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FIELD TESTING STUDY PLAN FOR THE APACHE LEAP TUFF SITE: *CNWRA* DATA NEEDS

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1 INTRODUCTION AND REGULATORY BACKGROUND

Yucca Mountain (YM) was originally selected as a candidate repository site because: (i) it is situated in a remote location, (ii) the general area is characterized by a low population density, and (iii) it is characterized by a thick (several hundred meters) unsaturated zone (U.S. Department of Energy, 1986). The last condition led scientists to presume that high fluxes of water would not readily reach the repository, thus rendering unlikely the occurrence of corrosion and spent fuel dissolution problems. The complex hydrologic regimes associated with highly heterogeneous rocks, nonisothermal flow, and conductive fracture and fault zones, however, have stressed the need for further research regarding the suitability of the site for High Level Waste (HLW) disposal.

Research requirements dealing with such site characteristics as groundwater travel time (GWTT), favorable conditions (FACs), and potentially adverse conditions (PACs) relate to support of the US Nuclear Regulatory Commission (NRC) staff's License Application Review Plan (LARP) (Nuclear Regulatory Commission, 1994a). For example, understanding the subregional (site) and regional hydrogeology is required in order to determine the GWTT in the unsaturated and saturated zones. Other processes and phenomena of importance include, but are not limited to, the potential for flooding of the repository as a consequence of water table rise from meteorological or climatic changes, volcanism, or faulting. Furthermore, it will be necessary to assess the inherent variability and distribution of hydrogeologic and transport properties, initial and boundary conditions, hydro-geostratigraphic unit interfaces, and coupled effects modeling strategies used by the US Department of Energy (DOE) to support its estimation of GWTT and moisture fluxes.

In the NRC LARP (Nuclear Regulatory Commission, 1994a), these research requirements are expressed in the context of several Key Technical Uncertainties (KTUs) that are influenced, or pertain to, various subregional hydrogeologic flow and transport processes. These are: (i) developing a conceptual groundwater flow model that is representative of the YM site groundwater flow system, (ii) developing a mathematical groundwater flow model that is representative of the YM site groundwater flow system, (iii) determining the fastest path of likely radionuclide travel from the disturbed zone to the accessible environment, (iv) uncertainties associated with determining characterization parameters, (v) uncertainty in modeling the formation of perched zones, (vi) conceptual model representations of the natural and engineered systems, (vii) variability (temporal, spatial, etc.) in model parametric values, (viii) appropriateness of assumptions and simplifications in mathematical models, and (ix) validation of mathematical models. In the case of the YM site, these issues are complicated by the highly heterogeneous and nonlinear nature of the subsurface flow processes. It will be useful to describe briefly some aspects of the hydrogeologic conditions prevailing at the site before formulating the specific objectives of this research.

First, the proposed repository, is intended to be situated deep in relatively dry, unsaturated tuffs, about 300 m below land surface and 250 m above the water table (U.S. Department of Energy, 1988). Secondly, in addition to the presence of markedly distinct geologic units and tectonic faults, the geologic units are also variably fractured. For example, the Topopah Spring welded unit, where the proposed repository is to be located, is a low-porosity welded tuff believed to be densely fractured, while the underlying Calico Hills, nonwelded-vitric or zeolitized unit is a higher porosity, nonwelded tuff with seemingly much lower fracture density (U.S. Department of Energy, 1988). Finally, the net annual infiltration from rainfall and surface water over YM has not been determined yet, but may vary from

−1.0 to 5.0 mm/yr, from a mean annual rainfall of about 150 mm/yr. These mean values do not take into account the more extreme rainfall rates that may occur due to inter-annual fluctuations, inter-seasonal fluctuations, and individual storms. In addition, these values only reflect contemporary rainfall and infiltration conditions.

