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# Vadose Zone Transport Field Study: Detailed Test Plan for Simulated Leak Tests

A. L. Ward
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Prepared for the U.S. Department of Energy
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# Summary

The U.S. Department of Energy (DOE) Groundwater/Vadose Zone Integration Project Science and Technology initiative was created in FY 1999 to reduce the uncertainty associated with vadose zone transport processes beneath waste sites at DOE's Hanford Site near Richland, Washington. This information is needed not only to evaluate the risks from transport, but also to support the adoption of measures for minimizing impacts to the groundwater and surrounding environment.

The principal uncertainties in vadose zone transport are the current distribution of source contaminants and the natural heterogeneity of the soil in which the contaminants reside. Oversimplified conceptual models resulting from these uncertainties and limited use of hydrologic characterization and monitoring technologies have hampered the understanding contaminant migration through Hanford's vadose zone. Essential prerequisites for reducing vadose transport uncertainty include the development of accurate conceptual models and the development or adoption of monitoring techniques capable of delineating the current distributions of source contaminants and characterizing natural site heterogeneity.

The Vadose Zone Transport Field Study (VZTFS) was conceived as part of the initiative to address the major uncertainties confronting vadose zone fate and transport predictions at the Hanford Site and to overcome the limitations of previous characterization attempts. Pacific Northwest National Laboratory (PNNL) is managing the VZTFS for DOE. The VZTFS will conduct field investigations that will improve our understanding of field-scale transport and lead to the development or identification of efficient and cost-effective characterization methods. Ideally, these methods will capture the extent of contaminant plumes using existing infrastructure (i.e., more than 1300 steel-cased boreholes).

The objectives of the VZTFS are to conduct controlled transport experiments at well-instrumented field sites at Hanford to

- identify mechanisms controlling transport processes in soils typical of the hydrogeologic conditions of Hanford's waste disposal sites
- reduce uncertainty in conceptual models
- develop a detailed and accurate database of hydraulic and transport parameters for validation of three-dimensional numerical models
- identify and evaluate advanced, cost-effective characterization methods with the potential to assess changing conditions in the vadose zone, particularly as surrogates of currently undetectable high-risk contaminants.

This plan provides details for conducting field tests during FY 2000 to accomplish these objectives. Details of additional testing during FY 2001 and FY 2002 will be developed as part of the work planning process implemented by the Integration Project.

# Acronyms and Initialisms

| | |
|---|---|
| ARA | Applied Research Associates |
| AT | advanced tensiometer |
| C | clay |
| CDE | convective-dispersive transport model |
| CEMI | crosshole electromagnetic imaging |
| CERCLA | Comprehensive Environmental Response, Compensation, and Liability Act |
| CLT | convective-lognormal transport model |
| CRT | crosshole radar tomography |
| CS | coarse sand |
| CST | crosshole seismic tomography |
| DC | direct current |
| DOE | U.S. Department of Energy |
| EMI | electromagnetic resolution imaging |
| EMSP | Environmental Management Science Program |
| ERDF | Environmental Restoration Disposal Facility |
| ERT | electrical resistance tomography |
| FS | fine sand |
| GPS | global positioning system |
| HMS | meteorological station |
| HRR | high-resolution resistivity |
| ILAW | Immobilized Low Activity Waste |
| LANL | Los Alamos National Laboratory |
| LMHC | Lockheed Martin Hanford Company |
| MOSA | methods of soil analysis |
| OM | organic matter |
| PDF | probability density function |
| PNNL | Pacific Northwest National Laboratory |
| PSD | particle size distribution |
| PTF | pedotransfer functions |
| QA | Quality Assurance |
| RPP | River Protection Project |
| S | silt |
| SAC | system assessment capability |
| SAP | sampling and analysis plan |
| SBMS | Standards-Based Management System |
| SCA | soil contamination area |
| SDF | submarine disposal facility |
| SNL | Sandia National Laboratories |
| STCG | Site Technology Coordination Group |
| TDR | time domain reflectometry |
| UBC | University of British Columbia |

| | |
|---|---|
| URL | universal resource locator |
| URMA | underground radioactive materials area |
| VEA | vertical electrode array |
| VZTFS | Vadose-Zone Transport Field Study |
| WIDS | Waste Information Data System |
| WMA | waste management area |
| WMFS | Waste Management Federal Services |
| XBR | cross-borehole radar |

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# 1.0 Introduction

At the U.S. Department of Energy's (DOE's) Hanford Site near Richland, Washington, mobile contaminants, such as chromate, technetium, tritium, and nitrate, among others, have been found in elevated concentrations in groundwater beneath tank farms (e.g., near SX-115), burial grounds (e.g., 618-11), and past-practice liquid discharge sites. More information is needed about the processes controlling transport beneath Hanford waste sites. This information is needed not only to evaluate the risks from transport, but also to support the adoption of measures for minimizing impacts to the groundwater and surrounding environment.

There has been and will continue to be reliance on numerical models to support selection of remediation technologies and to evaluate risks. However, numerical models are highly susceptible to uncertainty, and predictions from even the most sophisticated transport model are no more reliable than the input parameters used to describe the initial contaminant distribution and site heterogeneity. As a result, reduction of the uncertainty associated with vadose zone processes has been identified as a Hanford Site need by the Site Technology Coordination Group (STCG) and the National Research Council (2000a) and is a key aspect of the site's Science and Technology Initiative (DOE 1999a).

In relation to vadose zone transport, the principal uncertainties are the current distribution of source contaminants and the natural heterogeneity (over a range of spatial scales) of the soil in which the contaminants reside. The Hanford vadose zone consists of highly heterogeneous glacial-fluvial sediments. As illustrated in Figure 1.1, heterogeneities can range from localized phenomena, such as silt or gravel lenses, fractures, and clastic dikes, to large-scale lithologic discontinuities.

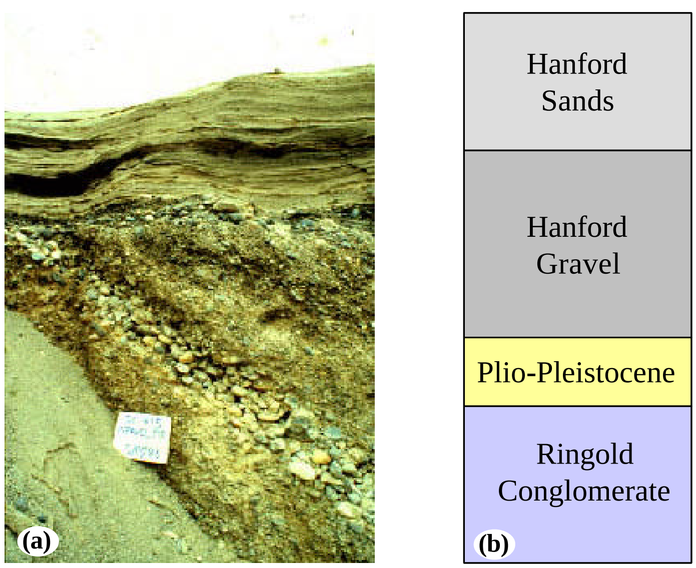


**Figure 1.1**. Hanford Vadose Zone (a) Example of heterogeneous Hanford formation, (b) Simplified lithologic model zone commonly used in numerical models

Based on circumstantial evidence, these hydrogeologic features have been implicated in funneling and fingering, physical mechanisms that can alter, and possibly accelerate, the transport of contaminants to underlying groundwater, bypassing much of the soil matrix. There are little or no quantitative data to support these implications, and past characterization and modeling efforts have had limited success in reproducing observed groundwater contaminant plumes (e.g., Phillips et al. 1980; Johnson and Chou 1998).

The occurrence and impact of spatial and temporal variability in hydrologic and chemical properties of natural soils is well established (Roth et al. 1991; Wierenga et al. 1991; Russo and Bouton 1992). Information on variability is critical to the prediction of contaminant spreading (Russo 1993) and the effectiveness of remediation (Berglund and Cvetkovic 1996). Consequently, successful interpretation of existing contaminant plumes and prediction of future transport through the vadose zone is dependent on our ability to identify the dominant transport processes and characterize spatial and temporal variability in soil properties that govern flow and transport.

Considerable information has been obtained about the physics of unsaturated flow and transport and the corresponding parameters via laboratory experiments and pore-scale models (van Genuchten et al. 1999; Or and Tuller 1999). However, even over relatively short distances, there are heterogeneities in the physical structure of porous media and structural differences between repacked soil cores and field sites from which materials initially came. Many of the parameters required for simulations are also collected at scales different from (usually smaller than) the ones used to discretize porous media in numerical models. For example, saturated hydraulic conductivity ($K_{sat}$) and matric potential-water content relationship ($\psi[\theta]$) are often measured with cores at a scale on the order of centimeters to meters, while numerical models often require measurements representative of tens to hundreds of meters. Also, because the length scales of the resulting data are quite different from those required for field-scale interpretations and predictions, it is important that studies aimed at understanding the effects of heterogeneity be conducted at the appropriate scale (Rockhold et al. 1999). Nevertheless, transport modeling at the Hanford Site relies mostly on input data derived mostly from small cores (Khaleel and Freeman 1995; Khaleel and Relyea 1995; Piepho 1999) as very little in situ data are currently available (Ward et al. 1998a,b).

A number of large-scale transport studies conducted internationally during the last decade have identified important vadose zone transport processes. Studies include transport tests in the U.S. at Las Cruces, New Mexico (Wierenga et al. 1990; Hills et al. 1991; Rockhold et al. 1996); at Idaho National Engineering Laboratory in Idaho Falls, Idaho (Wood and Norrell 1996); and at Maricopa, Arizona (Young et al. 1996). Studies outside of the U.S. include those of van Wesenbeck and Kachanoski (1994) in Canada and Schulin et al. (1987) and Hammel et al. (1999) in Europe. These studies have consistently shown that flow and transport are controlled, to a large extent, by site-specific hydrologic properties and subsurface structural features such as layering, sediment discontinuities, and fracture zones. There were essentially two features common to these studies (Hammel et al. 1999). First, the local vertical dispersion of solute strongly appears to depend on the measuring volume; it is generally smaller for small volumes such as boreholes than for the volume of field at which scale results are desired. Second, horizontal redistribution of solutes leads to accumulation in areas of local water flux convergence and depletion in divergent areas. These features have mostly been attributed to subsurface heterogeneity and textural discontinuities. Consequently, extrapolation of hydrologic characterization at one site to different soil textural classes at another site or to larger spatial and temporal scales at the same site and to different experimental/boundary conditions has proven to be problematic and has lacked the required technical basis. This difficulty is due mostly to a lack of appropriate techniques for scaling heterogeneities.

Understanding contaminant migration through Hanford's vadose zone has been hampered, not only by oversimplified conceptual models, but also from limited use of hydrologic characterization and monitoring technologies. In the past, contaminant plumes in Hanford tank farms and at Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) past-practice disposal sites have been characterized with gross and spectral gamma techniques. Contaminant migration rates have been inferred from changes in gamma logs (e.g., DOE 1996) or by observation of contaminants in groundwater monitoring wells. Spectral gamma, however, does not allow full description of contaminant plumes. Because the dominant gamma emitters (e.g., $^{137}Cs$, $^{90}Sr$) are reactive, they are retarded in Hanford sediments. Non-reactive contaminants such as technetium, tritium, nitrate, which move readily with the water, are not gamma emitters and are therefore difficult to detect in situ with spectral gamma. The inability to track these species highlights an important need for technologies and methods to characterize and monitor vadose zone plumes and to determine processes controlling contaminated transport to the groundwater at Hanford (GAO 1989). Innovative geophysical logging, using three-dimensional subsurface-imaging techniques (National Research Council 2000b), that can be used with existing steel-cased wells in harsh environments, may prove useful in documenting concentrations and movement of contaminants in the Hanford vadose zone.

Recent characterization efforts have employed a core-sampling technique in the T and SX tank farms (Freeman-Pollard et al. 1994; Myers et al. 1998) and trenching at Gable Mountain Pond. These methods have been used successfully to map localized zones of contamination, often at levels that saturate the spectral gamma system, and additional coring is being performed. Unfortunately, these analyses are too sparse (limited to a few boreholes) to properly delineate the extent of contaminant plumes and are extremely expensive. Drilling and analysis costs have exceeded $1M per borehole in the T and SX tank farms, and sample analyses can take several months to complete (LMHC 1999a). These localized measurements rarely provide enough data to uniquely parameterize a region into meaningful zones and allow determination of transport properties for each zone. Consequently, information is limited to present distributions and is of limited use in predicting future migration patterns.

Essential prerequisites for reducing the uncertainty in vadose transport include the development of accurate conceptual models and the development or adoption of monitoring techniques capable of delineating the current distributions of source contaminants and characterizing natural site heterogeneity. The Vadose Zone Transport Field Study (VZTFS) was conceived as part of the U.S. Department of Energy Groundwater/Vadose Zone Integration Project Science and Technology initiative to address the major uncertainties confronting vadose zone fate and transport predictions at Hanford and to overcome the limitations highlighted above. The VZTFS is intended to conduct field investigations that will improve our understanding of field-scale transport and lead to the development or identification of efficient and cost effective characterization methods (DOE 1998a). Ideally, these methods will capture the extent of contaminant plumes using existing infrastructure (i.e., more than 1300 steel-cased boreholes). Pacific Northwest National Laboratory (PNNL) is managing the VZTFS for DOE.

## 1.1 Scope of Activities

The scope of the VZTFS is to conduct a series of field tracer experiments at Hanford to allow identification of the principal uncertainties limiting the interpretation of current contaminant distributions and prediction of future migration through the vadose zone at tank farms and past-practice waste disposal sites. Activities will include conducting a series of tracer experiments to determine the dominant transport processes and parameters in the Hanford formation and producing a detailed and accurate database for validation of three-dimensional numerical models of vadose zone flow and transport. The VZTFS scope will also include hydrogeologic investigation and characterization of uncontaminated sites and will address current data gaps related the mobile contaminants by making in situ measurements of surrogate variables using emerging monitoring technologies. The VZTFS plans to conduct four controlled tracer tests at two or more uncontaminated sites and near-surface experiments to simulate a tank leak at an existing site followed by several tracer studies in deeper Hanford formation sediments.

## 1.2 Objectives

The objectives of the VZTFS are to conduct controlled transport experiments at well-instrumented field sites at Hanford to

- identify mechanisms controlling transport processes in soils typical of the hydrogeologic conditions of Hanford's waste disposal sites

- reduce uncertainty in conceptual models

- develop a detailed and accurate database of hydraulic and transport parameters for validation of three-dimensional numerical models

- identify and evaluate advanced, cost-effective characterization methods with the potential to assess changing conditions in the vadose zone, particularly as surrogates of currently undetectable high-risk contaminants.

This report provides details for conducting field tests during FY 2000 to accomplish these objectives. Details of additional testing during FY 2001 and FY 2002 will be developed as part of the work planning process implemented by the Integration Project.

A short list of monitoring and characterization technologies, derived from candidates discussed during an Advanced Characterization Workshop, is developed for use in the FY 2000 field tests. Details on field sampling, laboratory analyses, waste management, health and safety protocols, and data analysis and interpretation are discussed in the appendices. Background information related to waste characteristics that may influence constitutive properties, information on the range of boundary conditions that might influence transport, and a review of previous efforts to study vadose zone transport at Hanford are summarized in the Broad Test Plan, posted on the web at http://etd.pnl.gov:2080/vadose/.

In general, the experiments are designed to ensure the measurement of flow and transport properties and their geostatistical properties in the same soil volume. This will facilitate the development of an upscaling methodology and the extrapolation of parameters derived from controlled field investigations at uncontaminated sites to contaminated sites with less characterization. These data will then be used to improve conceptual models, select remedial actions, and select compliance monitoring technologies that can be applied across a range of waste management areas. These products will support the development of the vadose zone component of the System Assessment Capability (SAC).

## 1.3 Project Linkages

Specific linkages to the science and technology endeavor of the Integration Project, the core projects, and SAC can be found in the revised roadmap (DOE 1999a). The contributions of the VZTFS to these activities are described in that document. Common goals among core projects include collecting field data, establishing a contamination baseline, and developing conceptual models of vadose zone flow and transport. To identify future changes from the contamination baseline, advanced technologies are needed. These technologies should be capable of not only using the existing infrastructure to detect contaminants, but locating in situ the high-risk, often difficult-to-detect contaminants. There are challenges in transforming geophysical measurements to the constitutive properties required for model input, extrapolating results over multiple spatial scales, and extrapolating from one site to the next. In heterogeneous environments, such extrapolation can only be accomplished after the spatial-scale dependence of flow and transport properties are known.

In the broad framework of determining constitutive properties, characterizing subsurface heterogeneities, and developing time and cost-efficient subsurface imaging technologies, four Environmental Management Science Program (EMSP) projects are linked to the VZTFS. These projects are summarized in Table 1.1. Personnel from three of these projects, 070187, 070193, and 070220, are participating in the FY 2000 experiments and contributing to the overall planning and execution of the field tasks. Personnel from the final project, 070115, are indirectly involved and will use the VZTFS test site to collect data to validate techniques that are developed in their research. The VZTFS will support the core projects and the SAC though provision of data for model testing and assessment, and improvement of conceptual models using data obtained from controlled field experiments. Support will also come from identification of advanced monitoring and characterization technologies.

Conceptual models generally simplify the real system and provides a description of system geometry, initial and boundary conditions, physical and chemical processes occurring within the system and constitutive properties that describe these processes. At Hanford, the physical system has been partially characterized and consequently, conceptual models requiring simplification are a major source of uncertainty in transport predictions. The VZTFS will provide results of transport experiments under controlled conditions to support the selection of initial and boundary conditions, model dimensionality, transport volume (matrix vs. preferential flow), the choice of steady-state or transient conditions, the importance of structural features and stratigraphy, and solute retardation mechanisms.

