PNNL-13857

Pacific Northwest National Laboratory
Operated by Battelle for the U.S. Department of Energy

Vadose Zone Transport Field: FY 2002 Test Plan

A.L. Ward
F.W. Gee

May 2002

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

PACIFIC NORTHWEST NATIONAL LABORATORY
operated by
BATTELLE MEMORIAL INSTITUTE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC06-76RL1830

PNNL-13857

Vadose Zone Transport Field Study FY 2002 Test Plan

A. L. Ward
G. W. Gee

May 2002

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

Pacific Northwest National Laboratory
Richland, Washington 99352

Summary

The National Academy of Sciences recently identified significant knowledge gaps in conceptual model development as being partly responsible for the discovery of subsurface contamination in unexpected places (National Academy of Science 2000). Inadequate conceptualizations can limit, not only the understanding of long-term fate and transport, but also the selection and design of remediation technologies. Current conceptual models are limited partly because they often do not account for the random heterogeneity that occurs under the extremes of very nonlinear flow behavior typical of the Hanford vadose zone.

This project will use a combination of geophysical and soil-physics techniques to investigate the infiltration and redistribution of water and dilute tracers in a controlled field experiment at the Army loop Road clastic dike site. In the FY 2002 tests, surface-deployed ground-penetrating radar will be used to identify the discrete pattern of horizonation that comprises the coarse component of the heterogeneity along a 60-m (197-ft) transect. Undisturbed cores from major sedimentary facies will be used to quantify hydraulic properties in the laboratory. The transect will be instrumented to allow water to be applied along its length from a line source. Local-scale water content, matric potential, and tracer concentrations will be monitored as a function of spatial scale by multipurpose Time Domain Reflectometry (TDR) probes and suction lysimeters. The tension infiltrometer will be used to measure mobile-immobile parameters. The resulting data will be used to characterize fine-scale heterogeneity as well as correlation lengths of hydraulic and transport parameters. Tracer-breakthrough data will be used to determine longitudinal and transverse dispersivities and their scale dependence. Parameters will be analyzed to identify a suitable averaging (upscaling) procedure for field-scale infiltration predictions. Distributions of water and solute will be used to validate a numerical model for forward predictions and the applicability of upscaled parameters to processes that typically occur under transient flow and at impracticably large spatial and temporal scales.

The results of this study will help to bridge the gap between local-scale transport observations and field-scale transport behavior. It will allow the validation of recently developed inverse procedures for predicting field-scale parameters and will improve our prediction capability for heterogeneous sediments at Hanford. The improved conceptualizations will permit the U.S. Department of Energy to make defensible corrective and remedial action decisions at Hanford and other waste sites.

Reference

National Academy of Science. 2000. *Research Needs in Subsurface Science.* National Academy Press, Washington, D.C.

Glossary

DOE	U.S. Department of Energy
EMI	Electromagnetic Resolution Imaging
EMSP	Environmental Management Science Program
ERDF	Environmental Restoration Disposal Facility
ERT	Electrical Resistance Tomography
HRR	High Resolution Resistivity
HMS	Meteorological Station
ILAW	Immobilized Low Activity Waste
INEEL	Idaho National Engineering and Environmental Laboratory
LMHC	Lockheed Martin Hanford Company
PNNL	Pacific Northwest National Laboratory
QA	Quality Assurance
RL	U.S. Department of Energy/Richland Operations Office
RPP	River Protection Project
SAC	System Assessment Capability
SCA	Soil Contamination Area
SAP	Sampling and Analysis Plan
SDF	Submarine Disposal Facility
SNL	Sandia National Laboratory
SBMS	Standards-Based Management System
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
WMA	Waste Management Area
WIDS	Waste Information Data System
XBR	Cross-Borehole Radar
XBS	Cross-Borehole Seismic
MOSA	Methods of Soil Analysis

Contents

Figures

Tables

1.0 Introduction

The United States Department of Energy's (DOE's) Hanford Site in southeastern Washington State contains, within its vadose zone, wastes created from nine nuclear reactors and four reprocessing plants. The reactors and processing plants were used for plutonium production during the Cold War and generated nearly $2{\cdot}10^6$ m^3 ($5.283{\cdot}10^8$ gal) of high-level tank waste. Liquid evaporation, discharge to the ground, and tank leakage has reduced that volume by 90% to about $0.2{\cdot}10^6$ m^3 ($5.283{\cdot}10^7$ gal), the remainder of which is currently stored in underground tanks. The stored waste at Hanford is nearly 60% of all the tank waste that exists in the DOE complex (Gephart 2001). The tanks contain about 195 million curies of radioactivity and 220,000 metric tons of chemicals. The discharged and leaked wastes are estimated to contain several times these amounts of radioactive and hazardous wastes. Massive cleanup efforts will be required to remediate the Hanford Site. The DOE needs improved conceptual and predictive models to guide the selection, development, and deployment of effective remediation technologies. However, the formulation of good a conceptual model requires sound theory and sufficient data of good quality (National Academy of Science 2000), and such data are generally lacking.

Many of the practical problems related to soil and groundwater remediation at Hanford require predictions of solute transport over relatively large temporal ($\geq 10^3$ yr) and spatial ($\geq$ 1 km) scales. In most cases, direct observation of flow and transport over these scales is infeasible or simply impractical. Consequently, there is a need for methods to extrapolate the observations of short-term, relatively small laboratory and field experiments to the relevant temporal and spatial scales.

A major hindrance to extrapolating small-scale observations to relevant spatial and temporal scales has been to realistically incorporate the effects of heterogeneity into predictive models. Two types of uncertainty result from an attempt to describe heterogeneity in porous media. The first type is parameter uncertainty and is due to our limited ability to accurately describe the spatial variation of the relevant parameters. The second, parameter-estimation uncertainty, results from estimating parameters from limited data. Uncertainty in parameter estimation is perhaps the most important, yet it is usually ignored. The importance of parameter uncertainty is well documented in groundwater hydrology where it is reported that the unknown patterns of spatial variation in hydraulic conductivity are a more important source of uncertainty than errors in estimating the mean and standard deviation of the hydraulic conductivity distribution (Smith and Schwartz 1981).

There are a number of possible approaches for predicting transport over large scales. The most common approach is the use of deterministic models in which different stratigraphic layers are homogeneous, and discretization reflects the observed zonation. A major limitation to this approach is that it ignores intra-layer heterogeneity. A second approach is also deterministic, but attempts to capture the complex three-dimensional (3-D) variability of the hydraulic properties. The main limitation of this method is that it requires highly detailed measurements of the distribution of hydraulic properties. The final approach treats natural heterogeneity in a stochastic sense. In this approach, intra-layer heterogeneity is represented as spatially random fields characterized by a relatively small number of statistical parameters. Solutions to the flow-and-transport problem take the form of probability distributions and the moments of these distributions. Regardless of the method chosen, there are basic data requirements, either in terms of actual measures of the flow-and-transport parameters in space, or the statistical characteristics of these parameters. This information is not available for the Hanford Site, and while there have been suggestions that it may be easily attainable from existing data, this is generally not the case.

Ideally, flow parameters are determined by calibrating the Richard's water-flow equation to observations of water content and matric potential while transport parameters are obtained by calibrating the advective-dispersive equation (ADE) to observed solute-concentration profiles. However, the data required to estimate objectively the spatial correlation structure of transport properties are mostly unavailable, and the cost of experiments to collect these data from several different sites can be prohibitive.

1.1 Knowledge Gaps

1.1.1 Geohydrological Knowledge Gaps

The largest collection of data that might be useful for estimating hydraulic parameters is neutron-probe measurements taken in the tank farms. However, these data are unreliable because of the large number of probe types used over the years and the absence of cross-calibration relationships to assure data continuity (Engelman et al. 1995a; Meisner et al. 1996). Even without the uncertainty in water-content data quality, the utility of these data for parameter estimation might still be limited. In a recent sensitivity analysis of van Genuchten parameters, Zhang et al. (2002a) showed that if the data are limited to θ, then α is unidentifiable and non-unique (Figure 1.1).

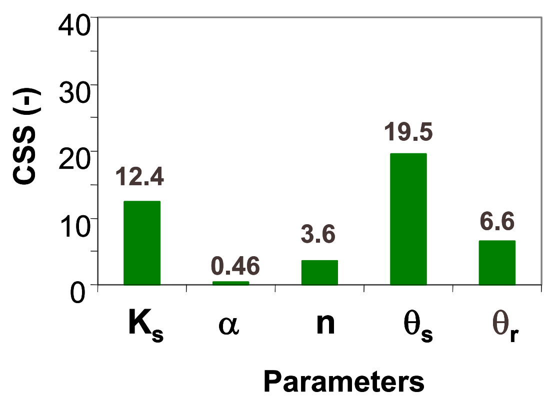

Figure 1.1. Cumulative Scales Sensitivity of van Genuchten Model Parameters (van Genuchten 1980) When Data Used for Parameter Estimation Are Limited to Water Content, θ

When the only available data are the pressure head or matric potential, ψ, then none of the parameters are identifiable or unique (Figure 1.2).

However, if *both* θ and ψ are available, all of the model parameters are unique and identifiable, making it possible to estimate K_S, α, θ_s and θ_r, simultaneously (Figure 1.3). Recently, simultaneous measurements of recharge, water content, and matric potential commenced in B Tank Farm (Gee et al. 2001). The data available for calibrating the ADE and estimating transport parameters are even scarcer. It has been suggested that parameters could be estimated using existing data on contaminant plumes. However, at contaminated sites, there is generally never enough data to allow reliable determination of the necessary parameters. At the Hanford Site, this problem is further compounded by the large uncertainty in the source term and recharge rates. Uncertainty in the source term and its history decreases the reliability of any parameters obtained by calibrating transport models to measurements from the so-called "natural experiments." Even in cases where there is less uncertainty, the existing data are useless for estimating the spatial statistics because for most parameters, the correlation lengths are less than the distance between the sampling points, which are typically about 20 m (65.6 ft) horizontally and 1 m (3.3 ft) vertically.

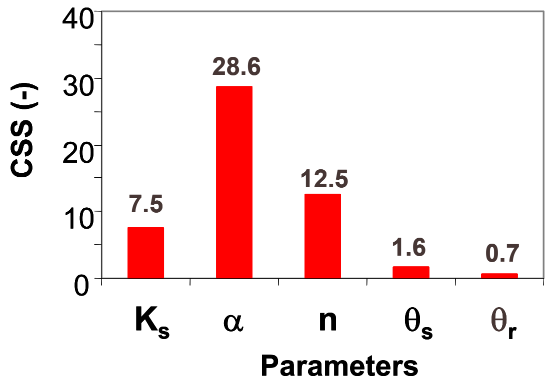

Figure 1.2. Cumulative Scales Sensitivity of van Genuchten Model Parameters When Data Used for Parameter Estimation Are Limited to Matric Potential, ψ

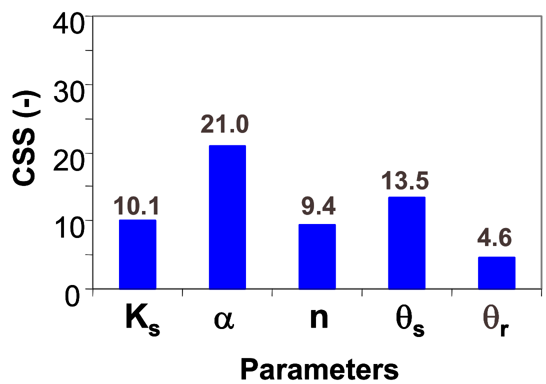

Figure 1.3. Cumulative Scales Sensitivity of van Genuchten Model Parameters when both Water Content, θ, and Matric Potential, ψ, Data Are Used for Parameter Estimation

Interpreting existing contaminant plumes and predicting future fate and transport with numerical models requires knowledge of the average *in situ* hydraulic parameters as well as the magnitude and characteristic length scales of the variations of those properties. However, very few experimental designs have considered this requirement, and in those that have, measurements were limited to shallow depths (≤ 1.0 m [3.3 ft]) and relatively short (≤ 7.0 m [23 ft]) transects (Ward et al. 1998, 1999; Murray et al. 2001). Several cores extending down to the water table have been retrieved and analyzed for hydraulic properties (Reidel and Horton 1999; Fayer et al. 1999). However, core locations were isolated, and selective sampling along their lengths makes it impossible to determine the spatial-scale dependence of parameters or to establish any relationship to observed flow-and-transport phenomena. Consequently, there is little basis for quantifying the effects of heterogeneity on 1) flow-and-transport processes, 2) the support scales necessary for accurately predicting these processes, or 3) the relationship between properties measured at different scales. The vadose-zone transport field studies are intended to resolve these issues.

Within the Vadose Zone Transport Field Study, both the original experiment (Sisson and Lu 1984) and the FY 2000 tests showed considerable lateral spreading of the plume in what appeared to be relatively uniform sandy sediments. Water movement and chemical transport in the subsurface 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 (4 in.) or less in thickness, and 1 to 5 m (3.3 to 16.4 ft) in length. There is also evidence of preferential flow in the vertical direction.

The episodic appearance of contaminants in groundwater beneath the Hanford Site has drawn much attention to transport processes occurring in the unsaturated zone beneath past-practice disposal sites. While the hydraulic conductivity, K, and water-holding capacity of the soil matrix may greatly influence the transport water and solutes, the transport of contaminants to groundwater can actually occur through preferential pathways that bypass most of the matrix. Domain models have been developed to partition soil water into mobile, θ_m, and immobile, θ_{im}, domains with solute exchange between the domains characterized by the mass-exchange coefficient, α. However, before such models can be routinely used, their applicability must first be evaluated and the necessary parameters obtained. Successful application at the field scale will also require information about spatial trends and the relationship between these parameters and surface boundary conditions, particularly the water flux density, J_w. These mechanisms were difficult to test with the leak-simulation tests in the FY 2000 and FY 2001 experiments, but will be amenable to testing with the upcoming tests.