Under ambient conditions, it is likely that radionuclides released from the repository zone will be transported predominantly in the unsaturated flow regime. However, locally saturated flow conditions may also occur in the vadose zone, possibly due to short and intense rainfalls, or due to extremes in climatic fluctuations on larger time scales, or due to elevated temperatures. The potential for existing or future perched-water bodies of this nature is identified in 10 CFR 60.122(c)(23) as a PAC for the storage of HLW in a geologic repository. This is of concern, due to the possibility of either flooding portions of the repository or providing a faster pathway for groundwater traveling from the repository to the accessible environment. Perched-water bodies tend to be transient features that are formed where there is a contrast in hydrologic properties (Freeze and Cherry, 1979). Contrasts may result from differences between stratigraphic units. For example, matrix hydraulic conductivity at YM tends to decrease with increased welding of the tuff units. Contrasts may also occur due to the juxtaposition of low conductivity strata adjacent to more permeable and conductive strata along a structural feature such as a fault, or any other form of identifiable (e.g., through geophysical testing) persistent geological discontinuity. The rotation of these blocks may create a structural trap to permit accumulation of infiltrating water, allowing a perched-water body to form. This will also depend on whether the fault/fracture acts as a barrier to fluid flow or a conduit. Preliminary analyses of the role of fault zones have been presented by Bagtzoglou and Muller (1994) who indicated that, depending on the properties of the surrounding material, fault zones can interchangeably act as both barriers and conduits to flow. Mineralogical changes within or between strata may also cause a change in permeability due to changes in volume during mineral formation. One example is the formation of relatively impermeable layers in response to alteration of primary phases such as feldspar to secondary clays such as kaolinite and smectite. It should be noted, however, that there exist many different processes capable of altering permeability, even without changes in volume, such as cementation of flow paths in the saturated zone due to geochemical processes.

Perched-water is typically identified by encountering water flow at elevations above the regional water table. Perched-water flows from seeps in the zeolitized Tunnel Beds of the Indian Trail Tuff in the U12n tunnel at Rainier Mesa, approximately 50 km to the northwest of YM (Thordarson, 1965; Russell et al., 1987; Wang et al., 1993a). Many of the volcanic units are similar at both locations, but precipitation is approximately twice as great at the higher elevations of Rainier Mesa. Hydrochemistry and mineral chemistry provide a means of distinguishing different water bodies in geologic systems. Hydrochemical evidence indicates that seep waters from the Indian Trail Tuff are chemically similar to pore waters from the unsaturated zone below the Indian Trail Tuff, but are more dilute and chemically distinct from the pore waters in stratigraphically higher units (Wang et al., 1993a). Stable isotope (δD and $\delta^{18}O$) evidence indicates that the waters in the perched-zone are similar to the modern meteoric water at Rainier Mesa (Russell et al., 1987). This similarity suggests that recharge is relatively quick, and predominantly from winter storms.

Evidence for perched-water may also have been encountered at YM (U.S. Department of Energy, 1992) in drill holes USW UZ-1 and USW H-1 where flowing water was observed. There is still some question, however, whether this water occurred naturally or resulted from drilling fluids used in completing these and other nearby wells. Recent drilling has also encountered perched-water at depths of about 400 m in the northern part of YM (U.S. Department of Energy, 1994; Nuclear Regulatory Commission, 1994b), although no data on the hydrochemistry of these samples have been published. Perched-water has also been encountered at the Apache Leap Tuff Site (ALTS), one of the NRC-sponsored hydrology research sites. More specifically, a perched-water table has been identified within the tuff section at the Deep Slant Borehole (DSB) site at ALTS (Bassett et al., 1994). Perched-water has also been reported at the Peña Blanca Natural Analog Site (Pearcy et al., 1993).

One method of evaluating the possible formation of future perched-water zones is to use water and mineral chemistry to identify where these zones might have occurred in the geologic past, possibly under different climate conditions. Hydrochemical facies (Hem, 1985) have been used to establish relationships between bodies of water. Environmental tracers such as the stable isotopes of oxygen, carbon, hydrogen, and sulfur have long been used to distinguish between water bodies (such as waters in the unsaturated and the saturated zones), to estimate temperatures, and to identify potential flow paths, recharge areas, and fluid sources (e.g., Welhan, 1987; U.S. Department of Energy, 1988; National Academy of Sciences, 1992; Conrad, 1993; Mazor, 1991). Radiometric age dates can be determined for groundwaters using isotopes such as ^{14}C, tritium, ^{36}Cl, and uranium-series disequilibrium. If the length of the flow path is known or can be determined, these ages can be used to provide estimates of rates of fluid flow, and timing of changes in the paleohydrology of the site.

