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Washington, D.C. 20555

Dear Mr. Conti:

I am responding to your letter of June 15 requesting my thoughts about information, measurements, and data needed to describe hydrologic systems for a repository in basalt. Since this is to help prepare the NRC staff for a review of Environmental Assessments from DOE, my comments will be specific to the Columbia Basalts in the Pasco Basin.

The Columbia Basalts have unique features which must be thoroughly understood before one embarks on measuring and describing their hydrologic properties. The basalts have been deposited in the form of lava sheets having considerable lateral extent and variable thickness. Cooling of the lava has created two types of local fracturing within most individual flow interiors: vertical columnar jointing known as collonade, and denser fan-shaped jointing known as entablature. In both the collonade and the entablature, fracture density is large compared to the thickness of the flow interior so that it is practically impossible (and theoretically unnecessary) to describe the properties of individual fractures. The field testing as well as modeling of the flow interior should therefore be done from the viewpoint that, for practical purposes, the basalt in the flow interior can be represented by an equivalent anisotropic porous medium. The anisotropy of this medium stems from the nature of its fractures: in the collonade, vertical hydraulic conductivity is expected to be larger than horizontal hydraulic conductivity. The extent to which vertical conductivity exceeds the horizontal is unknown, as there has not been a single field test in which the former had been measured. Expert opinion allows the range of vertical to horizontal hydraulic conductivity ratios in the flow interior to vary from less than 0.1 to more than 10^3, with the most favored ratio being 10. Current opinion about the low permeability of flow interiors is based on available packer tests of horizontal hydraulic conductivity in single boreholes and the intuitive feeling on the part of some that vertical conductivities must therefore also be low. The question, in my opinion, is far from settled.

Avenues for horizontal groundwater motion are provided primarily by basalt flow tops and sedimentary interflows. Most hydraulic testing has been conducted in these layers, which have more of a porous nature and thus are more easily amenable to conventional testing procedures (such as packer and pumping tests). Classical concepts of groundwater hydrology in layered media suggest that flow is often horizontal in high-permeability units, and sub-vertical in low-permeability units. If this holds true in the Pasco Basin, then the two values of hydraulic conductivity one needs to be concerned with are the horizontal conductivity of the flow tops and interbeds, and the vertical conductivity of the flow interiors. The latter, as we mentioned, is currently unknown.

The Pasco Basin basaltic sediments are deep seated in the center and tend to crop out in the margins. The mode of outcrop as well as surface and subsurface topography must be well understood as they affect regional recharge, discharge, and thereby both surface and subsurface flow patterns. Not less important is the need to recognize the presence of local structural features such as domes, synclines, anticlines, and associated tectonic faults or fractures which may cause local flow anomalies. Uncertainty regarding the location and hydraulic properties of vertical tectonic fractures is especially critical as these may act as (1) lateral flow barriers, (2) partial lateral flow barriers, and (3) vertical conduits allowing water to flow with relative ease from one high-permeability unit to another, across flow interiors which otherwise may have a low-permeability.

Much information about structural anomalies as well as the thickness and lateral extent of individual hydrogeologic units can be obtained from geological and geophysical studies. However, the hydrologic effect of such structural features cannot be ascertained solely from geological and geophysical data. A more direct way to discover the presence of hydrologic anomalies such as vertical faults acting as barriers to lateral flow, or conduits shortcircuiting different horizons, is through hydraulic head and hydrochemical data. For this, it is necessary to have reliable measurements of formation head at numerous points in three-dimensional space and chemical analyses of water from different locations in key units. A distinct difference in hydraulic head between two high-permeability layers separated by a flow interior indicates the presence of a vertical hydraulic gradient between them. This does not necessarily mean that vertical flow is taking place from one layer to the other across the flow interior. If head in the flow interior is higher than in the two overlying and underlying high-permeability units, flow takes place out of the flow interior into both units. Such a situation appears to be indicated by head data from several boreholes near the proposed Hanford repository site. It suggests that the system is not at steady state, as under the latter regime flow would take place across, not out of, low-permeability units. To help decide which is the case, head measurements are needed not only from the high-permeability units where they are performed with relative ease (and therefore with relative frequency), but also from the intervening flow interiors.

In taking head measurements, it is important that the data represent in-situ formation head (leakage around packers, across vertical fractures near the borehole, and incorrect pressure data due to local disequilibrium are common problems in low-permeability units; temporal fluctuations are a major cause of noise corrupting head data from high-permeability units). To use such data in flow calculations, they must be corrected for density variations with depth due to temperature and salinity effects.