**Table 1.1**. FY 2000 Environmental Management Science Program Projects Collaborating with the Vadose Zone Transport Field Study

| Project | Investigator | Institution | Title | Summary |
|---|---|---|---|---|
| 070187 | P. D. Meyer | PNNL | Quantifying Vadose Zone Flow and Transport Uncertainties Using a Unified, Hierarchical Approach | Develop and demonstrate a general approach for modeling flow and transport in a heterogeneous vadose zone. The approach will use geostatistical analysis, media scaling, and conditional simulation to estimate soil hydraulic parameters at unsampled locations from field-measured water content data and a set of scale-mean hydraulic parameters. Results will help elucidate relationships between the quantity and spatial extent of this characterization data and the accuracy and uncertainty of flow and transport predictions. |
| 070193 | C. J. Murray | PNNL | Influence of Clastic Dikes on Vertical Migration of Contaminants in the Vadose Zone at Hanford | Investigate the possibility that clastic dikes provide preferential pathways that enhance the vertical movement of moisture and contaminants through the vadose zone. New characterization techniques to be demonstrated in the project could be applied across the Hanford Site, as well as at other sites where vertical faults influence the contaminant transport through sediments. |
| 070220 | G. Newman | SNL | High Frequency Electromagnetic Impedance Imaging for Vadose Zone and Groundwater Characterization | Address the use of magnetotelluric inversion codes to interpret data and limiting factors of 2-D and 3-D inversion schemes. Results will help DOE develop better ways to characterize the subsurface and thereby predict contaminant transport in the vadose zone. |
| 070115 | R. Knight | UBC | The Use of Radar Methods to Determine Moisture Content in the Vadose Zone | Focus on two specific aspects of the link between radar images and moisture content. The research will improve the usefulness of radar as a way to characterize moisture content in the vadose zone. |

# 2.0 Selection of Test Sites

The Vadose-Zone Transport Field Study (VZTFS) involves two types of experiments:

1. **Leak simulation experiments**. These are designed to investigate flow and transport from a source that is small relative to the observation area. Such experiments are applicable to leaks from point sources and will provide crucial information about the early time behavior of contaminants released from tanks, transfer lines within tank farms, buried water lines, cribs, and trenches. Sampling will be mostly nondestructive, and preferably, these experiments will be conducted at an existing instrumented site that has undergone some prior characterization.

2. **Trench experiments**. These are designed to allow observation of flow and transport under a more widely distributed surface flux and are applicable to migration of more widely distributed contaminants. Such experiments are critical to understanding field-scale transport and will allow measurement of flow and transport properties and characterization of their geostatistical structure. This information will support the reduction of uncertainty in vadose zone conceptual models and facilitate calibration of numerical models for field-scale transport at the Hanford Site. These experiments will involve a combination of nondestructive and destructive sampling and will be performed at opportunistic sites to leverage excavation and sampling costs. Opportunities include the Environmental Restoration Disposal Facility (ERDF) in the 200 West Area, the Submarine Disposal Facility (SDF) in 200 East Area, the proposed Immobilized Low Activity Waste (ILAW) disposal site, the gravel pit at the Hanford Site Batch Plant, and the US Ecology site.

The strategy for VZTFS site selection was based partly on the analogous site concept used in the 200 Areas Remediation Strategy (DOE 1998b) to reduce the amount of site characterization and evaluation. In the analogous site concept, a site that represents the main waste disposal scenario is chosen after taking into account location, geology, waste site history, and contaminants. Because the VZTFS is concerned with the uncertainty associated with contaminant source distributions and hydrogeologic controls of transport, greater emphasis will be placed on the hydrogeologic component and the degree to which sites have been previously characterized. Cost for infrastructure, including excavation permits, electricity, and water accessibility are also factored into the selection process.

## 2.1 Leak Simulation Test Site

The Sisson and Lu site was selected for the leak simulation experiments that will be conducted during FY 2000 and FY 2001. The site's physical layout and extensive array of steel-cased wells make it ideal for investigating a variety of leak scenarios and their associated flow and transport behavior. The steel-cased wells allow testing of advanced characterization technologies with potential for imaging the subsurface in culturally noisy environments. Such technologies are needed to reduce the uncertainty in source contaminant distributions.

The Sisson and Lu test site is just east of the Immobilized Low Activity Waste (ILAW) disposal site and southwest of the PUREX facility (Figure 2.1) in the 200 East Area. The site offers easy access to vehicles and equipment. The site has been relatively well characterized hydrologically and has been the subject of several modeling investigations. Directly east of the site is the 216-A-38-1 crib. The area immediately west and south (part of the ILAW facility) has been used in experiments to characterize Hanford surface sediments and the upper Hanford formation in support of the Hanford ILAW Performance Assessment (Ward et al. 1998a,b). At additional sites farther southwest, adjacent to the planned ILAW disposal, the ILAW project has collected geologic, geochemical, and hydraulic data from boreholes site in the 1998 performance assessment (LMHC 1999b; Reidel and Horton 1999; Fayer et al. 1999). East of borehole 299-E17-21 is the long-term plume migration field site at which the vadose zone transport of high-salinity fluids is being investigated under an Environmental Management Science Program (EMSP) (FY 1998) project (Ward and Gee 1998). The setting of the Sisson and Lu site and the area surrounding it have been described by Fayer et al. (1993, 1999).

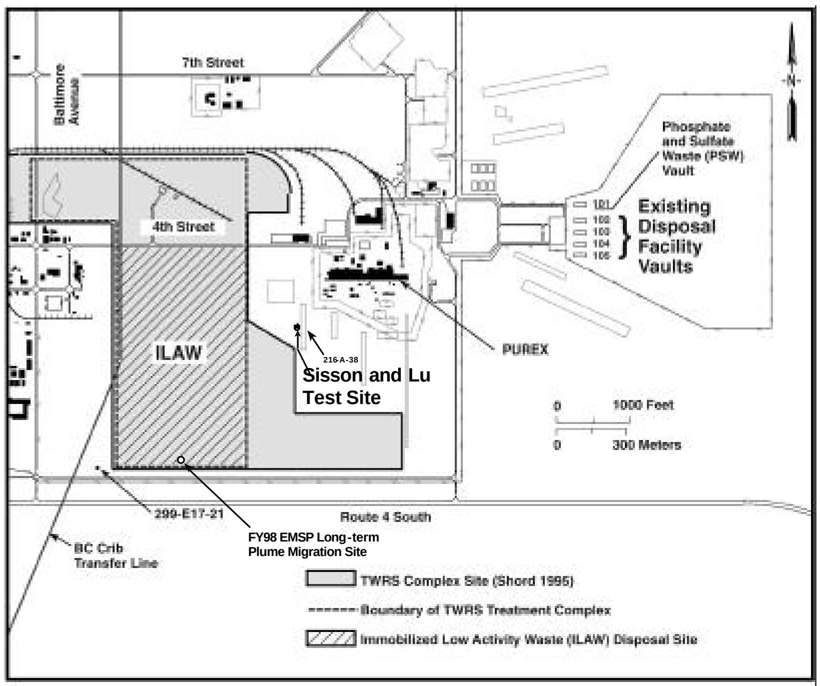


**Figure 2.1**. Location of the Leak Simulation Test Site. The site is at the old Sisson and Lu Test Site in the Hanford Site 200 East Area (after Fayer et al. 1999).

### 2.1.1 Hydrogeology

The site is located in the 200 East Area of Hanford's elevated 200 Area Plateau. The climate is arid with cool, wet winters and hot, dry summers. Precipitation at the Hanford Meteorological Station, located about 10 km west of the test site, has averaged 174 mm y-1 since 1946. Nearly half of the precipitation comes in winter months (November through February). Average monthly temperature ranges from -1.5°C in January to 25°C in July. Humidity ranges from 75% in winter to 35% or less in summer.

The upper portion of the 200 Area Plateau was formed during catastrophic glacial flooding. Flood sediments were deposited when ice dams in western Montana and northern Idaho were breached, and massive volumes of water spilled across eastern and central Washington. This process repeated itself numerous times before about 13,000 years ago, bringing to the Plateau a thick sequence of sediments known as the Hanford formation (Tallman et al. 1979; Reidel and Horton 1999). The Hanford formation at the Sisson and Lu site extends to about 60 m below the surface, and the water table is more than 90 m deep.

### 2.1.2 Soils and Vegetation

The surface soil at the site is coarse sand, locally known as a Quincy sand and associated with the Quincy soil series (mixed, mesic, Xeric Torripsamments). The soil has a high infiltration capacity (>50 mm h-1), thus precipitation infiltrates readily with little or no runoff. The vegetation at the site before the experiment was a mixture of sagebrush and cheatgrass. The shrubs on the site were “grubbed” off in March 1980, and since then the site has been dominated with a sparse cover of cheatgrass, tumble mustard, and tumbleweed (Fayer et al. 1993).

### 2.1.3 Infrastructure and Well Installation

Figure 2.2 shows a plan view of the existing well configuration at the Leak Simulation Test Site. A central injection well is surrounded by 32 observation wells. The wells were constructed from three 6-m (20-ft) sections and one 1.5-m (5-ft) section of 0.15-m- (6-in.-) diameter schedule 40 steel casing. The sections were welded to form watertight joints that were then reinforced with four steel straps welded symmetrically around the casing. During installation, the 1.5-m (5-ft) section of casing was driven into the soil, then the 6-m (20-ft) section was welded on, and the driving continued until the top of the casing was beyond the reach of the drive hammer.

Soils within the casing (drill cuttings) were removed by advancing 6 m (20 ft) with an air rotary. Cuttings were blown out of the casing and collected near the point of drilling. Samples were collected of these cuttings and stored in containers and selected samples were analyzed for hydraulic properties (Khaleel and Freeman 1995; Khaleel et al. 1995; Rockhold et al. 1999).

### 2.1.4 Previous Tests and Monitoring

A tank leak was simulated at the Sisson and Lu site by introducing water and tracers (nitrate, chloride, barium, rubidium, and calcium) including the short-lived radionuclides $^{134}Cs$, and $^{85}Sr$, into the central injection well. Eleven injections, ranging from 3200 L to 5500 L and totaling 42,000 L, were made from September 22, 1980 to February 2, 1981 (Fayer et al. 1993). Monitoring of the subsurface was accomplished by lowering sensors to the desired depths in the observation wells and recording sensor output. The sensors included neutron probe (for water content), gamma-gamma (for formation density), and Geiger-Muller and spectral gamma (for tracer radioactivity).

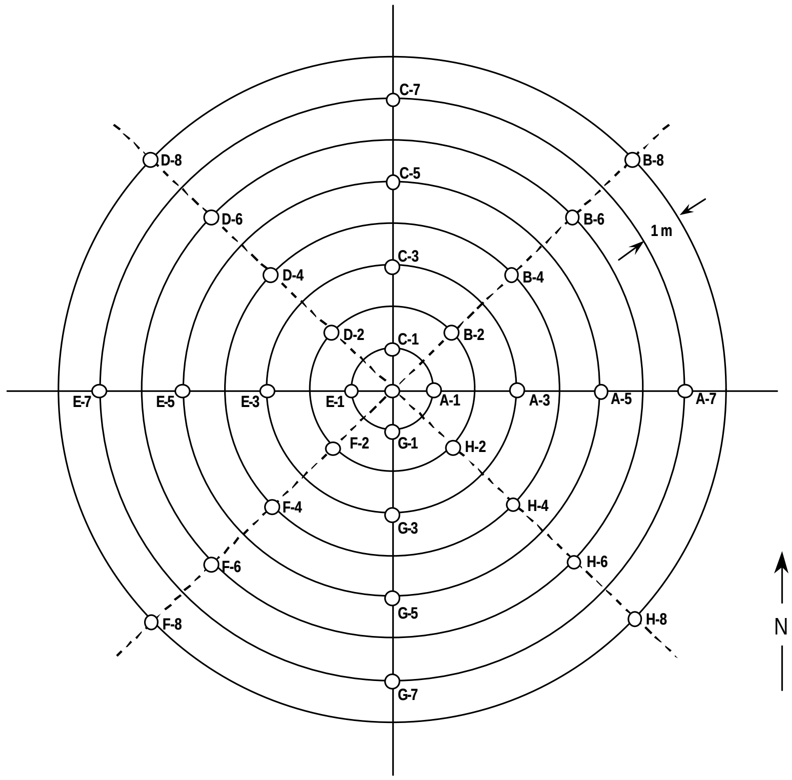


**Figure 2.2**. Well Array at the Leak Simulation Test Site in the 200 East Area at Hanford (after Sisson and Lu 1984).

In 1994, additional monitoring of the site was undertaken using CNT-G (neutron-neutron logging for water content), APS (pulsed neutron logging for water content), LDS (litho-density sonde for wet density using gamma scattering) and HNGS and RLS (gamma logging for radionuclides). These geophysical tools were deployed by Schlumberger Wireline Services after calibration of the two water content probes. Description of the logging equipment and results of these additional tests can be found in (Engleman et al. 1995a,b) and Fayer et al. (1995).

The density data collected from geophysical logging were subsequently used by Rockhold et al. (1999) to estimate spatial distributions of porosities and to estimate saturated water contents of subsurface sediments at this site. Inspection of the gamma-log data for bulk density (Fayer et al. 1995) suggests that the values may be lower than the actual field densities. Only wet density data are available, and these values appear to be low by as much as 20%, particularly at depths below 7 m. Wet densities reported for depths from 12 to 15 m in Well E-1 were less than 1.3 g cm-3, and the reported water contents were slightly more than 6 vol%. The computed bulk density for this zone would be less than 1.25 g cm-3, which is unusually low for Hanford sediments, most of which have normal bulk densities in the range from 1.5 to 1.7 g cm-3. The average bulk density for the entire profile of Well E-1, as estimated from the LDS density probe, is 1.4 g cm-3, or about 15% lower than typical Hanford sediments (Engleman et al.

1995a). Fayer et al. (1995) noted that the LDS gamma-gamma sensor had not been calibrated for site conditions, so the data are in question. Further deployment with the LDS sensor will require calibration under site-specific conditions.

More recently, the surrounding area has been investigated under the ILAW Performance Assessment and an existing EMSP project. A series of experiments to characterize the Hanford surface sediments and the upper Hanford formation were performed to the west (Ward et al. 1998a,b). Also as part of the site characterization activities for the ILAW disposal facility, sediment samples were obtained from a borehole (299-E17-21) southwest of the injection site (Figure 2.1). East of borehole 299-E17-21 is a long-term plume migration field site at which the vadose zone transport of high salinity fluids is being investigated under a FY 1998 EMSP study. This research is focused on the effects of wetted path geometry, salinity gradients, and vapor flux on the migration of highly saline wastes (Ward and Gee 1998).

### 2.1.5 Previous Data Analysis and Modeling

Modeling of the Sisson and Lu experiment has met with mixed success (Sisson and Lu 1984; Lu and Khaleel 1993; Smoot and Lu 1994; Smoot and Williams 1996; Rockhold et al. 1999). Because the radioactive tracers were short lived and retarded by the sediments, tracer data collection was confined to wells within a 2-m radius of the injection point. The focus of most of the data analysis and modeling was on the spatial and temporal distribution of water. For water transport analysis, the entire well network has been used, and the data set is quite extensive. In general, lateral spreading of the water plume has been significantly under-predicted by past modeling efforts. Apparently, small-scale heterogeneities (either thin silt or fine sand lenses) inadequately described in the numerical models act to retard the vertical transport of the water plume beyond that which has been computed using typical grid spacings of 0.5 m or greater.

Small-scale layering in sands, even with modest size differences (gradation changes), have been shown to cause significant horizontal spreading (Stephens and Heermann 1988). No undisturbed core samples have been taken from the site for hydrologic analysis. However, a few sediments obtained from cuttings during air rotary drilling have been repacked and analyzed for water retention characteristics (Fayer et al. 1993). Scarcity of data, including lack of cores for direct physical measurements of hydraulic properties of sediments, has hampered studies to address the effects of hydraulic variability on the lateral spreading of plume at this site (Khaleel and Freeman 1995; Khaleel et al. 1995; Rockhold et al. 1999).

Flow and transport measurements from the ILAW site east of the Sisson and Lu test site were used to determine flow and transport properties, including unsaturated hydraulic conductivity and dispersivity, as well as their geostatistical features to a maximum depth of 2 m (Ward et al. 1998a,b). Of the 45 undisturbed cores obtained from the ILAW borehole, 20 were analyzed to determine particle size distributions, water retention, and saturated and unsaturated hydraulic conductivity (Fayer et al. 1999).

## 2.2 Opportunistic Experimental Sites

The principal processes governing transport through the vadose zone are generally considered to be advection and dispersion. The dispersion parameter, dispersivity ($\lambda$), is regarded as a unique and measurable property of the porous medium and is often used to account for all unknown velocity variations related to heterogeneity. While several field-scale observations of solute dispersion have been reported in the literature, the reliability of $\lambda$ reported values is questionable (Gelhar et al. 1992). Analyses of transport in natural environments also suggest $\lambda$ increases with the scale of transport distance. Thus, the scale of observation of flow and transport is critical, and observations should be made at length scales comparable to the total transport distance of interest.

In selecting opportunistic sites, factors considered in relation to transport distance were

- dimensions of Hanford single-shell tanks—22.8 m wide, 13.5 m high with the base 15 m below ground surface. Mean location of the center of contaminant mass below leaked tanks is about 3 m into the Hanford formation.

- dimensions of other waste disposal structures—cribs (4 m long x 4 m wide x 3 m deep); French drains (typically gravel-filled trenches 3-175 m long, 3-20 m wide x 3-8 m deep). Contaminant transport primarily in the Hanford formation.

Five potential sites have been identified as being suitable for the trench experiments required to achieve the objectives defined in Section 1.2:

1. The Environmental Restoration Disposal Facility (ERDF) in 200 West Area (a sand-dominated facies of the Hanford formation)

2. The Submarine Disposal Facility (SDF) in the 200 East (a sand-dominated facies of the Hanford formation)

3. The proposed Immobilized Low Activity Waste (ILAW) disposal site (a sand-dominated facies of the Hanford formation)

4. The gravel pit at the Hanford Site Batch Plant (a gravel-dominated facies of the Hanford formation)

5. The US Ecology site (a sand-dominated facies of the Hanford formation).

Some of these sites are currently excavated to depths of 15 to 25 m and could potentially be used for short-term flow and transport studies. The advantage of such opportunistic sites include:

- relatively easy access to the deeper Hanford formation sediments for in situ testing in a cost-effective manner.

- the ability to measure both horizontal and vertical correlation lengths of constitutive properties, which would provide data that would be invaluable for developing and testing upscaling methodologies

- readily quantifiable effects of clastic dikes and other large-scale features on flow and transport.

The above list is not final, and it is recognized that the user/contractor schedules and timelines may very well preclude the use of some of these sites. Nevertheless, all efforts will me made to coordinate site selection and test plans with Hanford Site User Representatives to aid in the identification of a mutually beneficial and accessible site for the studies. Sites such as these offer the potential to examine the effects of clastic dikes and other large-scale features (e.g., paleosurfaces, giant ripple marks, and other prominent sedimentary features) on flow and transport. Mapping the cut faces of some of these sites have shown clastic dikes above the 20-m depth. Excavation of these dikes and characterization using geophysical techniques, field hydrologic methods, and dye tracers would assist in resolving the importance of these features on flow and transport. Test strategies and specific plans involving a combination of non-invasive and destructive excavation will be developed once an opportunistic site has been identified.