Finally, high-intensity rainfall events, occurring episodically, may drastically modify the subsurface flow regime from that which would be inferred using an average infiltration rate model. Perhaps the shortest significant time scale of climatic inputs to the system may be taken to be storm duration, typically on the order of hours or even less. This short term period is indeed much smaller than the time scale of interest for contaminant migration, say on the order of 10^3 to 10^4 yr or more. The problem to be investigated is the evaluation of various approaches for estimating subregional-scale infiltration and groundwater recharge fluxes. This problem involves assessment of the transient nature of infiltration, groundwater recharge and vapor migration coupled to surface (e.g., evapotranspiration, precipitation, snowmelt, and surface drainage features), and subsurface (e.g., focused recharge due to alluvial channels and vertically extensive discontinuities) processes and conditions. The amount and location of water infiltration are controlling factors in the movement of water through the subsurface. In fractured, unsaturated rock, such as that found at the YM site, the occurrence of sporadic high-intensity rainfall events may drastically modify the subsurface flow regime from that calculated (or predicted) from an average infiltration rate model. The DOE has concluded that the spatial and temporal distribution and magnitude of infiltration into the system may be the most important independent parameters influencing flow path development (U.S. Department of Energy, 1992). Typically, groundwater flow assessments are made using simplistic, average infiltration rate models. This methodology may not be satisfactory for compliance demonstrations. The NRC needs to be cognizant of alternative infiltration models that could be applicable to the YM site.

Data derived from field testing may be used to test flow and transport codes developed by the Center for Nuclear Waste Regulatory Analyses (CNWRA) researchers prior to their application at the YM site and region. The University of Arizona (UA) studies at the ALTS have produced databases for evaluating pneumatic, geochemical, hydrologic and transport processes on a site scale. Information is available for assessing fracture versus matrix flow conditions for unsaturated fractured tuff over a range of scales. Inclined boreholes at the 10-m scale have been used to evaluate pneumatic testing methods. A deep inclined borehole penetrating perched-water zones with associated core and water samples, is available to test site-characterization methods and strategies for determining effective field properties. The geochemical data allow for independent confirmation of groundwater mixing and residence times for fracture-dominated, as opposed to matrix-dominated, flow systems. The ALTS is located in fractured tuff with climatic and topographic conditions very similar to that of the region around YM, Nevada. It is, therefore, a very good, small-scale analog of the YM site. More importantly, however, it provides the unique opportunity to independently study flow, transport, and travel time issues in fractured unsaturated tuff.

CNWRA staff will interact with the UA researchers to design field experiments and collect field data in order to develop datasets that will allow for testing various modeling approaches. The project team will make the necessary field visits and coordination meetings as determined by the NRC project manager in order to accomplish the joint cooperative studies at the ALTS. This letter report constitutes the first step in this collaborative effort and describes in some detail the CNWRA data needs.

The field studies to be jointly pursued relate to: (i) infiltration and recharge processes, (ii) perched-water zone formation, and (iii) groundwater flow and transport assessments. Potential collaborative research ventures, that will be pursued at ALTS include field-scale experiments at: (i) the Covered-Borehole site (CB), (ii) the small watershed study at the DSB site, and (iii) the Never-Sweat Tunnel/Queen Creek (NST/QC) site. These studies are discussed in detail in Section 2.

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2 DATA NEEDS

2.1 INFILTRATION AND RECHARGE PROCESSES

In general, assessment of the transient behavior and spatial variability of infiltration, groundwater recharge, and vapor migration requires the use of mathematical models incorporating an abstraction of the active processes. The effects of various assumptions in the mathematical models will be explored, with the intention of identifying critical parameters and data requirements for each model.

Recharge of deep zones is affected by processes active in the near-surface zone, including evaporation, transpiration, liquid water flow, and vapor flow. Each of these processes is governed by several factors. For example, precipitation has been found to vary substantially over the YM region, both spatially and temporally, and winter storms are, in general, more uniform and severe than summer storms (Hevesi et al., 1992a,b; 1994). Similarly, evaporation from the ground surface is affected by air temperature, atmospheric vapor pressure, wind speed profile, incident solar radiation, surface soil and rock texture, plant activity, surficial temperature, and surficial moisture content. As key factors influencing groundwater recharge are identified, the location of potential high-recharge factors can be identified. It is anticipated that significant factors governing infiltration will include depth and character of the alluvial/colluvial cover, geologic layer underlying the alluvial cover, surface slope and orientation, fracture characteristics, and vegetative distribution.