Another design consideration is that of correlation-length scales. The problems that arise in using the ADE are, in part, a problem of scale. Work on the effect of heterogeneity of porous medium properties on dispersion in saturated systems has shown that it may be possible to use an equation similar to the ADE, but with a scale-dependent dispersion coefficient (Mishra et al., 1990). This scale dependence arises from the way in which individual solute particles will gradually sample more and more of the velocity fluctuations associated with the aquifer heterogeneity. Eventually, every particle will effectively sample the range of the velocity distribution for steady flow in a large enough system with second order variability in space. The dispersion coefficient should approach a constant value. The distance required to reach this value is the so-called Lagrangian length scale of the system, and realistic estimates for unsaturated transport suggest that this scale may be a minimum of 15 to 20 integral scales and a maximum on the order of 50 to 60 integral scales, or on the order of 100 m (328 ft) (Mishra et al., 1990). For unsaturated water flow, the same basic principles apply, but the physical picture becomes more complicated because of nonequilibrium effects of preferential flow. Parts of the pore space as well as the vertical heterogeneity of the soil may be bypassed because of preferential flow. This may result in very distinct changes in soil water and transport characteristics. The Lagrangian length scale of heterogeneous soils is typically greater than the soil depth. However, the dominant mechanism of effective dispersion may still be the variation in local pore-water velocity arising from differences in the hydraulic conductivity with dispersion having only a second order effect (Russo and Dagan 1991). Thus, measuring variations in local pore-water velocity over a transect of 60 to 100 m (328 ft) should allow the horizontal Lagrangian length scales to be identified.

In FY 2000, studies initiated at the Hanford Site evaluated the processes controlling subsurface transport and form the basis for developing a reliable database for vadose-zone transport-model calibration. The well-characterized "Sisson and Lu" site, located in the 200 E Area, was the site used for a series of leak-simulation tests. To assess the importance subsurface features and fluid properties on field-scale solute transport, injections of solute-free and hypersaline waters were made in two consecutive years. Data from these tests clearly show that an interaction between small-scale horizontal stratification and fluid properties controlled the subsurface distribution of both fluid types (Figure 1.4). These observations emphasize the need to consider local-scale textural discontinuities in conceptual models of field-scale transport at the Hanford Site because they appear to cause lateral spreading of vadose-zone plumes.

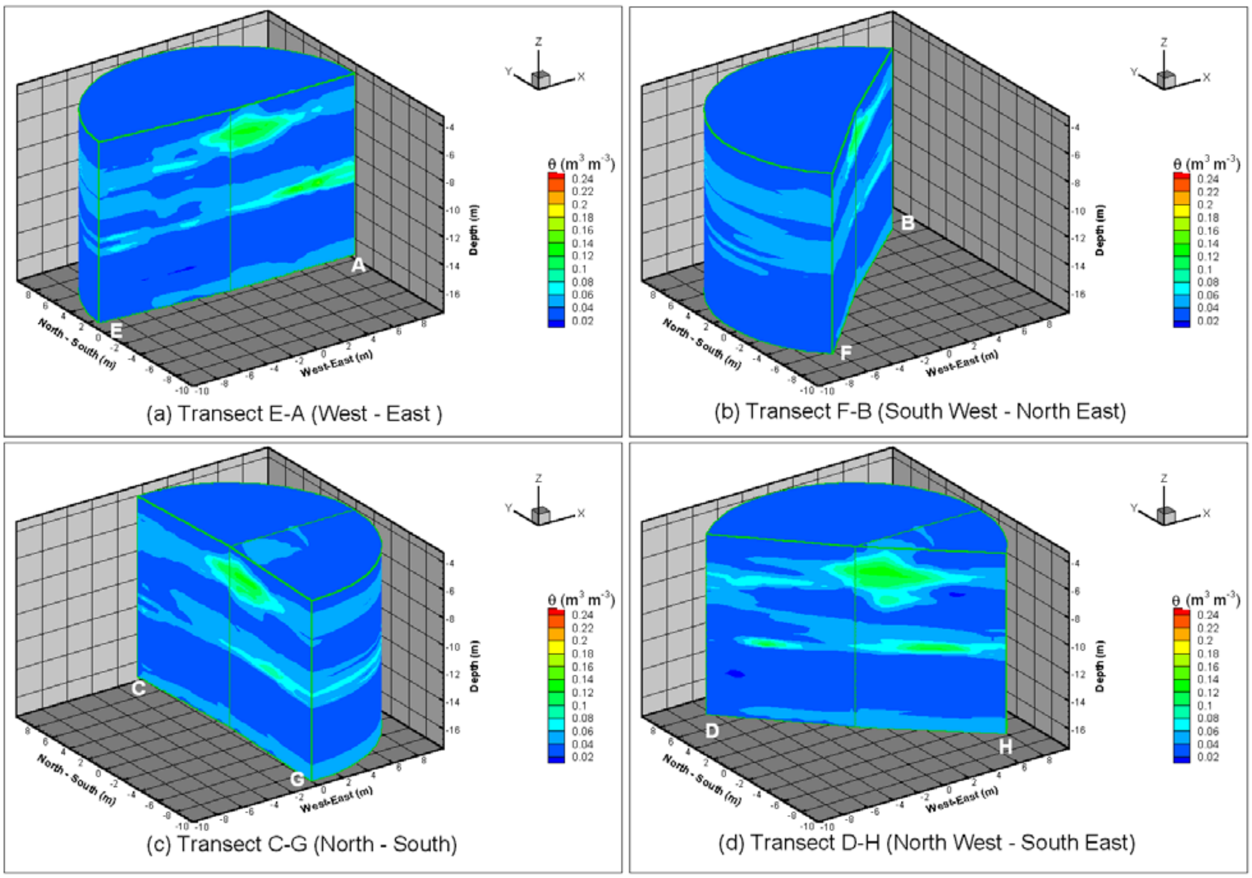

Figure 1.4. Spatial Distribution of Soil Water Content, θ, interpolated from Neutron Probe Measurements in the 32 Wells at Vadose-Zone Test on June 02, 2000, After an Injection of 4000 L (1057 gal) of Salt-Free Water: (a) Transect E-A, (b) Transect F-B, (c) Transect C-G, and (d) Transect B-F

As shown in Figure 1.5, observations of lateral spreading of contaminant plumes in the vadose zone are quite common (DOE-GJPO 1998). These data represent the distribution of selected radionuclides in the vadose zone beneath BX Tank Farm as identified by spectral gamma logging. At this site, contact

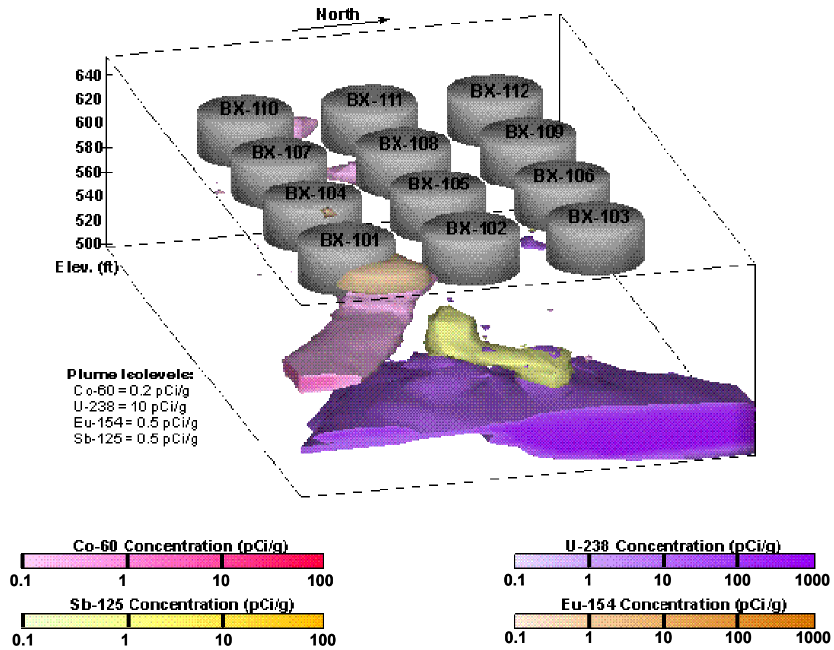

Figure 1.5. Visualization of the ^{60}Co, ^{238}U, ^{154}Eu and ^{125}Sb Contamination in Hanford's BX Tank Farm Viewed From Above the Tanks From the Southeast

between the coarse-grained and fine-grained facies of the Upper Hanford Formation occurs at a depth of 55 ft (16.7 m), and the fine-grained sediments appear to play a major role in transport. Much of the ^{238}U, (the most mobile of the detected radionuclides), ^{60}Co, ^{125}Sb, and ^{154}Eu contamination is in the eastern region and appears to have emanated from Tanks BX-101 and BX-102 (DOE-GJPO 1998). Thus, contaminants appear to have migrated laterally more than 100 ft (30.5 m) within the fine-grained sediments. However, attempts to describe and predict similar distributions within Tank Farms have been mostly unsuccessful because this aspect of flow and transport has proven quite difficult to predict at the Hanford Site with current conceptual models (White et al. 2001).

Distributions of the dilute and hypersaline fluids in the field experiments at Sisson and Liu were modeled using Pacific Northwest National Laboratory's (PNNL's) Subsurface Transport Over Multiple Phases (STOMP) simulator. These simulations treated the site as a heterogeneous system with parameters conditioned on initial water-content distributions (Rockhold et al. 1999). The model discretized the domain into over 20,000 soils, each with a unique set of parameters. While these simulations have come closest to reproducing field observations thus far, there is still some discrepancy. The general features of the water-content distributions are similar to those observed in the field (Figure 1.6). However, it is clear that the current conceptual model and parameterization of the system does not adequately describe the extensive lateral spreading observed in the field. Work is continuing on the development of a conceptual model that incorporates the interactions between fluid and hydraulic properties and that honors the small-scale heterogeneity observed in the field (Gee and Ward 2001). However, model parameterization for field-scale simulations continues to be a major limitation. The physical and hydraulic properties of undisturbed cores from the test site were recently analyzed to reduce the uncertainty in model parameterization for the test site. While the resulting data provide insight into the vertical correlation length scales of flow-and-transport parameters, there is still limited information about the horizontal correlation length scales. In view of this, work is ongoing to evaluate the processes that can cause accelerated transport of hypersaline plumes and to develop techniques to facilitate upscaling and parameterization of field-scale models (Gee and Ward 2001; Zhang et al. 2002a,b). The tests described in this plan will further reduce uncertainty in the patterns of spatial variation in hydraulic and transport properties as well as the errors in estimating their mean and standard deviation.

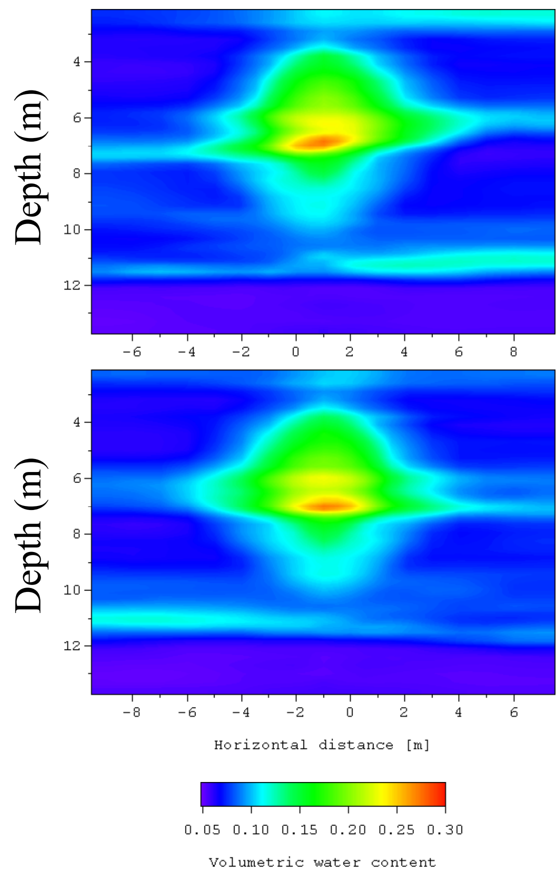

Figure 1.6. Simulated Water Content Distributions on June 23, 2000; 1 Day After Fourth Injection in the VZTFS

1.1.2 Geochemical Knowledge Gaps

The ADE is widely employed to describe field-scale contaminant transport. The principal physical effect of the field-scale application of the ADE is the temporal growth in the dispersion tensor (Kabala and Sposito 1991). In heterogeneous soils, the temporal growth in dispersion has been described using stochastic theory with the assumption that the growth is due to the random spatial variability in the advective velocity. While information on the spatial variation in the velocity can be derived from the tests suggested above, the utility of the information may limit its application to reactive tracers. As with conservative tracers, it is expected that the dispersion tensor will grow temporally in response to spatially variable advective velocities. However, solute spreading is further complicated by the variability in the parameters that characterize reactivity of the solute, whether it be k_D or the distribution and accessibility of reactive surfaces.

