of these preferential flow paths may not be too important for current climatic conditions, this needs to be confirmed by additional field evidence (such as addressing the current uncertainty about the presence of bomb-pulse ^{36}Cl and ^{3}H in deep subsurface layers), and through modeling. Several models have been developed and applied to YM. Prominent among UZ fast flow models is the Active Fracture Model (AFM) of Liu et al. (1998; 2003) that accounts for gravity fingering through continuous fractures, and associated diminished contact between fractures and the matrix. I very much support the conceptual basis of this model. Still, it seems that the AFM is only one of several numerical formulations that could be based upon this conceptualization (i.e., various perturbations of the model could be hypothesized equally well). The AFM was tested against a large flow/transport data set obtained using Alcove 1 of the Exploratory Studies Facility (ESF). While the flow part of the model could be fitted reasonably well against the data, the solute (Br) transport part required adjustments that effectively increased (enhanced) diffusion interactions between the fractures and matrix. Experimental and test results for Alcove 8/Niche 3 similarly showed the importance of enhanced matrix diffusion. It is important that alternative numerical models be devised and investigated to the fullest.

2. Unsaturated zone fracture-matrix interactions

One possible alternative conceptualization causing limited fracture-matrix interactions for flow is a lower effective hydraulic (saturated and unsaturated) hydraulic conductivity of the matrix-fracture interface. The permeability could have been altered by inorganic coatings (some of which may not always be clearly visible), organic matter and colloid deposition, wettability problems, or other reasons. Similar situations are known to occur frequently in macroporous soils. While low-conductivity fracture coatings would primarily affect liquid flow interactions between fractures and the matrix, their presence would to a far lesser extent impede matrix diffusion. Experiments such as those by Thoma et al. (1992) could confirm or refute this alternative conceptualization. Relatively simple imbibition experiments on small cores with or without the fracture skins removed may need to be carried out for this purpose, and/or perhaps related unsaturated and saturated conductivity experiments using the centrifuge method (e.g., Conca, 1993).

Additional work to identify the importance of these different processes (alternative AFM numerical formulations, fracture coatings) and their inclusion in numerical models is important, not only for understanding UZ flow/transport processes under current climate conditions, but also to infer the effects of climate change on future flow and transport processes in YM.

3. Lateral Flow in PTn

Different opinions exist about the amount of lateral flow in the PTn, based in part on calculations with different models, and on experimental data. It is important that these differences be further investigated, and that hopefully some consensus be reached within the scientific community about the significance of PTn lateral flow, and how such lateral may produce fast flow paths during faults, and/or fractures at various interfaces within and immediately below PTn.

4. Flow around ESF tunnel

Some discussions during the meeting concerned the amount of water being routed around the ESF tunnels and, once constructed, around the repository, and how much of a drift shadow effect would occur below the tunnels. Such processes will be affected also by thermal loadings, evaporation and condensation. While intended only as schematic, one slide shown at the meeting illustrating the drift shadow concept, may not have been too realistic (i.e., suggesting little or no advective transport to areas under the tunnels). Liquid flow above, around and below tunnels are relatively easy to calculate using models for flow in fractured media (e.g., using dual-porosity/permeability models, or more simplified approaches based on the standard Richards equation but with composite hydraulic functions accounting for matrix and fracture contributions). The attached figure shows such a calculation for a non-fractured, homogeneous medium textured soil carried out with the HYDRUS-2D software package. Some bending of flow lines is apparent near the lower corners of the tunnel, with significantly lower velocities in the drift shadow. Whether or not this bending is significant for fractured rock systems, and how it affects possible infiltration and transport from tunnel floors, under current and future climate conditions may warrant further study.

5. Hydraulic properties of unsaturated rock

Resolution of the above issues (especially items 3, 4 and 5 above) require UZ model computations using UZ using reasonable estimates of the hydraulic properties of unsaturated fractured rock. Experimental techniques for measuring such properties have greatly improved with recent advances in centrifuge methods and tension infiltrometry. For example, USGS recently produced a newly designed tension infiltrometer for fractured rock that can measure infiltration rates of as little as 5 mm/year (roughly equivalent to the current average percolation rate through YM). Use of such a tension infiltrometer could greatly help also in analyzing the relative importance of fracture and matrix flow in different Units at YM, including how fluid would infiltrate from the bottom of a tunnel. As compared to centrifuge methods applied to very small cores, an important advantage of tension infiltrometers is that they can measure infiltration rates over relatively large surfaces.

6. Colloid and colloid-facilitated transport

Colloid-facilitated radionuclide transport remains a concern. The UZ and SZ site models should incorporate reasonably realistic colloid and colloid-facilitated transport features, possibly erring on the conservative side. Indeed, most processes that tend to slow down colloid migration are

currently approximated in a relatively conservative fashion, often by neglecting their effect on transport (e.g., porous media and film filtration, and possible accumulation at air-water interfaces). One exception is the use of an equivalent retardation factor for SZ colloid transport (and hence also colloid-facilitated radionuclide transport) based on the assumption of equilibrium colloid adsorption/desorption. Colloids are known to sometimes move faster through than can be calculated with this assumption because of nonequilibrium (kinetic) sorption and size exclusion.

Concluding remarks

The YM project is facilitating excellent basic and applied research that not only advances the state-of-the-art as such, but is immediately relevant for understanding YM flow and transport processes, and appreciating the role of natural UZ and SZ hydrogeologic barriers to radionuclide transport. It is important that much of this research be discussed within the larger scientific community, including through publication of research results (e.g., the comprehensive JCH special issue by Bodvarsson et al., 2003). Additionally, it is important for the scientific community to be able to scrutinize the numerical models being used in this research, the appropriateness of the various processes incorporated in those models, and the accuracy of the model parameters. The YM/DOE research infrastructure must be able to allow for some flexibility in developing alternative conceptual models that cover all possible flow/transport scenarios at YM such that no major surprises will be encountered in the near future.

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Figure: Flow velocity vectors (m/day) around 4-m wide tunnel.
Medium-textured soil; HYDRUS-2D (Simunek et al., 1999)