Alternative conceptual models of infiltration include 1D, 2D, and 3D representations of a system. In order to explicitly incorporate the effects of evaporation, transpiration, and vapor-phase transport, various mathematical representations of the active processes can be made. An extremely detailed model would consider the flow of liquid water and water vapor, including nonisothermal effects and possibly air-phase movement. In addition, vegetation can strongly affect the movement of water: directly, by extracting water for transpiration within a root zone, and indirectly, by shading the ground surface and attenuating winds near the ground surface. Thus, a detailed model would incorporate such effects. Finally, a detailed model would require appropriate surficial boundary conditions. Typical models that might be used for ground-surface boundary conditions require estimates of some or all of the following: windspeed profile, atmospheric vapor density, atmospheric temperature, atmospheric pressure, solar radiation, precipitation, and cloud cover (Richardson, 1984).

An excellent method for assessing the predictions of alternative infiltration models is to test the predictions against field observations. Not only is the numerical coding of the mathematical model stressed, but the conceptual model itself is tested against ground truth. A discussion on the issue of validation of flow and transport models for unsaturated soils is presented by Nicholson et al. (1989). A number of field studies have been performed at the ALTS, and facilities are in place or can easily be established to help support infiltration studies on a small watershed and sub-watershed scale, including a meteorological metering station, runoff weirs, neutron probes, time-domain reflectometer (TDR) probes, solution samplers, and tensiometers. Ideally, these facilities will help to test models that range from simple 1D recharge models, through hillslope transect models, all the way through full watershed models.

The simulations considering the widest range of physical phenomena tend to be restricted to 1D models, simply due to the computational burden of considering higher dimensions. Perhaps one of the most effective comparisons of infiltration predictions with ground truth for such models can be performed with weighing lysimeters, where the overall moisture content in a large block of soil or alluvium can be

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monitored with an accuracy of grams or better. This can be done even with plant growth representative of natural conditions. Within such large devices, it is possible to emplace smaller measuring devices, such as TDR probes and thermometers, to obtain temperature and moisture profiles (Rogers and McConnell, 1993). Tracer tests can also be performed and closely monitored. With all this information, the predictions of the simulators can be closely monitored, thus providing excellent feedback on the performance of the model. At present, there exists no specific plan to install and operate weighing lysimeters at the ALTS. However, the UA researchers have plans for operating such devices at the Maricopa field site, near Phoenix, Arizona. Lysimeter data collected at this site could be extremely helpful for testing and calibrating the CNWRA models.

One of the areas of uncertainty at the YM site is the potential for focused recharge due to runoff into the washes, cropping out of different geologic units and possible preferential pathways arising from fracture exposures. In order to address the focused recharge issue, a series of detailed simulations will be performed incorporating variability representative of the ALTS. Data gathered and mapped by the UA research team will be used to provide input on the spatial variability of factors pertinent to recharge. Based on these data, a number of 1D survey simulations will be performed, in order to assess extreme behavior expected for the site. Finally, a representative number of simulations will be used to estimate the magnitude of focused recharge across the site, both in space and in time. These simulations will be conducted for various topographic locations, such as ridgetops, sideslopes, and alluvium channels in order to sample a broad spectrum of conditions.

The specific approach to estimating infiltration at a wash or mountain scale, tested here, relies on Geographic Information Systems (GIS) technology. The approach uses the spatial distribution of elevations, fracture distributions, and hydraulic properties, together with simple flow models, to do a complete water balance at the wash or mountain scale. The methodology can be tested at the ALTS, to a certain extent, by comparing model-predicted runoff with flume flow measurements given the same meteorological inputs. Meteorological and flume flow data, already being collected at the ALTS, are an identified CNWRA data need. Through careful instrumentation, the DSB watershed study can provide estimates of runoff, evapotranspiration and, ultimately, infiltration. Assuming that flow in fractures is the dominant subsurface redistribution mechanism, in order to use the methodology it would be necessary to measure the fracture characteristics over the watershed. Accordingly, field work would be required to collect information regarding fracture trace and aperture distributions over the wash. It is anticipated that in addition to CNWRA researchers, several UA students will participate in this activity, upon approval by the NRC project manager. Also, infiltration measurements performed on one or more representative fractures will be necessary to estimate the hydraulic properties of the fractures in the wash. Since the CNWRA GIS-based approach makes use of qualitative class differences, it would be very useful to have these infiltration tests conducted at three locations where, for example, a small, medium, and large aperture fracture is exposed. Results from these tests will help calibrate the infiltration model BREATH (Stothoff, 1995) before it is applied to perform the ALTS watershed analysis.