In general, the chemistry on reactive surfaces in unsaturated porous media has not been studied extensively, and there is little information for Hanford sediments. Given the extreme heterogeneity of sediments of the Upper Hanford Formation, it is conceivable that subsurface flow regime and water-distribution patters could limit access to reactive surfaces, thereby affecting the distribution of sorbed contaminants. Predicting reactive contaminant transport requires accurate description of the sorption processes for conditions where the soil is not saturated and water content is changing, i.e., transient flow in unsaturated systems. However, this aspect of transport has received little attention in experimental procedures. The closest analogy is the study of the relationship between saturated hydraulic conductivity, K_S, and the distribution coefficient k_D. Field-scale studies of strontium migration at the Borden Site in southern Ontario show significant spatial variability in what appears to be a homogeneous sand at the macroscopic scale (Robin et al. 1991). Observed k_Ds ranged over seven fold from the largest to smallest value and with horizontal correlation lengths ranging from 0.3 to 2 m (1 to 6.6 ft) and vertical correlation lengths ranging from 0.30 to 0.70 m (1 to 2.3 ft). Numerical simulations show that the variability of K_S and k_D and the correlation between the two are key factors controlling solute behavior (Burr et al. 1994; Rabideau and Miller 1994). However, there has been only one reported study of this relationship, and it was conducted in the saturated zone (Robin et al. 1991).

The limitations of applying these theories to the unsaturated zone become quite clear when one examines the two basic assumptions commonly employed. At present, the two common assumptions for most reactive tracer modeling are 1) the system is at steady-state moisture conditions and 2) all of the pore space is contributing to transport. In other words, all reactive sites are expected to be equally accessible, regardless of saturation. Thus, there is no accounting for any bypass, diffusion-limited mass transfer between pores, or the effects of flow regime. Both assumptions are invalid for Hanford's conditions, and the resulting errors will hinder our ability to interpret and predict distributions of reactive contaminants. There is laboratory evidence of an immobile water fraction affecting solute distribution under transient flow conditions, but not steady-flow conditions (Bond and Wierenga 1990).

This apparent conflict may be due to different water-flow patterns arising from the two flow regimes and raises questions about current conceptual models used at Hanford. Multi-region (mobile-immobile water) transport and the exchange of solutes between regions of high pore-water velocities and comparatively immobile regions may give rise to early breakthrough and asymmetric breakthrough curves if the time required for complete mixing between the two regions is large compared with the time for advection of solute over a similar distance. Such a phenomenon would limit exposure to the bulk of reactive sites in an unsaturated system and in systems exposed to unsteady flow. This aspect of transport has received little attention in terms of theoretical development or experimental procedures, and little is known about the importance of initial saturation, flow regime, and sensitivity to micro-structural variability. It is clear, however, that if advective velocity, distributions of reactive surfaces, and the percentages of immobile water are significantly different for steady and unsteady flow, then there is need for extreme caution in extrapolating the results of studies carried out under one flow regime to a different flow regime and in extrapolating results from one waste-management scenario to the next.

The effect of these phenomena can be easily determined by analyzing the cross correlation between advective velocity and the effective retardation coefficient and how it relates to the growth in the dispersion tensor as a function of spatial scale. Robin et al. (1991) reported a weak but significant negative correlation between K_S and k_D for strontium at Borden. Theoretically, a weak relationship between K_S and K_d in the saturated zone is not implausible because k_d is dependent on mineralogy while k_S is related to pore structure. In the vadose zone, it is possible that the relationship between pore structure, flow regime, and wetted (reactive) surface area may lead to a time dependent but stronger relationship between advective velocity and k_D. The distribution of the reactive sites at the pore or "subgrid" scale could be where correlations between advective velocity and k_D are the most variable, but what happens when the density of reactive surface sites is preferentially distributed in pore sizes that are not strongly participating in the transmission of liquids is as yet unknown. Another unknown is how the local-scale heterogeneity (fines and textural breaks) affects access to reactive sites. Identification of the relationships identified above is needed as a precursor to a more rigorous method of modeling reactive transport in heterogeneous systems. Such relationships can be derived only in field-scale tests where variations in local pore-water velocities and reactivity parameters can be observed simultaneously. The inclusion of reactive tracers in a field test will help identify the relationship between flow regime and the pore class accessed by migrating liquids. The resulting information will provide considerable insight into the fundamental behavior of reactive contaminants in unsaturated systems.

1.2 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 FY 2000 and FY 2001 tests, the study is designed to assure the measurement of flow-and-transport properties in the same soil volume, a pre-requisite for developing techniques for extrapolating parameters derived from investigations at clean representative sites to contaminated sites with minimal characterization.

Hanford's soils are inherently heterogeneous, and the constitutive properties (for example, the water retention function $\psi[\theta]$, the hydraulic conductivity tensor, $\mathbf{K}[\theta]$, dispersivity, λ, and the retardation coefficient, R) can be expected to vary in space. These soils also exhibit structural elements (lenses, clastic dikes) that redirect and focus water and solute fluxes at the local scale. Consequently, it is necessary to characterize the soil at length scales comparable to the total transport distance to derive parameters useful for describing infiltration and transport behavior. In the FY 2002 tests, we propose to measure the mean, variance, and spatial structure of flow-and-transport properties from the sediment core scale to the intermediate (≈60 m [197 ft]) scale and to establish the relation between these properties and observed infiltration and transport behavior.

The scope of the FY 2002 test is limited to flow-and-transport observations. The resulting data will support the development of a better understanding of how information about depositional processes can be used to characterize hydrogeological heterogeneity. These data will be critical for improving vadose-zone conceptual models and selecting remedial actions. An added benefit 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 product will be an improved understanding of the relationships between the spatial variations in constitutive properties, observed flow and transport phenomena, and their scale dependence. This will improve our ability to develop representative conceptual and numerical models of vadose-zone flow and transport. This result, in turn, will overcome a major hindrance to the evaluation of remediation and disposal options at different waste sites.

1.3 Project Linkages and Integration

The detailed test plan (Ward and Gee 2000) outlines important project linkages between the VZTFS, the Hanford 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, Groundwater, and River, all of which contribute to the final System Assessment Capability (DOE 1998a). Currently, the River Protection Project (RPP), the 200 Area Soil Remediation Project, and the Immobilized Low Activity Waste (ILAW) are performing or will perform assessment activities in the 200 Areas.

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, initial and boundary conditions as well as physical and chemical processes occurring within the system, and constitutive properties that describe these processes.

2.0 Test Site

The distribution of lithofacies, their sedimentary architecture, and other structural features are of fundamental importance to the analysis of transport behavior. However, many of the important subsurface features are often deep in the vadose zone and not directly accessible for observation. Representative outcrop analogues are the next best option for studying these features at the local scale. One such outcrop is located at the clastic dike site on the Army Loop Road.

The Clastic Dike Site on the Army Loop Road was used as the primary test site for an EMSP-funded study (70193) of the effects of clastic dikes on vertical transport (Murray et al. 2001). The site is located near Antiaircraft Site H-42. The Washington State Plane coordinates are approximately 128500 N and 573500 E. Figure 2.1 shows the location of the site as just off the Army Loop Road due south of the 200 East Area. The site is essentially clean with no documented history of contamination. Ecological and Cultural Resource reviews of the site conducted during FY 2000 and FY 2001 found no impact due to proposed project activities.

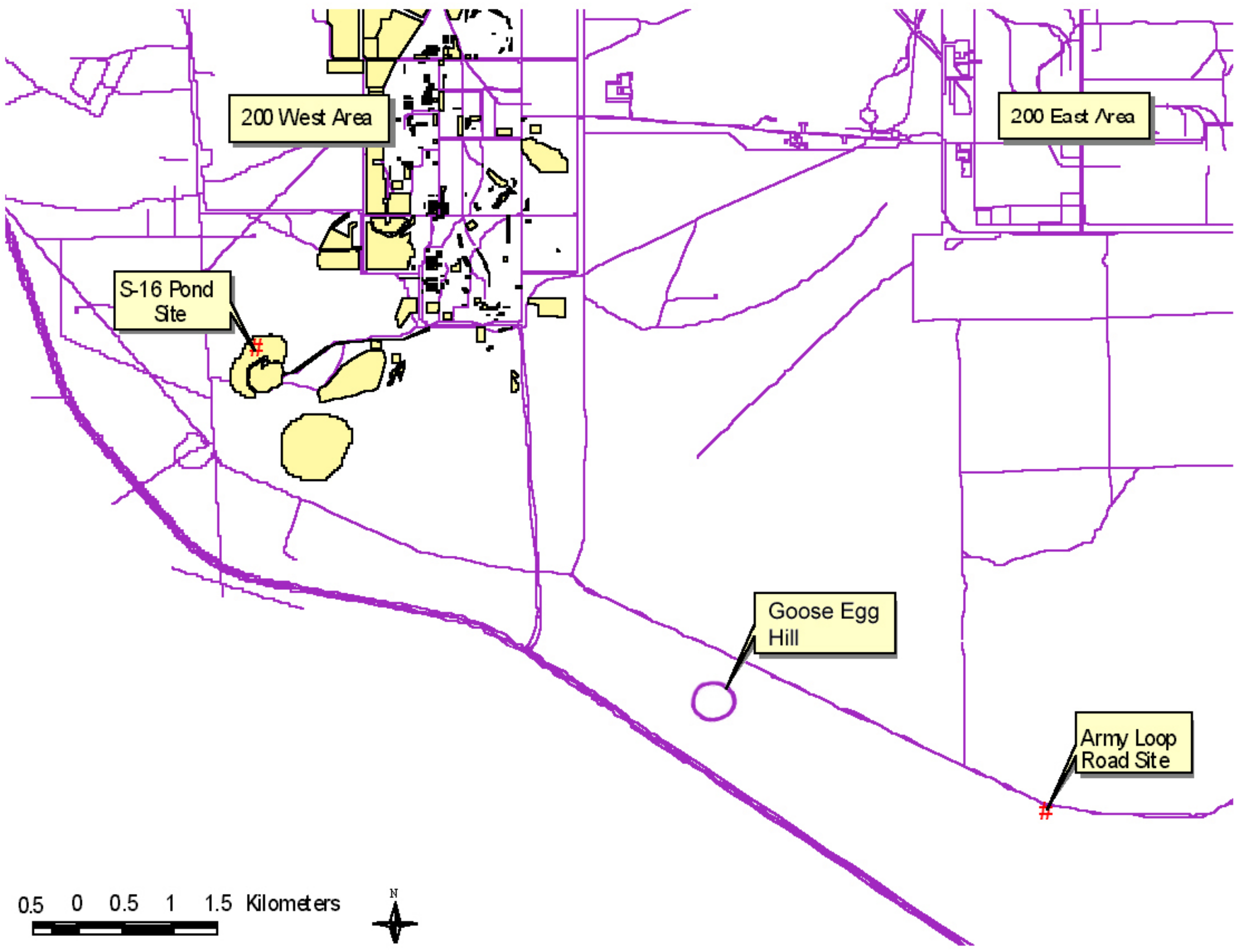

Figure 2.1. Location of the Primary and Secondary Sites for the Clastic Dike Study

2.1 Hydrogeology

The site is located in the 200 East Area of Hanford's elevated 200 Area (Figure 2.1). More specifically, it is about 3 km south of the 200 East Separations Area, about 100 m (328 ft) south of Army Loop Road, and 1.5 km (0.9 mi) east of Goose Egg Hill. The climate at the Hanford Site is arid with cool, wet winters and hot, dry summers. Precipitation at the HMS, located about 10 km (6 mi) west of the test site, has averaged 174 mm (6.85 in.)/yr^{-1} since 1946. Nearly half of the precipitation normally comes in winter months (November through February). Average monthly temperature ranges from -1.5^{o}C in January to 25^{o}C in July. Humidity ranges from 75% in winter to 35% or less in summer.

The upper portion of the 200-Area plateau 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, bringing to the Plateau a thick sequence of sediments known as the Hanford formation (Reidel and Horton 1999).

The hydrogeology of clastic dikes, however, is uncertain. In plan view, the dikes form polygonal structures at the surface (patterned ground) identified by lush vegetation growth along the dike. This pattern of lush vegetation cover is referred to as a vegetation polygon. In the Columbia Basin, dikes typically occur in swarms and form four types of networks: 1) regular-shaped polygonal-patterns, 2) irregular-shaped, polygonal-patterns, 3) pre-existing fissure fillings, and 4) random occurrences. Regular polygonal networks, which are the most common type near the 200 West Area, resemble 4- to 8-sided polygons. Figure 2.2 shows an aerial photograph of the site in which the vegetation polygons are clearly visible. The demarcated circles (e.g., LF-KS, KS-KF) represent the endpoints of transects surveyed by surface-ground penetrating radar (GPR) and seismic methods (Freeman et al. 2000).

Clastic dikes are typically vertical, sedimentary features that crosscut horizontal lithologic bedding. They are thought to have been caused by surface loading, which caused vertical injection of fine particulate material from below, but several different theories exist with regard to their origin. These events occurred due to cataclysmic flooding 13,000 years ago during the Pleistocene period. Dikes generally consist of laminated sand and silt, often with sand at the center and silt along the outer edges (silt/clay skins). The dikes in these networks typically range from 3 cm (1.2 in.) to 1 m (3.3 ft) in width, from 2 m (6.6 ft) to greater than 55 m (180 ft) in depth, and from 1.5 to 100 m (5.0 to 328 ft) along the strike. The material adjacent to the dikes in this area is sand to gravelly sand.

