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Vadose Zone Transport Field Study: FY 2001 Test Plan

A.L. Ward
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Prepared for the U.S. Department of Energy
under Contract DE-AC06-76RL01830

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Summary

Conceptual models of flow and transport in the Hanford vadose zone are in their developmental stages. As part of the Hanford Site Science and Technology Initiative, the U.S. Department of Energy (DOE) contracted the Pacific Northwest National Laboratory (PNNL) to undertake a detailed study of contaminant transport in the vadose zone. This study has been designed to provide data to support the modeling efforts by appropriately analyzing and selecting initial and boundary conditions and model dimensionality, and by investigating transport volumes and their migration pathways (matrix vs. preferential flow).

The first near-surface leak simulation test was conducted in FY2000 at the 299 E24-111 Injection Test Well Site in the 200 E Area of the Hanford Site near Richland, Washington. The second test will be conducted this year at this same location and is the subject of this test plan. The detailed test plan outlines important project linkages between the Vadose-Zone Transport Field Study (VZTFS), its benefactor, the Hanford Groundwater/Vadose Zone (GW/VZ) Integration Project, and other site activities, including the River Protection Project characterization work, the 200 Area Soil Remediation Project, the Immobilized Low Activity Waste project, and specific Environmental Management and Science Program activities that are focused on Hanford issues. The GW/VZ Integration Project was established to integrate Hanford's entire groundwater and vadose zone activities.

This document describes the test site, including its hydrogeology, soils and vegetation, and infrastructure and well installation. The test plan includes the rationale for test strategies and fluid injections. Monitoring technologies include geophysical methods, tracer methods, and sampling and analysis methods. Experimental data will be analyzed to determine parameters and properties, and their spatial representation will follow techniques started in FY 2001 and will continue throughout this year. The work will be conducted in an environmentally compliant manner that includes radiation protection to workers. PNNL will be responsible to manage wastes and residuals. These activities will be accomplished according to specific procedures followed during drilling and sampling operations and in compliance with a memorandum of understanding that has been developed between PNNL and Bechtel Hanford Incorporated (BHI) to facilitate the use of the site for experimental purposes.

Acronyms and Abbreviations

AT	Advanced Tensiometer
BHI	Bechtel Hanford Incorporated
BP	Before Present
CNT-G	Compensated Neutron Tool
CPT	Cone Penetrometer
DOE	U.S. Department of Energy
DOE-RL	U.S. Department of Energy-Richland Operations
EMSP	Environmental Management Science Program
ERT	Electrical Resistance Tomography
GW/VZ	Groundwater/Vadose Zone
HMS	Meteorological Station
HNGS	Hostile Environment Natural Gamma Ray Sonde
ILAW	Immobilized Low Activity Waste
INEEL	Idaho National Engineering and Environmental Laboratory
IRMS	Isotope Ratio Mass Spectroscopy
LDS	Litho-Density Sonde
LLNL	Lawrence Livermore National Laboratory
LMHC	Lockheed Martin Hanford Company
PNNL	Pacific Northwest National Laboratory
PUREX	Plutonium Uranium Extraction
QA	Quality Assurance
REDOX	Reduction Oxidation
RLS	Radionuclide Logging System
RPP	River Protection Project
SAC	System Assessment Capability
SAP	Sampling and Analysis Plan
SCA	Soil Contamination Area
SNL	Sandia National Laboratory
S&L	Sisson and Lu (Site)
SBMS	Standards-Based Management System

UBC	University of British Columbia
URL	Universal Resource Locator
URMA	Underground Radioactive Materials Area
VEA	Vertical Electrode Array
VZTFS	Vadose-Zone Transport Field Study
WMA	Waste Management Area
WIDS	Waste Information Data System
XBR	Cross-Borehole Radar
XBS	Cross-Borehole Seismic
XWR	Cross-Well Radar
MOSA	Methods of Soil Analysis

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1.0 Introduction

At the U.S. Department of Energy's Hanford Site near Richland, Washington, mobile contaminants such as chromate, nitrate, technetium, and tritium, among others, continue to be found in increasing concentrations in groundwaters beneath tank farms (e.g., near SX-115) and burial grounds (e.g., 618-11). There is an urgent need for more information about the transport of contaminants as they move through the vadose zone to the underlying water table at the Hanford Site.

Conceptual models of flow and transport in the Hanford vadose zone are in their developmental stages. This study has been designed to provide data to support the modeling efforts by appropriate analysis and selection of initial and boundary conditions, model dimensionality, and investigations of transport volumes (matrix vs. preferential flow). The Vadose-Zone Transport Field Study (VZTFS) will also be helpful in assessing impacts of steady-state or transient conditions, the importance of structural features and stratigraphy, and the importance of solute retardation mechanisms. The contribution of the VZTFS will be maximized through integration with ongoing EMSP and site projects. Integration will lead to data sharing and subsequent cost reductions through coordination of monitoring/characterization efforts. A recent EMSP workshop held in Richland in November 2000 confirmed the concept that the integration of vadose zone research activities focuses on processes controlling transport beneath Hanford waste sites. This information is needed not only to evaluate the risks from accelerated transport, but also to support the adoption of measures for minimizing impacts to the groundwater and surrounding environments.

As part of the Hanford Site Science and Technology Initiative, the U. S. Department of Energy (DOE) contracted the Pacific Northwest National Laboratory (PNNL) to undertake a detailed study of contaminant transport in the vadose zone. A test plan was prepared (Ward and Gee 2000), and field tests were implemented in FY 2000.

The detailed test plan (Ward and Gee 2000) outlines the overall scope of a VZTFS. General objectives of the VZTFS include addressing the principal uncertainties that limit our understanding of current contaminant distributions under Hanford waste sites and improving the prediction of future migration through the vadose zone. Activities focus on hydrogeologic investigation and characterization of representative sites and addressing current data gaps related to indexing the status of mobile contaminants by making *in situ* measurements of surrogate variables using emerging monitoring technologies (Ward and Gee 2000). The plan calls for conducting a controlled series of tracer tests at two uncontaminated sites between FY2000 and FY2003. These tests include two near-surface tracer experiments designed to simulate a tank leak at an existing site, followed by two tracer studies in deeper Hanford formation sediments.

The first near-surface leak simulation test was conducted in FY2000 and is summarized in a subsequent section. The second test will be conducted this year and is the subject of this test plan. Plans for the FY 2001 test call for injecting a concentrated salt solution at the same site as the FY 2000 test. Migration of the wetting front and salt plume will be monitored using techniques similar to those employed in the first test. The objectives and FY 2001 test details, safety plan, and collaboration activities are described the sections that follow.

1.1 Objectives and Scope

The primary objective of the VZTFS, as identified by Ward and Gee (2000), is to obtain hydrologic, geophysical, and geochemical data from controlled field studies to reduce the uncertainty in vadose zone conceptual models and to facilitate the calibration of numerical models for water flow and contaminant transport through Hanford's heterogeneous vadose zone. A secondary objective is to 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. As with the first experiment, this test is designed to ensure the measurement of flow and transport properties in the same soil volume. This is a pre-requisite for developing techniques for extrapolating parameters derived from investigations at clean representative sites to contaminated sites with minimal characterization. The resulting data will be critical to the improvement of vadose zone conceptual models and to the selection of remedial actions. They may also apply to the selection of compliance monitoring technologies to support tank waste retrieval as well as plume delineation at a range of waste management areas. The overall result will be data sets and conceptualizations of vadose zone processes to support the development of the vadose zone component of the System Assessment Capability (SAC) and other analysis strategies that may be deployed by DOE to address Hanford Site needs. The scope of the field testing for the FY 2000 and FY 2001 test is limited to transport and characterization studies, primarily in the 200 E area at the Hanford Site. However, the vadose zone transport analysis and advanced characterization techniques and methodologies developed in this study are expected to be applicable to other waste sites at Hanford as well as other waste sites located throughout the DOE complex. This is particularly the case in areas where steel-cased wells are part of the existing infrastructure and can be used for monitoring points.