The question whether vertical flow takes place across flow interiors at steady state, or out of these interiors under a transient regime, can also be addressed on the basis of water chemistry. In the first case, waters of different chemistry (and isotopic composition) emanating from two flow interiors into a high-permeability unit between them mix with the water of this unit, a pattern which can sometimes be recognized (I believe that I have seen evidence of this happening at Hanford). In the second case, one should expect to see a continuous evolution of groundwater chemistry along streamlines crossing the system.

Lateral variations of hydraulic head, when combined with water chemistry data, are often indicative of large-scale lateral discontinuities such as vertical faults. One should be especially aware of the need to collect many such data in the vicinity of structural anomalies suggested on the basis of geological or geophysical considerations.

Hydraulic head and water chemistry data are important in the delineation of regional flow patterns and recharge/discharge boundaries. The location and magnitude of recharge and discharge into or out of a system are difficult to determine and often form the subject of intense speculation. NRC reviewers should be keenly aware of the need to support claims concerning recharge and discharge on hard hydrologic and hydrochemical evidence. Groundwater dating is one tool of hydrochemical analysis which is often useful in this context.

I mentioned that vertical hydraulic conductivities of the flow interiors have not yet been measured. Horizontal values have been determined in various layers by single-hole packer tests, single-hole pumping tests, and interference tests. Single-hole tests yield values representing only a limited volume of rock mass close to the test interval; if the intervals are short, the results may fluctuate severely between very low and very high values. This is useful information, indicating the range between extreme values encountered in the rock. Most hydrologic models, however, require effective hydraulic conductivities of rock masses on a larger scale. The latter can be obtained by appropriate averaging of smaller scale measurements (provided there is enough data and the averaging process is theoretically sound; arithmetic and harmonic means are seldom appropriate, though most often quoted) or by performing tests on a space-time scale compatible with modeling needs. Such large-scale long-duration tests can be performed only in selected high-permeability units. Therefore, in the absence of numerous smaller scale tests, hydraulic conductivity will remain a highly uncertain parameter.

Hydraulic conductivities in directions other than horizontal can be obtained from packer tests in single inclined boreholes or, on a somewhat larger scale, by cross-hole tests between neighboring boreholes which need not be inclined. Since such tests are expensive and time consuming, and the technology of cross-hole testing is relatively new, they must by force be limited to selected rock volumes near the intended repository site. This means that a high level of uncertainty regarding average and extreme vertical permeabilities will remain even if a number of such tests are performed.

To predict disturbances in the natural flow regime due to elevated temperatures in the repository, one needs to know the thermal conductivity and heat capacity of the rock. These are not expected to vary as much as hydraulic properties and can be deduced with fairly good accuracy from surface or near surface experiments. The prediction must account for the effect of temperature on water viscosity, density, and possible changes in rock hydraulic properties.

To predict radionuclide migration, one must know not only hydraulic conductivities and gradients, but also effective (kinematic) porosity, dispersivity, and retardation factors. The only known way to determine effective porosities is by means of tracer tests; only one such test has been conducted in a single flow top at Hanford, yielding a value close to 10^{-4}. Expert opinion (based mainly on intuition) places the figure within a range from 10^{-6} to 10^{-1} for various types of units at Hanford. This large uncertainty is disturbing as groundwater seepage velocity under a given hydraulic gradient is inversely proportional to effective porosity. Predictions which do not address this uncertainty explicitly may be misleading.

Dispersivities can be determined in tracer tests or theoretically from the spatial variation of hydraulic conductivities. The number of hydraulic conductivity data at Hanford does not seem sufficient to apply the second approach; the first has yielded a single value for a flow top. Dispersivities in the basalts are thus highly uncertain.

Retardation occurs due to complex physico-chemical processes that are poorly understood. There is a controversy whether K_d values determined in the laboratory are at all representative of anticipated field conditions. As far as I know, retardation has not been measured at Hanford under field conditions, and the parameter must be regarded as highly uncertain.

In reviewing the Environmental Assessments from DOE, it is important for NRC staff members to recognize that uncertainties in system description arise from conceptual difficulties, spatial variability of rock properties, and technological constraints. Since these uncertainties cannot be eliminated but only reduced by additional testing, it is important that they be explicitly recognized and their impact analyzed by DOE.

Sincerely,

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Professor of Hydrology

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