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 sand matrix has a high infiltration capacity (>50 mm [>2 in.]/hr^{-1}); thus, precipitation infiltrates readily with little or no runoff. At the microscopic or local scale, the clastic dike is composed of an outer lining or skin of clay and/or silt with coarser in-filling material or inclusions (Figure 2.3). The linings are commonly 0.03 to 1.0 mm (0.0012 to 0.04 in.) in thickness, but can be as thick as 10 mm (0.4 in.). These linings may have a great influence on water flow and transport. The width of individual in-filling layers ranges from as little as 0.01 mm (0.0004 in.) to more than 30 cm (11.8 in.), and their length can vary from about 0.2 m (0.66 ft) to more than 20 m. In-filling sediments are typically poor to well-sorted sand, but may contain clay, silt, and gravel (Figure 2.3 inset). At the macroscopic or regional scale, the vertical structures may serve as

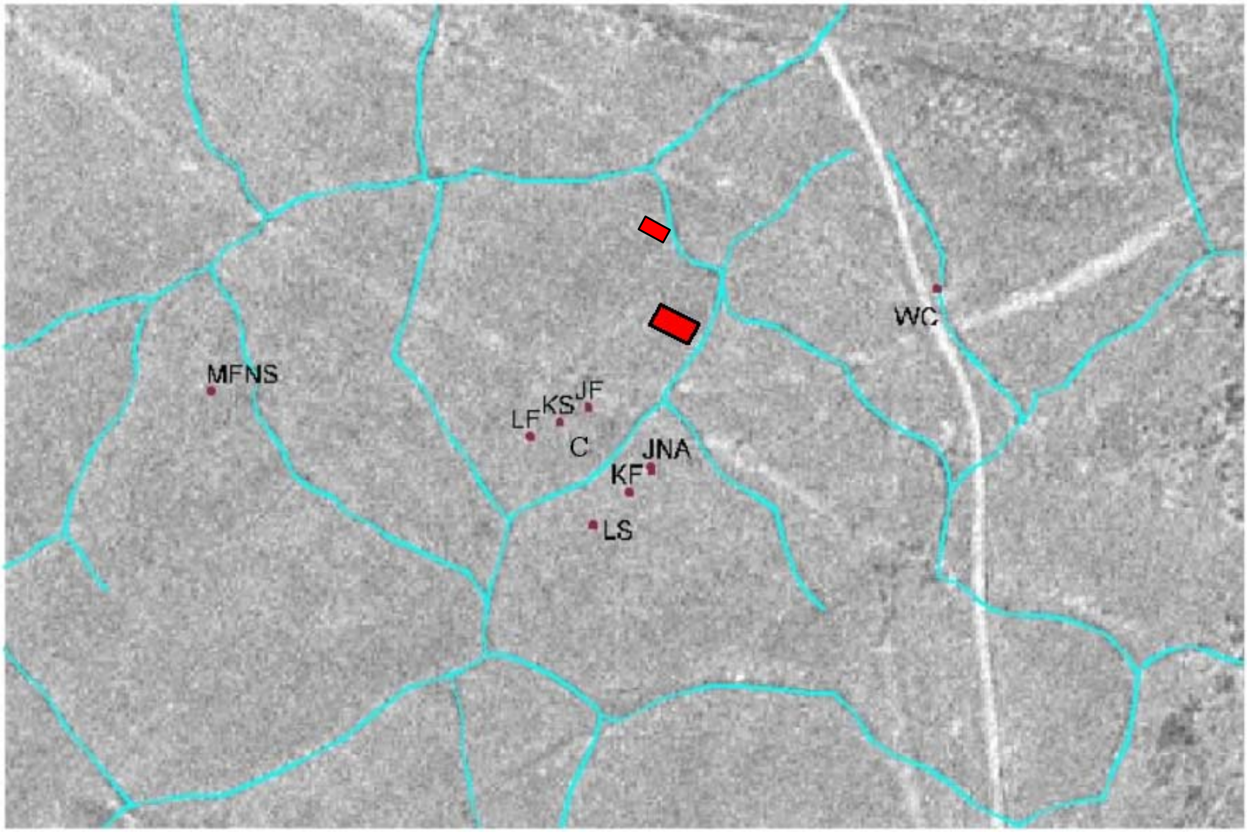

Figure 2.2. Aerial Photograph from July 13, 1996, Showing the Location of the test Site. The site is located near Anti-Aircraft Site H-42 at Coordinates 128500 N and 73500 E on the Washington State Grid. Red lettered circles represent the endpoints of transects surveyed by ground-penetrating radar and seismic methods (Freeman et al. 2000).

preferential paths, or impediments to flow, depending on the flow regime whether conditions are saturated or unsaturated. The horizontal structures may act as capillary breaks, redirecting flow laterally until conditions are such that these layers can be penetrated. Given the range of structural, hydrogeological features present at this site, a wide range of geochemical characteristics might also be expected. However, very little is known about transport properties at this time.

Vegetation at the site was originally a mixture of sagebrush and cheatgrass until the shrubs were destroyed by fire in the mid 80s. Before the tests in FY 2001, vegetation at the site was dominated with a sparse cover of cheatgrass.

2.3 Monitoring Infrastructure

Unlike the test site used in FY 2000 and FY 2001, the clastic dike site is not very well instrumented. There are no vadose-zone monitoring instruments in place to permit deep monitoring. Instrumentation is limited to near-surface Time Domain Reflectometry (TDR) probes for measuring soil moisture and electrical conductivity, and tensiometers for measuring matric suction. In addition, eight PVC access tubes (2-in. OD) were installed to a depths ranging from 5 to 8 m (16.4 to 26 ft) to facilitate monitoring of water content by cross-hole radar and neutron probe (Figure 2.4).

The access tubes were all intended to reach a depth of 10 m (33 ft). However, problems during installation prevented this depth from being achieved. Tube 1 extends to a depth of 5.1 m (16.7 ft); Tube 2 extends to 7 m (23 ft); Tube 5 extends to reach 6.4 m (21 ft); tube 6 is only 4.8 m (15.7 ft) deep. Subsequent excavation of trenches at the site show that thin layers of cemented sands were most likely responsible for the early refusal on the cone penetrometer. These layers appear to be quite prevalent at depths greater than 6 m (20 ft), although some have been observed at shallower depths.

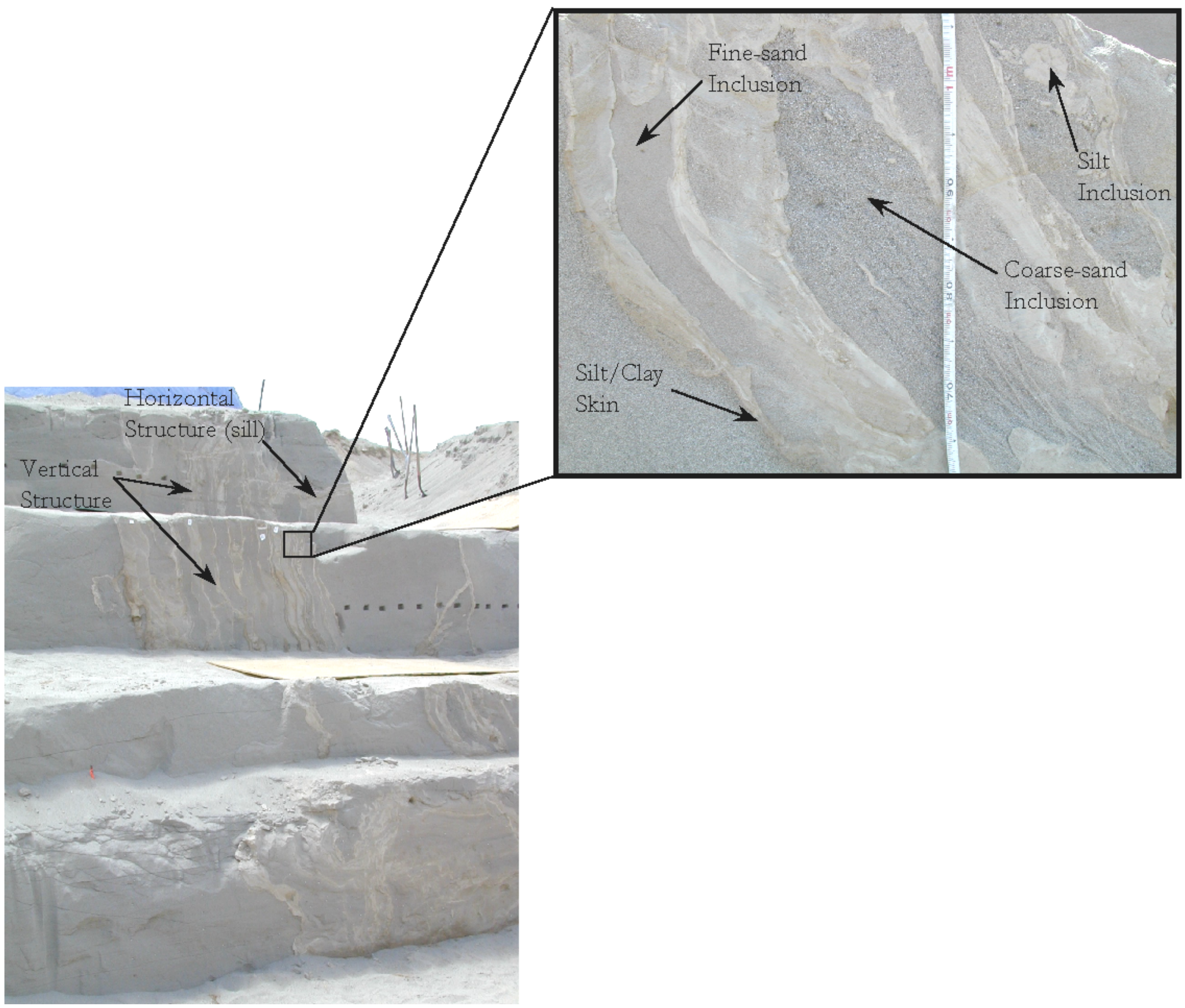

Figure 2.3. Microscopic and Macroscopic Heterogeneity in a Typical Dike Outcrop From the Army Loop Road Site. Note the Vertical and Horizontal Structures, the Fine-textured Skins, and the Inclusions of Varying Texture.

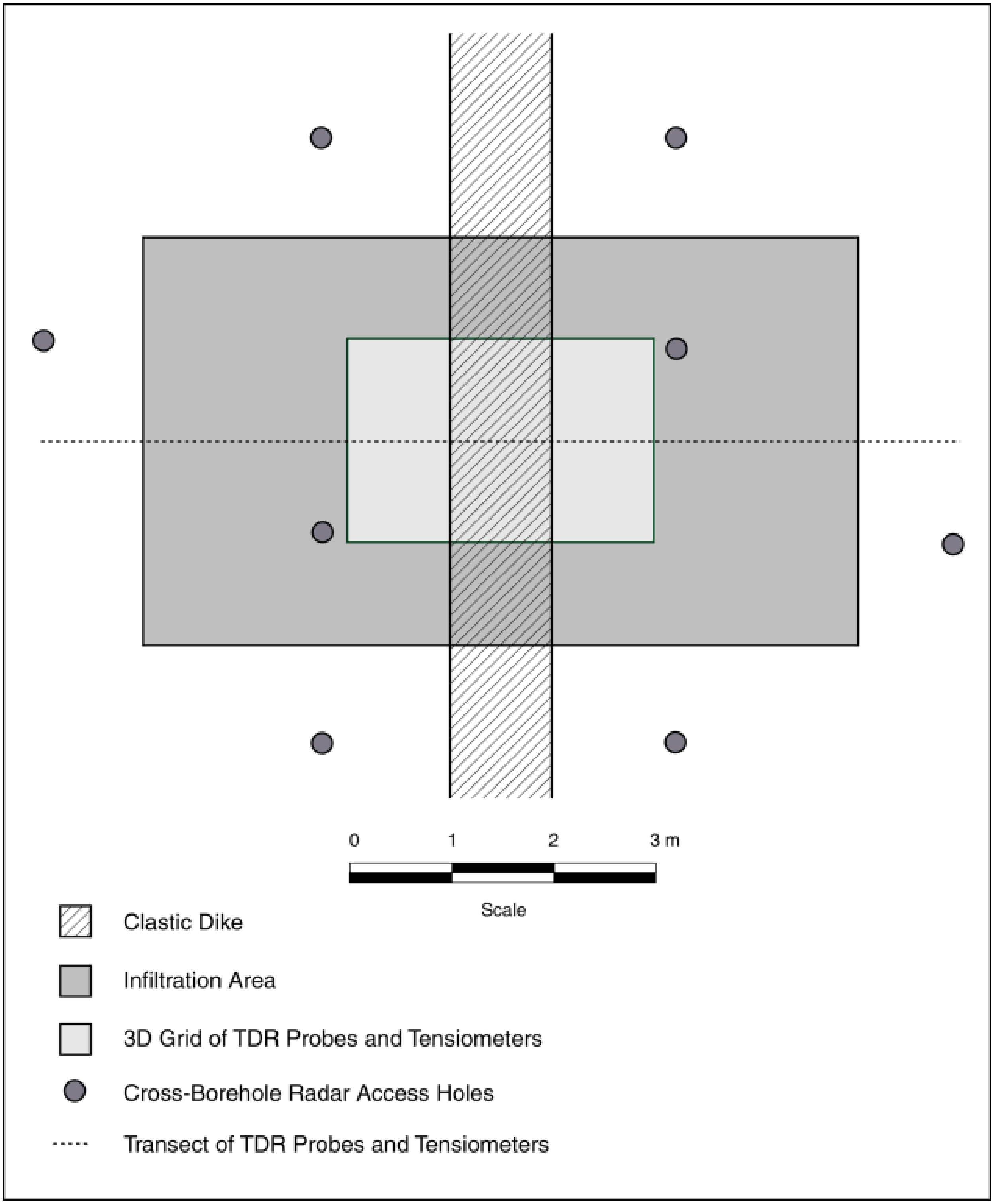

Figure 2.4. Layout of Experimental Plot in the FY 2001 EMSP Test. CPT installed eight access tubes for use with cross-hole radar and neutron probe.

2.4 Previous Tests and Monitoring

2.4.1 Hydraulic Properties

Efforts to measure the hydraulic properties of clastic dikes have been limited. Until recently, the only known measurements were those reported by Fecht et al. (1998), who used laboratory and small-scale field tests to determine the hydraulic conductivity of clastic dikes and their host sediments. At the center of dikes, the average saturated hydraulic conductivity was reported to be about 10^{-5} m s^{-1}. Across the clay linings, the saturated hydraulic conductivity varied from 10^{-6} to 10^{-9} m s^{-1}. The saturated hydraulic conductivity of the host sediment was about 10^{-5} m s^{-1}.