1.2 Project Linkage and Integration

The detailed test plan (Ward and Gee 2000) outlines important project linkages between the VZTFS, its benefactor, the Hanford Groundwater/Vadose Zone (GW/VZ) Integration Project and other site activities, including the River Protection Project (RPP) characterization work, the 200 Area Soil Remediation Project, the Immobilized Low Activity Waste (ILAW) project, and specific Environmental Management and Science Program (EMSP) activities that are focused on Hanford issues. The GW/VZ Integration Project was established to integrate Hanford's entire groundwater and vadose zone activities. Within the Integration Project, there are eight linked technical elements, four of which require technical information and data about the subsurface environment. The four include Inventory, Vadose Zone, and Groundwater and River, all of which contribute to the final SAC (DOE 1998). Currently, the RPP, the 200 Area Soil Remediation Project, and the ILAW are performing or will perform assessment activities in the 200 Areas. Four out of 13 FY-2000 EMSP projects add directly to the efforts of the VZTFS. The projects are briefly reviewed below.

The SAC is a collection of conceptual models, databases, and predictive tools that will be used to assess the site-wide effects of contamination. Such assessments will form the basis of regional decision-making in relation to remediation of the vadose zone and groundwater, and ultimately, protection of the Columbia River. The SAC includes a vadose zone flow and transport component and will be supported by the VZTFS.

The mandate of the RPP is to determine the nature and extent of contamination originating from tank leaks, pipeline leaks, and surface spills and to establish a baseline of contamination. This baseline will be used for comparison with future borehole monitoring data to assess changing conditions in the vadose zone (Mann et al. 1998). The RPP has cored and analyzed samples from selected Hanford-Site Single-Shell Tank Farms (e.g., S-SX) and are formulating plans for characterizing the B-BX and T-TX-TY tank farms.

The 200 Area Remediation Project has grouped waste sites into operable units based on similarity in location, geology, waste site history, and contaminants. Characterization efforts are focused on a limited number of specific waste sites representative of a set of operable units. Such efforts provide a snapshot in time of current distributions, but will be constrained in making predictions about future movement, especially for all sites within a group.

The ILAW project has collected geologic, geochemical, and hydraulic data from boreholes within and adjacent to the new ILAW disposal site in the 1998 performance assessment (LMHC 1999b; Reidel and Horton 1999; Fayer et al. 1999). The four boreholes drilled near the southwest corner of the disposal site provide information on the nature of the sediments within the depth of the facility excavations (expected to be 10–15 m). A new characterization borehole is currently being drilled at the ILAW site, just to the northwest of the Sisson and Lu site.

A common goal among core projects is to collect field data and develop conceptual models of VZ flow and transport. The ability to identify changes from the baseline contamination determined by the RPP also demands the identification of advanced technologies capable, not only of using the existing infrastructure to detect contaminants, but also locating *in situ* the high-risk, often difficult-to-detect contaminants using surrogate measurements. There are major challenges in transforming geophysical measurements to the constitutive properties required for model input and in extrapolating results over multiple spatial scales and 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 and determined.

In the broad framework of determining constitutive properties, characterizing subsurface heterogeneities, and developing time and cost-efficient subsurface imaging technologies, four EMSP projects are clear fits. These projects are summarized in Table 1.1. Personnel from three of these projects, 070187, 070193, and 070220, are participating in the FY 2001 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 VZTFS test sites to collect data to validate techniques that are developed in their research.

Table 1.1. FY 2000 EMSP Projects Collaborating with the Vadose Zone Field Study

Project	Investigator	Institution	Title	Summary
070187	P. D. Meyer	PNNL	Quantifying Vadose Zone Flow and Transport Uncertainties Using a Unified, Hierarchical Approach	To 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 to 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	To 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(1)	High Frequency Electromagnetic Impedance Imaging for Vadose Zone and Groundwater Characterization	To address the use of magnetotelluric inversion codes to interpret data and limiting factors of 2D and 3D 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(2)	The Use of Radar Methods to Determine Moisture Content in the Vadose Zone	To focus on two specific aspects of the link between radar images and moisture content. The research will improve the usefulness of radar as a means of characterizing moisture content in the vadose zone.

(1) SNL = Sandia National Laboratory
(2) UBC = University of British Columbia

The VZTFS will support the core projects and ultimately the SAC by identifying advanced monitoring and characterization technologies, providing data for testing assessment models, and improving conceptual models using data obtained from controlled field experiments. Conceptual models generally simplify the real system and provide a description of system geometry and initial and boundary conditions as well as physical and chemical processes occurring within the system and constitutive properties that describe these processes.

Collaboration with EMSP projects is being implemented and proving to be successful. An EMSP workshop on Hanford-related activities held in November 2000 demonstrated how a significant number of EMSP projects were interacting with the Hanford S&T research program and meeting site research needs. A successful American Geophysical Union Special Session in San Francisco on transport of radioactive and mixed waste in the vadose zone featured a large number of Hanford site studies. These included the VZTFS research effort, further illustrating the collaborative efforts in vadose zone research at the Hanford Site.

2.0 Test Site Description

The FY 2001 test will be conducted at the 299 E-24-111 Experimental Test-Well Site (also known as the Sisson and Lu site). This site is the location of the first controlled contaminant transport field study conducted at the Hanford Site (Sisson and Lu 1984) and the location of the FY 2000 test (Ward and Gee 2000). Site selection for the VZTFS was based partly on the analogous site concept, used in the 200-Areas Environmental Restoration Project, to reduce the amount of site characterization and evaluation. In the analogous site concept, a site representative of the main waste disposal scenario is chosen after taking into account location, geology, waste site history, and contaminants. Because the VZTFS is concerned with uncertainty associated with contaminant source distributions and hydrogeologic controls of transport, emphasis was placed on the hydrogeologic component and the degree to which sites have been previously characterized. Costs for infrastructure, including excavation permits, electricity and water accessibility, were also factored into the selection process.

The Sisson and Lu site was selected because it is ideal for investigating a variety of leak scenarios and their associated flow and transport behavior. The existing steel-cased wells allow for testing advanced characterization techniques that show potential for imaging the subsurface in culturally noisy environments. Such techniques are needed to reduce the uncertainty in source contaminant distributions.

The Sisson and Lu site and the area surrounding it have been described in some detail by Fayer et al. (1993, 1999). The Sisson and Lu test site is immediately east of the ILAW disposal site and southwest of the Plutonium Uranium Extraction (PUREX) facility. Figure 2.1a shows an aerial photograph of the site while the schematic in Figure 2.1b shows the test site location relative to the location of the proposed ILAW disposal facility. The site offers easy access to vehicles and test equipment. The site has been characterized for its geology and hydrology (Sisson and Lu 1984; Fayer et al. 1993, 1995; Khaleel and Freeman 1995; Khaleel and Relyea 1995) and has been the subject of several modeling investigations (Sisson and Lu 1984; Lu and Khaleel 1993; Smoot and Lu 1994; Smoot and Williams 1996; Rockhold et al. 1999). In support of ILAW Performance Assessment activities, the hydrologic properties of near-surface sediments have been characterized (upper Hanford Formation) at a location to the immediate west and south of the Sisson and Lu site.(3) At additional sites further to the southwest, adjacent to the planned ILAW disposal, the ILAW project has collected geologic, geochemical, and hydraulic data from the boreholes site in the 1998 performance assessment (LMHC 1999b; Reidel and Horton 1999; Fayer et al. 1999). To the east of borehole 299-E17-21 is the long-term plume

(3) A. L. Ward, R. E. Clayton, and J. C. Ritter. 1998a. *Hanford Low-Level Tank Waste Performance Assessment Activity: Determination of In Situ Hydraulic Parameters of Hanford Sediments.* Letter Report for Activity 4b, submitted to Lockheed Martin Hanford Company, September, 1998.