2.2 PERCHED-WATER ZONE FORMATION

The objective here is to identify and study, if possible, areas where perched-water zones may have formed in the geologic past under different hydrologic conditions, or might form in the future. The problem to be investigated is an assessment of the causative mechanisms and conditions that either have created perched-water zones, or exhibit a potential for creating future perched-water zones. A perched-water zone is a locally saturated groundwater system separated from the deeper regional water table by

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an unsaturated zone. The focus shall be on evaluating strategies and information needed to model perched-water development at the scale of the YM site. In the unsaturated zone, there is the potential for saturation levels to reach 100 percent in isolated zones above the regional water table. The potential for existing or future perched-water bodies of this nature is identified in 10 CFR 60.122(c)(23) as a PAC for the storage of HLW in a geologic repository. This is of concern due to the possibilities of flooding portions of the repository and providing faster groundwater pathways from the repository to the accessible environment. Identification of perched-water zones in the present or in the past can help to constrain conceptual and mathematical models used to predict future hydrologic conditions.

As part of the DOE Site Characterization effort at YM, hydrochemical data will be obtained for the unsaturated zone at YM under Study Plan 8.3.1.2.2.7 Hydrochemical Characterization of the Unsaturated Zone (U.S. Department of Energy, 1988). The USGS has already obtained a large amount of data on water chemistry in the unsaturated zone (Yang et al., 1988, 1993; Yang, 1992), mineralogy (Levy, 1991), and mineral chemistry (e.g., National Academy of Sciences, 1992; Whelan and Stuckless, 1992; Peterman et al., 1992; Paces et al., 1993; Marshall et al., 1993; Whelan et al., 1994). Many of these data, particularly those on secondary calcite from the unsaturated zone, may provide information on interconnections between different water bodies and their sources. Age dating can be used to relate these data to known changes in the paleoclimate and paleohydrology.

It may be possible to provide a first level screening for those areas that have a good potential for the development of perched-water zones based on the hydrologic properties of the units at YM and the geologic structure. For example, those areas where faulting has juxtaposed units of contrasting hydraulic conductivity may be identified as areas favorable for perched-water zone formation. First-level screening criteria will be developed and used to the extent possible to identify possible areas for perched-water zones. The availability of geochemical data is likely to be one of the limiting factors in selecting those areas for more detailed examination.

Perched-water has been reported in volcanic tuffs under semi-arid to arid conditions at Rainier Mesa (Russell et al., 1987), at the Peña Blanca Natural Analog Site near Chihuahua, Mexico (Pearcy et al., 1993), and at the UA ALTS (Bassett et al., 1994). The ALTS can be used as an analog site in an effort to define those chemical parameters that are sensitive to the presence (or absence) of perched-water zones. Sensitive parameters may include water chemistry, water ages, and mineral chemistry. A focused effort may find the mechanisms responsible for perched-water development in one or more of these locations. Much of the data will be site specific, and not necessarily representative of conditions at YM. Nevertheless, this type of information might be useful to constrain and test flow models, providing additional confidence in the modeling results.

A detailed description of the petrology and mineralogy of the tuffs immediately above, below, and within the perched water body would be useful to document changes in mineralogy around a perched zone. Mineralogy, petrologic relationships, and mineral chemistries are all important to interpret potential relationships to flow and transport in a comprehensive manner. As noted in the "Project Plan for Field Studies at the Apache Leap Tuff Site" submitted by the UA to NRC (Bassett et al., 1995), changes in mineralogy may affect stratigraphic permeability. Reductions in permeability due to alteration minerals such as clays or silica precipitation in fractures could result in hydraulic conductivity contrasts sufficient to result in the formation of perched water. Because there is still uncertainty regarding flow and transport in fractured, unsaturated tuffs, both fracture and matrix mineralogy and mineral chemistries should be documented at ALTS to the extent possible.

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Correlations between mineralogy and perched water at ALTS would be compared to mineralogical and petrological information available from site characterization activities (e.g., Levy, 1991) at YM to evaluate the potential for similar hydrologic conditions at the proposed repository site. This may provide some insight into identifying areas that are likely to be favorable for the formation of future perched water at YM due to mineralogical and petrological changes. Mineral chemistries and petrology around the perched water at ALTS may also serve as a means to fingerprint where perched water may have existed in the geologic past at YM. Once site characterization data become available on the mineralogies associated with known or suspected occurrences of perched water at YM (e.g., UZ-14), similarities may be noted increasing confidence in the use of mineralogical indicators of perched zones.