In the FY 2001 EMSP tests, a series of infiltration experiments was conducted at the site. Permeability measurements were conducted using air, water, and concentrated sodium thiosulfate as the permeants. Samples collected during the FY 2001 EMSP field tests are currently analyzed to determine particle-size distributions.

Figure 2.5 shows a cross-sectional view of one of the exposed tiers of the dike site. The host matrix is coarse sand with a mean K_{fs} of 3.24×10^{-4} m s^{-1}; the mean K_{fs} of the dike was 2.58×10^{-5} m s^{-1}; the mean K_{fs} of the sill was 5.9×10^{-6} m s^{-1} (Table 2.1). Measurements were also made at isolated locations using a Guelph Permeameter. Results are separated into sand matrix, composite (sand plus fine textured in the middle of the dike) and a horizontal lens. Figure 2.5 shows the distribution of saturated hydraulic conductivity measured along a transect intersecting the dike. Measurements were taken every 0.3 m (1 ft) along a 7.5-m (24.6-ft) transect using mini-permeameters filled with deionized water.

It is clear that a single set of hydraulic and transport properties will be inadequate for describing this site. There is an order-of-magnitude difference between the sand (2.29×10^{-4} m s^{-1}) to the dike composite (2.04×10^{-5} m s^{-1}) with the lens (9.68×10^{-5} m s^{-1}) being almost five times slower. The mean K_s in the dike material was 1.48×10^{-8} m s^{-1}. The standard deviation is also much larger. These properties can be expected to vary spatially, and eventually temporally, depending on the flow regime. All of the conductivity measurements are summarized in Table 2.1.

2.4.2 Water-Content Profiles

During the CPT installation of the access tubes for cross-hole radar and neutron probe of the field site, water content was measured as a function of depth using a capacitance probe. During the FY 2001 experiments, the wetting front's movement was tracked using neutron probe and cross-hole GPR. Figure 2.6 show plots of relative counts of slow neutrons derived from hydroprobe measurements in the various access tubes. The data show elevated neutron counts at depths of 2 to 5 m (6.6 to 16.4 ft) on the west side of the dike, but not on the east side. There is currently no calibration relationship for converting neutron-probe counts to volumetric water content. However, from neutron moderation, relatively low count ratios, i.e., relatively low θ, can be expected in coarse-textured soils, and relatively high count ratios, or high θ, are observed in finer-textured soils such as fine sands, silts, and clays. Thus, spikes in water content are generally coincident with silty fine-to-medium–fine sand. These observations of higher count ratios on the east side are consistent with the sill shown on the top-most tier of Figure 2.3.

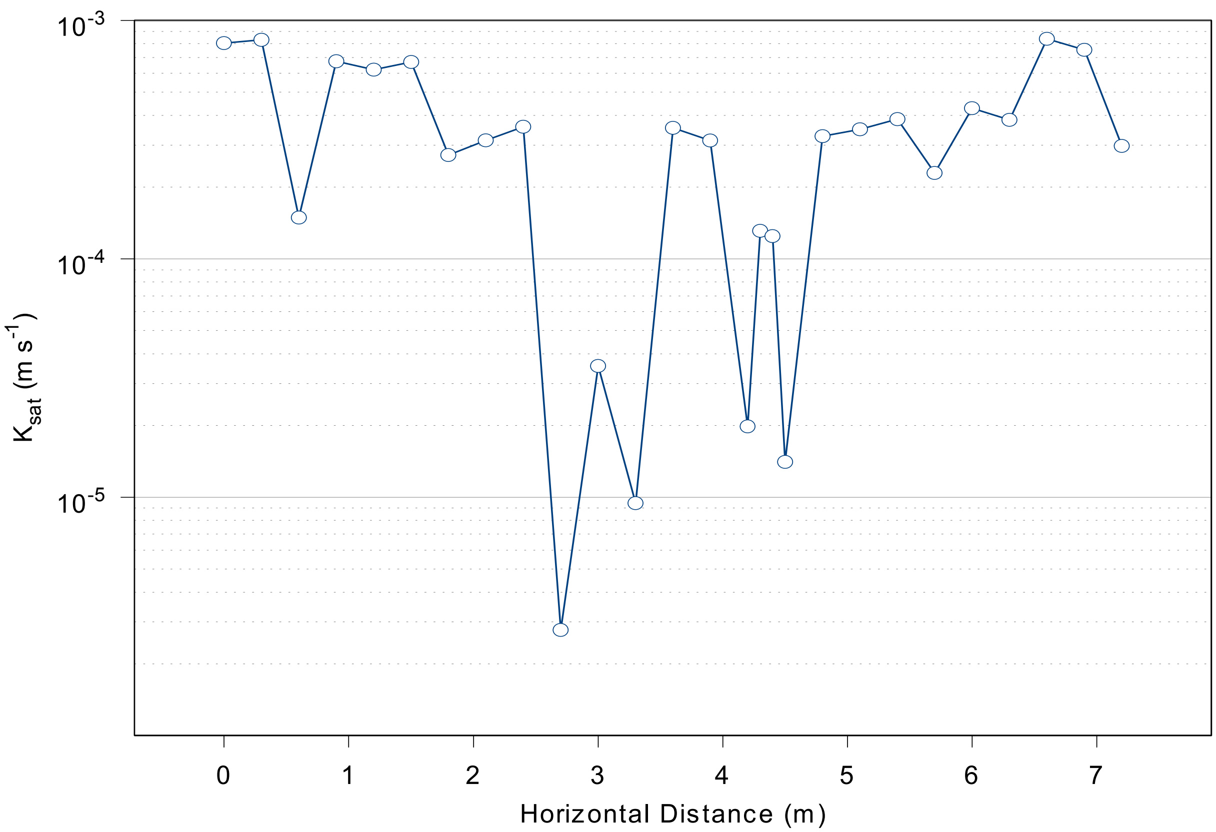

Figure 2.5. Saturated Hydraulic Conductivity Measured by Mini-Permeameter Along a Transect at the Army Loop Road Clastic Dike. The dike is located approximately between 2.5 and 5 m.

Table 2.1. Saturated Hydraulic Conductivity Measured by Mini-Permeameter Along a Transect at the Army Loop Road Clastic Dike. Measurements made using the Guelph Permeameter are shown for comparison.

Tier No.	X (m)	K_{fs} (m s^{-1})		
1	1.0	3.04×10^{-4}		
2	0.3	3.97×10^{-5}		
2	5.5	3.43×10^{-4}	2.29×10^{-4}	1.65×10^{-4}
1	3.0	4.51×10^{-5}		
2	2.2	4.38×10^{-6}		
3	3.8	1.83×10^{-5}	2.04×10^{-5}	1.74×10^{-5}
Lens		5.90×10^{-6}		
All Measures			9.68×10^{-5}	1.41×10^{-5}
2	0–7.5		3.59×10^{-4}	2.67×10^{-4}

2.4.3 Ground-Penetrating Radar

In last 2 years, two surface geophysical methods were used at the site to identify the structure and extent of the dike. The first used surface-ground penetrating radar (GPR) and was conducted along three 30-m (98-ft) transects, LF-KS, KS-KF, and JF-INA, shown in Figure 2.2 (E.L. Majer, personal communication). A second surface GPR survey was repeated along transects KS-KF and JF-INA by Freeman et al. (2000). A third surface radar survey was conducted along seventeen 60-m (197-ft) transects spaced at 2-m (6.6-ft) intervals in 2001 (Murray et al. 2001). Four 30-m (98-ft) lines were also surveyed perpendicular to the main transect at 0, 20, 40, and 60 m (0, 65.6, 131, and 197 ft) along the main transect and a series of cross-hole radar measurements were conducted during the course of the infiltration experiments (Murray et al. 2001). The layout of the experimental plot and the locations of the access tubes are shown in Figure 2.4. This test plot was located at a position approximated by the red box in Figure 2.3.

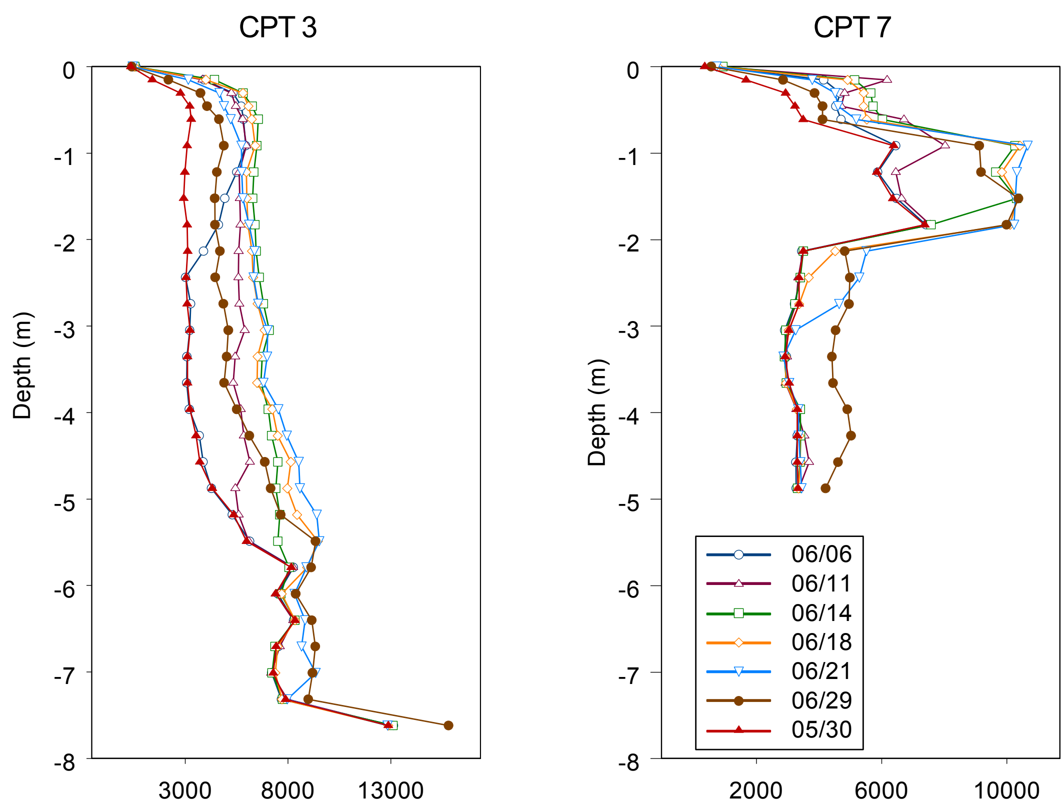

Figure 2.6. Neutron Probe Counts on the West and East Sides on the Dike During the Infiltration Tests. Note the large Increase in Count Ratio at CPT7, Located on the East Side of the Dike, that is absent on the West Side, CPT3.

The outlines of dike polygons that are easily visible from the surface were also easily detected by GPR through their strong attenuative properties. The dike is composed mostly of fine-textured materials that are characterized by high surface charge and therefore high-bulk electrical conductivity. High conductivity increases the dielectric loss of radar signals, resulting in reduced strength of the reflections.

Several coherent reflections were observed in the data (Figure 2.7). In the upper 3 m (1 ft) on the south side of Figure 2.7, a dipping event (A) is seen from 42 to 60 m (138 to 197 ft). This event dips from 1 m (3.3 ft) at 42 m (138 ft) of the profile to 4.5 m (14.8 ft) at the southern end. This reflector may be a bounding surface separating two different units or facies. A strong reflection (B), seen at about 2-m (6.6-ft) depth on the northeast side and at about 42-m (138-ft) depth at the southwestern side, is easily observed in the GPR profiles. This reflection is the strongest event observed at this site. Reflection B may be the base of a channel that scoured the existing sediments. Reflection B is clearly cut by the dikes in the survey area. Beneath Reflection B, a weaker reflection (C) is apparent at about 4.5 m (14.8 ft) on the northeast side of the survey. Another event, (D), dipping to the southwest, is on the southwest side of the section. These events may be continuous, but the attenuation zone and Reflection B overprint reflections C and D, so their continuity is questionable. Although the overlying radar section has few coherent events, the reflection character is similar across the survey. Thus, reflections C and D may delineate a bedding plane or a formation contact. The location of dikes from the GPR data is based on the reflection character in the radar section. In general, the most obvious dikes show diffractions near the surface and a loss of coherence in the underlying reflector (Figure 2.7). The diffractions often define the edges of the dikes. Also, the dikes commonly disrupt or weaken the continuity of underlying reflections. These discontinuous zones are especially apparent in the Army Loop Road data. The interference with the underlying reflections implies that the dikes extend to at least the depth of the reflector, approximately 8 m (26 ft) below the land surface (Figure 2.7). At the Army Loop Road site, the obvious attenuation anomaly along the reflections may indicate that the dikes extend to at least the depth of the reflector. Alternatively, the attenuation may occur at the surface, resulting in a lack of energy returning from the reflector. In this case, the dikes may be a very shallow feature and not extend to the reflector's depth.