A. L. Ward, R. E. Clayton, and J. C. Ritter. 1998a. *Hanford Low-Level Tank Waste Performance Assessment Activity: Determination of In Situ Hydraulic Parameters of the Upper Hanford Sediments.* Letter Report for Activity 4b, submitted to Lockheed Martin Hanford Company, December, 1998.

migration field site at which the vadose zone transport of high salinity fluids is being investigated under an EMSP (FY-1998) project (Ward et al. 1997).

2.1 Hydrogeology

The site is located in the 200 East Area of Hanford's 200-Area Plateau. The climate is arid with cool, wet winters and hot, dry summers. Precipitation at the Meteorological Station (HMS), located about 10 km west of the test site, has averaged 174 mm yr^{-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.

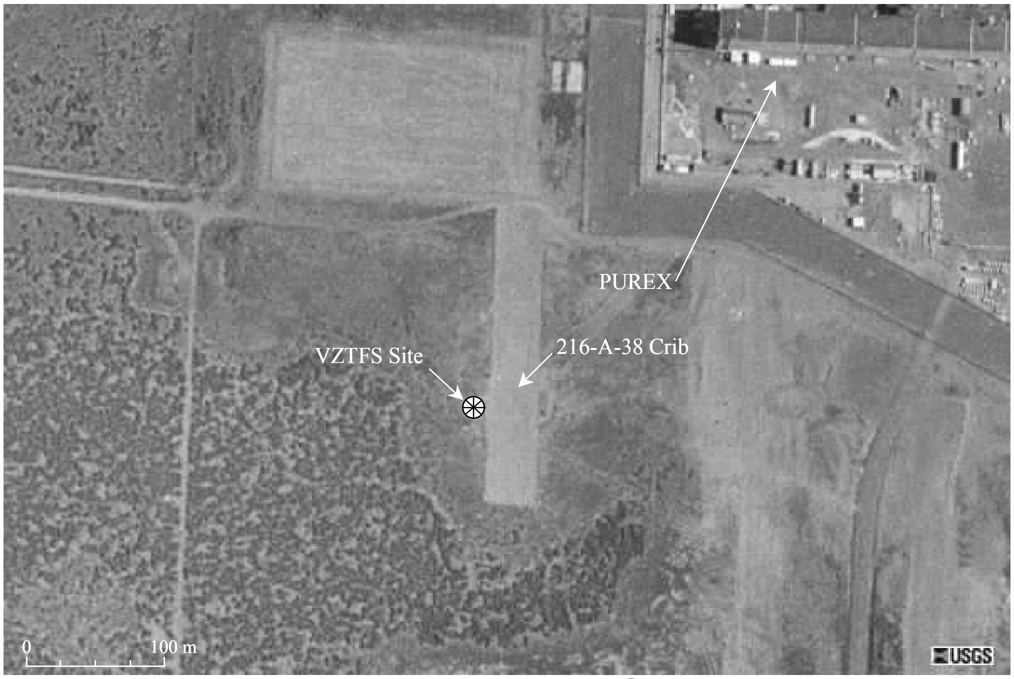

Figure 2.1a. Aerial photograph from July 13, 1996, Showing the Location of the Test Site. The injection site is adjacent to the 216-E24-111 crib and southwest of the PUREX Plant. (Image courtesy of the U.S. Geological Survey at http://terraserver.microsoft.com/)

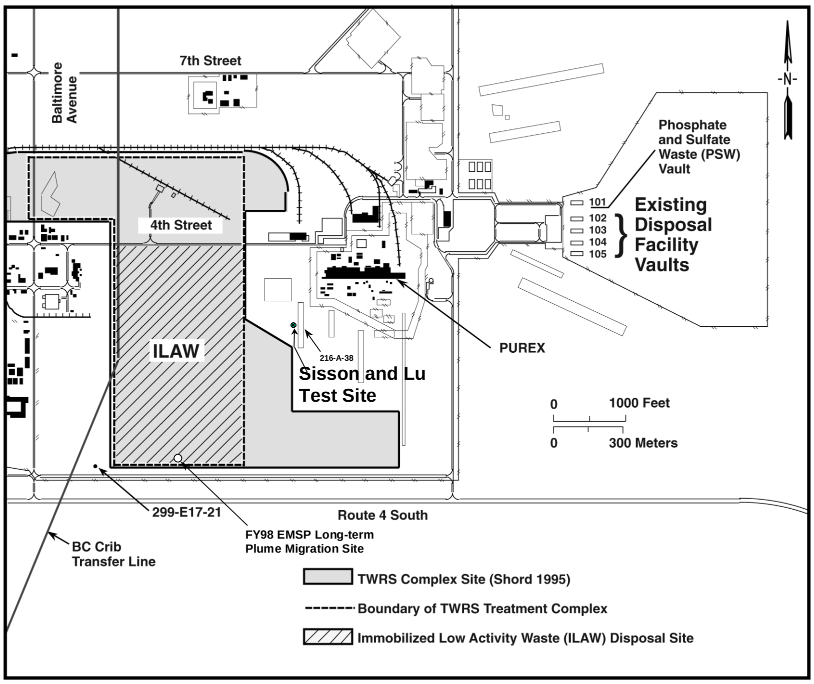

Figure 2.1b. Location of the Leak Simulation Test Site. The Site is at the old Sisson and Lu Test Site in the 200 East Area of Hanford (Modified after Fayer et al. 1999).

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 BP (before present), 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.

2.2 Soils and Vegetation

The surface soil at the site is a coarse sand, locally known as a Quincy sand, which is associated with the Quincy soil series (mixed, mesic, Xeric Torripsamments). The soil has a high infiltration capacity (>50 mm hr^{-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 that time the site has been dominated with a sparse cover of cheatgrass, tumble mustard, and tumbleweed (Fayer et al. 1993).

2.3 Infrastructure and Well Installation

Figure 2.2 shows a plan view of the original 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.

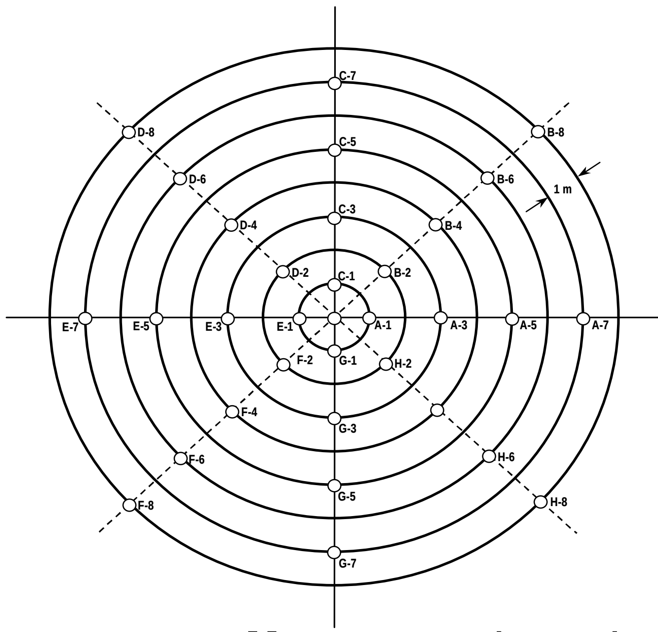

Figure 2.2. Well Array at the Leak Simulation Test (old Sisson and Lu) Site in the 200 East Area at Hanford (after Sisson and Lu 1984)

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 and Relyea 1995; Rockhold et al. 1999).

During the FY 2000 field test, a series of new boreholes and instruments was installed using a combination of auger and cone penetrometer drilling technologies. Soil samples were also retrieved to analyze physical and chemical properties and to determine water contents and tracer concentrations. All installations were in accordance with technical procedures and specifications described in the FY 2000 Test Plan (Ward and Gee 2000). Figure 2.3 shows the layout of the FY 2000 instrument arrays and sampling points overlain on the original well configuration.