# 3.0 Planned Testing

## 3.1 Rationale for Test Strategy

The results of the original Sisson and Lu (1984) experiment demonstrated that there was considerable lateral spreading of the plume in the relatively uniform sandy sediments. Water movement and chemical transport appeared to be controlled by thin layers of fine-textured soils that impeded vertical water movement but allowed accelerated horizontal transport. In Hanford sediments, these fine-textured regions are often relatively thin, pinched lenses generally about 10 cm or less in thickness and 1 to 5 m in length and will impose certain limits on the testing and monitoring.

Selected characterization methods must be able to map, in 3-D, the thin, fine-textured soil features to accurately represent transport. For such features to be seen, selected methods must be capable of measuring lithological changes to within 10 cm vertically and 100 cm horizontally. Once the lithology is mapped, unsaturated hydraulic properties will be determined, for at least a representative set of the units, with more emphasis on the units with lower permeability because these units control water movement. One method that will be explored during the FY 2000 experiment will be the application of minimally invasive techniques using a down-well video camera directed through a clear plastic access port installed by cone penetrometer.

The motivation for a large-scale trench study is the realization that the mechanism of contaminant spreading at the field scale is dominated by the spatial variability of hydraulic properties. The principal processes governing transport through the vadose zone are generally considered to be advection and dispersion. As stated previously, the dispersion parameter, dispersivity ($\lambda$), is regarded as unique and measurable property of the porous medium and is often used to account for all unknown velocity variations related to heterogeneity. Estimates of dispersivity are often derived from calibration of the advection-dispersion model to observed solute concentrations. In most practical situations of contaminated soils, there are rarely sufficient data, in space or time, to allow reliable determination of dispersivity. In cases where there may be sufficient data, the history of the source is often unknown, and the uncertainty in calibration to estimate dispersivity can be quite large. Large-scale controlled trench experiments would overcome this limitation at Hanford.

The procedure to be adopted by the VZTFS for both the simulated leak and trench studies is to measure water content and solute concentrations at a large number of points in 3-D space at a few fixed times. These measurements will be used to compute the spatial moments of the wetting fronts and solute plume at selected times, which will then be compared with theoretically determined moments to identify the appropriate transport models and parameters. The leak simulation experiments will provide invaluable information on transport from point sources and information about the vertical correlation lengths of transport parameters without the need for much more infrastructure. Attempting to get all of the information from this site would render it essentially useless. The trench study will focus on collecting information on horizontal correlation lengths of flow and transport parameters and will not attempt to monitor to depths as extensive as the leak test experiment.

The resulting spatial and temporal moments will form the basis for upscaling laboratory-derived parameters and properties to the field scale. Upscaling techniques are critical to the development of more realistic models for the field-scale transport. Data and models developed from these studies will support remediation decisions by allowing the evaluation of remediation options, especially on uncharacterized sites, over a range of conditions. Currently, there is a limited basis for making any deterministic or probabilistic predictions because the data are not available. For the systems-level simulation, the results of the tasks performed by the VZTFS will support defensible simplifications that will be needed.

The initial measurements at the leak simulation site and the selected trench site will focus on three state variables (water content, water potential, chemical concentrations) controlling water movement. One conclusion made at the Advanced Characterization Workshop held January 19-21, 2000, in Richland, Washington, is that point measurements of the state variables provide time series data that will require geophysical methods for interpolation between points. While geophysical methods can provide estimates of spatial distributions of properties, the measurements are indirect and must be correlated/calibrated with the point measurements to obtain reliable volumetric estimates of the state variables needed. Although no one geophysical method may provide the needed information at the resolution required, there may be an optimal combination of methods that provides the necessary information. Thus, combinations of geophysical and point sensor methods are needed to address tank-farm management needs.

## 3.2 Simulated Leak Tests

The FY 2000 experiment at the injection site will be similar to the original flow and transport experiment conducted by Sisson and Lu (1984). A major difference will be the use of improved monitoring and characterization tools developed since the first test was conduced nearly 20 years ago. Coring for soil hydraulic and chemical properties will be conducted before, during, and after the tests. The tests will be monitored nondestructively with geophysical tools, including through-casing resistivity methods, advanced tensiometers, solution samplers, and down-well sensors for density and water content. Figure 3.1 shows the layout of the new monitoring infrastructure. A Sampling and Analysis Plan is presented in Appendix A.

The installation of automated devices for monitoring the major state variables describing water and contaminant movement will allow the site to be used as a demonstration site for both the public and regulators. Real-time measurements of variables such as water content, matric potential and resistivity will allow demonstration of water movement and transport through different geologic materials at Hanford.

The basic test will include the following:

- Simulated leak testing consisting of five injections of 4000-L increments over a 5-week period.
- Tracer application during the third injection.
- Geophysical logging of water content; water potential, resistivity; dielectric permittivity; acoustic wave velocities.
- Monitoring for soil solution concentrations using soil cores and pore water samples.

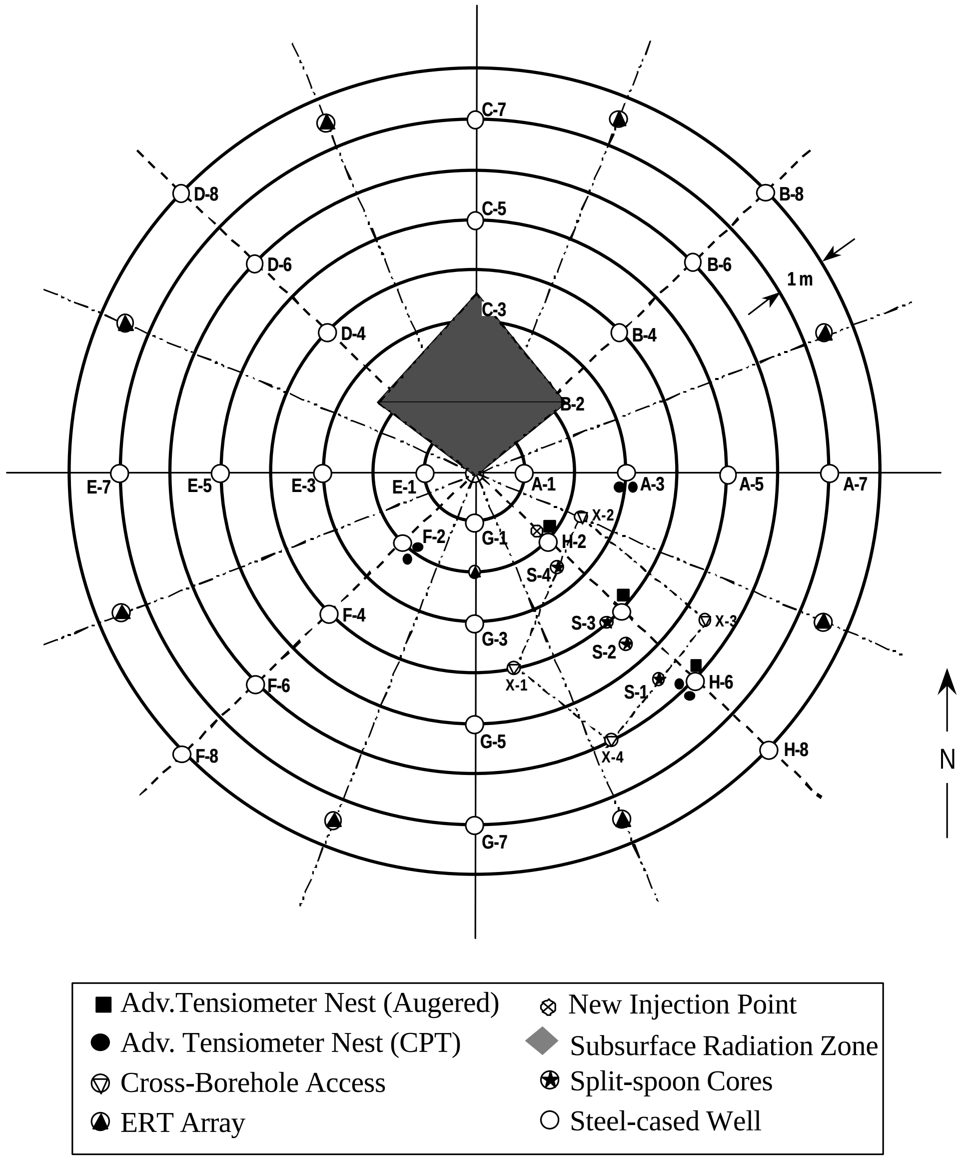


**Figure 3.1**. Plan View of FY 2000 Test Site Showing Proposed Locations of New Monitoring Infrastructure

Geophysical logging will include monitoring with neutron probe, electrical resistance tomography (ERT), crosshole radar (CRT), high-resolution resistivity (HRR), crosshole electromagnetic imaging (CEMI), and seismic crosshole tomography for lithologic characterization. Core samples will be taken at four locations to depths of 18 m (60 ft). Data analysis will include an evaluation of the ability of the sensor arrays to adequately monitor migration of the wetting fronts from the leaks and to track the spread of the tracer plume as a function of the site geology and hydrologic characteristics.

Data will be managed as described in Section 6.0. Data will be processed for display on a secure web site on which injection patterns, water content changes, and pressure profile responses can be observed in near real time by collaborators and interested parties.  An example of near real-time display of vadose zone monitoring data, including soil water content, matric potential, and drainage responses to both natural and controlled boundary conditions is located on the Vadose Zone Transport web site at http://etd.pnl.gov:2080/vadose/tensiometer.htm.  These data are being collected from the Buried Waste Test Facility, near Hanford's 300 Area, which has been instrumented with water content, pressure, precipitation, and drainage sensors and is remotely monitored daily.

## 3.3 Trench Flow and Transport Tests

Although a list of potential trench experimental has been identified, final site selection has not been done.  The approach for characterizing the trench site will be to employ the geophysical techniques from the simulated leak tests to initially characterize a transect 30 m long by 4 m wide.  Because the trench tests will not be performed until the FY 2001 and FY 2002, details of the experiments are not presented here.  However, preliminary plans for trench testing are presented in Appendix B.  Additional details for trench tests to be performed during FY 2001 and FY 2002 will be developed as part of the detailed work planning process implemented by the Integration Project.

# 4.0 Monitoring Technologies

## 4.1 Geophysical Methods

Past deployments of geophysical techniques at the Hanford Site have been focused on the detection of buried objects with a few attempts to detect water and contaminants. Traditionally, imaging of subsurface contaminants has been accomplished with spectral gamma logging while water content is traditionally measured by neutron probe. While these methods have provided important information, they do not delineate contaminant plumes of mobile species such as technetium, nitrate, or chromate.

To aid in identifying emerging vadose zone monitoring technologies to be used in the Vadose-Zone Transport Field Study (VZTFS), an Advanced Characterization Workshop was held at Hanford January 19-21, 2000. Proceedings are available online at http://etd.pnl.gov:2080/vadose/. The more than 20 technologies presented at the workshop were screened to identify those that could be used to reduce the uncertainty in plume delineation when used alone or in conjunction with others. With this objective in mind, a short list of candidate technologies was identified based on the following criteria:

- the ability to identify key geologic features controlling water movement with a vertical resolution of 0.1 m or better and a horizontal resolution of 1 m or better

- the ability to locate wetting fronts and a change in water content of 0.01 $m^3\ m^{-3}$ or better with a repeatability of at least 0.01 $m^3\ m^{-3}$

- the ability to determine shape and extent of non-gamma-emitting contaminant plumes or their surrogates

- the ability to function and produce useful results in environments that are culturally noisy.

The technologies resulting from the screening process including neutron moisture logging, advanced tensiometry/suction lysimetry; electrical resistance tomography (ERT); crosshole radar tomography (CRT); crosshole seismic tomography; crosshole electromagnetic induction (CEMI); and high-resolution resistivity (HRR). Additional technologies to be employed include time domain reflectometry (TDR), tracers (including isotopes), and coring. Table 4.1 presents a summary of the methods, their application, information on the properties measured, and spatial resolution. A brief review of the techniques, including their mode of operation, is presented the following sections.

### 4.1.1 Neutron Moisture Logging

Neutron probes have been used to monitor water content at the Sisson and Lu injection site in the past (Sisson and Lu 1984; Fayer et al. 1993, 1995). These probes are used routinely to monitor field water contents at the Hanford Site (e.g., Ward and Gee, 1997; Fayer et al. 1999; DOE 1999b).

**Table 4.1**. Characterization and Monitoring Technologies Selected for FY 2000 Field Tests

| Method | Application | Properties Measured/Derived | Resolution | Status |
|---|---|---|---|---|
| Neutron-Neutron | Moisture content, porosity (saturated), identification of aquitards, lithology | Hydrogen concentration | ≤10 cm | Provides precise measure of hydrogen concentration. Multiple detector systems are borehole compensated. Epithermal systems are less affected by lithologic variation than thermal systems. |
| Tensiometry/ Suction Lysimetry | Derivation of matric potential; water content, hydraulic conductivity; pore water samples | Matric potential, Collect pore water samples for chemical analysis | Point | Established technology with traditional methods. Advanced tensiometers/lysimeters now being applied in boreholes and at environmental scales. |
| Electrical Resistivity Tomography | Monitor changes in bulk resistivity | DC electrical resistivity | ≥1 m | Continuous monitoring of resistivity in either a plane of a volume. Requires the installation of a series of electrodes in at least two monitoring wells. Now commercially available. |
| Crosshole Radar | Moisture distribution, lithology, soil disturbances, buried materials | Dielectric permittivity | 5-60 cm depending on frequency | Depth of penetration may be quite limited (<30 cm) if formation is electrically conductive; it can be as high as 9 m in nonconductive formations. Measures continuous vertical profile. Interpretation may be difficult in complex situations. |
| Crosshole Seismic Tomography | Porosity, mechanical rock properties, lithology | Compressional and shear travel times, fracture estimation | ≤15 cm | Most systems require fluid-filled borehole. All require either open hole, or good contact between casing and formation. Effective transducer coupling may require water columns of 76 m or more. Borehole compensated. |
| Crosshole Electromagnetic Induction | Moisture distribution, identification of shallow contaminant plumes, lithology through steel casing | Electrical conductivity, Dielectric permittivity | 1.5 to >4.5 m | Measurements can be made rapidly. Depth of investigation is 1-60 m. Sensitive to signal interference from transmission lines. Can measure continuous profiles. |

**Table 4.1**. (contd)

| Method | Application | Properties Measured/Derived | Resolution | Status |
|---|---|---|---|---|
| High-Resolution Resistivity | Moisture, Lithology, geologic structure, buried materials, identification of shallow contaminant plumes | DC electrical resistivity | >1 m | Rapid measurements. Can measure continuous profiles to a depth of -60 m. Sensitive to signal interference from transmission lines. Improved data acquisition and incorporation of topography into volume calculations. |
| Time Domain Reflectrometry | Monitoring flow and transport, lithology | Dielectric permittivity, Electrical conductivity | ≥2 cm depending on probe length | Capable of providing continuous measurement. Limited depth of investigation. Traditional probes may not operate effectively in saline waters. Requires direct contact with formation. |

Conventional nuclear moisture logging devices use a technique called neutron moderation. The probe used in this technique, commonly referred to as a neutron probe, contains a source of neutrons (the neutral particle inside the nucleus of an atom), usually 50 mCi of americium-241 and beryllium, and a neutron detector. The neutrons given off by the source (called "fast" neutrons) collide with the hydrogen atoms in any water present. Because the fast neutrons and the hydrogen atoms have the same mass, the fast neutrons are slowed down by this process, much like a billiard ball hitting a stationary ball of the same size and each moving away with equal speeds (one slowing down and the other speeding up). If the neutrons collide with other much more massive elements, they retain the same speed, much like a billiard ball colliding with a large fixed object. The detector is set up only to measure these resulting slow neutrons; therefore, the amount of slow neutrons detected is directly related to the amount of hydrogen present. The main source of hydrogen in most sites is bound up in the water molecules; therefore this type of sensor is very effective for measuring soil moisture. Higher counts reflect higher water contents.

Use of the neutron probe requires cased access tubes. The probe is either lowered in vertical access tube or towed through horizontal access tubes, for example those installed below hazardous waste sites, to measure soil moisture. The neutron probe, which is slightly under 5-cm o.d., will be used to monitor through steel the 15-cm i.d. steel casings. This can be done without need for centering devices, provided the probe is adequately calibrated (Tyler 1988; Engleman et al. 1995b; Fayer et al. 1995). For FY 2000, one of the neutron probes used by Fayer et al. (1995) is available. Two additional probes are also available for use and will be cross-calibrated with one of the probes calibrated by Fayer et al. (1995).

### 4.1.2 Advanced Tensiometry/Lysimetry

Tensiometers are water-filled porous cups placed in contact with soils to measure matric potential (Cassel and Klute 1986). The water pressure inside the porous cup is subsequently monitored with a pressure gauge or electronic transducer and related directly to the matric potential of the soil water. The matric potential is a key state variable for describing water flow in unsaturated soils. To date, there have been only limited measurements made of this variable in Hanford soils or sediments (Fayer et al. 1999).

Various configurations of tensiometers have been used over the years to measure matric potentials in the near surface (generally the top 3 m of the soil profile), but recent advances have been made in tensiometer design so that tensiometers can be placed at almost any depth (Hubble and Sisson 1996, 1998). The new tensiometer is known as the advanced tensiometer. Two configurations of the advanced tensiometer will be tested during the FY 2000 experiment. The first is a standard nest configuration where tensiometers are placed together in a hole with a split-spoon auger device. The tensiometers are connected to the surface via a 2.54-cm PVC pipe to accommodate both pressure transducer wiring and water refilling, are placed at selected depths, and the hole is subsequently backfilled. The second is a less-intrusive method where individual tensiometers are placed at the depth of interest by pressing them into the ground using a cone penetrometer. Both methods recently have been deployed successfully at the Hanford Site as part of the Science and Technology Initiative (DOE 1999a). A description of the advanced tensiometers and examples of real-time data can be found at http://etd.pnl.gov:2080/vadose/tensiometer.htm.

Tensiometers fail when dry soil pulls water out of the tensiometer cup, air displaces water in the cup, and continuity is lost between the pressure sensor and the cup water. This occurs generally when the matric potentials are less than -600 mbar pressure (~600 cm water pressure). In soils having recent drainage, matric potentials are typically greater than -100 mbar, so failure is generally not a problem and periodically adding water to the cup cures the problem. Performance of the advanced tensiometers in Hanford sediments suggests that the matric potentials below the 1-m depth persist at values greater (i.e., wetter) than -70 mbar (<70 cm suction). Thus, we do not expect hydraulic failure of tensiometers in the FY 2000 experiment, where the soil has been draining for the past 20 years. Tensiometer measurements are fully automated for easy data review.