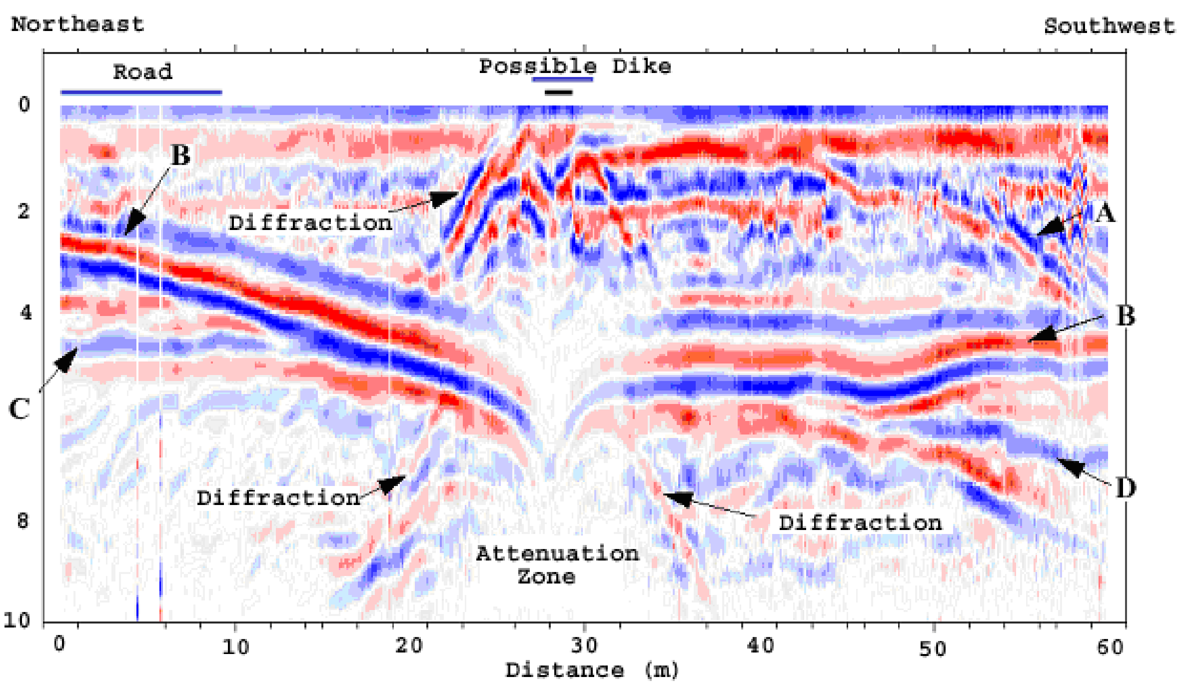

Figure 2.7. GPR Profile from the Army Loop Road Survey Acquired at 24 m (78.7 ft) of the Main Survey. Note the diffractions at the edges and the discontinuous reflection underlying the surface outcrop of the dike. Events labeled A, B, C, and D are discussed in the text.

However, many of these disrupted reflection zones are bounded by diffractions, indicating a change in the EM properties at the edges (e.g., dielectric constant or conductivity). The presence of diffractions at the edges of the disrupted zone strongly indicates a dike penetrating the reflector.

The results presented above show that surface GPR effectively imaged the subsurface at the proposed test site and can provide aerially continuous data in a manner that is non-intrusive and cost effective. The depth of penetration is limited to about the upper 8 m (26 ft), which is sufficient for the field site along the Army Loop Road. The resulting data can be analyzed using geostatistical methods to identify correlation lengths in water content, which can be related to hydraulic properties. These data will also permit an analysis of the spatial-scale dependence of these properties.

2.4.4 High-Resolution Seismic

In May 2001, a field study was conducted to determine whether spatially continuous images of the sediment layers could be derived by high-resolution seismic methods and whether these data could be used to characterize field-scale heterogeneity. During the period May 2–8, a series of 2-D and 3-D, high-resolution seismic measurements were conducted along a 30-m (98-ft) transect (KS-KF, Figure 2.2) at the site. Figure 2.8 shows the wiggle plot of the transect surveyed over the dike. A hyperbolic, diffraction pattern is clearly visible at the dike. The fact that this was a 2-D survey prevented determining the direction from which the diffraction was coming. A better understanding of the seismic results could be achieved by comparing the GPR data with the seismic data. At the clastic dike site, the seismic profile did image the dike structure; however, it was not as pronounced as the image previously derived from GPR.

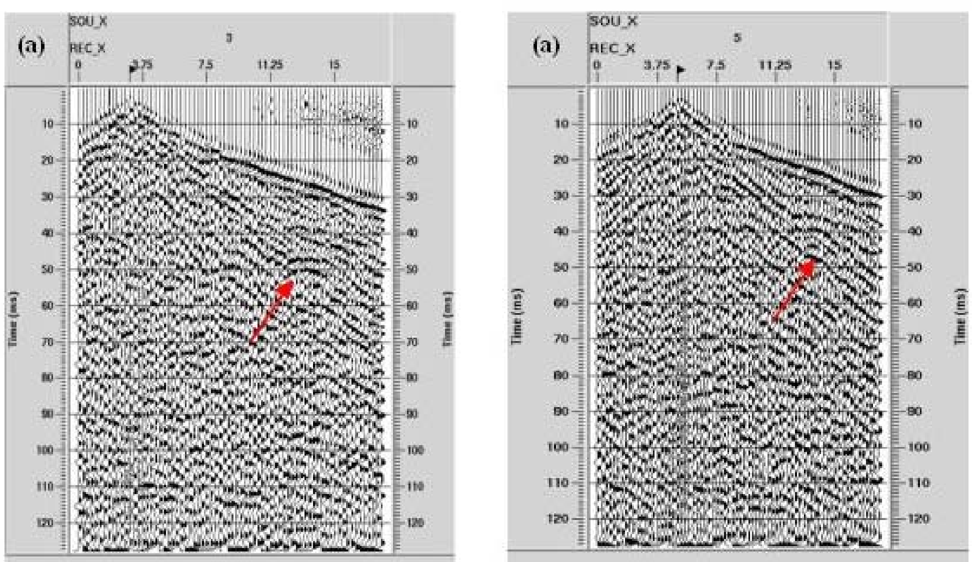

Figure 2.8. Two 300-Hz Filtered and Arc-Filtered Shot Gather Shows the Diffraction Pattern Caused by the Clastic Dikes on the Seismic Data: (a) Shot Gather Source at x=3 m; (b) Shot Gather Source at 5 m

The seismic method appears capable of imaging distinct lithologies in the unsaturated zone at this site. In addition, structural features that can affect the spatial variability of fluid flow were easily identifiable, including some that have never been detected by other means (Freeman and Bachrach 2001). While the experimental design used in the dike test allowed imaging of the dike structure, the resolution was somewhat limited. The resolution for these data is on the order of 0.5 m (1.6 ft); therefore, other methods need to be explored to evaluate smaller-scale structures in the sediments. Nevertheless, these results confirm the utility of the technique and show that when used in conjunction with other techniques like surface GPR, a useful dataset can result. The data are sufficient to support geostatistical analyses that would reveal the spatial-correlation structure for the regions surveyed.

2.5 Previous Data Analysis and Modeling

Most flow-and-transport models for contaminant migration in the vadose zone at the 200 Areas, including the Tank Farms, have been based on relatively simple hydrogeologic models that assume perfectly stratified sediments (Mann et al. 1998; DOE-GJPO 1998), with no preferential vertical flow paths. At least three modeling studies attempted to simulate the effects of clastic dikes on vertical transport through the vadose zone. The studies were sensitivity analyses within larger modeling studies and were based on the assumption of uniform material oriented vertically within a 1-m-thick (3.3-ft-thick) zone (Wood et al. 1996; DOE 1998b). The results of those studies showed minimal impact of the dikes on transport to the water table. However, no actual data on the dimensions or hydrogeologic properties of clastic dikes were used in developing the sensitivity analyses, and the fluxes were orders of magnitude lower than those expected under leaking tanks. A modeling study was also conducted in FY 2000 that addressed sloped sediment layers and clastic dikes. The data package for that study (Khaleel et al. 1999) specified that a 0.3-m-wide (1-ft-wide) dike ran vertically from the base of a single-shell tank to the Plio-Pleistocene layer. The data package called for the dike to be modeled with uniform properties and a K_s value of 1.2×10^{-4} m s^{-1}. Results essentially showed that as specified, the clastic dikes had no effect on flow and transport. It should be noted that these values are at least one order of magnitude higher than those observed in the field. Infiltration tests conducted in FY 2001 are expected to generate additional information to quantify the effects of clastic dikes.

3.0 Planned FY 2002 Testing

Solute transport processes, perhaps with the exception of advection, are still not very well understood, and adequate databases are clearly needed to support a better understanding of these processes. In addition, conceptual models of flow and transport in the Hanford vadose zone are in their developmental stages. Because of these limitations, transport models tend to do well when used to test hypotheses and investigate natural processes, but do poorly when used to determine precise concentrations in the subsurface or to predict future migration with any reasonable degree of certainty. Unlike the FY 2000 and FY 2001 experiments in which water was injected at a point below the surface, these experiments will use surface applications. The experiment is designed to allow measurement of the temporal and spatial relationships of constitutive properties up to a scale of about 100 m (328 ft) during infiltration and drainage. The tests outlined in the following section are intended to provide a data set to test hypotheses about flow and transport while supporting the development of upscaling methodologies. Tests will be conducted along the two transects, A-B and C-D, shown in Figure 3.1.

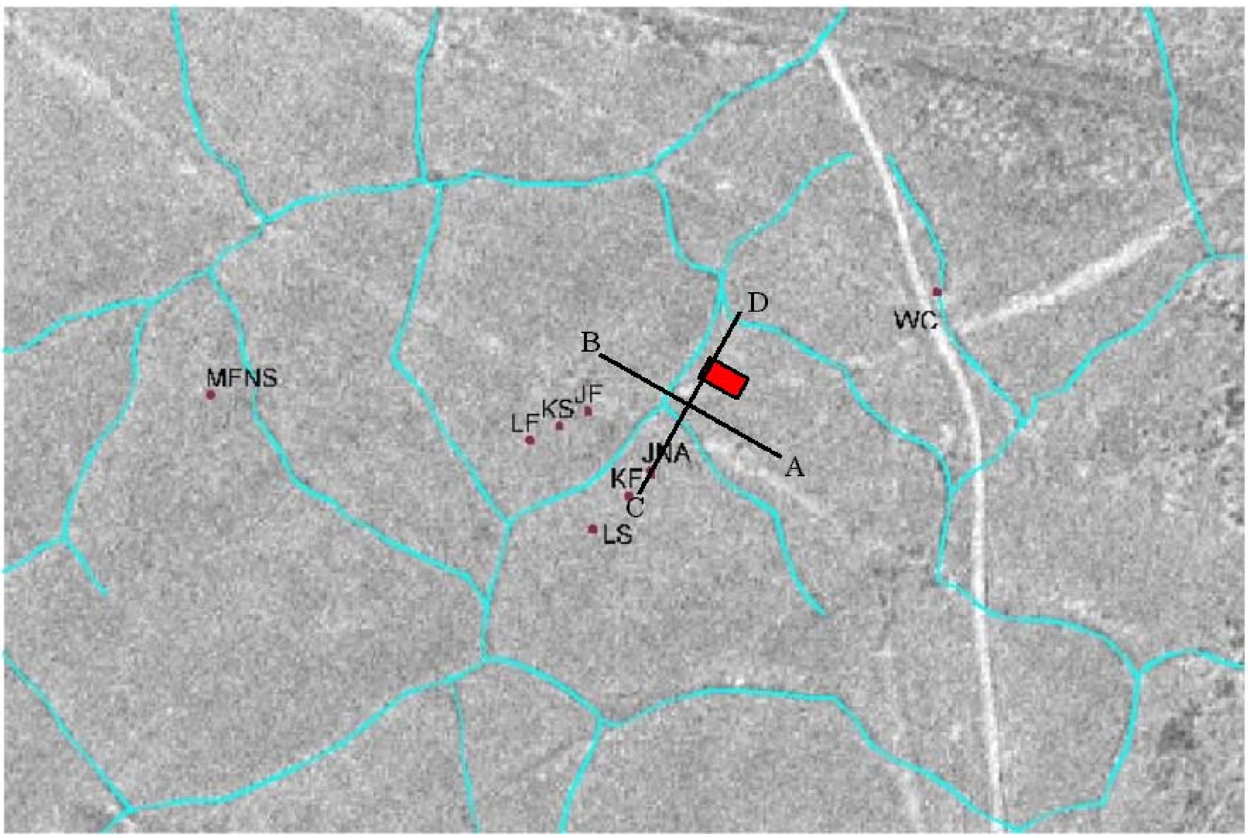

Figure 3.1. Aerial Photograph from July 13, 1996, Showing the Proposed test Site and the Location of the two Monitoring Transects, A-B and C-D

Measurements of θ, ψ, water storage (W), water and solute mass flux, transport volume (θ_t), and wetted surface area, A(θ), that govern capillary and adsorption phenomena can be obtained at the local scale under 1-D, 2-D, or 3-D flow conditions. Permeameters and infiltrometers allow measurement of constitutive properties in 3-D space and changing the size of the volume of interrogation. Thus, coupling these techniques with non-invasive electromagnetic techniques (such as electromagnetic induction and ground-penetrating radar) for use in the Hanford vadose zone will be used to answer questions on 1) the effects of heterogeneity on unsaturated flow and transport, 2) the scale of heterogeneity definition required for predicting these processes, and 3) the relationship between constitutive properties measured at different support scales or in different volumes of investigation. At the same time, a unique data set to support the development of scaling laws applicable to unsaturated, heterogeneous soils would be obtained.

The proposed study will

- quantify the spatial covariance of local water and solute flux at different support scales under 1-D, 2-D, and 3-D flow conditions
- investigate the wetting and drying phenomena through changes in the surface tension of water
- identify the criteria to be satisfied by the scaled properties, and subsequently determine these properties.

Results will allow description of the temporal and spatial relationships of vadose-zone flow and transport, identification of the soil characteristics that influence the scaling behavior of constitutive properties, and identification of the criteria to be satisfied by the scaled properties and subsequently the determination of these properties.