For the purposes of modeling flow through the unsaturated zone and around a perched water zone, hydraulic properties are clearly a critical need. Values for hydrologic properties such as hydraulic conductivities, characteristic curves, porosity, and permeability, determined through laboratory, and field experiments are necessary to provide the boundary and initial conditions of flow models used to evaluate the potential formation of perched water.

Neuman (1995) has outlined the type of measurements that can be made at the DSB site. These include fracture characterization, single-hole pneumatic testing, and infiltration and tracer experiments using additional shallow boreholes. Laboratory experiments with drill core can be used to provide saturated conductivities and characteristic curves of unsaturated hydraulic conductivity. These data will be used to constrain conceptual models of flow through the unsaturated zone, and boundary and initial conditions for flow and transport models.

Water and mineral chemistry can be used to identify where perched water zones might have occurred in the past and to provide boundary conditions for flow and transport models. Hydrochemical facies (Hem, 1985) can be used to establish relationships between bodies of water. Tracers such as stable isotopes have long been used to distinguish water bodies (e.g., unsaturated and saturated zones), and also to identify potential flow paths, recharge areas, and fluid sources (e.g., Welhan, 1987; National Academy of Sciences, 1992; Conrad, 1993). Age dates determined for groundwaters using isotopes such as ^{14}C, tritium, and ^{36}Cl can be used to provide estimates of rates of fluid flow, and timing of changes in paleohydrology.

Water chemistry data including major and trace elements should be compiled on the perched zone and on end-member fluids such as the saturated zone, surface runoff, precipitation, and unsaturated zone pore waters where possible. Isotopic signatures for these waters, both for stable isotopes and radiogenic isotopes should also be gathered. Chemical and isotopic definition of the perched water and the potential sources for these waters is a critical step in identifying and modeling water-rock interactions. Radiogenic age dates of waters using ^{14}C, ^{36}Cl, and tritium would also be useful in calibrating flow models. Some of these data have already been published (Bassett et al., 1994), and will be augmented by additional data (Bassett et al., 1995). These data sets are an identified CNWRA data need.

Geochemical data obtained on the chemistry and ages of waters at ALTS will be used by CNWRA staff in cooperation with University of Arizona researchers to develop conceptual models for perched water formation in fractured tuffs in an arid environment. Insight gained at ALTS would provide guidance as to what data are important, and how to interpret available data at YM.

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2.3 GROUNDWATER FLOW AND TRANSPORT ASSESSMENTS

The SUFLAT methodology and suite of codes (Bagtzoglou and Muller, 1994) will be evaluated regarding its capability to simulate the subregional-scale groundwater flow and transport conditions considered plausible at the YM site. Analysis of field data from the ALTS, collected in conjunction with the UA researchers, will facilitate a critical investigation of differences between various alternative models. Based on this analysis, modifications or enhancements to the SUFLAT methodology will be made if deemed necessary.

At the CB site, one research venture will select a small area containing several large fractures, over which water and tracers may be applied at a controlled rate. Through careful instrumentation of the area with neutron probe access tubes, TDR probes, tensiometers, and solution samplers, the advancing water and tracer fronts can be monitored. Field results can then be compared with selected model predictions. Inclined boreholes at the 10-m scale have been used at the CB site to evaluate pneumatic testing methods. As a consequence, the CB is a very-well characterized site. The permeability data sets at the 0.5, 1.0, and 3.0 m support scale are an identified CNWRA data need. Other types of information, such as geophysical logs will also be very useful to identify the location and extent of geological features that exhibit very long correlation structures (i.e., significant spatial continuity). Features with these characteristics are often called persistent discontinuities and could enhance preferential flow and transport processes. These data will enable CNWRA researchers to perform pilot flow and transport modeling activities which will, in turn, facilitate the UA/CNWRA team to better design the CB experiment.