### 4.1.3 Electrical Resistance Tomography

Electrical resistivity tomography (ERT) has been demonstrated to be a useful characterization tool, providing details of the lithostratigraphy between wells (e.g., Newmark et al. 1994), subsurface processes such as fluid infiltration (Daily et al. 1992), and steam injection and ohmic heating (Ramirez et al. 1993) by mapping the spatial and temporal changes in soil resistivity resulting from changes in liquid saturation and temperature. Because tank wastes at Hanford are generally rich in high ionic strength electrolytes, resistivity should be an ideal surrogate for locating difficult to detect contaminants. In general, ERT has been conducted using a cross-borehole geometry, using multiple electrically-isolated electrodes placed in vertical arrays. This geometry has the potential to produce relatively high-quality, high-resolution images when the aspect ratio of vertical to horizontal spacing is equal to or greater than 1.5:1.0. Typical electrode installations involve multiple electrodes strung on nonconductive casing (e.g., plastic or fiberglass) in conventionally installed boreholes, or as instrumentation strings installed using cone penetrometers. Both designs have been effective in shallow to moderate depths (most recently >395 m), but deeper installations require significant and more costly modifications.

The method of ERT data collection and processing has been described in detail by Ramirez and his colleagues (e.g., Ramirez et al. 1993). The forward and inverse modeling codes are described by LaBrecque et al. (1996). The forward solution is implemented using the finite difference technique with Newman boundary conditions at the ground air interface and Dirichlet boundary conditions along the other faces of the cube. The inverse solution employs an objective function, which aims to minimize data misfit and model roughness. The minimization of the objective function is done iteratively.

The ability to obtain ERT images using existing conventional steel casings would increase the applicability of the technique and make it particularly useful for deployment in tank farms. Recent simulations of ERT with vertical casings as electrodes show that there is distinct signature indicative of the changing resistivity across the field, which is well above the noise level in the simulations. However, vertical resolution may be limited (Newmark et al. 1994)

### 4.1.4 Crosshole Radar

Crosshole radar measurements provide information about the porous medium rock between two boreholes. Radar is analogous to the seismic reflection technique, except that radar (microwaves) is used rather than acoustic waves. The primary information obtained is the variation of dielectric properties of the subsurface. Because of the large contrast in the dielectric constant between water ($\kappa$ = 80) and most earth materials ($\kappa$ =3 to 5), volumetric water contents can be easily inferred from radar data (Hubbard et al. 1997). Also inferred is the lithology and distribution of different soil types. Media with strong discontinuities (e.g., fracture zones) delay pulse arrival times and attenuate the transmitted radar pulse. The late arrivals and reduced pulse amplitudes are measured and analyzed using tomographic processing. Even later arrivals from reflectors are also analyzed. The velocity and amplitude of the data are recorded as a function of time resulting in a series of data in the time domain. However, the data are often reduced to the frequency domain to infer attributes of the data indicative of various subsurface properties. Normally, numerous rays are measured, and the data are usually collected in a tomographic mode, which is then inverted to provide a tomogram of either velocity or attenuation properties. The data can also be collected in a more rapid fashion in just a limited crosshole configuration. The data can also be processed to give reflection images in stratigraphic sequences.

### 4.1.5 Crosshole Seismic Tomography

Crosshole seismic tomography (CST) involves measuring the travel time of seismic energy transmitted between two or more boreholes to derive information on the dynamic elastic properties of the intervening porous medium (Majer et al. 1997). Such data can then infer lithology, bed geometry and continuity, fracture and fault properties, porosity, and in some cases, the fluid distribution. The CST uses a transmitter in one hole and either single or multiple receivers in an adjacent hole or holes. Energy is transmitted at multiple positions in the transmitter well and received in the receiver well(s) with sensors. In practice, a three-component wall-locking geophone and a directional downhole seismic source are initially lowered to the bottom of two boreholes. The two probes are then moved together in intervals of 30-60 cm so that a near horizontal ray path is maintained between them. Average shear (S) and compressional (P) wave velocity values are obtained by calculating wave travel times between the source and receiver boreholes. Accuracy of the data require that the boreholes be installed as vertically as possible and be cased with steel or PVC. The technique requires that the boreholes be sealed at the bottom so they can be filled with water. At the test site, steel-cased boreholes (15-cm i.d.) are already in place, but their verticality is unknown. The bottoms of these wells are also unsealed. Inflatable packers that can be removed after the test will be used to seal the boreholes. A deviation survey will first be run to determine the verticality of the boreholes. Measurements will be made at the end of the flow and transport experiments.

### 4.1.6 Crosshole Electromagnetic Induction

Electromagnetic induction (EMI) uses the principle of induction to measure the electrical conductivity of the subsurface between two boreholes. The technique can provide high-resolution images of the subsurface between existing wells up to 1000 m apart. The CEMI system consists of a transmitter tool deployed in one well and a receiver tool deployed in a second well. The transmitter uses a vertical-axis coil wrapped with 100-300 turns of wire tuned to emit a single low-frequency sinusoidal signal that induces currents to flow in the surrounding soil. The optimum operating frequency depends on borehole separation and background resistivity, but generally the frequency ranges between 40-100 kHz. A frequency that is too low limits the resolution, while one too high limits the range of the measurement. At the receiver borehole, a custom-designed coil detects the total magnetic field, consisting of the magnetic field from the induced currents as well as the primary magnetic field generated by the transmitter. The receiver section consists of a magnetic field sensor and a commercial lock-in amplifier located at the surface. The lock-in amplifier operates like a radio by measuring only those signals that are coherent with the transmitted signal while rejecting incoherent background noise. By positioning both the transmitter and receiver tools at various levels above, below, and within the zone of interest, images of the resistivity distribution between the wells can be generated. The EM data are interpreted by inverse modeling to produce a tomogram.

The field study will include both surface-based EMI and CEMI. The surface-based EMI will consist of two orthogonal lines approximately 20 m long across the expected leak zone. The operation frequency will be between 100-20,000 Hz. The surface-to-borehole measurements will make use of at least two and surface transmitter locations transmitting into all four PVC wells and at least 12 steel-cased wells. The operation frequency will be from 100-20,000 Hz. The PVC wells will allow the highest frequencies to be collected while the steel-cased wells will admit, at most, 1000 Hz. The surface lines will be done first (May 23, 2000) with the surface-to-borehole data acquired on May 24 and May 25.

### 4.1.7 High-Resolution Resistivity Tomography

Electrical surveys undertaken by a direct current (DC) resistivity device involve placement of electrodes in the ground. There are various geometries for the electrode layout, but most have all four electrodes in line. The Wenner and Slumberger arrangements are the most popular. The two outer electrodes are the current source and sink; self-contained batteries drive current. The two inner potential electrodes sense the electrical potential at the surface while current is flowing between the outer electrodes. The potential measured varies with electrode spacing in a predictable way, and also changes as the strata and contained fluids vary laterally and vertically. High-resolution resistivity (HRR) is an evolutionary development in DC electrical resistivity differing from conventional, industry-standard approaches by modification of the field data acquisition procedures (Fink 1980, 1994) and subsequent data processing (Fink 2000). Determining the volume under investigation gives a physical basis for the manner in which the data are presented. HRR has proven itself in extremely rugged terrain by incorporating the topography into the volume calculations. HRR is particularly useful in mapping the distribution and time-dependent changes of moisture in the subsurface. HRR is optimally based on the pole-pole electrode geometry but may be derived from any array of electrical sensors including steel well casings

Two modes of operation are common: a) depth sounding and b) profiling. In the depth sounding mode, all four electrodes are placed in the ground initially with very short spacing between adjacent electrodes. A reading is taken, and then the array is reset with an incremental increase in spacing. Another reading is taken, and the array is, in turn, progressively expanded in this manner until the maximum depth to be investigated is reached. The current and potential sense progressively deeper layers as the array is expanded. In the profiling mode, a constant electrode spacing is selected that senses the subsurface geology to the depth of interest, and this constant array is “leap frogged” along a profile line to measure lateral variations that have geologic meaning.

HRR will be applied to the vadose-zone at the test to demonstrate whether HRR can quantitatively monitor the movement of the injected solution. A two-dimensional electrode array will be installed on the surface of the injection site for surface-only measurements. The specific number of electrodes to be installed and the array dimensions will be determined onsite. In addition, the 32 steel casings will be used as electrodes by connecting them to the tops of the casings and installing electrodes in the bottoms of the wells. An electrode will also be placed in the bottom of the PVC injection well. Potential measurements will be made using various combinations of the surface and downhole electrodes. The results will be presented in color-contoured plan maps of potential distribution as a function of depth, two-dimensional profiles showing interesting changes in time and distance, and in a three-dimensional format showing wet-volume changes as a function of time.

### 4.1.8 Time Domain Reflectometry

The TDR method is based on the dependence of the soil's dielectric constant, κ, on volumetric water content (Topp et al. 1980). The main components of the TDR system are a signal generator that produces the voltage pulse and measures the return signal and transit time, transmission lines or probes, and coaxial cable. The velocity of a voltage pulse generated along a probe by a TDR unit is used to calculate κ. The dielectric constant for water is 80, while it is between 3-5 for the solid soil, and 1 in air. Because the soil is a mixture of solid, water, and air, with a fixed amount of the solid phase, the value of κ is strongly dependent on the amount of water present. Thus different combinations of water, air, and soil will lead to different effective values of κ, from which volumetric water content, θ, can be determined with the appropriate calibration relationship.

A major advantage of TDR is its insensitivity to textural differences, allowing measurement of θ over a range of soils without the need for extensive calibration. A set of specially designed TDR probes based on the remote-shorting diode concept (Hook et al. 1992) will be used to make automated, real-time measurements of soil water content. The TDR technique can also be used to obtain real-time measurements of bulk electrical conductivity from which breakthrough curves of ionic tracers can be inferred (Ward et al. 1994). The system does not require the use of access tubes but will require a borehole to allow access to the deep vadose zone. A set of 14 probes will be installed in the borehole from which the first set of split spoon samples will be taken. Probes will be installed at 1-m intervals and the borehole backfilled. The probes will be connected to a central multiplexing system controlled by a Campbell Scientific Inc., CR-10 datalogger. Profiles of water contents will be logged at 1-h intervals and transmitted to a base station for analysis and storage.

## 4.2 Tracer Methods

A series of tracer tests will be conducted to obtain data to support the reduction of uncertainty in vadose zone conceptual models and to facilitate calibration of flow and transport models. For the FY 2000 experiment, the objectives of the tracer-testing component are to

1. define flow paths for an accurate conceptual model of the site

2. identify the mechanisms controlling contaminant transport in Hanford sediments.

To meet these objectives, both reactive and conservative tracers will be used. The tracers have been selected based on their ability to meet certain criteria. Tracers were required to have low background concentration and to be stable while posing few problems for management of residuals or regulatory concern over their use.

Tracers will be added to the water in the third injection (see Section 8.0). Before tracer injection, a core will be collected from the site and the existing concentrations of major cations and isotopes to be injected will be characterized.

### 4.2.1 Nonreactive Tracers

The nonreactive tracer selected for water flow is potassium bromide, KBr. Bromide was selected because of its stability, low background concentrations at Hanford, and the relative ease of chemical analysis. Bromide has been used successfully in other vadose zone studies as a non-reactive tracer to study flow paths and arrival times (Wierenga et al. 1991; Killey and Moltyaner 1988). Tracer distributions will be determined from core and pore water samples. The core for analysis of bromide will be prepared using leaching methods described in the Sampling and Analysis Plan (Appendix A). Pore water extracts and solution samples will be analyzed by PNNL to determine tracer depth and time breakthrough curves. Tracer distributions will be analyzed to locate the center of mass (time or depth) and the variance about the mean. Tracer distributions will be fit to various models to quantify the transport velocity and degree of transverse and longitudinal dispersion. Pore water and soil core data will be used to resolve mass balance.

### 4.2.2 Radioactive Tracers

Sisson and Lu (1984) used radioactive tracers; however, in the FY 2000 experiment, radioactive tracers will not be used. In out-years there may be some justification to use tracers, and we will discuss these briefly for the purpose of looking at future testing. The collaborators identified in Appendix C would perform isotopic analysis in the event that such tracers are used. Major issues related to use of radioactive tracers are regulatory and health and safety concerns. However, radioactive tracers provide useful information on retardation/sorption and are easy to detect using downhole instrumentation. Background concentration issues are also generally easily resolved.

Moltyaner (1987) and Killey and Moltyaner (1988) described the Twin Lake Experiment, which was a saturated zone test in a sand and gravel aquifer where both solution samplers and sodium-iodine (NaI) detectors were used simultaneously to describe tracer transport. They used $^{131}I$, with an 8.04-day half-life, and NaI detector measurements were made through 3.1-cm i.d. PVC pipes. Iodine-131 is a gamma emitter, so it is possible that it could be used as a water tracer at the Sisson and Lu site. The results of the Twin Lake Experiment were that the radioactive tracer using the through-the-wall detector was comparable to tritium measured by the solution sampler.

Tritium can be used as a radioactive tracer if pore water samples are being collected, and background concentrations are not confounding. Tritium was used at the Las Cruces trench experiment (Wierenga et al. 1991), and Killey and Moltyaner (1988) used tritium to compare to the iodine measured by the NaI detector. Other radionuclides such as strontium or cesium can be cored or used with solution samplers, but the reactive properties of these radionuclides with materials that comprise the sampling device are a concern.

### 4.2.3 Isotopic Tracers

A suite of isotopic tracers will be included with the water in the third of five planned leaks. There are two major objectives to the use of these tracers. The first objective is to evaluate retardation of cations in comparison to the transport of water and conservative species (e.g., Br-) and to evaluate whether strongly sorbed species can be transported significant distances via colloids or some other means. The second objective is to evaluate the effects of chemical modification of the leaked fluids by precipitation, dissolution of soil minerals, and evaporation.

The isotopic tracers selected for the tests are deuterium oxide ($D_2O$) and carbonate carbon ($^{13}C$). The cationic tracer isotopes are $^{87}Rb$, $^{87}Sr$, $^{145}Nd$, $^{207}Pb$, and $^{179}Hf$. The cationic tracer isotope concentrations will be low, so the tracers will not affect the exchange properties of the soils. The tracers selected have valences of +1 (Rb), +2 (Sr), +3 (Nd), and +4 (Hf). Lead represents the transition metals. The chemical effects can be expected to be small or nonexistent in this first test, but the data will provide baseline information for future tests where more concentrated salt solutions will be used.

### 4.2.4 Tracer Injection CaBr

Tracer injection will follow an approach similar to that of Sisson and Lu (1984). The KBr will be mixed in a 4000-gal tank equipped with a stirrer for 2 days before injection. The salt will be added at a rate of 1000 mg $L^{-1}$ Br. Water will be injected at a depth of 5 m below the ground surface and allowed to redistribute. As indicated previously, a series of five injections of 4000 L each are planned. Tracer will be added during the third of five injections. The tracer injection will be made at the same rate as the other water injections (4000 L applied in 8 h or at the rate of 3.2 gpm). The FY 2000 test will have a total of 20,000 L, about half of the amount used in the Sisson and Lu experiment. In the Sisson and Lu experiment, water moved vertically but also spread laterally and moved beyond the boundary of the experiment. In using only 20,000 L, we anticipate that the wetting front will be confined to the monitored volume allowing a reasonable mass balance to be performed. Details of the water application and tracer test schedule are described in Section 8.0.

## 4.3 Sampling and Analysis

Details of the sampling and analysis to be performed are provided in the Sampling and Analysis Plan in Appendix A. Before water and tracer injection, the entire site will be logged by neutron probe to determine moisture distributions.

Drilling of the boreholes to provide access for the geophysical instrumentation provides an opportunity to collect samples for geochemical characterization. One of four planned boreholes will be installed before starting the experiment. Background concentrations of selected tracers, isotopic profiles, and major anions will be determined from this core. In addition, water content and bulk resistivity profiles will be collected by cone penetrometer before ERT arrays are installed and during the installation of the advanced tensiometers and installation of the PVC access tubes for cross-borehole radar. Cross-borehole radar and ERT profiles will be collected before testing.

Subsamples of the split spoon core will be analyzed to determine soil physical and hydrologic properties. Parameters to be measured include gravimetric soil water content, matric potential (filter paper), bulk resistivity, particle size distributions, water retention, and the saturated and unsaturated hydraulic conductivity. Background measures of resistivity will be made by ERT.

Periodically during the course of the experiment, water content, matric potential, resistivity and tracer concentrations will be monitored. Tracers will be sampled using a combination of soil cores (split spoon samples) and pore water samples obtained from suction lysimeters. Selected advanced tensiometers will serve the dual purpose of monitoring matric potential and collecting pore water samples. Similar determinations will be made on pore water samples. Following the tracer injection, pore water samples and three additional cores will be collected and prepared according the Sampling and Analysis Plan (Appendix A). The resulting time and depth history of tracer movement will be used to characterize transport properties using spatial and time moment analyses as well as vadose zone transport models.

# 5.0 Equipment and Materials

This section describes the laboratory and field equipment and materials required to conduct the field tests. The layout of the field site including the new instrument installations are shown in Figure 3.1.

- A total of nine Vertical Electrode Arrays (VEAs) will be installed at the test site to facilitate ERT imaging of the subsurface. Each array consists of 15 stainless steel electrodes. The VEAs and associated materials will be provided by Applied Research Associates (ARA). Testing ,and data acquisition equipment and associated materials will be supplied by responsible collaborators listed in Appendix C.

- A total of four access tubes will be installed to accommodate subsurface imaging by XBR, CST, and CEMI. Installations will be performed by ARA. Crosshole access tubes and associated materials will be provided by ARA. Testing and data acquisition equipment and associated materials will be supplied by collaborators listed in Appendix C.

- A new 15-cm i.d injection point will be installed by Waste Management Federal Services (WMFS). All materials and equipment will be provided by WFMS.

- Materials required infiltration and tracer testing include:

  - Mixing tank (4000 gal)
  - Delivery metering system capable of delivering approximately 700 L/h (3 gpm)
  - Ion-specific probe for bromide
  - pH/mV/Ion/Conductivity Meter
  - Sample vials
  - Extraction pump for moving samples from solution samples.
  - Site trailer
  - Refrigerator for samples
  - Portable computer for sampling and data collection with Excel.

  These materials will be provided by PNNL.

# 6.0 Data Management

A project database will be established and maintained to collect, organize, store, verify/validate, and manage laboratory and field data. A project data custodian will be designated to control and maintain the data and to make them available on a secure project web site. The data will be stored electronically in mutually agreeable format or software package, and task leaders will provide hard copies to the data custodian for storage in the project files. During the course of the experiment, data access will be vital to the success of each test, and data sharing and their interpretation are encouraged. The following information must be included, as a minimum, in the database:

- sample identifier
- sample spatial location
- sampling time
- sampling date
- analysis date
- laboratory name
- variable measured and value
- measurement unit.