A new injection well was installed about 0.3 m (1 ft.) northwest of local well H2 (Hanford Well E24-104). In addition, eight ERT vertical electrode arrays (VEAs) were installed by the cone penetrometer at a radial distance of 8.0 m from the central injection site to facilitate ERT imaging of the subsurface. The VEAs consisted of 15 stainless steel tubes (0.15 m long, 3.175 cm diameter) spaced at 1-m intervals with the first electrode located 5 m below the surface. An additional VEA was located 2 m south of the central injection well, i.e., between local wells G-1 and G-3. In support of EMSP Project 070187 (Table 1.1), four geotechnical boreholes were drilled by auger. They were installed southeast of local well C0 and spaced about 2 m apart. These boreholes were used to obtain continuous split-spoon samples from the surface to a depth of 18 m and were subsequently decommissioned according to the FY 2000 sampling and analysis plan. Selected potions of these samples are being analyzed for their chemical, radiological, and physical characteristics at PNNL and at the U.S. Salinity Laboratory. In addition, three Cone Penetrometer (CPT) wireline samples were obtained at locations WL-1, WL-2, and WL-3 for tracer analysis.

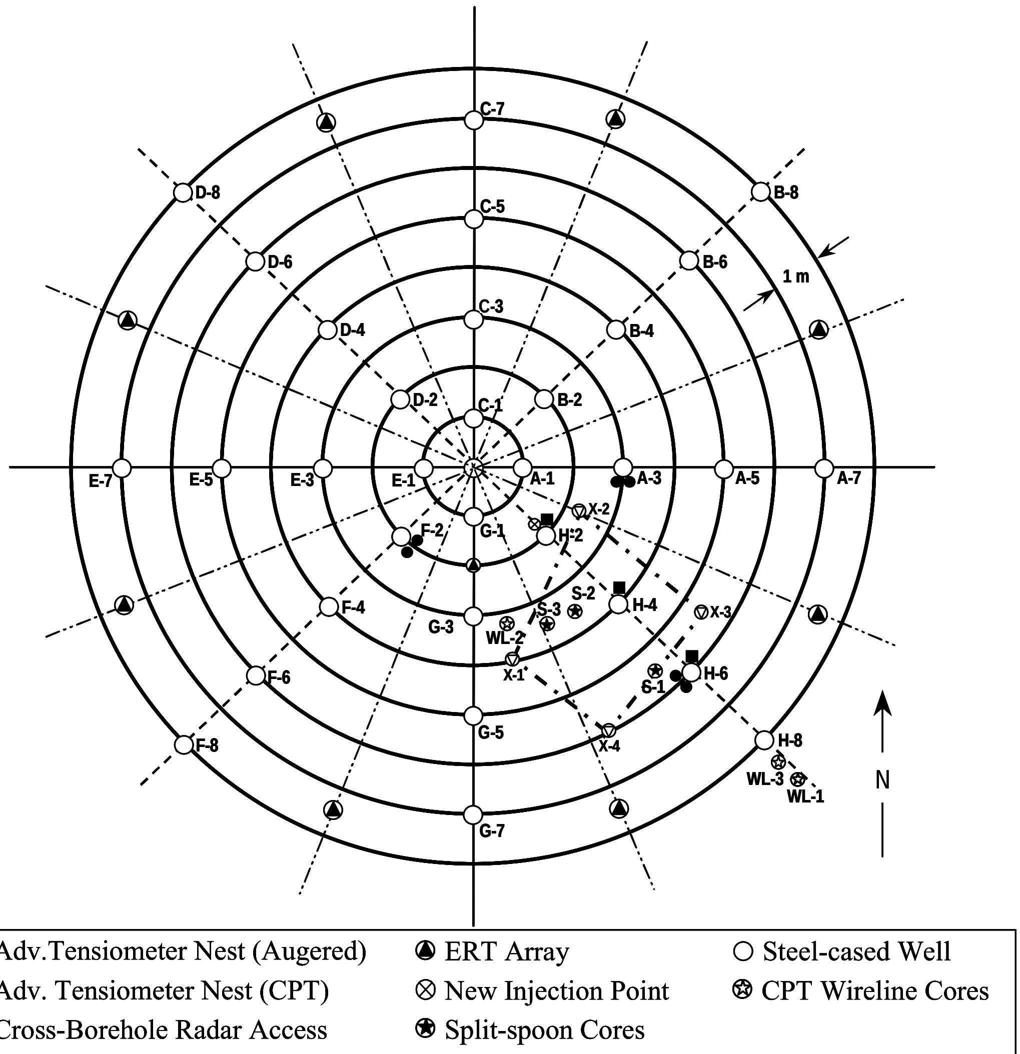

Figure 2.3. Layout of New Instrument Array and Sampling Points Overlain on Well Array at the Leak Simulation Test in the 200 East Area at Hanford

Three advanced tensiometer (AT) nests were also installed to monitor soil matric potential and collect pore-water samples for laboratory analysis. They were all installed by rotary auger with the first located 30 cm (1 ft) north of local wells H2 (Hanford Well E24-104); H4 (Hanford Well E24-105) and H6 (Hanford Well E24-106). Three additional AT nests were installed by cone penetrometer, including one about 0.3 m (1 ft) south of local well A-3 (Hanford Well E24-77); one southeast of local well F-2 (Hanford Well E24-96); and one south west of local well H-6 (Hanford Well E24-106). In a nest near A-3, one AT was driven to a depth of 6 m (20 ft) while the second was driven to a depth of 8.2 m (27 ft). In the nest near F-2, one AT was driven to a depth of 5.8 m (19 ft) while the second was driven to a depth of 9.5 m (31 ft). In the nest near H-6, one AT was driven to a depth of 5.8 m (19 ft) while the second was driven to a depth of 10.9 m (36 ft).

Four PVC access-tubes (X-1 through X-4) were installed by cone penetrometer to facilitate monitoring by cross-well radar and high-frequency electromagnetic impedance measurements as well as cross-hole seismic. Tube X-1 was located 1.0 m southeast of local well G-3 (Hanford Well E24-101). Tube X-2 was located 1.0 m south southeast of local well H-2 (Hanford Well E24-104); tube X-3 was located 1.5 m east southeast of local well H-4 (Hanford Well E24-105); while tube X-4 was located 4 m west southwest of local well H-4 (Hanford Well E24-105).

2.4 Previous Tests and Monitoring

In the 1980s, the first 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). The subsurface was monitored 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).

In 1994, additional monitoring of the site was undertaken using a compensated neutron tool CNT-G (neutron-neutron logging for water content), litho-density sonde (LDS) (pulsed neutron logging for water content), and hostile-environment natural gamma ray sonde (HNGS), and radionuclide logging system (RLS) (gamma logging for radionuclides). Schlumberger-Wireline Services deployed these geophysical tools after calibrating the two water-content probes (Engleman et al. 1995b). Description of the logging equipment and results of these additional tests can be found in Fayer et al. (1995).

The dry-soil-density data collected during the geophysical logging were subsequently used by Rockhold et al. (1999) to estimate spatial distributions of porosities and subsequently 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 above

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 Hanford sediments 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.

The surrounding area has been investigated under the ILAW Performance Assessment. A series of experiments to characterize the Hanford surface sediments and the upper Hanford formation was performed to the west.(4) Sediment samples were also obtained from a borehole (299-E17-21) to the southwest of the injection site (Figure 2.2) as part of the site-characterization activities for the ILAW disposal facility. To the 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 a FY 1998 EMSP Award. This research is focused on the effects of wetted path geometry, salinity gradients, and vapor flux on the migration of highly saline wastes (Ward et al. 1997).