In addition to the CB, the NST/QC site provides a unique opportunity to investigate matrix-fracture interactions. Two potential field-scale experiments are under consideration: (i) burial of a tracer at a shallow depth below the QC bed, directly above the NST, so that rainy-season flow in the creek will provide a pulse of water and tracer that can be monitored in the underlying NST; and (ii) damming off a 30 to 40 m section of QC during the dry season, so that ponded water (containing some tracer) will infiltrate downward and, similarly, provide an advancing water and tracer front to be monitored in the underlying NST. In either case, data on experimental tracer (e.g., K-Br) tests will be useful in evaluating hydrologic properties such as matrix imbibition and fracture flow in partially saturated porous media. The Magma Mine Company has developed detailed geological maps, which can be used to infer fracture pattern characteristics and other pertinent information. These maps, if available for distribution, could prove very useful for the NST/QC site efforts.

One additional use for mineralogical and petrological information is to provide boundary and initial conditions for reactive transport models that incorporate precipitation/dissolution reactions. Predicting the stability of minerals such as clays in response to HLW thermal loading is one aspect of the flow and transport calculations. Using mineralogical information from ALTS can be an important part of building confidence in these models. Reactive transport simulations for the ALTS will be conducted, accounting for geochemical interactions such as aqueous speciation, sorption, and mineral precipitation/dissolution reactions. 1D simulations will be carried out along streamlines in the flow fields. It is proposed to use the codes GEM (Lichtner, 1994) and MPATH (Lichtner, 1992) for the reactive transport calculations. Currently both GEM and MPATH apply to fully saturated conditions and will need to be modified for unsaturated flow. The code GEM provides for advective/diffusive and dispersive transport in a single spatial dimension. It accounts for a variety of chemical reactions including aqueous speciation, mineral precipitation/dissolution, sorption, and electrochemical migration. In its present form, however, the solvent water is presumed to be in abundance and is not explicitly considered. The fluid

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velocity is set by an external parameter and is held constant. Modifications to GEM necessary for carrying out this task include adding Darcy's law for fluid transport and constitutive relations, such as the van Genuchten relationships, describing partially saturated porous media. In addition, it will be necessary to add a two-phase fluid flow component to model vapor transport. These modifications are an ongoing activity that will lead to the development of the numerical code MULTIFLO (Lichtner, 1995).

Data on environmental isotope profiles and other chemical indicators of mineral alteration during weathering will be useful in reactive transport modeling. Especially useful are data on mineral alteration products produced during weathering of the tuff at the ALTS. These data will be useful for understanding the possible ateration of tuff at YM and testing numerical models of reactive transport in partially saturated porous media. Moreover, observed amount of calcium sulfate precipitated as a function of depth from the surface at the ALTS will aid in understanding the evaporation process in the subsurface and the amount of water infiltrating into the tuff rock. It will also be useful in testing models involving reactive transport in the partially saturated zone.

Although calcite is observed to form near the surface at the YM site, calcite is absent at the ALTS (private communication with R. Bassett). This is presumed to be because of the high sulfate concentration in rainwater and the absence of a soil zone and hence relatively low CO_2 concentrations, which results in precipitation of calcium sulfate rather than calcium carbonate. In spite of this difference between the two sites, the data for calcium sulfate precipitation should be extremely useful for understanding hydrologic and chemical processes in the unsaturated zone and will provide an indirect means for understanding quantitatively calcite deposition at YM.

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3 SUMMARY

In summary, the following are identified data sets that would facilitate the CNWRA/UA collaborative research effort at the ALTS.

- Lysimeter data collected at the UA Maricopa site
- Meteorological and flume flow data collected at the ALTS watershed site
- Infiltration measurements performed on representative fractures and estimates of hydraulic properties for the fractures in the ALTS watershed
- Information regarding fracture trace and aperture distributions in the ALTS watershed
- Mineralogy, petrologic relationships, and mineral chemistries collected at the DSB site
- Fracture and matrix mineralogy and mineral chemistries collected at the DSB site
- Isotopic signatures for waters, both for stable isotopes and radiogenic isotopes, collected at the DSB site
- Hydrologic properties such as hydraulic conductivities, characteristic curves, porosity, and permeability, determined through laboratory, and field experiments at the DSB site
- The permeability data sets at the 0.5, 1.0, and 3.0 m support scale at the CB site
- Other ancillary types of information, such as geophysical logs at the CB site
- Data on experimental tracer (e.g., K-Br) tests
- Data on environmental isotope profiles and other chemical indicators of mineral alteration during weathering
- Data on mineral alteration products produced during weathering of the tuff at the ALTS
- Observed amount of calcium sulfate precipitated as a function of depth from the surface at the ALTS

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