3.1 Pre-Injection Measurements

3.1.1 Surface-Ground Penetrating Radar

There is a gap between the typical local-scale measurement and scale of practical interest, which is often much larger. Ground-penetrating radar, GPR, will be used to fill this gap while also providing information on lithologic contacts. The test site will be surveyed by surface GPR before the infiltration tests. GPR measurements will be conducted using two approaches to determine the velocity of the subsurface. The first method is the traditional common midpoint (CMP) method (Greaves et al. 1996). The second method involves studying the changes in the arrival time of known radar events and then converting this time to velocity (Figure 2.10). This second method, known as Wide Angle Reflection and Refraction (WARR), is not widely applied in GPR surveys, but offers great potential to provide spatially densely sampled velocity measurements that can be converted to the desired parameters, such as the dielectric constant or soil-moisture content.

Because the depth to the different interfaces is quite variable and generally unknown *a priori*, the velocity of the ground wave will first be determined to allow calculation of the propagation velocity at the site (Du and Rummel 1994). Radar data are collected as a measurement of signal amplitude versus time. To convert data to a display in terms of depth, the velocity at which the EM wave travels through the subsurface must be known. Data can be acquired by using a common midpoint (CMP) configuration, where two antennas are gradually moved apart during data collection. Thus, the initial set of measurements will consist of WARR measurements. For the WARR, measurements will start with the antenna located on the transect after which acquisition will proceed with a stepwise increase in antennae spacing with one antenna remaining fixed on the midline of the transect. The direct path of the groundwave between the source and receiver should result in a linear relationship between travel time and antenna separation from which the ground wave can be identified simply as the slope of the groundwave line (Figure 3.2).

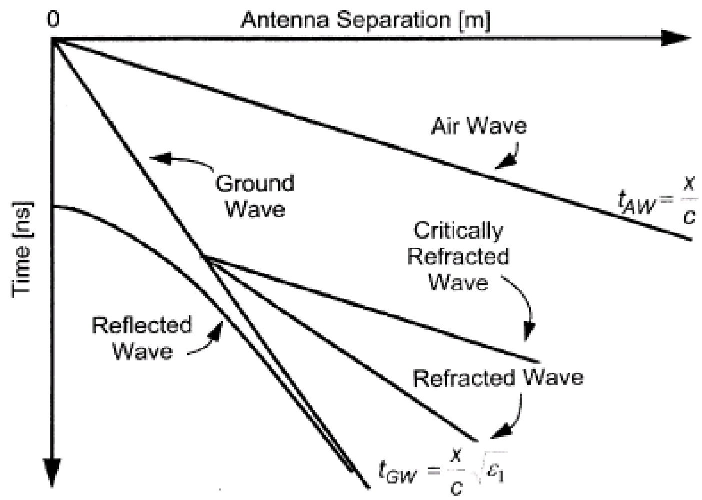

Figure 3.2. Schematic of WARR Measurement Showing the Ground and Air Waves

The data for the WARR surveys will be acquired by first setting the antenna 1.0 m (3.3 ft) apart. Subsequent measurements will be made by moving the receiving antennae in 0.1-m (0.33-ft) increments until the antenna separation reaches 3 m (9.8 ft). Both antenna will be moved about 0.25 m (0.8 ft) per trace, keeping a constant antenna separation of 3 m (9.8 ft). This acquisition geometry should allow easy identification of the ground wave as well as tracking of the event across the WARR profile. This procedure is rather time consuming and will be used only to determine the ground-wave velocity. The results will also be used to determine the optimal antenna separation for recording the ground wave without interference from the ground-coupled airwave and reflected waves from deeper in the profile. Measurements will be repeated along the two transects using a 50-MHz antenna, with an antenna separation of 1.0 m (3.3 ft) and station spacing of 0.2 m (0.66 ft).

Subsequent GPR measurements will use the common midpoint (CMP) technique to determine the spatial and temporal variation in κ as well as lithology along the two transects. Since the acquisition parameters are not expected to change after the initial set of readings, subsequent changes can be attributed to changes in the soil composition, or more specifically, to changes in the soil-moisture content. Measurements will start with 0.1-m (0.33-ft) antenna separation with subsequent increases of about 0.1 m (0.33 ft) (each antenna is moved 0.05 m [0.16 ft] away from the other) about their common midpoint. The data will be analyzed for hyperbolic reflections and linear direct arrivals (Figure 10). The two main direct arrivals are the energy propagating through the air and through the ground.

While higher frequency antennae provide the resolution required to characterize the moisture distribution, lower frequency antennae penetrate deeper. Based on the work of Freeman et al. (2001), a 200-MHz antenna should provide the best resolution down to a depth of about 4 m (13 ft). Freeman et al. showed that in comparison with the data from 50- and 100-MHz antennae, reflections could be seen at ~5, ~6, and ~8 m (~16, ~20, and ~26 ft) with the 200-MHz antennae, but these reflectors would have been difficult to identify without the lower frequency data. The 100- and 50-MHz data show a greater depth of penetration than can be obtained by the lower frequencies, but also show a loss of resolution. The 100-MHz dataset reliably images to a depth of ~10 m (~33 ft), while the 50-MHz data images to a depth of ~16 m (~62 ft).

3.1.2 Surface Hydraulic and Transport Properties

While the hydraulic conductivity and water-holding capacity of a soil can greatly influence water and solute transport, much of the chemical transport to groundwater can occur through preferential flow pathways. Simplified, preferential flow, mobile-immobile models partition the water content, θ, into mobile (θ_m) and immobile (θ_{im}) domains, with solute exchange between the domains characterized by a mass-exchange coefficient (α). However, before such models can be routinely used, their applicability must first be evaluated and the necessary parameters obtained. Successful application at the field scale will also require information about spatial trends and the relationship between these parameters and surface boundary conditions, particularly the water-flux density, J_w.

In the FY 2002 tests, an *in situ* method will be used to determine the mobile-immobile model parameters, θ_m and θ_{im}, along the main transect (A-B) after the site has been surveyed by GPR and before the injection test. This method is based on a sequential tracer application technique and uses a tension infiltrometer to apply a series of four fluorobenzoate tracers at different pressure heads (Clothier et al. 1995). In this test, pressure heads of 10, -30, -60, and -150 mm (0.4, -1.2, -2.36, and -5.9 in.) will be used. The statistics (mean and variance, correlation length) of the flow and transport properties will be determined for the sequence of ψ, starting at the highest value and decreasing. Saturated hydraulic conductivities will also be measured along transect using the Guelph permeameter. Relationships between the parameters will be identified and correlated to pore-water velocities and reactivity parameters determined later in the infiltration tests.

3.2 Infiltration Tests

The experiments will be conducted along a 60-m (197-ft) long transect at the clastic dike site. The proposed transect is depicted as A-B in Figure 3.1. Figure 3.2 shows a schematic of the proposed setup. The transect will be instrumented with TDR and stainless steel solution samplers/tensiometers down to a maximum depth of 1.0 m (3.3 ft). Probe lengths will be 0.2, 0.4, 0.6, 0.8 and 1.0 m (0.66, 1.3, 2.0, 2.6, and 3.3 ft), and lateral spacing along the transect will be 0.3 m (1 ft). At the intersection of A-B and C-D, probes of a short (1-m [3.3-ft]) transect will be instrumented to two depths (0.2 and 0.4 m [0.66 and 1.3 ft]) with a lateral spacing of 0.15 m (0.5 ft) to provide additional information on lateral spreading. TDR rods will be constructed of ¼-in. stainless steel rod and will be spaced 3 cm (1.2 in.) apart. Probes will be multiplexed to a Tektronix 1502B reflectometer using Dynamax multiplexers. A computer will control data acquisition. Once inserted, all of the TDR probes will be tested and used to determine the initial water contents and the bulk electrical conductivity.

Matric potentials will be measured using the stainless steel porous cup lysimeters. Each lysimeter will be fitted with a temperature-compensated pressure transducer and multiplexed using Cambell Scientific's AM416 multiplexers. Data acquisition will be controlled by a CR10 datalogger. Following instrumentation, the soil surface will be raked level, and a 2-cm-thick (0.8-in.-thick) layer of pea gravel will be applied to protect against wind erosion and crust formation and will act as an evaporation barrier.

This approach is preferred to plastic sheeting as it will still facilitate monitoring with GPR and other instruments. Net infiltration rates will be determined from flux measurements using a water-flux meter.

Water will be applied from a surface-line source centered over the 1.0-m (3.3-ft) deep probe (Figure 3.3). Water will be applied at three rates, 0.1, 0.01, and 0.001 K_s, which for typical Hanford soils translates roughly into flux values of 10^{-3}, 10^{-4}, and 10^{-5} cm s^{-1}. Application will start with the lowest rate and will proceed until steady state has been attained. Measurements of θ, ψ, and water storage, W, will be measured at frequencies varying from 30 min to 2 h, depending on the probe depth and the stage of the infiltration. During wetting, the soil profile will be monitored for θ, ψ, and W. At each flux, a direct measure of a K(θ) and ψ(θ) point on the wetting curve will be obtained. At steady state, a conservative tracer will be applied and a solute mass flux measured, from which the spatial distribution of the mean and variance of solute travel-time (*t*) will be determined. The solute front was tracked using pore-water samples and TDR measurements of conductivity. Measurements made during subsequent drainage will provide the drainage branch of ψ(θ). The flux will be incremented once the tracer has been leached from the profile. Water and tracer fronts will be monitored using neutron probe and high-resolution resistivity (HRR) as well as surface and cross-borehole radar.

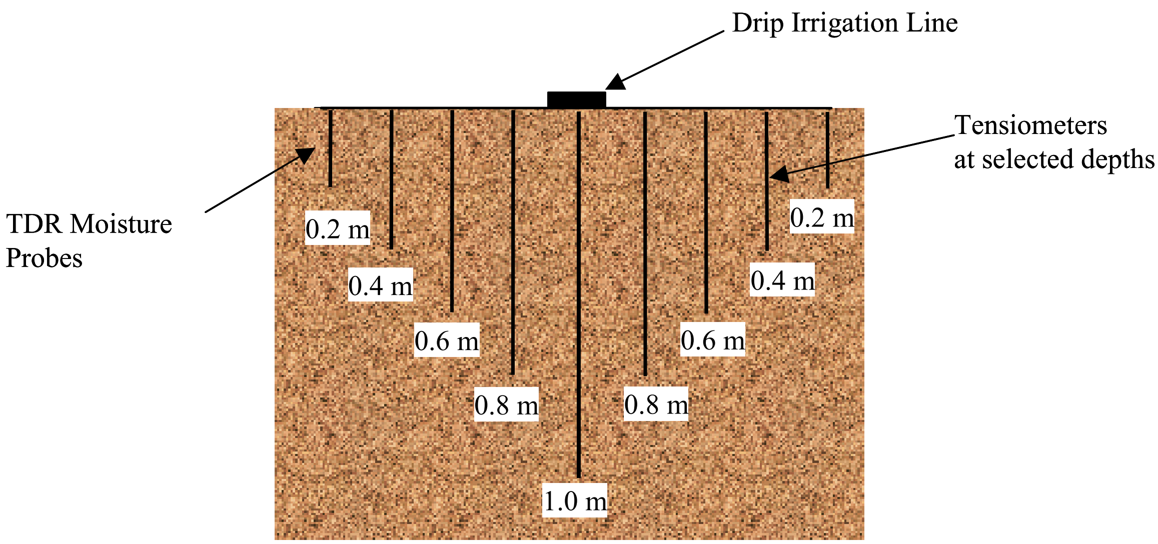

Figure 3.3. Schematic of Experimental Layout

The steady-state measurements of ψ, W, and *t* will be also used to determine the constitutive properties through inverse methods. Relating each flux to the resulting equilibrium water content provides a direct measure of the unsaturated conductivity function. The water content and matric potential data provide a direct *in situ* measurement of the θ(ψ) function. Steady-state distributions of θ, ψ, and W will also be analyzed by inverse methods to determine the macroscopic capillary length, α, and the saturated hydraulic conductivity, K_s, using the method of Zhang et al. (2000). This method is based on an analytical solution for steady flow from a surface line source and is discussed in more detail in Section 6.

Solute breakthrough curves derived from electrical-conductivity measurements and pore-water analysis will be used to determine the longitudinal (D_L) and transverse (D_T) dispersion coefficients, as well as their spatial-scale dependence. Data analysis will take advantage of the analytical solutions to the advective-dispersive equation presented by Leij and Dane (1990). This method assumes that the ADE at the local scale adequately describes solute transport and that flow is steady with 1-D advection and 2-D or 3-D dispersion (Figure 2.12). Steady-state profiles of $C=C(x,z,\infty)$ will be used to determine DT after which values of DL are determined by an iterative procedure. Details of this method are presented in Section 5.