In FY 2000, PNNL and its collaborators completed the first of four contaminant-transport tests as part of the Science and Technology initiative. Nine characterization and monitoring technologies methods were used to document plume distributions and migration rates in the Hanford vadose zone. These methods included neutron logging, electrical resistance tomography, high-resolution resistivity, electromagnetic imaging, cross-borehole radar, crosshole seismic, advanced tensiometers, tracers, and coring. The study focused on a well-characterized site, located in Hanford's 200 East Area, where the water table is 90 m below the soil surface. The first test started in May 2000 with drilling and baseline monitoring. Water injections began in June and consisted of five 4000-L pulses of Columbia River water, discharged weekly at a depth of 5 m. The third pulse included 1000-ppm bromide and a suite of isotopic tracers, sampled by split spoon and wireline coring. Cores were also taken to analyze hydraulic properties. Pre-test modeling of the site predicted significant lateral spreading of the plume in a southeasterly direction, and these predictions were confirmed by geophysical logging. Fine sand/coarse silt lenses at 6 and 12 m below the soil surface appear to control the plume migration at this test site. Summary reports for the FY 2000 tests can be found at the following Universal Resource Locator (URL) address: http://etd.pnl.gov:2080/vadose/contrepts.htm. Analysis of the data is continuing through FY 2001, and a final report describing the FY 2000/2001 testing will be published in September 2001.

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(4) A. L. Ward, R. E. Clayton, and J. C. Ritter. 1998a. Hanford Low-Level Tank Waste Performance Assessment Activity: *Determination of In Situ Hydraulic Parameters of Hanford Sediments.* Letter Report for Activity 4b, submitted to Lockheed Martin Hanford Company, September, 1998.

A. L. Ward, R. E. Clayton, and J. C. Ritter. 1998a. Hanford Low-Level Tank Waste Performance Assessment Activity: *Determination of In Situ Hydraulic Parameters of the Upper Hanford Sediments.* Letter Report for Activity 4b, submitted to Lockheed Martin Hanford Company, December, 1998.

2.5 Previous Data Analysis and Modeling

Previous modeling of the Sisson and Lu experiment met with mixed success (Sisson and Lu 1984; Lu and Khaleel 1993; Smoot and Lu 1994; Smoot and Williams 1996; Rockhold et al. 1999). Since the radioactive tracers were short-lived and retarded by the sediments, collection of tracer data was confined to wells within a 2-m radius of the injection point. The focus of most of the data analysis and modeling has been 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 the past modeling efforts. Apparently, small-scale heterogeneities (either thin silt or fine sand lenses) not adequately described in the numerical models act to retard the vertical transport of the water plume beyond what 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), has 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 a plume at this site (Khaleel and Freeman 1995; Khaleel and Relyea 1995; Rockhold et al. 1999).

Flow and transport measurements from the ILAW site east of the leak 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.(5) 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).

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(5) A. L. Ward, R. E. Clayton, and J. C. Ritter. 1998a. *Hanford Low-Level Tank Waste Performance Assessment Activity: Determination of In Situ Hydraulic Parameters of Hanford Sediments.* Letter Report for Activity 4b, submitted to Lockheed Martin Hanford Company, September, 1998.

A. L. Ward, R. E. Clayton, and J. C. Ritter. 1998a. *Hanford Low-Level Tank Waste Performance Assessment Activity: Determination of In Situ Hydraulic Parameters of the Upper Hanford Sediments.* Letter Report for Activity 4b, submitted to Lockheed Martin Hanford Company, December, 1998.

3.0 Planned FY2001 Testing

In the following sections, a rationale is provided for the test strategies, and specific details are given for the field tests planned in FY 2001.

3.1 Rationale for Test Strategies

Both the original experiment (Sisson and Lu 1984) and the FY 2000 tests showed considerable lateral spreading of the plume in relatively uniform sandy sediments. Water movement and chemical transport through the Hanford sediments appeared to be controlled by thin layers of fine-textured soils that impeded vertical water movement and accelerated horizontal chemical 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. Therefore, characterization methods designed to describe flow and transport for a chosen site may be required to map thin fine textured soil features in 3-dimensions to accurately model chemical transport. For such features to be seen, geophysical methods were selected based on their potential to measure lithological changes to within 10 cm vertically and 100 cm horizontally. Once the lithology is completely mapped, unsaturated hydraulic properties will be determined for at least a representative set of the units. More emphasis will be placed on the units with lower permeability since these units appear to control water movement.

All of the tests thus far have focused on relatively low concentrations of solutes and tracers. These tests are justified in that they allow determination of the physics of flow and transport and identification of the main processes without too many complications. These studies, however, did not address the significance of density-concentration, viscosity-concentration, or surface tension-concentration relationships and their impact on transport. It has been recognized for some time that high-level waste tank fluids are not similar in either physical or chemical character to that of pure water. Because of their unique properties (e.g., high density, viscosity, and electrical conductivity), the leaking fluids could possibly move deeper and faster than water when subjected to the same surface and boundary conditions in a similar porous medium. Nevertheless, most transport experimental and numerical transport studies at Hanford have assumed that free convection due to density of the solute is negligible relative to the forced advection resulting from hydraulic gradients and dispersion (Ward et al. 1997).

There is now increasing evidence that the assumption of negligible effects of fluid properties, while valid for contaminant plumes of low concentrations, is probably not correct for the types of waste disposed of at Hanford. Thus, the observed deep movement of contaminants under leaking tanks could be in part the result of the fluid properties of the leak effluent. For this reason, when tank leaks at the Hanford Site SX tank farm were simulated by Ward et al. (1997), the unique properties of high (1.4) fluid density and elevated (>1) viscosity were considered. The simulations indicated that dense fluids moving through coarse gravel layers, in the presence of non-uniform water fluxes (e.g., from meteoric water shedding off buried tank surfaces), can give rise to accelerated transport due to fingering (i.e., movement of fluids in narrow channels or rivulets as compared to large scale movement throughout the entire flow cross-section).

Inorganic solutes can increase the density, $^{9}_{9}$w, the dynamic viscosity, $^{s}_{3}$ and, with the exception of a few salts (H_4OH, HNO_3, HCl), the surface tension, $^{P}_{D}$sol, of aqueous solutions. In general, inorganic salts increase $^{P}_{D}$sol by 1.2 mN m-1 per unit increase in normality (Weast 1986). However, this effect has not always been detectable in field soils because soil organic matter and humic acids in the root zone can reduce $^{P}_{D}$sol to less than 72 mN m^{-1} and the surface tension of pure water, $^{P}_{D}$w, at 25oC (Tschapek et al. 1978). In subsurface soils and soils lacking organic matter, Tschapek et al. (1978) also found $^{P}_{D}$sol and $^{P}_{D}$w to be almost identical, leading them to conclude that $^{P}_{D}$sol is independent of salt content. While this may be true for cultivated soils in which salt concentrations are typically kept low, it may not be true for soils used to dispose of radioactive brines.

At Hanford, for example, Reduction Oxidation (REDOX) wastes are typically hypersaline ([$NaNO_3$] ≥ 10 N); caustic (pH ≥ 14); dense ($^{9}_{9}$L ≥ 1.4 g cm^{-3}); viscous ($^{s}_{3}$ ≥ 1.2 cP); and elevated in surface tension ($^{P}_{D}$LV ≥ 85 mN m^{-1}). Such changes in fluid properties have the potential to influence capillary-flow phenomena, soil-water retention characteristics, and, ultimately, infiltration and transport processes. However, the effect of concentrated aqueous electrolytic solutions, or hypersaline fluids, on capillary flow phenomena and wettability in unsaturated porous media is still mostly unknown. Much of what is known about the effects of fluid properties on transport is based on studies performed in saturated media. In general, these studies suggest that a viscous fluid displacing a less viscous fluid (favorable viscosity ratio) tends to suppress the effect of packing and permeability heterogeneities and results in a more uniform displacement (Krupp and Elrick 1968). Others have observed the development of fingers of displacing fluid when the displacing fluid is less viscous than the displaced fluid. Such fingers are accelerated through the medium, bypassing the liquid originally present. Conversely, an unfavorable density ratio (denser fluid displacing a less dense fluid) usually causes gravity fingering, while a favorable density ratio tends to suppress dispersive mixing to produce a more uniform displacement.