Collaboration on peer-reviewed publications is strongly encouraged but cannot be enforced. The leader of a given task will retain first publication rights to data collected on that task. To ensure that project milestones are met in a timely fashion, it may be necessary to publish data in reports before task leaders have the opportunity to develop peer-reviewed publications. In such instances, publication of data in project reports supercedes the rights of task leaders.

# 7.0 Data Analysis and Interpretation

To be useful for flow and transport interpretation and modeling, images of subsurface heterogeneity derived from experiments under the VZTFS must be correlated to spatial variations in hydraulic and transport properties at the field sites. This section provides an overview of how data collected during the course of the experiments will be analyzed to determine flow and transport parameters and their spatial characteristics as well as establishment of the linkage between these parameters and geophysical measurements. A review of quantitative methods for analyzing heterogeneity in aquifers is presented by Koltermann and Gorelick (1996). A combination of direct and indirect methods will be used to determine the required parameters.

## 7.1 Estimation of Hydraulic Parameters

Hydraulic properties are more commonly described with mathematical functions of matric potential as a function of water content, $\psi(\theta)$, and hydraulic conductivity as a function of water content, $K(\theta)$, with unknown parameters. Several methods have been devised for measuring these parameters and for estimating them from basic soil properties such as particle size distribution (PSD) and dry bulk density ($\rho_\beta$) through pedotransfer functions (PTF).

### 7.1.1 Direct Determination

Core samples obtained from the test sites will be used to measure water retention at 10 values of $\psi$ between 0 and 15,000 cm. Cores will also analyzed using pressure plate apparatus and multi-step outflow methods. The $\psi(\theta)$ function will be described according to van Genuchten (1980):

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{\left[1 + |\alpha \psi|^n\right]^m} \qquad (7.1)$$

where $\theta$ is the volumetric water content, $\theta_s$ is the saturated water content, $\theta_r$ is the residual water content, $\alpha$, n and m are empirical shape factors, and $\psi$ is the imposed soil water pressure head. The parameter $\alpha$ is inversely related to the air-entry pressure.

In the FY 2000 experiments, direct measurement of $\psi$, using advanced tensiometers and $\theta$, using neutron probe and TDR will allow direct description of the $\psi(\theta)$ function under field conditions.

Hydraulic conductivity data will be described either by Gardner (1958)

$$K(\psi) = K_s \, e^{\alpha\psi} \qquad (7.2)$$

where $K_s$ is the saturated hydraulic conductivity, and $\alpha$ is an empirical parameter; or by the equation of van Genuchten (1980):

$$K(\text{ø}( = K_s \frac{\left\{\left[1+|\text{áø}|^n\right]^m - |\text{áø}|^{n-1}\right\}^2}{\left[1+|\text{áø}|^n\right]^{m(l+2)}} \tag{7.3}$$

The Gardner equation is an ideal form for incorporation into analytical solutions to the linearized Richards' equation and is the basis of several inverse procedures for estimating hydraulic parameters from observations of infiltration (Ward et al. 1994; Si et al. 1999).

### 7.1.2 Indirect Determination

Pedotransfer functions (PTF) will be used to obtain indirect estimates of hydraulic parameters. The PTF technique has become quite popular in recent times, and discussions have been presented by Goncalves et al. (1997) and Pachepsky et al. (1999) among others. Core samples obtained from the simulated leak experiments at the Sisson and Lu site will also be analyzed in the laboratory to determine basic soil properties. These properties will include soil texture [coarse sand (CS), fine sand (FS), silt (S), and clay (C)], mean particle diameter, geometrical standard deviation, organic matter (OM), content, pH, and $\rho_b$ as functions of sampling depth (z). In a simplified form, multiple regression analyses will be performed to formulate PTFs for different soil groupings to allow prediction of hydraulic parameters from the basic soil properties within a group. The PTF has the general form

$$y = a_0 + a_1 x_1 + a_2 x_2 + a_3 x_3 + \ldots \tag{7.4}$$

where y is the predicted parameter; $a_0$, $a_1$, $a_2$, and $a_3$ are the regression coefficients; and $x_1$, $x_2$, and $x_3$ are the measured variables in the PFT. Selected water retention data and conductivity data (e.g., $K_s$) will also be included in the regression analyses for water retention and hydraulic conductivity predictions. Further details can be found in Meyer et al. (1999).

### 7.1.3 Inverse Methods

This approach will be applied to both the injection and trench tests. It applies to direct field measurements of matric potential ($\psi$), pressure head (h), water storage (W), or solute travel time (T). The general inversion is

$$G_i = \hat{G}_i(\alpha, K_s, \theta_s) + \varepsilon_i;\ i = 1, 2, ..., N; \tag{7.5}$$

where $G_i$ is the field-measured variable and can be $\psi$, h, W, or T; $\hat{G}_i(\alpha, K_s, \theta_s)$ is the model prediction; $\varepsilon_i$ is measurement error; and N is the number of measurements. Combinations of different sets of measurements (e.g., $\psi$+W, $\psi$+T, or W+T) will be used in Equation (7.4). The objective function is the sum of squared error and a constraint term, $S_p(\alpha, K_s, \theta_s)$, for the nonlinear model:

$$S_p(\alpha, K_s, \theta_s) = \sum_{j=1}^{n_j} w_j \sum_{i=1}^{n_i} w_i [G_{ji} - \hat{G}_{ji}(\alpha, K_s, \theta_s)]^2 + w_{\theta s}(\theta_s - \theta_{sp})^2 \tag{7.6}$$

where $n_j$ = 1, 2, or 3, is the number of combining sets of measurements used, $n_i$ is the number of measurements in a particular set, $w_j$ is the weights associated with a particular measurement set, $w_i$ is the weights associated with a single measurement, $w_{\theta s}$ is the weight associated with $\theta_s$, and $\theta_{sp}$ is the value of $\theta_s$ determined using prior information. Si et al. (1999) recently presented examples of the field application of this method. Several analytical forms of $\hat{G}_i(\alpha, K_s, \theta_s)$ have also been presented for handling flow in 1-D, 2-D, and 3-D systems.

## 7.2 Estimation of Transport Parameters

The tracer tests will provide information that can be used to infer flow and transport properties of the subsurface. Data will be analyzed to determine both solute concentrations as a function of time and depth and solute travel times to a given observation plane. Two different methods will be used to obtain transport parameter from these data:

- inversion of the convective-dispersive transport model (CDE)
- transfer functions; for example, the convective-lognormal transport model (CLT)
- moment analysis.

Differences between the three approaches lie in the assumptions made about the transport process.

### 7.2.1 Convective-Dispersive Transport

The CDE is essentially the far-field limit for solute transport. It assumes that the transport velocity, *v*, is the same at every location, and differences in arrival time at an observation plane are due to random diffusion/dispersion processes. Thus, travel time of a solute particle to a depth z is assumed to be uncorrelated to its travel time in the next depth increment.

A generalized form of the CDE may be written as:

$$\frac{\partial c}{\partial t} = \nabla(v \cdot c) - \nabla \cdot (D \nabla c) = \frac{c' W}{\theta_e} \tag{7.7}$$

where D [$L^2$ $T^{-1}$] is the dispersion coefficient, $\bar{v}$ [L $T^{-1}$] is the mean pore water velocity, t [T] is time, and *c* is concentration [M $L^{-3}$]. The dispersion coefficient can also be expressed as $\lambda\bar{v}$, where λ [L] is the dispersivity of the soil, controlled by the geometry of the transport volume. The local dispersion tensor, D, is related to the longitudinal and transverse local dispersivity, $\lambda_l$ and $\lambda_t$, by

$$D_{ij} = [\lambda_L - \lambda_T] v_i\, v_j / |v| + [\lambda_T |v| + D_0] \delta_{ij} \qquad (7.8)$$

where $D_0$ is the coefficient of molecular diffusion, vi and vj are the ith and jth components of the average pore water velocity and $v = (v_x^2 + v_z^2)^{1/2}$, and $\delta_{ij}$ is the Knoecker delta (i.e. $\delta_{ij}$=1 if i = j and $\delta_{ij}$=0 if i≠j). Different solutions exist for this equation depending on the surface boundary condition, and concentrations can be defined as resident or flux concentrations. The local dynamics of solute transport can be described by the CDE in which it is assumed that the volumetric water content is equal to the transport volume, $\theta_t$. Consequently, the pore water velocity may be defined as $v = j_w/\theta$, where $j_w$ is the volumetric water flux obtained from solution of the Richards' equation. The transport velocity can also be obtained from analysis of solute BTCs. With measured v, the actual transport volume can be derived as $\theta_t = j_w/v$, which can be different from θ, especially when preferential flow processes are operational. Numerical solutions of Equation (7.7) can also be inverted with tracer data alone or in conjunction with geophysical data (e.g., seismic) to obtain parameters a 3-D flow field.

For soil cores taken from the test leak injection site and information on tracer distributions obtained from cut face sampling and geophysical measurements, resident concentration solution is applicable. The solute mass recovered in a given profile will be determined by summing the product of the resident concentration and volumetric water content over all depths:

$$M_s = \sum_{k=1}^{N} C_R (z_k, t) \theta_k \Delta z \qquad (7.9)$$

where $CR(z_k, t)$ is the resident concentration of the $k^{th}$ of N sampling intervals of Δz length, and $\theta_k$ is the volumetric water content. Values of $\theta_k$ will be obtained by neutron probe and TDR.

For solution samples, concentration is obtain as a function of time and the flux concentration solution is applicable. The forms of the applicable model $\hat{G}_i$(λ, v,) have been presented by several authors, including Butters et al. (1989) and Jury and Roth (1990). These models will be used to obtain estimates of λ, the dispersion coefficient, and the transport velocity. Estimates of the transport volume will also be determined for comparison with the volumetric water content to identify whether preferential flow processes are active.

### 7.2.2 Transfer Functions

In contrast, the CLT does not require any particular assumption about the underlying transport process except that it is linear and stationary. Information on the transport process is implicit in the measured transfer function. At any particular location, v is constant with depth, but it varies in the horizontal plane. Thus, solute spreading at the field scale is attributed to the horizontal spatial variability in vertical transport velocity.

Because the vertical solute velocity at any given location is constant with depth, the horizontal spatial pattern of travel times to an observation plane at z is correlated with the spatial pattern of travel time in the next depth increment. The CLT can be used for all transport regimes and is not restricted to near- or far-field limits. However, because of the assumptions of linearity and stationarity, this form of the CLT is not applicable to contaminants that exhibit nonlinear interactions with soil components, or to situations of transient water flow. In addition, it provides an integral description of transport from the surface to depth L, and there are no provisions for either predicting transport to depths shallower or deeper than the measurement depth.

### 7.2.3 Moment Analysis

The method of moment is a direct method and makes no assumption about the transport process. Moments can be used to determine parameters of any stable, linear process that can be represented by a transfer function. Flux or resident breakthrough curves are first normalized to generate probability density functions (pdfs) of solute travel time, $f_L(t)$ or solute travel depth, $f_L(z)$. For the simulated leak test, $f_L(z)$ will be obtained at four different times from the four core samples and from the geophysical logging. In the trench experiments, $f_L(z)$ will be obtained during cut face analysis, while $f_L(t)$ will be obtained from solution samplers and TDR measurements.

For a pdf, $f_L(s)$, the $n^{th}$ moment is given by

$$M_n = \int_0^\infty f_L(s) s^n \, ds \tag{7.10}$$

The mean travel time (or depth) of the system is equal to the first moment, $M_1$; the second moment, $M_2$, is a measure of the dispersion, while the third moment, $M_3$, is related to the skewness. The main problem with ordinary moments is that higher moments are unreliable because of magnification of small errors in the tail. Nevertheless, for a particular flow model, specific relations exist between the moments and the model parameters. The dispersivity for the CDE, $\lambda_{CDE}$, can be calculated as:

$$\lambda_{CDE} = \frac{D}{v} \tag{7.11}$$

An equivalent dispersivity for the CLT, $\lambda_{CLT}$, is calculated as

$$\lambda_{CLT} = \frac{L}{2}[\exp(\sigma^2) - 1] \tag{7.12}$$

while from moment analysis method, $\lambda_{MOM}$ is calculated as

$$\lambda_{MOM} = \frac{L}{2} \frac{Var_{LT}}{E_{LT}^{2}} \tag{7.13}$$

The total solute mass recovered per unit area as a percentage of the total applied mass may be used to gauge the efficiency of the sampling techniques and the reliability of the data. For flux concentrations, the mass recovered at each depth is given by the zeroth moment:

$$M_N = \int_0^\infty C_F(z_0, t)\,dt \tag{7.14}$$

Because there are no known sources of bromide in the soils, mass recovery should be close to 100%. Any variations will likely be due to differences in actual drainage flux at a given depth and the amount of water assumed applied at the surface. Sample extraction at a rate greater than the drainage flux can also cause an overestimation of the mass recovered when samples are treated as true flux concentrations.

## 7.3 Geostatistics

Spatial interdependence of hydrologic and transport parameters will be quantified by calculating the autocorrelation functions (correlogram). Parameters derived from the analyses above include the mean travel time, <t> or depth <z>; and the variance of travel time, $var(t)= \langle t^2 \rangle - \langle t \rangle^2$, or variance of travel depth, $var(z)= \langle z^2 \rangle - \langle z \rangle^2$. The variogram, $R_c(k)$, of N pairs of observations $G(x_i)$ spaced a distance h apart is estimated as:

$$R_C(k) = \frac{1}{N_y (N_x - k)\sigma_C^2} \sum_{j=1}^{N_y} \sum_{i=1}^{N_x - k} \left[G(x_{i+k}, z_j) - \langle G \rangle\right]\left[G(x_i, z_j) - \langle G \rangle\right] \tag{7.15}$$

Here, k is the lag index which may be transformed to the lag by $h_x = k\,\Delta x$; $N_x$ and $N_y$ are the upper vertical and horizontal index bounds, respectively, $\sigma_C^2$ is the variance, and $\langle G \rangle$ is the expectation of the parameter within the considered band.

# 8.0 Schedule

A number of individual tests will be run during the course of the experiment by a multi-disciplinary team comprising collaborators from other national laboratories, commercial vendors and consultants. The participants are listed in Appendix C. Thus, the importance of the need for open communication on the schedule cannot be overemphasized.

Planning meetings with collaborators have been by via teleconferencing and will continue as work progresses. The project schedule, developed from the planning meetings, is shown in Table 8.1. During the course of these meetings, incompatibilities (e.g., electrical interferences) between various geophysical techniques were identified. This has required proper sequencing of measurements which has played heavily in the development of the final schedule. For example, there is some incompatibility between EMI, HRR, and ERT, and they will be run sequentially rather than simultaneously. In contrast, there is no compatibility problem with ERT and XBR, so these tests will be run simultaneously. The schedule is shown in Table 8.1 and as constructed has only a limited amount of flexibility.

Note that in Table 8.1, each injection will be 4000 L. The third injection will include potassium bromide as a tracer. Each sediment core will be 10.16 cm in diameter, cased in lexan (15-cm long sleeve), and capped.

**Table 8.1**. Preliminary Schedule for FY 2000 Experiment

| | | Method 1 | Method 2 | Method 3 | Method 4 | Method 5 | Method 6 | Method 7 | Method 8 | Method 9 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Date** | **Action** | **Neutron** | **AT Tens.** | **ERT** | **XB Radar** | **Seismic** | **EMI** | **HRR** | **Isotopes** | **Coring** |
| 04-May | Pre-leak | Read 35 (cross-calibrate) | | | | | | | | |
| 09-May | | | | CPT Install (3 days) | | | | | | |
| 12-May | | | CPT Install (2 days) | | | | | | | |
| 15-May | | | | | CPT Install (2 days) | | | | | |
| 18-May | | | Install Nest (2 days) | | | | | | | |
| 22-May | | | | Set up/read (3 days) | Set up/read (2 days) | | Set up/read (3 days) | | | |
| 23-May | | | Read-continuously | | | | | | | |
| 26-May | | | | | | | | Set/read (3 days) | | |
| 30-May | | | | | | | | Read | | Install Injection pt. |
| 31-May | | | | | | | | Read | Samples | Core |
| 01-Jun | 1st Leak (inject) | | | | | | | | | |
| 02-Jun | | Read 32 | | | | | | | | |
| 03-Jun | | | | | | | | | | |
| 05-Jun | | | | | | | Read | | | |
| 06-Jun | | | | | | | Read | | | |
| 08-Jun | 2nd Leak | | | | | | | | | |
| 09-Jun | | Read 32 | | | | | | | | |
| 12-Jun | | | | | Setup | | | | | |
| 13-Jun | | | | Setup | Read | | | | | |
| 14-Jun | | | | Read | Read | | | | | |
| 15-Jun | 3rd Leak | | | Read | Read | | | | | |
| 16-Jun | | Read 32 | | | | | | | | |
| 19 Jun | | | | | | | | | Samples | CPT core |
| 21-Jun | | | | | | | | Setup | | |
| 22-Jun | 4th Leak | | | | | | | Read | | |
| 23-Jun | | Read 32 | | | | | | Read | | |
| 24-Jun | | | | | | | | | | |
| 29-Jun | 5th Leak | | | | | | | | | |
| 30-Jun | | Read 32 | | | | | | | Samples | CPT core |
| 10-Jul | | | | | | | | | Samples | Core |
| 11-Jul | Post Leak | Read 32 | | Read | Read | | | | | |
| 12-Jul | | | | Read | Read | | | | | |
| 13-Jul | | | | | | | Read | | | |
| 14-Jul | | | | | | | Read | | | |
| 17-Jul | | | | | | | | Read | | |
| 18-Jul | | | | | | | | Read | | |
| 19-Jul | | | | | | Setup/read | | | | |

# 9.0 Health and Safety

Excavation permit DAN 1559 has been obtained for work at the site. The work will be conducted in an environmentally compliant manner that includes radiation protection to workers. Safety and health issues relating to the VZTFS are addressed in site-specific safety documents (Appendix D) that identify radiological and industrial safety health hazards as well as other measures to protect against these hazards. Safety documents include specific training requirements that must be met by all site workers and visitors. Job-specific Health and Safety Plans for drilling, instrument installation activities, and sampling activities are also specified in Appendix D. Briefings will be conducted with all site visitors to ensure that health and safety issues are understood and that safe practices will be followed during the course of the experiments. All VZTFS participants are required to read and sign the Health and Safety Plan before entering the field site.

# 10.0 Waste and Residuals Management

## 10.1 Management Activity A – Solid Waste Management Plan for Cone Penetrometer/Tensiometer Installation

**Scope:** This plan covers waste disposition for the waste generated from installation of cone penetrometers and tensiometers for the Vadose Zone Transport Field Study.

**Anticipated Waste Streams**: Based on the project test plan, the only anticipated waste streams from the above activities are nonregulated, nonhazardous solid wastes, which may include paper, plastic, rags, etc. These materials have been designated as nonhazardous. The determination has also been made that the test site is a nonradiological area, and therefore, none of the waste would be classified as radiological low-level waste.

**Waste Management**: The waste stream described above will be disposed of to a normal "trash" receptacle. The management of any other unanticipated solid waste will be in accordance with PNNL internal waste management procedures.

**Contingency Plan**: In the event of a spill or accidental release of a material to the environment, the procedure for spill response (http://sbms.pnl.gov/standard/0e/0e00t010.htm) will be in effect.

If a spill occurs, call **375-2400**.

## 10.2 Management Activity B – Soil Management Plan

**Scope:** This plan covers the disposition of the soil generated from drilling activities for the Vadose Zone Transport Field Study at the 299-E24-111 (Sisson and Lu) experimental test well site.

**Anticipated Waste Streams**: Based on the project test plan, for the drilling activities, including drilling the injection well and drilling to install tensiometers and other instrumentation, there are no anticipated waste streams from these activities.

The soil from the drilling activity is environmental media and, other than soil samples to be taken for characterization and analysis, all will be returned to the cores from which it came.

If solid waste is produced during these activities, it is anticipated that it would be nonregulated, nonhazardous solid wastes, which may include paper, plastic, rags, etc. These materials have been designated as nonhazardous. The determination has also been made that the test site is a nonradiological area, and therefore, none of the waste would be classified as radiological low-level waste.

**Waste Management**: The waste stream described above (paper, plastic, etc.) will be disposed of to a normal "trash" receptacle.

The management of any other unanticipated solid waste will be in accordance with PNNL internal waste management procedures.

**Contingency Plan**: In the event of a spill or accidental release of a material to the environment, the procedure for spill response (http://sbms.pnl.gov/standard/0e/0e00t010.htm) will be in effect.

If a spill occurs, call **375-2400**.

# 11.0 Quality Assurance

All work conducted by the Pacific Northwest National Laboratory (PNNL) shall be performed in accordance with appropriate standards of quality, reliability, environmental compliance, and safety based on client requirements, cost and program objectives, and potential consequences of malfunction, or error. To provide clients with quality products and services, PNNL has established and implemented a formal Quality Assurance (QA) Program. These management controls are documented in the PNNL Standards-Based management System (SBMS). The standards and procedures of SBMS are based on the requirements of DOE Order 414.1, Quality Assurance, and 10 CFR 830.120, Energy/Nuclear Safety Management/Quality Assurance Requirements.

# 12.0 References


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# Appendix A

# Vadose-Zone Transport Field Study Sampling and Analysis Plan

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# Vadose-Zone Transport Field Study Sampling and Analysis Plan

## A.1 Introduction

The focus of this Sampling and Analysis Plan (SAP) is the vadose zone transport field study to be conducted in the 200 Area of the Hanford Site. In situ monitoring, sampling and analysis of boreholes will occur in the vicinity of the Sisson and Lu experimental site to meet the objectives of this investigation. The Sisson and Lu site is located in the 200 East Area at Hanford east of the Immobilized Low Activity Waste (ILAW) test site and south-west of the PUREX facility (Sisson and Lu 1984). The site is instrumented with thirty-two 6” diameter steel-cased monitoring wells that extend to a depth of 18 meters. This site was used of a series of injection experiments in 1984 and has been monitored with a variety of geophysical tools subsequent to the initial experiment.

## A.2 Purpose and Objective

This plan provides details for the field and laboratory activities to be performed in support of the investigation to be conducted at field site and is designed for use in conjunction with the detailed test plan and referenced procedures. Preliminary field activities and investigations addressed in this SAP are as follows:

- Installation of a new injection well 0.3 m (1 ft) northwest of local well H2 (Hanford Well E24-104). Technical procedures or specifications related to this work include Waste Management Federal Services (WMFS) sampling and geophysical surveying procedures; and Sample and Mobile Laboratories Procedures (WMFS 1997).

- Installation of eight ERT vertical electrode arrays (VEAs) at a radial distance 8.0 m from the central injection well in the existing array. The VEAs will consist of 15 stainless steel tubes (0.15 m long, 3.175 cm diameter) spaced at 1 m intervals. The VEAs will be installed by cone penetrometer with the first electrode being placed 5 m below the surface. The space between electrodes will be sealed with Bentonite as the cone penetrometer is extracted. Technical procedures or specifications related to this work include Applied Research Associates (ARA) Cone penetrometer and Geophysical Surveying Procedures (ARA 2000) and ARA Cone Penetrometer Drivepoint Installation Procedure (ARA 1999).

- Installation of one ERT VEA 2 m south of the central injection well; that is, between local wells G-1 and G-3. The VEAs will be installed by cone penetrometer with the first electrode being placed 5 m below the surface. The space between electrodes will be sealed with Bentonite as the cone penetrometer is extracted. Technical procedures or specifications related to this work include ARA Cone penetrometer and Geophysical Surveying Procedures (ARA 2000) and ARA Cone Penetrometer Drivepoint Installation Procedure (ARA 1999)

- Installation of four boreholes starting 2.5 m southeast of the central injection well and spaced not more than 2 m apart. These boreholes will be installed by 20-cm (8-in.) rotary auger and continuous split-spoon samples will be collected from the surface to 18 m below ground surface. Selected potions of these samples will be analyzed for their chemical, radiological and physical characteristics at PNNL and at the U.S. Salinity Laboratory. Following completion of sampling, the holes will be decommissioned per the State of Washington Administrative Code (WAC) requirements.

- Installation of three advanced tensiometer (AT) nests by rotary auger 30 cm (1 ft.) north of local wells H2 (Hanford Well E24-104); H4 (Hanford Well E24-105) and H6 (Hanford Well E24-106). Technical procedures or specifications related to this work include WMFS sampling and geophysical surveying procedures; and Sample and Mobile Laboratories Procedures (WMFS 1997).

- Installation of three AT nest by cone penetrometer 0.3 m (1 ft) south of local wells A-3 (Hanford Well E24-77); south east of local well F-2 (Hanford Well E24-96); and south west of local well H-6 (Hanford Well E24-106). In nest near A-3, one AT will be driven to a depth of 6 m (20 ft) to the mid-point of the porous steel cup while the second will be driven to a depth of 8.2 m (27 ft) to the mid point of the porous cup. In the nest near F-2, one AT will be driven to a depth of 5.8 m (19 ft) while the second will be driven to a depth of 9.5 m (31 ft) to the mid point of the porous cup. In the nest near H-6, one AT will be driven to a depth of 5.8 m (19 ft) while the second will be driven to a depth of 10.9 m (36 ft) to the mid point of the porous cup. These devices will be used to monitor soil matric potential and collect pore water samples for laboratory analysis.

- Installation of four PVC access-tubes (X-1 through X-4) by cone penetrometer. Tube X-1 will be located 1.0 m southeast of local well G-3 (Hanford Well E24-101). Tube X-2 will be 1.0 m south southeast of local well H-2 (Hanford Well E24-104); tube X-3 will be located 1.5 m east southeast of local well H-4 (Hanford Well E24-105); and tube X-4 will be located 4 m west southwest of local well H-4 (Hanford Well E24-105). These tubes will be used for cross well radar and high frequency electromagnetic impedance measurements.

The SAP describes four distinct field campaigns and is therefore dividing into four parts:

- Part I – Cone Penetrometer Installation of ERT vertical electrode arrays and access tubes for crosshole radar and electromagnetic induction

- Part II – Installation advanced tensiometer nests

- Part III – Installation of injection well by rotary auger

- Part IV – Sediment sampling performed in conjunction with the installation of boreholes by rotary auger

- Part V – Sampling protocol for field monitoring.

Technical procedures or specifications related to the field component of this work include ARA Cone penetrometer and geophysical surveying procedures (ARA 2000); WMFS sampling and geophysical surveying procedures; and Sample and Mobile Laboratories Procedures (WMFS 1997). Technical procedures or specifications related to the laboratory component of this work include Leaching of Soil and Rock Samples for Anions (Newman 2000) shown in a subsequent section.

The Health and Safety Plan for this work, Appendix D, specifies procedures for the occupational health and protection of all participants in this study. All participants are expected to read and sign in concurrence with the Health and Safety Plan. Data management will be conducted according to protocol described in Section 6.0.

### A.2.1 PART I – Cone Penetrometer Installation of ERT Vertical Electrode Arrays and access Tubes for Crosshole Radar and Electromagnetic Induction

During installation of the VEAs, the CPT truck will be required to maneuver amongst the existing infrastructure, including the wells. Note that there is an Underground Radioactive Materials Area (URMA) north of the central injection well which is posted and fenced. The current excavation work permit (DAN 15559) does not cover drilling or sampling in this area. Personnel or vehicles entering this area will have to undergo a radiological survey before leaving the test site.

A total of nine VEAs will be installed at the test site to facilitate ERT imaging of the subsurface. Each array consists of 15 stainless steel electrodes (15 cm long x 3.175 cm o.d). Installation of the VEAs will first require the installation of a hole to accommodate the array. This will be accomplished by pushing a 3.8-cm o.d. PVC pipe behind the cone tip down to a depth of 20 m. The first electrode will be put in place and the cone pulled back to the next level for installation of the next electrode. The location of VEAs will be logged by GPS and subsurface drift off the vertical will be minimized. Figure A.1 shows a schematic of an ERT vertical electrode array and data acquisition system.

Changes in water content cause changes in the resistivity of the soil, which is detected by introducing a current through an electrode pair and monitoring the voltage between another pair. Individual electrodes on the array will be spaced 1 m apart and the region between electrodes will be grouted with Bentonite.

Eight of the VEAs will be installed at a fixed radial distance of 8 m from the central inject well. The eight peripheral arrays will be installed midway along the arc between radial well installations as shown in Figure A.2. The ninth array will be installed near the center, 1 m south of local well G-1 (Hanford Well E24-100).

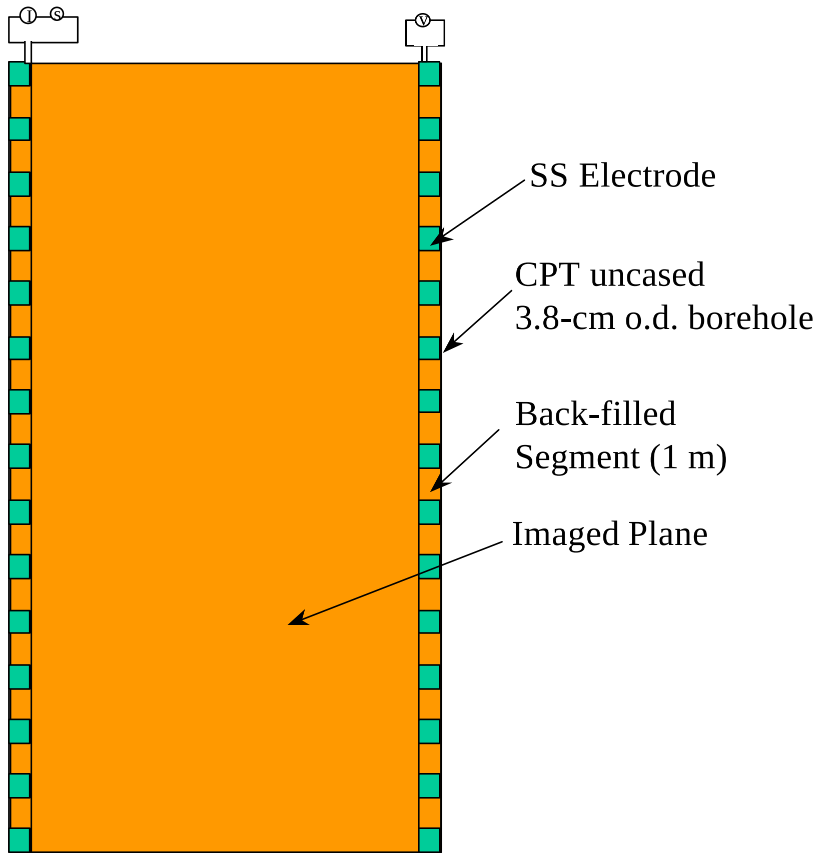


**Figure A.1**. Schematic of an ERT VEA (after Narbutovskih et al. 1996)

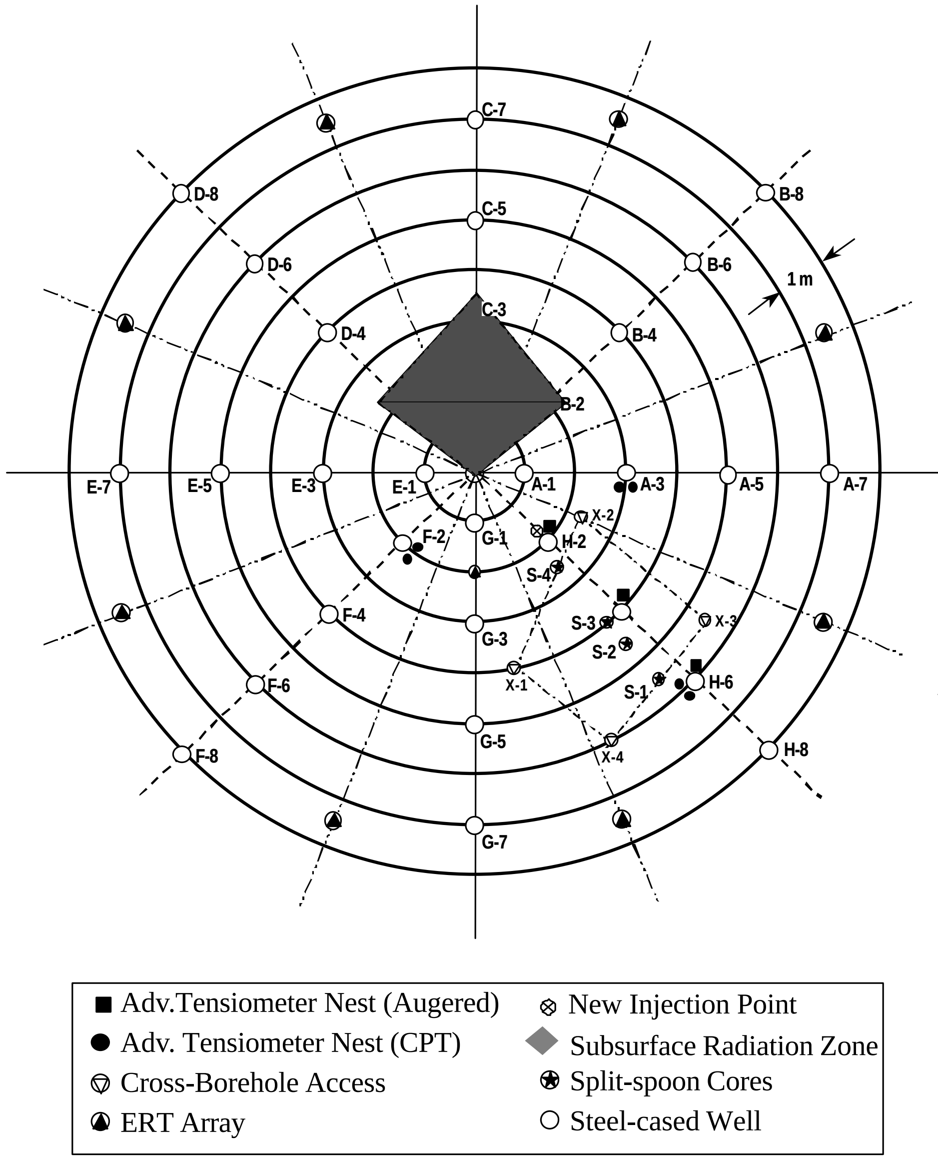


**Figure A.2**. Plan View of FY 2000 Test Site Showing Proposed Locations of Cores, Access Tubes and VEAs

Installation of the crosshole radar holes will be to the south east of the central injection well and should not encounter the URMA located north of the well. Work on this task is covered under the current excavation work permit (DAN 15559). Personnel or vehicles entering this area will not be required to undergo radiological surveys before leaving the test site.

A total of four access tubes will be installed at the test site to facilitate crosshole radar and crosshole electromagnetic induction surveys. Each hole will be installed by cone penetrometer to a depth of 20 m and will be cased with 3.8 cm o.d schedule 80 PVC pipe. Installation of the tubes will involve pushing a 3.8-cm o.d. PVC pipe behind a sacrificial cone tip down to a depth of 20 m. Figure B.1 shows the relative location of the access tubes. The layout is designed to allow verification of the crosshole radar and EMI tomograms with the 4 core samples to be taken at different times during the experiment. The lateral plane joining tubes X-1 and X-2 will be intersected by core same S-4 while the plane joining tubes X-3 and X-4 will be intersected by core sample S-1.

### A.2.2 PART II – Installation of Advanced Tensiometer Nests

Two different techniques will be used to install seven advanced tensiometer nests. One set of nests will be pushed into place by cone penetrometer and the second will be installed by rotary auger. Advanced tensiometer installations will be made outside of the fenced URMA and is covered the current excavation work permit (DAN 15559). Personnel or vehicles entering the site to install the tensiometer nests will not be required to undergo radiological surveys before leaving the test site.

Three nests will be installed by auger adjacent to local wells H-2, H-4 and H-6. The nest adjacent to H-4 will be used periodically to collect water samples. Installation depths were determined based on the migration of the wetting fronts observed and the water content profiles observed during the Sisson and Lu injection tests in 1980. Technical procedures or specifications related to this work include WMFS sampling and geophysical surveying procedures; and Sample and Mobile Laboratories Procedures (WMFS 1997). Figure A.3 shows a schematic of the three auger installations.

Three advanced tensiometer nests will be installed be cone penetrometer adjacent to local wells A-3, F-2 and H-6. Each nest will consist of two tensiometers and will therefore require two separate penetrometer pushes per nest. Tensiometer installation depths were determined based on the migration of the wetting fronts observed and the water content profiles observed during the Sisson and Lu injection tests in 1980. Technical procedures or specifications related to this work include ARA Cone penetrometer and Geophysical Logging Procedures (ARA, 2000) and ARA Cone Penetrometer Drivepoint Installation Procedure (ARA, 2000). Figure A.4 shows a schematic of the three penetrometer installations. Each tensiometer will be installed not more than 30 cm from the adjacent steel-cased well and not more than 1 m from each other.