Fingering of waste leak fluids in Hanford sediments has not been observed directly in the field, but is the subject of an ongoing EMSP study currently underway.. This study, (29520 Rapid Migration of Radionuclides from High-Level Waste Tanks) is focused on understanding the effect of fluid properties on transport in unsaturated porous media using a series of laboratory experiments and field studies (Ward et al. 2000). Preliminary results with 5M $NaNO_3$ plumes suggest that fluid properties can in fact alter the shape of the wetting front through a combination of effects due to elevated surface tension, density, and enhanced vapor flux in response to the osmotic gradient. The elevated surface tension also appears to have an effect similar to soil particle hydrophobicity, leading to an increase in initial wetting angle and preferential flow. It is now clear that under certain conditions, exclusion of these mechanisms could result in inaccurate predictions of water and solute movement in the vadose zone (Ward et al. 2000). While density-driven transport may be an important phenomenon, it is not known at what depth it might be attenuated due to dilution or heterogeneities. Although there is some speculation that enhanced water-vapor flux due to elevated osmotic gradients may be active at a scale of tens of meters, the impact of such a mechanism is also unknown. Thus, knowledge of the effect of surface tension, density, and viscosity difference on the movement and displacement of liquids in porous media at the field-scale is basic to understanding these more complex problems.

3.2 Fluid Injections

The FY 2001 experiment at the injection site will be similar to the original flow and transport experiment conducted by Sisson and Lu (1984) and nearly identical to the test conducted in FY 2000, but will be distinctly different from the previous tests in the following ways.

1) A high concentration salt tracer will be added. This will allow us to investigate the impact of density, surface tension, and wetting angle on the plume shape and distribution, which previously have been assumed to be similar to water.

2) Solution sampling will be implemented. This will allow us to monitor tracer transport and breakthrough at specific locations as a function of time.

3) Through casing, resistivity will be monitored. The resistivity of the formation and its changes with time will be monitored as a surrogate measurement of salt concentrations and potentially the high risk and currently undetectable species like ^{99}Tc.

The fluid selected for injection in the FY-2001 tests is concentrated sodium thiosulfate pentahydrate ($Na_2S_2O_3 \cdot 5\ H_2O$). Selected properties of sodium thiosulfate at various concentrations are listed in Table 3.1. The tabulated data suggest that concentrated sodium thiosulfate would be a good surrogate for tank waste in terms of density, viscosity, and electrical properties, specifically, since tank leak fluids have similar characteristics.

Table 3.1. Selected Properties of $Na_2S_2O_3 \cdot 5\ H_2O$ (after Weast 1986)

wt% (atomic)	Specific Gravity	Concentration (g/L)	Relative Viscosity	Conductivity (mmho/cm)
0.50	1.0041	5.0	1.010	5.7
4.00	1.0333	41.3	1.088	35.6
8.00	1.0673	85.2	1.197	40.2
16.00	1.1385	181.8	1.534	108
26.00	1.2350	320.5	2.351	135
40.00	1.3852	553.1	5.747	118

Sodium thiosulphate ($Na_2S_2O_3 \cdot 5\ H_2O$), when prepared as a concentrated solution (at 40% atomic weight), has a specific gravity of nearly 1.4 (Table 3.1). When such a dense solution is applied to unsaturated Hanford sediments, the solution moves at rates different from that of water. We conducted some preliminary tests to evaluate the movement of saturated sodium thiosulfate in Hanford sediments.

In a test cell (28 cm wide x 23 cm high x 2 cm thick), 50 mL of a 40% solution of $Na_2S_2O_3 \cdot 5\ H_2O$, equivalent to 1 cm of fluid height, was applied to a 6-cm-thick layer of dry Hanford sand and placed over a graded (d50=1.5 mm) quartz sand layer that was 7 cm thick. The $Na_2S_2O_3 \cdot 5\ H_2O$ solution wicked through the Hanford sand, and within a few minutes fingered through the quartz sand into an underlying silt layer. After several days, the plume had spread little (e.g., plume diameter was less than 7 cm), suggesting that in fine (silt) materials, the dense fluid diffuses very slowly. In contrast, when we repeated the same experiment with tap water, 1 cm of tap water wicked into the 6-cm-layer of dry Hanford sand without penetrating the underlying coarse sand and silt layers. The difference in movement is attribute to differences in solution properties (e.g., density, surface tension, and wetting angle) between saturated sodium thiosulfate and tap water.

Additional testing demonstrated the difference between the penetration of saturated sodium thiosulfate and water into fine-textured (silt) materials. When a 2 cm (100 mL) increment of tap water was applied to a 6-cm-thick Hanford layer of dry sand, the water wicked into the Hanford sand initially, but then fingered through the coarse sand and into an underlying silt layer. Over several weeks, the water diffused out into the silt layer creating a diffuse halo of water with a diameter exceeding 18 cm. In contrast, when a similar volume of thiosulfate solution was applied, the fluid fingered into the silt and diffused outward, but left a sharp wetting front even several weeks after the injection.

To further evaluate the effect of fluid properties, a series of capillary rise experiments using a modified Washburn method (Washburn 1921) was also conducted in the laboratory. Capillary-imbibition experiments were conducted with methanol, assumed to be a perfectly wetting fluid with a contact angle (θ) of zero, deionized water, and a 40% solution of $Na_2S_2O_3 \cdot 5\, H_2O$ in Hanford sand. Results from these tests show a dramatic difference in the wetting properties of the three liquids, which translates into a higher advancing contact angle for concentrated electrolytes.

These bench-scale tests illustrate that saturated sodium thiosulphate at the field scale will likely behave quite differently than water when injected into the Hanford formation sediments. The tests suggest that there will be a relatively high probability that the thiosulfate will move more rapidly through coarse sand layers, but may be retarded in the fine sands or silts. At present, not enough is known about the effects of fluid properties on transport in the vadose zone to accurately predict the distribution of these fluids during the field test. Nevertheless, as a first step, a conceptual model will be developed using what is currently known. This is based on bench-scale experiments injecting the high salt (thiosulphate) plume that was simulated using the Vadose Zone Modeling Team capabilities. The results from the field test should allow refinement of the conceptual model by the end of the tests.

As indicated in the previous test plan (Ward and Gee 2000), the installation of automated devices for monitoring the major state variables describing water and contaminant movement allows the site to be used as a demonstration site. Real-time measurements of variables, such as water-content matric potential and resistivity, will allow us to quantify both water movement and transport through Hanford formation materials and specifically to investigate the extent of lateral spreading of the plume at this test site. The impact of the lateral spreading on the capability to detect leak losses from underground storage tanks will be evaluated.

The FY 2001 test will include the following:

- Simulated brine leak consisting of five injections of 4000-L increments over a 5-week period using a saturated sodium thiosulfate (non-regulated fluid).
- Tracer applications of sodium chloride (0.5%) during the first five injections.
- Three injections (4000-L each) of river water after brine injection.
- Geophysical logging of water content; water potential, resistivity; dielectric properties.
- Monitoring for soil-solution concentrations using soil cores and pore-water samples.

Geophysical logging will include monitoring with a neutron probe, electrical resistance tomography (ERT), cross-borehole radar (XBR), and seismic methods for plume and lithologic delineation. Core samples will be taken at four locations to depths of 18 m (60 ft). We will analyze the data to evaluate the capability 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 display capabilities for observing vadose zone water content changes, pressure profile variations, and drainage responses to both natural and controlled boundary conditions is found by viewing the current Vadose Zone Transport web site where a Hanford test site (the Buried Waste Test Facility) near the 300 Area has been instrumented with water content, pressure, precipitation and drainage sensors and is remotely monitored daily. These data can be found at http://etd.pnl.gov:2080/vadose/tensiometer.htm.