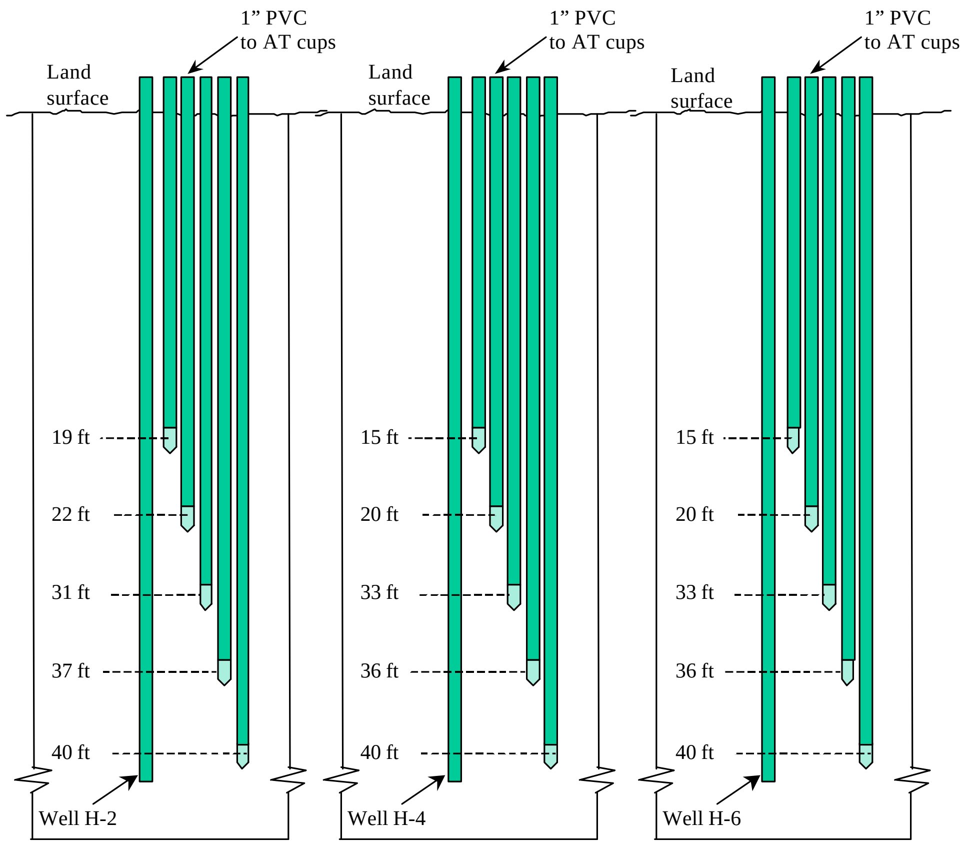


**Figure A.3**. Schematic of Augered Advanced Tensiometer Nests Adjacent to H-2, H-4, and H-6. Depths represent depth to mid point of porous cups.

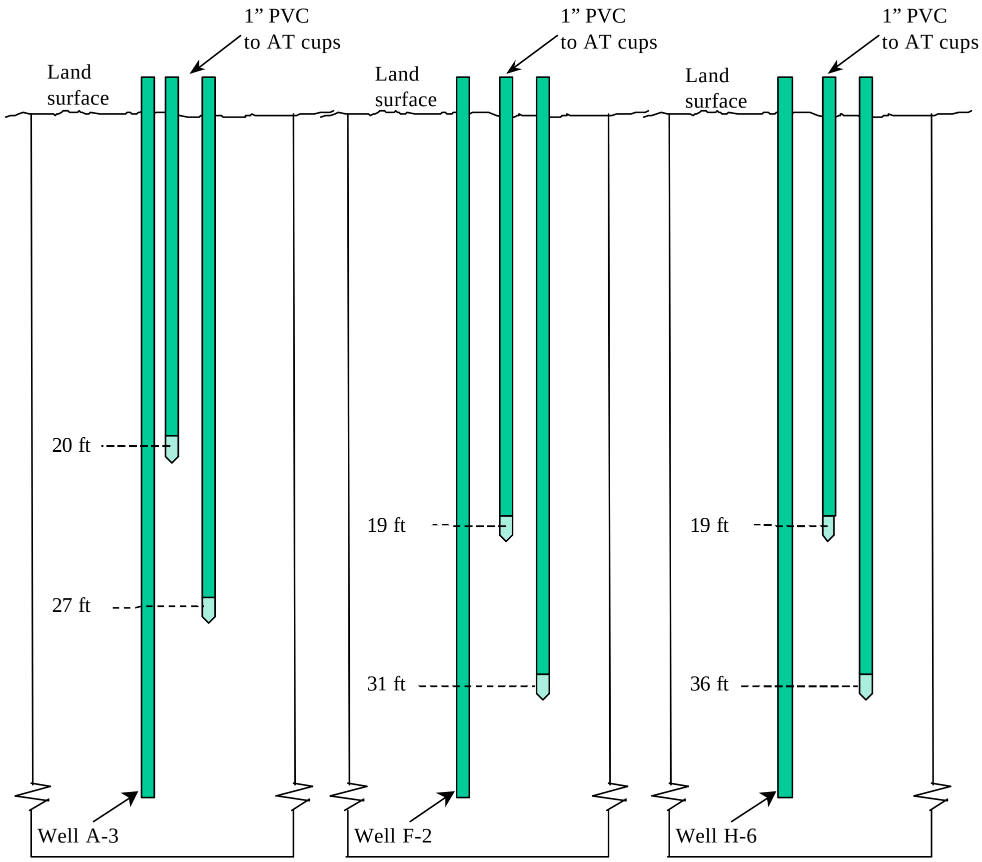


**Figure A.4**. Schematic of Pushed Advanced Tensiometer Nests adjacent to A-3, F-2, and H-6. Depths represent depth to mid point of porous cups.

### A.2.3 PART III – Installation of Injection Well By Rotary Auger

A new injection well will be installed to facilitate the entry of water and tracers into the system. As in the previous experiment, the well must be able to withstand localized high water pressures and minimize movement due to settling should washing take place at the injection point (Sisson and Lu, 1984). Unlike the previous experiment, this injection well will be constructed of 15-cm o.d (6 in.) schedule 80 PVC so that it can also serve as an access tube for some of the geophysical tools. The well will be installed 1.7 m southeast of the central injection well, adjacent to well H-2, and to a depth of 15 m. Installation will be via rotary auger and the bottom will be finished with a gravel pack to ensure a high enough permeability to accommodate an expected injection rate of 0.18 L $s^{-1}$ (3 gpm). The technical procedure related to this work is WMFS sampling and geophysical surveying procedures. Figure A.5 shows a schematic of the rotary auger installation.

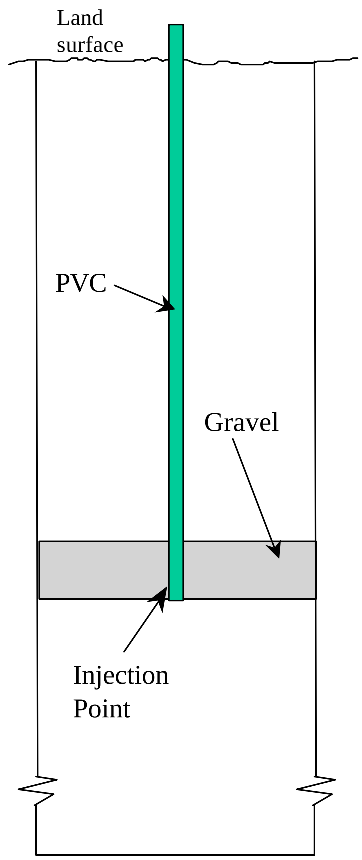


**Figure A.5**. Schematic of Augered Injection Well to be located 1.7 m southeast of the central injection well (adjacent to well H-2).

### A.2.4 PART IV – Soil Sampling Performed During Installation of Four Boreholes

Continuous split-spoon samples will be collected during coring at locations S-1, S-2, S-3, and S-4. Subsamples will be selected from stratigraphic units of interest and analyzed for chemical and physical and hydrogeologic characteristics. A detailed description of the chemical analysis is presented in procedure Leaching of Soil and Rock Samples for Anions (Newman 2000). Details of the hydrogeologic analyses are presented in Meyer and Rockhold (1999). All analyses will be conducted in accordance with Methods of Soil Analysis and ASTM procedures (Table A.1).

**Table A.1**. Planned Analyses for Split-spoon Cores from Test Site

| Property | Sample | Analytical Method | Analytical Procedure |
|---|---|---|---|
| Particle Size Distribution | Bulk sediment | | ASTM D422-63<br>ASTM D854-83 |
| Bulk density | Bulk Sample | Gravimetry/volume | PNL-MA-567-SA-8 |
| Moisture content | Bulk Sample | Gravimetry | PNL-MA-567-SA-7 |
| Matric Potential | Bulk Sample | Filter Paper | PNL-MA-567-SA-10 |
| Water Retention | Bulk Sample | Multi-step Outflow | MOSA |
| Saturated Conductivity | Bulk Sample | Constant Head | PNL-MA-567-SA-? |
| Unsaturated Conductivity | Bulk sample | Multi-step outflow | MOSA |
| Anion Conc. | Water Extract | ISE Colorimetric | MOSA |
| Cation Conc. | Bulk Sediment | ICP-MS | PNL-ALO-211 |
| CEC/$K_d$ | Bulk Sediment | | MOSA |

## A.2.5 Part V – Sampling Protocol for Field Monitoring

Details of the monitoring and sampling schedule are presented in Table 8.1. This section provides details on the monitoring process.

### A.2.5.1 Neutron Moisture Logging

Neutron probes will be used to log volumetric water content in each of 32 wells surrounding the injection well. The logging will be done in 0.3-m (1-ft) increments over the 13-m interval from 4 m to 17-m depth. Depending on the placement of the new injection well, monitoring of the wells will continue weekly after each injection. A final logging will be completed after the last injection and geophysical logging has been completed. The schedule for the neutron probe logging events is shown in Section 6.0. Data will be downloaded from the neutron probe to a laboratory computer where it will be processed and subsequently displayed in graphical form on the Vadose Zone Transport Study web page.

### A.2.5.2 Crosshole Seismic Tomography

Measurements will be taken at the end of the flow and transport experiment to avoid any effect of the water used to fill the boreholes. Measurements will be made by at intervals of 30-60 cm, maintaining a near horizontal ray path between the source and receiver. Data reduction and interpretation will be limited to the identification of various seismic wave types, apparent velocity, and relation to true velocity. Wave velocity values will be obtained by calculating wave travel times between the source and receiver boreholes. Data will be presented in the form of 2-D tomograms.

### A.2.5.3 Tracers

Detection of the tracers will be done by measuring filtered and unfiltered pore fluid from core samples taken during and after the series of leaks. Pore fluid will be sampled by vacuum extraction (for

$D_2O$ and C-13) and by rinsing cored soils with deionized water (for cations). The elements of interest will be separated by ion exchange in the laboratory and measured for isotopic composition. Effort will be focused on core samples that coincide with maximum incursion of leaked water as measured by n-logs. Data for the cations will be presented in terms of ratios of measured versus predicted concentrations, using as a baseline for comparison a model using a simple Kd of the cations, coupled with the flow model for the test. Cation isotope ratios will be measured using thermal ionization mass spectrometry and multiple-collector ICPMS. The D/H and $^{13}C$ values will be measured by conventional dual inlet IRMS.

Tracer analysis will be primarily from solution extracts taken from soil cores. These cores will be obtained at four time intervals during the field testing (see Section 8.0). The soil samples will be analyzed using a pore water extraction procedure developed by Los Alamos National Laboratory (LANL) (see Appendix 2). Pore water samples will be collected by periodically modifying the advanced tensiometers to function as suction lysimeters. Advanced tensiometers will be constructed of porous stainless steel to minimize sorption of tracers on the sampler as is common with ceramic samplers. Steel construction also facilitates installation by cone penetrometer. Wick samplers will be used for the current experiment because of access limitations, but may be used in the deep trench experiments. A sampling schedule will be developed when the injection pulse duration has been established. A total of 20 porous samplers will be installed at various depths. The locations will be based on analysis of the Sisson and Lu results including the report of Fayer et al. (1995).

### A.2.5.4 Direct Coring

Soil coring will be used to obtain samples for both hydrologic and chemical data for test evaluation. The objectives for the coring are to

- Obtain undisturbed samples of sediment to the full depth of the test (18 m).
- Obtain core that can be analyzed for water retention, water content and density
- Obtain core that can be analyzed for tracers.

To accomplish this task, it is anticipated that split spoon core samples will be taken to depths of 18 m at four locations. The cores will be a maximum of 10 cm (4 in.) diameter and taken at intervals of a minimum of every meter (18 total per hole).

To best accommodate the overall test, coring will be staggered in time over four periods. A core will be taken before any injections have occurred to establish the initial condition for hydrologic conditions and tracer concentrations (see test schedule in Section 8.0). The periodic core sampling will be done in tandem with the neutron probe logging so that the can be some correlation with the This approach will allow some tracking of the tracer in addition to the solution sampling that will be done with the tensiometers (used as solution samplers).

### A.2.5.5 Laboratory and Field Analyses

In the FY 2000 test, soil cores will be collected and analyzed. The schedule for core collection is found in Section 8.0. There will be a limited number of water samples taken from solution sampling.

Water samples taken from cores and from the solution samplers will be analyzed for tracer concentration at PNNL. An ion specific probe for bromide be set up at the field site to provide rapid measures of bromide transport so that any changes to the input pulse or sampling intervals can be made in the field. A trailer at the site with the ion probe, a refrigerator for sample storage, a computer to record sampling events and data are recommended. The transport-modeling task has proposed geochemical modeling to better interpret contaminant transport at Hanford. The samples sent to the laboratory can be analyzed for major anions and cations if needed. The volume of sample required meeting requirements for field measurements, laboratory analyses, and stable isotope data is 30 ml. Characteristics of sampling devices and saturation of the soil affect the amount that can be collected through a porous sampling device. Waste disposal will be addressed using Hanford procedures.

### A.2.5.6 Leaching of Soil and Rock Samples for Anions

**Purpose**:

To leach soil and rock samples and measure amounts of major anions present using the ion chromatograph.

**Reagents**:

0.1 M $HNO_3$

NANOpure deionized $H_2O$ (>17 megohm)

**Procedure**:

Soil Drying: Follow standard gravimetric moisture content procedure. Acid wash and DI rinse all containers before introducing the sample.

Leaching: Approach 1: Acid wash a series of either 400 mL or 600 mL beakers and metal scoopers with 0.1 M $HNO_3$ and rinse three times with NANOpure diH2O. Allow them to completely dry. Calibrate the balance with several weights that span the range that you will be weighing. Weigh 100 g of each sample directly into a clean, dry 400 mL or 600 mL beaker that should be tared to zero. One should get within 0.01g of 100g for each sample weight. After weighing each soil sample, add 150g of di$H_2$0 to each sample with the same degree of accuracy as the soil. To facilitate reaching precisely 150.00 g di$H_2O$, a dropper can be used. Each sample weight is then recorded in a lab notebook, as well as on the beaker. Check scale calibration periodically to ensure accuracy. Reweigh samples if calibration is not satisfactory. Stir each beaker thoroughly with a separate, clean metal scooper. Also, one process blank should be set up in a separate 400 mL or 600 mL beaker for every 6 samples. The process blank consists of 200 g of NANOpure di$H_2O$. Then cover each beaker with foil to avoid any evaporation while leaching takes place. Label beakers both on the foil cover and on the actual beaker. Gloves should be worn and rinsed or replaced between dealing with the different samples to avoid any cross contamination. Samples should be allowed to equilibrate for at least 48 hours while leaching takes place and stirred at least twice a day with clean, dry glass stirring rods. Stirring rods should be used only once per sample and then cleaned with NANOpure di$H_2O$ before reuse. After letting the samples settle for a few hours or overnight, an aliquot of the leachate can be filtered into an ion chromatography sample vial. For high clay content soils, centrifugation may be necessary prior to filtration.  By knowing the amount of dry soil and water used, the bulk density of the materials, the in-situ gravimetric moisture content, and the leachate concentrations, estimates of the pore water concentrations can be calculated.

Approach 2:  Follow basic cleaning and weighing procedure above, except one can substitute Erlenmeyer flasks instead of beakers and put them on a shaker table to gently mix for 48 hours.  One can use 50 g of solid and 75 mL of DI water in a 250 mL flask with good results.

## A.3 References


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# Appendix B

# Preliminary Plans for Trench Flow and Transport Tests

# Appendix B

## Preliminary Plans for Trench Flow and Transport Tests

The approach will be to monitor flow and transport during a series of constant flux infiltration experiments in a 25-m-long by 4-m-wide transect. A minimum of six different water fluxes will chosen to allow investigation of the processes that dominate different flow fields and to allow adequate description of hydraulic properties in situ. The site will be instrumented to allow further evaluation of the geophysical techniques used in the simulated leak tests. Instrumentation will also include traditional vadose zone monitoring instruments such as TDR probes, tensiometers and solution samplers to allow real-time monitoring of low and transport.

An initial set of near-surface measurements of hydrologic properties (hydraulic conductivity, sorptivity etc.) will be made on a regular grid using a disk infiltrometer or similar type of instrument. These measurements will be made on at least three different supports along selected transects to allow identification of the effects of support, information that is important to the development of upscaling methodologies. The initial condition of the entire transect will also be determined using a combination of traditional vadose zone tools and geophysical techniques.

Following the initial measurements, the six different simulated rainfall rates will be applied in a random sequence using a rainfall simulator. The transect will be brought to steady state flow conditions at the selected water flux. The site will be covered with a large tent to minimize the effects of wind, evaporation and precipitation. Continuous monitoring will be performed with the automated instruments. Geophysical monitoring will be periodic and include the initial condition, a midpoint measurement and the steady state condition. At steady state conditions, a suite of conservative and reactive tracers, previously dissolved in water, will be applied to the soil surface at a specific mass (kg $m^{-2}$), sufficient to allow detection at the maximum depth of interest. This depth will be chosen, for example, to represent the mean depth of travel within a representative site under the assumption of piston displacement. The maximum depth to be interrogated with the geophysical tools is not expected to exceed 10 m. Pore water samples will be collected and the entire transect monitored periodically with the geophysical tools until the water and solute fronts pass the depth of interest. This routine will be repeated at the two remaining fluxes.

During the last experiment, the routine will be identical to the above except for one change. As before, the site will be monitored periodically to track the water and solute fronts. After the water and solute front reaches a predetermined depth, water application will be discontinued and a final set of readings taken and the transect covered to minimize further water movement. The site will then be sampled destructively. A vertical section will be excavated, mapped, characterized and sampled. Techniques including infrared thermometry, gas permeameter, and TDR will be used to rapidly characterize the dig face on a 0.2-m horizontal by 0.1-m vertical regular grid. The distribution of dye tracer will also be mapped. Core samples will be taken for verification of tracer concentrations and undisturbed cores will be taken to obtain water retention and conductivity measurements. Figure B.1 shows a schematic of a partially excavated hypothetical site.

After a dig face is fully characterized, another 0.20-m slice will be removed and the mapping repeated until the entire transect is mapped. Destructive sampling and mapping is not expected to exceed 4 m in depth. In Figure B.1, the small circles represent locations where field measurements and core samples are made for laboratory analysis of physical and hydrologic properties as well as concentrations of pore water and sorbed tracer after a predetermined amount of infiltration. Additional measurements would be taken as the new dig face is exposed along the dotted lines.

Because the trench tests will be conducted under constant flux infiltration, hydraulic parameters can de obtained direction based on the premise that given sufficient time a soil profile exposed to constant flux infiltration reaches an equilibrium water content ($\theta_e$) near the soil surface and to an adequate distance above the capillary fringe. Assuming unit gradient conditions at large time, the vertical flux density of water, $J_w$, near the soil surface is a direct measure of the hydraulic conductivity, $K(\theta_e)$. Thus, measurements of the flux density across the soil surface, $J_w|_0$, for water application rates less than $K_s$, and the associated $\theta_e$ provides a measure of the $K(\theta)$ function. Simultaneous measurements of $\psi$ allows direct

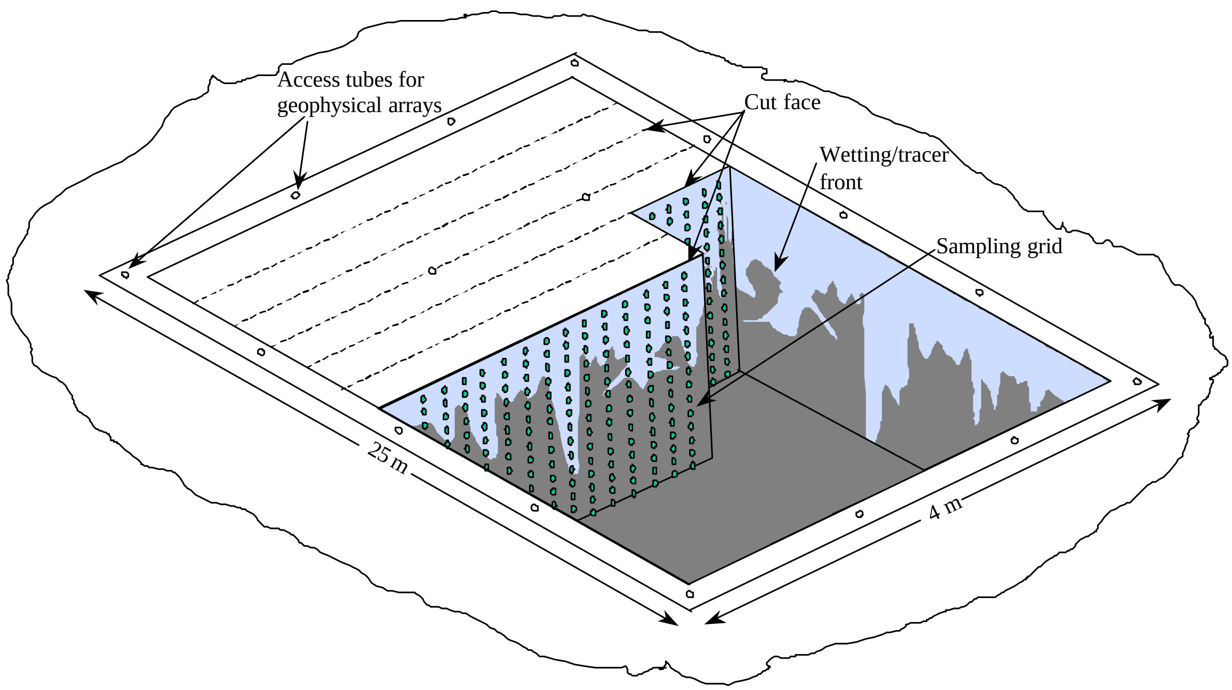


**Figure B.1.** Geometry of Hypothetical Field-Scale Trench Site. (The proposed transect is 25 m long by 4 m wide and would be monitored with a combination of noninvasive and minimally invasive geophysical tools. It would be destructively sample at the end of the experiments.)

determination of the water retention function, $\psi(\theta)$, as well as the unsaturated hydraulic conductivity function, $K(\theta)$. These data will then be fit to Eqs. (7.1) and (7.2) to allow functional description for inclusion into a numerical model.

These experiments will also provide water content and solute concentrations at a large number of points in 3-D space at a few fixed times during constant flux infiltration. Variability in downward transport at different locations will be determined by examining the extremes in the shapes of the tracer and water fronts monitored by different instruments at the same depth and finally the variation in the depth of penetration on the dig faces. These data will be used subsequently to compute the spatial moments of the wetting front and solute plume at selected times, which will then compared with theoretically determined moments to identify the appropriate transport models and parameters. The result will be a 3-D subsurface image of water, tracer, and dye distributions along with the hydraulic properties and associated geophysical characteristics. From these data, flow and transport parameters and their geostatistical characteristics will be inferred.

# Appendix C

# Collaborators in FY 2000 Field Tests

# Appendix C

# Collaborators in FY 2000 Field Tests

The FY 2000 test is a multidisciplinary and collaborative effort among National Laboratories, commercial vendors and geophysical consultants who are experts in vadose zone monitoring. Table C.1 is a list of the collaborators involved in the FY 2000 field tests.

**Table C.1**. Vadose Zone Transport Field Study Collaborators in FY 2000

| **Institution** | **Collaborator** | **Expertise** |
|---|---|---|
| Applied Research Associates | Wes Bratton | Geophysics |
| Electromagnetic Instruments Inc (EMI) | Mike Wilt | Geophysics |
| HydroGEOPHYSICS | Jim Fink | Geophysics |
| INEEL | Buck Sisson | Soil Physics |
| LANL | Everett Springer | Hydrology |
| | Brent Newman | Geochemist/Hydrol |
| LBNL | Ernie Majer | Geophysics |
| | Mike Hoversten | Geophysics |
| LLNL | Bill Daily | Geophysics |
| | Abe Ramirez | Geophysics |
| PNNL | Glendon Gee | Soil Physics/Hydrol |
| | Andy Ward | Soil Physics/Hydrol |
| | Phil Meyer | Hydrology |
| SNL | Greg Newman | Geophysics |
| U.S. Salinity Laboratory | Peter Shouse | Soil Physics |
| | Marcel Schaap | Soil Physics |

# Appendix D

# Sisson and Lu Injection Site Access and Conduct Requirements
# Health and Safety Plan and Site Safety Briefing

# Appendix D

# Sisson and Lu Injection Site Access and Conduct Requirements Health and Safety Plan and Site Safety Briefing

EFFECTIVE DATE: 5/2/00

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Pacific Northwest National Laboratory — Environmental Technology Division

Science and Technology Initiative
Vadose Zone Transport Field Study

SISSON AND LU INJECTION SITE ACCESS AND CONDUCT REQUIREMENTS

HEALTH & SAFETY PLAN AND SITE SAFETY BRIEFING

Approvals:

| | | |
|---|---|---|
| PNNL Project Manager | GW Gee | Date |
| PNNL Safety & Health Representative | PA Wright | Date |
| PNNL Line Manager | MJ Fayer | Date |

# Sisson and Lu Injection Site Access and Conduct Requirements

## D.1 Application and Scope

This document controls PNNL Science and Technology Project safety and the conduct of activities related to the Sisson and Lu Injection Site in the 200 East Area. It serves as the **site safety briefing** and provides **general requirements** for staff, contractors, and visitors involved in performing testing and monitoring activities on the Sisson and Lu Injection Site.

The Sisson and Lu Injection Site (formally known as 299-E24-111, Experimental Test Well Site) is located in the 200 East Area immediately adjacent to the 216-A-38-1 crib. The coordinates for the Sisson and Lu site are E 574,830.125, N 135,418.844. That familiar with the Hanford Site will recognize the site as located just to the southwest of the PUREX building about 1 km east of Baltimore Avenue and the 2750 Building. Figure E.1 shows the location of the test site.

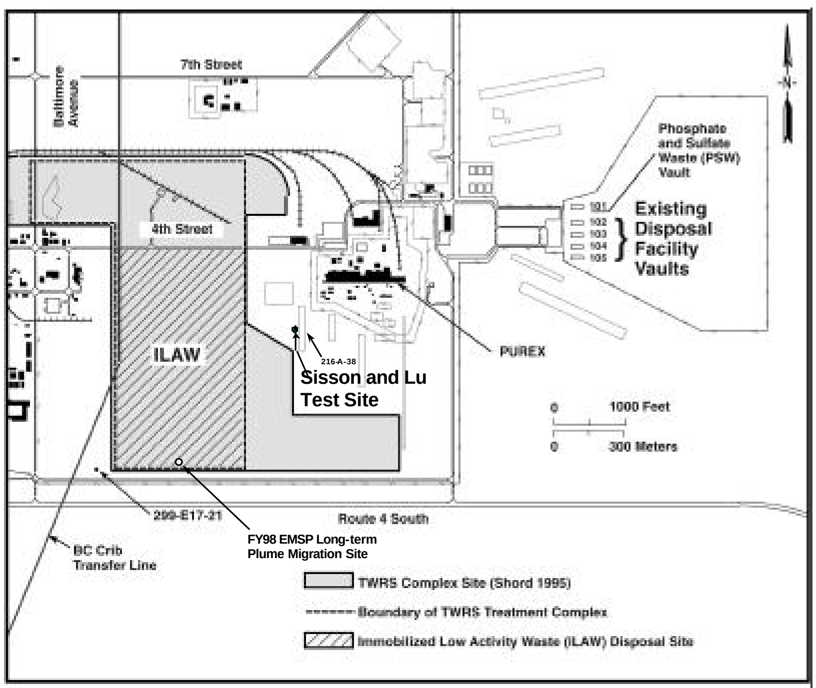


**Figure E.1**. Location of the Sisson and Lu Injection Site in the 200 East Area of the Hanford Site

Details of the site description and the past history of the site are found in the Waste Information Data System (WIDS) data base accessible on the Hanford Web. Records show that the Sisson and Lu (S&L) Site is a radiologically clean site that contains 35 steel-cased dry wells encompassed in a circle with a radius of 8 m (26 feet). The area adjacent is currently posted in two areas. A small (10x15 ft) area to the immediate south of the site is posted as a Soil Contamination Area (SCA) as is the adjacent crib, although both are radiologically clean. In addition a (10x10 ft) area in the center of the S&L Site is posted as an Underground Radioactive Material (URM) area. This posting delineates an area near which radioactive tracers, Sr-85 and Cs-134, both short-lived radionuclides were injected at a depth of 5 meters in late 1980 and early 981. The radionuclides have long since decayed to background levels but the posting remains.

Visitors, accessing the site must follow safety precautions that pertain to PNNL staff working on site. Signing of this document indicates that the individual has read the document and is willing to abide by the safety and access protocols specified herein.

Subsequent versions of this document may be prepared if access or conduct requirements change. Notification of subsequent versions will be made to project staff and authorized workers. Each new version of the document will require the review and signature of each worker before that person’s continued work at the site.

## D.2 Responsible Staff

The person responsible for this document is the PNNL project manager Glendon W. Gee is the project manager, and can be reached at 372-6096. The alternate responsible person is Anderson L. Ward who can be reached at 360-574-5874.

## D.3 Testing and Monitoring Goals

The goals of the tests at the Sisson and Lu site are to compare innovative and improved methods for quantifying vadose zone plumes and to obtain flow and transport data from the Hanford vadose zone useful for model calibration and verification. The planned work includes activities to monitor water and tracer flow in the vadose zone under controlled conditions, with a suite of methods under conditions of known applications of water and tracers. The goals of the project are important to the overall Science and Technology project in that actual field data will be obtained on which vadose zone flow and transport models can be calibrated. The tests will be conducted in collaboration with a number of highly qualified scientists and engineers from other national laboratories and research firms who are participating in the Science and Technology Initiative of the Ground Water Vadose Zone Project for the U.S. Department of Energy.

It is the responsibility of each person working at the site to ensure his or her activities do not jeopardize the integrity of the other monitoring activities that are ongoing at the site.

## D.4 Safety Requirements

Any accidents or immediate, uncontrollable safety concerns observed by workers at the site should be reported to site emergency services by calling 375-2400 or 911. Note that 911 calls from cellular phones maybe re-directed. For additional assistance, call 373-3800 (Hanford Patrol) or radio the Safety Net at Frequency KOB743 (monitored by Hanford Patrol and by the PNNL Control Room [Station 62]). In the event such communications are not available, a 24-hour First-Aid Station is located at the intersection of Baltimore and 4th Street (Building 2719EA).

Site access and safety requirements refer only to the area within and immediately adjacent to the Sisson and Lu site. Staff should be aware that radiological hazards potentially exist at the site. The Sisson and Lu site has a small portion of it designated as an Underground Radioactive Materials Area (URMA). An URMA is established to indicate the presence of underground items that contain radioactive materials. While there is no known radiological hazard at the site, the small (10 X 10 ft) area (in the center) is posted and protocol is such that no digging in this area will be allowed under the present excavation work permit (DAN 15559). Digging is permitted in the area outside of the URMA. Since the initial tracers emplaced in 1980 have decayed to background samples taken will be not require survey and waste will be treated as non-radioactive materials. The waste disposition will follow the protocols specified in the waste handling plan for this site.

### D.4.1 Warning Sirens

The following action should be taken relative to warning sirens:

- The PNNL emergency phone is 375-2400. Call if there are any questions.
- For all gongs and horns go to the staging area, Baltimore Ave, 2750 parking lot.
- Wavering Siren (Get in vehicle, call emergency phone # and follow directions)
- Howler (AH-OO-GAH). Get in vehicle drive off the Sisson and Lu Site and leave area away from the criticality area. Planned siren tests are frequent. Call Dyncorp Emergency Prep. (373-4308) if questions arise regarding specific siren tests.

### D.4.2 Accidents

The following actions should be performed if any accidents or immediate, uncontrollable safety concerns are observed by anyone at the site:

- Immediately stop work. Evaluate the scene for safety. If safe, lend medical aid or prevent further damage. If unsafe conditions exist, deactivate and turn off applicable electrical and mechanical systems before lending assistance.

- Immediately notify site emergency services (above). If a telephone is available, call the emergency assistance number (375-2400) and be prepared to describe the accident and your location (the site location is described above). If no phone is available, use a radio to contact Hanford Patrol. In the absence of communication devices, send someone for help to the First-Aid Station at Baltimore and 4$^{th}$ Street (Building 2719EA). Notify your line manager and the project manager (Glendon W. Gee 372-6096).

### D.4.3 General Work

For general work, when drill rigs are on the site and workers and collaborators are on the site, workers shall use hard hats, safety glasses and wear closed-top shoes. Steel toes in the shoes are not required for general work. For specific activities that pose additional potential hazards, such as digging or working with electrical or water supply systems, additional requirement may include, protective clothing (long-sleeve coveralls or equivalent work clothes), gloves, steel-toed shoes, or other safety needs. The project manager in cooperation with specific task leaders will analyze hazards and shall identify the additional appropriate combination of safety precautions (clothes, procedures, training, supervision, etc.) necessary for each type of work. Workers shall follow these requirements and only perform work for which they agree with procedural and safety requirements. Work shall not be performed when ambient weather conditions pose a threat to safety and health. Workers shall use caution in extended work in the full sun. To avoid heat stroke workers are encouraged to drink ample quantities of fluids.

A fire extinguisher shall be located on site.

### D.4.4 Additional Safety Requirements

The general requirements of this procedure are based on PNL-MA-43 and applicable Standards Based Management System (SBMS) subject Areas. Specific requirements for other activities typically conducted at the site include:

- Workers shall adhere strictly to all postings, caution, warning, and danger signs. Failure to do so shall result in immediate work stoppage. Workers shall pay attention to personal safety.

The need of a particular job to be controlled by a procedure shall be determined using applicable SBMS subject areas (e.g., working with chemicals, electrical safety, machine guarding). Workers performing these jobs must demonstrate a knowledge of hazards associated with the work before commencing work.

## D.5 Site Access Requirements

There are no formal site access requirements. Access is gained via gravel roads from Baltimore Avenue and vehicular traffic is encouraged to travel only on the gravel road ways. Parking of vehicles adjacent to the roads is permitted but the vehicle parking is restricted to the north side of the S&L injection site. Turn around of vehicles can be accomplished by driving on the gravel perimeter road that goes around Crib 216-A-38-1.

In general, workers and collaborators should be cognizant of monitoring activities and work together under the defined schedule for the selective monitoring activities that are ongoing throughout the duration of the project.

Because there is a possibility that radioactive contamination may migrate onto the site, it is recommended that staff working on the site be aware of the potential for surface contamination via biotic pathways. For this reason, no animal droppings (feces) are to be removed from the surface without first contacting radiation safety and the project manager.

## D.6 Potential Site Impact Requirements

Activities that pose the potential to significantly affect monitoring conditions must be authorized and documented by the project manager. Examples of activities that pose such potential include: 1) excavating sediments in unauthorized locations; 2) driving vehicles onto the S&L site when monitoring is ongoing unless a drill rig or similar vehicle is scheduled and has been authorized for access on to the site; 3) destroying, obscuring, or relocating radiation markers. This list is not intended to be complete but is included to provide examples of the type of activities that may pose a potentially significant impact.

It is the responsibility of the project manager to determine if an monitoring or site visit activity poses the risk to cause a significant impact based on the examples provided above and to obtain appropriate approval from the project manager. Before work, resolve with the project manager any uncertainty about the potential to cause a significant impact. Guidelines as outlined in SBMS Subject Areas.

An activity is authorized if approval is obtained from the project manager. It is the responsibility of the project manager to determine the level of documentation needed for each unusual activity (no action, memo-to-file, or other documentation).

Activities that pose the potential to affect the monitoring project must be documented in the project manager's site file. Workers who observe unexpected operations or conditions at the site must report the incident to the project manager (See Section 2.0)

## D.7 Training Requirements

Signing this document provides the authority to access the site and perform monitoring work at the Sisson and Lu Site.

Radiation Worker II training is required for operators of neutron probes. Training records for these activities will be on file with the individual worker and will be available upon request.

## D.8 References

SBMS. Standards Based Management System (http://sbms.pnl.gov/). Pacific Northwest National Laboratory, Richland, Washington.

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