4.0 Monitoring Technologies

A description of the various geophysical and geochemical methods that will be deployed in FY 2001 is provided in the following sections.

4.1 Geophysical Methods

As described in the Detailed Test Plan for the FY 2000 test (Ward and Gee 2000), an Advanced Characterization Workshop was convened at Hanford in February 2000 to identify technologies with potential for application at Hanford. Proceedings of the workshop are available online on the Vadose Zone Transport Study web page at http://etd.pnl.gov:2080/vadose/. Of the more than 20 technologies presented, techniques were sought that could 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 capability 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 capability 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 capability to determine the shape and extent of non-gamma emitting contaminant plumes or their surrogates
- the capability to function and produce useful results in environments that are culturally noisy.

Out of the initial screening, the techniques to be deployed in the FY 2001 include neutron probe logging, cross-well radar (XWR); advanced tensiometry/suction lysimetry; and ERT. Table 4.1 summarizes the methods and their application as well as information on the properties of 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 1999).

Table 4.1. Characterization and Monitoring Technologies Selected for FY-2001 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.
Cross Borehole 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 non-conductive formations. Measures continuous vertical profile. Interpretation may be difficult in complex situations.
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 or a volume. Requires the installation of a series of electrodes in at least two monitoring wells. Now commercially available.

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. Since 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 into vertical access tubes 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 the existing 15-cm i.d. steel casings. This can be done without a need for centering devices, provided the probe is adequately calibrated (Tyler 1988; Engleman et al. 1995 b; Fayer et al. 1995). For the FY-2001 test, one of the neutron probes used by Fayer et al. (1995) will be used. 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 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. Due to the large contrast in the dielectric constant between water ($\varepsilon = 80$) and most earth materials ($\varepsilon = 3 – 5$), 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 in order 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 are 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 cross-well configuration. The data can also be processed to give reflection images in stratigraphic sequences.

4.1.3 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, only limited measurements have been 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 were tested during the FY 2000 experiment. The first was a standard nest configuration where tensiometers were placed together in a hole by using a split-spoon auger device. The tensiometers, connected to the surface via a 1-in. PVC pipe to accommodate both pressure transducer wiring and water refilling, are placed at selected depths, and the hole was subsequently backfilled. The second was a less intrusive method, where individual tensiometers were placed at a depth of interest by pressing them into the ground using a cone penetrometer. Both methods have been deployed successfully at the Hanford site as part of the Science and Technology initiative. A description of the advanced tensiometers and examples of real-time data that have been collected during previous testing can be found at the Vadose Zone Transport Web Page at http://etd.pnl.gov:2080/vadose/tensiometer.htm.

In the FY 2000 test, some of the tensiometers failed due to rupture of the porous cups, and in some cases, the desired depths could not be achieved. In the FY 2001 test, a modified tensiometer will be used. The new design uses a smaller diameter cup, which should allow installation to deeper depths. Non-functional devices will be retrofitted in existing wells to allow collection of real-time data.

4.1.4 Electrical Resistance Tomography

ERT has been demonstrated to be a useful characterization tool, providing details of the stratigraphy 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, 1996) by mapping the spatial and temporal changes in soil resistivity resulting from changes in liquid saturation and temperature. Since tank wastes at Hanford were generally rich in high ionic strength electrolytes, resistivity could 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 over 395 m), but deeper installations require significant and more costly modifications.

The method of ERT data collection and processing has been described in detail (Ramirez et al. 1995). 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 capability 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 a 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).

4.2 Tracer Methods

A series of tracer tests will accomplish the primary objective of the VATFS, which is 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 FY2000 experiment, the objectives of the tracer-testing component were:

1. to define flow paths for a more accurate conceptual model of the site
2. to identify the mechanisms controlling contaminant transport in Hanford sediments.

To meet these objectives, both reactive and conservative tracers were used. These tracers were selected based on their capability 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.

4.2.1 Nonreactive Tracers

A combination of Na salts was chosen to mimic the high levels of Na present in tank effluents. The non-reactive tracer selected for use in FY 2001 is a 0.5% wt of sodium chloride, NaCl, which will be combined with a 40% sodium thiosulfate solution. The thiosulfate provides the increase in density, viscosity, and surface tension required to mimic tank waste at much lower concentrations than would be required with NaCl. However, thiosulfate is not easily detected with conventional analytical methods, so adding chloride will simplify tracking the solute migration by analyzing water samples and soil extracts for the chloride ion. Tracer distributions will be determined from core samples and from pore-water samples, and ion-specific electrodes that can detect chloride in the ppm range are readily available.

The core for analyzing chloride will be prepared using leaching methods described in the Sampling and Analysis Plan (Appendix D). PNNL will analyze pore-water extracts and solution samples 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 the degree of transverse and longitudinal dispersion. Pore water and soil core data will be used to resolve mass balance.

4.2.2 Tracer Injection

During the FY 2001 field tests, the tracers will consist of sodium chloride and sodium thiosulfate. Tracer migration rates will be determined by chloride sampling and by analysis of pore waters and core sampling for isotopes that were injected into the test area in FY 2000.

4.3 Sampling and Analysis

As in FY 2000, the entire site will be logged by neutron probe to determine moisture distributions before injecting water and tracers. Existing CPT pushed boreholes will provide access for the geophysical instrumentation. Cross-borehole radar and ERT profiles will be collected before testing. Soil samples will be collected in geotechnical boring that will be installed by CPT and decommissioned as the CPT string is withdrawn. Subsamples of the wireline cores will be analyzed to determine selected 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. Optional monitoring will include at least two additional placements of Vertical Electrode Arrays (VEAs) for ERT near the injection well and two more advanced tensiometers if needed.

Periodically during the course of the experiment, water content, matric potential, resistivity, and tracer concentrations will be monitored using some of the tensiometer installations. Tracers will be sampled using a combination of wireline sampling and pore-water samples obtained from suction lysimeters. 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 D). 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 equipment and materials (laboratory and field) required to conduct the field tests. Details on the instrumentation have been described by Ward and Gee (2000). In FY 2000, nine VEAs were installed at the test site to facilitate ERT imaging of the subsurface. No new VEAs are anticipated in FY 2001. Four PVC access tubes were installed to accommodate subsurface imaging by XBR and cross-borehole seismic (XBS). No additional access tubes will be installed in FY 2001. The FY 2001 tests will use existing infrastructure to monitor the leak tests.

PNNL will provide the following materials required for the FY 2001 field test:

1) Mixing tank (4000 gal)
2) Delivery metering system capable of delivering approximately 700 L /h (3 gpm)
3) Ion-specific probe for bromide and for chloride
4) Sample vials
5) Extraction pump—for moving samples from solution samples.
6) Site trailer
7) Refrigerator for samples
8) Portable computer for sampling and data collection with Excel.

6.0 Data Management

A project database has been established for storing and managing 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 a 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.

Processed data from FY 2000 have been posted on the VZTFS web site, and raw data are available on CD ROM. Papers representative of the FY 2000 field test were presented in a special session at the annual fall meeting of the American Geophysical Union (AGU) in December 2000. Some of these papers are also being prepared for publication in peer-reviewed journals.

As indicated in the Detailed Test Plan, 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

As the research proceeds, the scale at which one needs to understand and characterize the vadose zone may also change, which would imply that the resolution of the geophysics must change (either up or down). Through the series of planned tests, we can identify the scale at which characterization must be done in order to characterize contaminant plumes at the waste-site scale. Analysis of the experimental data to determine parameters and properties and their spatial representation will follow techniques started in FY 2001 and will continue through this year. The analysis of both field tests will be completed for inclusion in draft reports due in September 2001.

8.0 Schedule

There will be a number of individual tests run during the course of the experiment by a multidisciplinary team comprising collaborators from other National Laboratories, commercial vendors, and consultants. The participants are listed in Appendix A. 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. Thus, proper sequencing of measurements is required and has played heavily in the development of the final schedule. A tentative 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 first five injections will be saturated (40 wt%) sodium thiosulfate with 0.5 wt% NaCl as a tracer.

Table 8.1. Preliminary Schedule for FY 2001 Experiment

Date	Action	Method 1	Method 2	Method 3	Method 4	Method 5	Method 7	Method 8
		Neutron	AT Tens.	ERT	XB Radar	Seismic	Isotopes	Coring
12- Mar	Walkdown							
21 - Mar	Pre-Job Safety Meeting							
22 - Mar		Read 35 cross-calibrate) [2 days]		CPT Install (1 day)				
23 - Mar							samples	CPT-wire (2 days)
23-Mar			Read-c	(3 days) set up/read				
26-Mar								
28-Mar					1 day read			
29-Mar	1st Leak (inject)	Read 16/day						
30-Mar		Read 16/day						
5-Apr	2nd Leak	Read 16						
6-Apr		Read 16					Sample	core
12-Apr	3rd Leak	Read 16		Read (2 days)	Read (2 days)			
13-Apr		Read 16						
19-Apr	4th Leak	Read 16						
20-Apr		Read 16						
26-Apr	5th Leak	Read 16						
27-Apr		Read 16						
17-May	Post Leak			Read (2 days)	Read (2 days)			
22-May	Post Leak	Read 16					Sample	Core
23-May		Read 16				Read		
15-Jun		Read 16					Sample	Core

9.0 Environmental Health and Safety

The excavation permit #DAN 1559, which was issued for the FY 2000 tests, will also be used in FY 2001. 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 C) 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 C. 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. The following identifies the discharge permit that will be used for the FY 2001 testing.

Items 001 and **002** from **CDRR 29451** (SODIUM THIOSULFATE, SODIUM CHLORIDE, WATER) have been reviewed and approved for discharge to ground at the 200 East 299-E24-111 Well Cluster located southwest of PUREX. The Washington State Department of Ecology concurs with our stance that this discharge is covered under State Waste Discharge Permit (ST-4508) for Hydrotest, Maintenance, and Construction activities on the Hanford Site. In previous discussions with Ecology, they have also concurred that radioactive tracers used at this test site in 1980 have since decayed, and the site is not considered radioactively contaminated.

Please note the discharge conditions in the approval below. The conditions are taken directly from ST-4508 and the Pollution Prevention & Best Management Practices Plan, both of which can be found electronically at http://w3.pnl.gov/safety/ems/effluent_management/hydro.htm

Your main action is to be the "responsible party" for answering questions about the project and discharges should the need arise. I also suggest keeping a copy of this approval and the Best Management Practices Plan with project papers. Please let us know if you will be using any other materials or chemicals or if the quantities you use will change.

Thanks and please feel free to contact me if you have questions.
Liz Raney

DISCHARGE TO GROUND REQUEST

The Request to Discharge the Below Items:
From: Vadose Zone Transport Field Study Project
To: 200 East, 299-24 Well Cluster

Item(s): Item 1 – 8,000 LITERS SODIUM THIOSULFATE PENTAHYDRATE (40%) & SODIUM CHLORIDE (0.5%) IN WATER (conditions as described CDRR 29451)
Item 2 – 24,000 LITERS COLUMBIA RIVER WATER (conditions as described CDRR 29451)
Status: **APPROVED**

Discharge Conditions

1. Each discharge must be less than 10 gallons per minute averaged annually. Annual average flow is calculated for each discharge as total gallons discharged in a calendar year, divided by the number of minutes in that year.

2. Each discharge must be less than 150 gallons per minute instantaneously.

3. Single discharges with a volume greater than 14,500 gallons in a 24-hour period, or with a total volume greater than 50,000 gallons in a calendar year, must be reported to Effluent Management group prior to discharge.

4. The only allowed source waters to be used for hydrotest, maintenance, and construction activities are Columbia River water, potable water (treated Columbia River water or groundwater), or demineralized water (treated potable water).

General Requirements and Best Management Practices

1. Each discharge must meet WAC-173-200 Ground Water Quality Criteria (GWQC) unless the discharge is expected to have a contaminant that exceeds the GWQC solely because the source water has a contaminant that exceeds one or more of the GWQC. Discharges that exceed the GWQC at the effluent, but are prevented from impacting groundwater water quality, would be covered by this permit.

2. All discharges shall follow the appropriate Pollution Prevention and Best Management Practices (BMPs) listed below and those listed in the *Pollution Prevention and Best Management Practices Plan for State Waste Discharge Permits ST-4508, ST-4509, and ST-4510* (DOE/RL-97-67, Rev. 3, date 08/99).
   - No discharge shall be allowed within a surface contaminated area (areas with dangerous waste and/or radioactive contaminants).
   - No discharge shall be allowed within 300 feet horizontal radius of a known active or inactive crib, ditch, or trench used for disposal of dangerous and/or radioactive contaminants.
   - No discharge shall be allowed to affect an ecologically sensitive area.
   - Reasonable efforts shall be taken to prevent ponding due to discharge rates above the expected soil infiltration capacity.
   - There shall be no discharge of runoff of wastewater to any surface waters of the state or to any land not owned by or under control of the Permittee, except as authorized by a wastewater discharge permit.
   - Efforts shall be made to recycle, store, and reuse all water to the maximum extent practical.

3. Every discharge shall have an assigned responsible person on site who is familiar with the section of the *Pollution Prevention and Best Management Practices Plan* (DOE/RL-97-67, Rev. 3) that applies to the discharge. This responsible person should confirm compliance with the Plan and be prepared to answer any Ecology questions in the event of an inspection. The discharge of any wastewater not done as specified in the *Pollution Prevention and Best Management Practices Plan* (DOE/RL-97-67, Rev. 3) shall constitute a violation of the terms and conditions of the permits.

4. Collected screenings, grit, solids, sludges, filter backwash, or other pollutants removed in the course of treatment or control of wastewaters shall not be resuspended or reintroduced to the effluent stream for discharge.

Expires: January 31, 2002

10.0 Waste and Residuals Management

PNNL will be responsible to manage wastes and residuals. These activities will be accomplished according to specific procedures followed during drilling and sampling operations. This includes the CPT core sampling and the solution sampling from the solution samplers (tensiometers). In addition, a Memorandum of Understanding (MOU) has been issued between PNNL and BHI that delineates responsibilities for site cleanup and decommissioning. The waste and residual management activities follow the spirit and intent of that MOU as well as the discharge permit that is identified in Section 9.0.

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 and Water Sample Management Plan

Scope: This plan covers the disposition of the soil and solution samples 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. When the analysis is completed, it is not anticipated that any cores will be archived. The cores will be disposed of according to existing PNNL waste management procedures.

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.

When water samples are generated, they will be analyzed on site when possible. Some samples will be transported to the PNNL laboratories in Sigma 5 (Richland) for chemical analysis after which they will be discharge according to PNNL internal waste management procedures.

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 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). Staff at PNNL, Bechtel Hanford Incorporated (BHI), and DOE-RL can access the SBMS menu. PNNL staff can go to PNNL's internal home page at http://labweb.pnl.gov/ and select "Policies & Procedures (SBMS)." Offsite users can access SBMS by going to http://sbms.pnl.gov/. Netscape Communicator 4.5 is the recommended and supported World Wide Web browser at PNNL. This QA Plan also complies with the format requirements of QAMS-005/80 (Interim Guidelines and Specifications for Preparing Quality Assurance Project Plans). If other quality-related activities are later performed, the appropriate SBMS requirements and procedures shall be applied, unless specifically excluded.

12.0 References

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