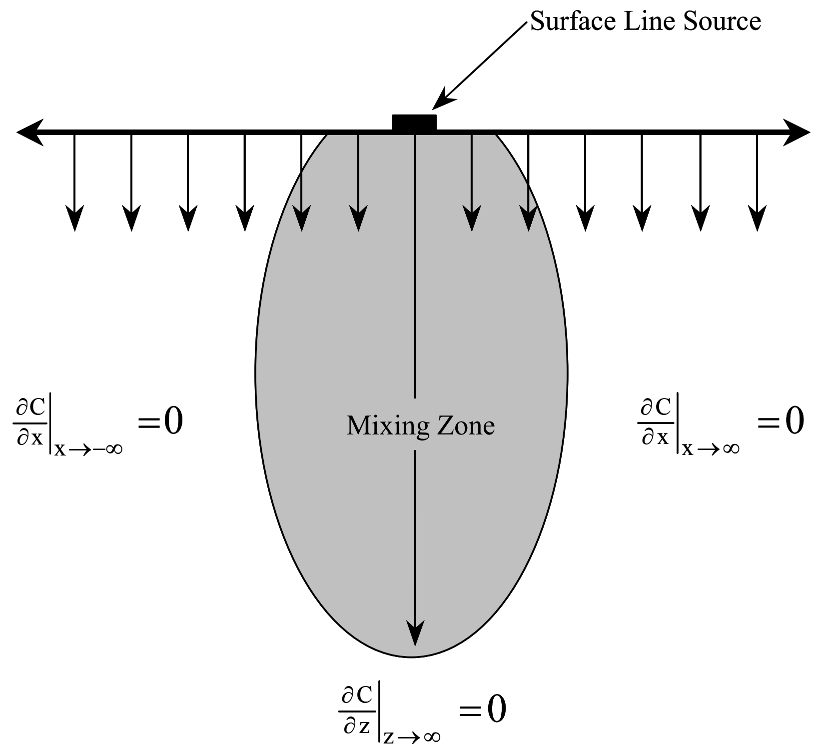

Figure 3.4. Schematic of 1-D Advection and 2-D Dispersion in a Half Plane of a Porous Medium

The resulting data will describe the local-scale flow-and-transport properties from which the spatial distribution of the mean and variance can be determined for evolving scales. The relationship between the volume of measurement and the constitutive properties will be established by quantifying the evolution of properties under the different flow conditions. These results will be compared with the sediment core data to establish the criteria to be satisfied by the scaled properties. To validate the scaling criteria, a water-methanol mixture will be injected with a depressed surface tension (γ) to conclude the infiltration experiment, and the parameters will be reanalyzed. Changing γ will change the $\psi(\theta)$ relationship of the soil in a predictable fashion without changing or deforming the existing pore structure and will allow validation of scaling methods developed.

The data derived from this study will be used to develop scaling theory applicable to unsaturated flow and transport in heterogeneous soils. The product will be an improved understanding of the relationships between the spatial variations in constitutive properties, observed flow and transport phenomena, and their scale dependence. This will improve our ability to develop representative conceptual and numerical models of vadose-zone transport. This result, in turn, will overcome a major hindrance to the evaluation of remediation and disposal options at different waste sites.

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.

3.3 Tracer Tests

A tracer cocktail containing 1.83 kg of KBr and 0.3 Kg of D_2O in 600 L of water will be applied to a 1-m-wide by 60-m-long strip after the system reaches steady-state flow conditions. The bromide ion, Br^-, will be used as a conservative tracer. The tracers will be dissolved in water and applied to the surface at a specific density of 10 g Br^- m^{-2} in 5 mm (0.2 in.) pulse of water. Tracer migration will be tracked using solution samples and conductivity measurements.

4.0 Monitoring Technologies

4.1 Geophysical Methods

In FY 2002, we will use the same techniques that were used in FY 2000: observation, photographs, sampling, and small infiltration tests. In addition to those activities, we will conduct a large-scale infiltration test. During the large-scale infiltration test, geophysical methods will be used to monitor the movement of water both within and outside of a clastic dike (see Table 4.1). The methods will include:

- Neutron Moisture Logging
- Tensiometry
- Crosshole ground penetrating Radar
- Surface ground penetrating Radar
- Time Domain Reflectometry.

These tools were evaluated in FY 2000 and shown to be useful at the Vadose Zone Test Facility (see Table 1.1, Project 30998, and the associated web site http://etd.pnl.gov:2080/vadose/). The boreholes emplaced for neutron logging and cross-borehole radar will also be used to establish a local datum to which all other measurements can be related spatially.

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).

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.

Table 4.1. Characterization and Monitoring Technologies Selected for FY 2002 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.
Ground Penetrating Radar	Moisture distribution, lithology, soil disturbances, buried materials	Dielectric permittivity	5 to 60 cm depending on frequency	The depth of penetration may be quite limited (< 30 cm [< 12 in.]) if formation is electrically conductive; it can be as high as 9 m (29.5 ft) 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 plane of a volume. Requires the installation of a series of electrodes in at least two monitoring wells. Now commercially available.

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 (2-in.) OD, will be used to monitor through steel the 15-cm-ID (6-in.-ID) steel casings. This can be done without the need for centering devices, provided the probe is adequately calibrated (Tyler 1988, Engleman et al. 1995b, Fayer et al. 1995). For the FY 2002 tests, one of the neutron probes used by Fayer et al. (1995) is still available. Two additional probes are also available for use and have been 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 (ε =80) and most earth materials (ε =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 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. The data 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, 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 [9.8 ft] 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 project. A description of the advanced tensiometers and examples of real-time data can be found at the Vadose Zone Transport Web Page at http://etd.pnl.gov:2080/vadose/tensiometer.htm.

In previous tests, 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 2002 test, tensiometers will be constructed with small-diameter porous steel cups and will be installed in the near surface (≤ 100 cm).

4.1.4 High Resolution Resistivity

Need supporting text.

4.2 Tracer Methods

To accomplish the primary objective of the VZTFS, i.e., obtain data to support the reduction of uncertainty in vadose-zone conceptual models and to facilitate calibration of flow-and-transport models, a series of tracer tests will be conducted. For the FY 2000 and FY 2001 experiments, the objectives of the tracer-testing component were to

- define flow paths for a more accurate conceptual model of the site
- 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

The non-reactive tracer selected for use in FY 2002 is a 0.5% wt of potassium bromide, KBr. No attempts will be made to mimic tank waste fluids. Tracer distributions will be determined from real-time electrical conductivity measurements with TDR and from pore-water samples. Ion-specific electrodes that can detect bromide in the ppm range will be used to analyze the water samples.

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 the degree of transverse and longitudinal dispersion. Pore-water samples will be used to resolve mass balance.

5.0 Sampling and Analysis

As in previous tests, the entire site will be logged by neutron probe and ground-penetrating radar to determine moisture distributions before water and tracer injection. Existing CPT-pushed boreholes will provide access for the geophysical instrumentation.

Periodically during the course of the experiment, water content, matric potential, resisitivty, and tracer concentrations will be monitored. Tensiometers will serve the dual purpose of monitoring matric potential and collecting pore-water samples. Similar determinations will be made on pore-water samples. 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.

5.1 Hydraulic Properties

Sampling will include 5-cm-OD (2-in.-OD) undisturbed cores to allow measurements of particle-size distributions, water retention, $\theta(\psi)$, saturated hydraulic conductivity, K_s, and bulk density, ρ_b. The $\theta(\psi)$ will be measured for drainage conditions by equilibrating samples on pressure plates at matric potentials, ψ, of -0.5, -1, -3.3, and 150 m (-1.6, -3.3, -10.8, and 492 ft) with water content, q, being determined by gravimetry after each equilibration. These cores will be taken at increments of 1 m (3.3 ft) along the horizontal and at depths of 0.25, 0.5, 1.0, and 2.0 m (0.8, 1.6, 3.3, and 6.6 ft) with more detailed sampling near interesting subsurface features. Larger undisturbed cores will be taken at selected locations for determining unsaturated hydraulic conductivity. Saturated hydraulic conductivity, K_s, will be measured using constant head techniques (Klute and Dirksen 1986), and the unsaturated hydraulic conductivity, $K(\psi)$, will be determined using an instantaneous profile method (Wessolek et al. 1994).

5.2 Tracer Concentrations

Tracer concentrations will be measured on soil-water extracts using ion chromatography. Samples for analysis of Br^- will be prepared using leaching methods described in the Sampling and Analysis Plan. 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 for each cutface. Tracer concentrations will be fit to various models to quantify the transport velocity and the transverse and longitudinal dispersion coefficients for both conservative and reactive tracers. Pore water and soil-core data will be used to resolve mass balance.

Tracer analysis will be also be conducted on solution extracts taken during the course of the experiment. These samples will be collected periodically by applying a vacuum to the array of solution samplers. The sampling schedule will be determined by premodeling the injection. However, the goal will be to obtain at least 15 samples per location to adequately describe the breakthrough curve.

6.0 Equipment and Materials

This section describes the equipment and materials (laboratory and field) required to conduct the field tests. The layout of the field site, including the new sampling locations, is shown in Figure 4. Ward and Gee (2000) described details on the instrumentation. In FY 2001, eight PVC access tubes were installed to accommodate subsurface imaging by crosshole radar. During excavation of the site for characterization, some of these tubes were removed or rendered unusable. Four additional tubes will be installed in FY 2002.

PNNL will provide the following materials, which will be required for infiltration and tracer testing for FY 2001:

- Mixing tank (15,142 L [4000 gal])
- Delivery metering system capable of delivering approximately 700 L (185 gal)/hr (3 gpm)
- Ion specific probe for bromide and for chloride
- Sample vials
- Extraction pump-for moving samples from solution samples
- Site trailer
- Refrigerator for samples
- Portable computer for sampling and data collection with Excel.

7.0 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 the FY 2000 and FY 2001 tests 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.

8.0 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 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 data from the field tests will be completed for inclusion in draft reports due in September 2002.

8.1 Hydraulic Properties

The physics that define the GPR method as specified in Topp et al. (1980) state that the dielectric constant of a soil is directly related to the water content of the soil. The electromagnetic wave propagation in the soil is related to the dielectric constant by the equation

$$V = \frac{C}{\sqrt{\varepsilon}} \tag{1}$$

where

V = radar-wave-propagation velocity
C = the speed of light in a vacuum
ε = the relative dielectric permittivity.

Topp et al. (1980) then fit a third-degree polynomial equation, which relates the dielectric constant to volumetric water content (θ), to the soil data for a broad textural variety of soils. This is given by

$$\varepsilon = 3.03 + 9.3\theta + 1460\theta^2 - 76.7\theta^3 \tag{2}$$

This method is particularly useful because the dielectric constant of most soil particles is about 3 to 5 while the dielectric constant of water is about 81, which means that water dominates the electromagnetic signature. The final product of the GPR survey is to develop soil-water distribution for a volume of porous material. Steady-state distributions of water content, pressure head, and water storage will be used with the solution of Zhang et al. (2000) to estimate the hydraulic properties by inverse methods. *In situ* measures of water content and pressure head at different fluxes will provide direct measurements of the water retention as a function of spatial scale.

8.2 Transport Properties

To describe 2-D and 3-D solute transport, both the longitudinal and transverse dispersion coefficients are needed. Zhang et al. (2000) extended existing steady-state solutions for constant-flux infiltration to obtain expressions for distributions of ψ, water storage, W, and solute travel time, T, for constant flux below a surface-line source. The solution of Zhang et al. (2000) will be used to estimate the hydraulic properties by inverse methods. Leij et al. (1991) presented an analytical solution for the 2-D ADE for semi-infinite media with 1-D flow using a double integral transform. This solution will be used to determine values of D_L during transient conditions and D_T during steady-state flow, provided the flow field is known or can be measured.

8.3 Geostatistical Determination of Spatial Correlation

Although sedimentary units typically show a great degree of spatial variability, they also tend to show a distinct, directional correlation, which is thought to be related to depositional processes. This variability has been shown to affect transport processes. Analysis of the degree of spatial variability and identification of spatial correlation length scales will be based on the theory of regionalized variables. In this approach, a value of a parameter Z (e.g., θ, ψ) measured at a given location is considered a single realization taken from a probability distribution. The set of such values measured at different locations is then treated as a spatial array of random values. Application of the theory is based on the assumption that Z is spatially stationary so that 1) each location is described by the same probability distribution, f(Z; x,y) and 2) spatial covariance depends only on the separation between the measurements and not on the absolute location. To calculate the properties of Z without knowing f, we require two assumptions: 1) staionarity and 2) ergodicity. Discrete measurements will be obtained at different times along the sampling transects and will be used to construct semivariograms. Experimental semivariograms will be calculated from the pre-injection GPR data as well as the water contents, pressure heads, water storage, and tracer travel times measured during the experiment. Semivariograms will be used to identify the spatial correlation structure and the correlation lengths (the distance at which a plateau in variance is reached) for each principle direction. The equation used to relate the directional correlation length for properties measured over an increasing spatial scale is

$$\gamma(h) = \left(\frac{1}{2N(h)}\right)\sum_{j=1}^{N(h)}\left[Z_j(x+h) - Z_j(x)\right]^2 \tag{3}$$

where the sum is taken over the set of all measured pairs of values a distance h apart; h is the separation distance, N(h) is the number of measurement pairs separated by distance h; and Z(x) is the value at position x. As the separation distance becomes greater along a given direction, s, γ(h) approaches an asymptotic value known as the correlation length, λ_s , which represents the distance beyond which measurements of Z are statistically independent. In some formations, γ(h) may oscillate, an indication of a cyclical property. This might be expected at locations of fine-textured layers in a coarse host matrix such as silt lenses or polygon boundaries of a dike. In such instances, a model, such as the hole-effect model, that takes this phenomenon would have to be considered. Methods such as those outlined above will be used to quantify the spatial correlation structure at the test site.

9.0 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.

Collaborators have used teleconferencing for planning meetings and will continue as work progresses. The project schedule, developed from the planning meetings, is shown in Table 9.1. 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 9.

Table 9.1. Preliminary Schedule for FY 2002 Experiment

Date 2002	Action	Neutron Probe	GPR survey	XBR	Solution Samples
29 Apr	trench excavation				
29-Apr	pre-injection site walk down				
16-May	baseline logging	X	X	X	
17-May	instrumentation placed				
20 May	all drip irrigation lines placed and covered				
22-May	start water injection				
23-May	monitor profile	X	X		
23-May	monitor profile	X			
24-May	monitor profile	X			
28-May	monitor profile	X	X		
31-May	collect samples	X			X
3-Jun	collect samples	X			X
7-Jun	inject tracers	X	X		X
11-Jun	collect samples	X	X		X
14-Jun	collect samples				X
17-Jun	collect samples	X	X		X
21-Jun	collect samples				X
24-Jun	collect samples				X
28-Jun	collect samples	X	X		X
1-Jul	collect samples				X
8-Jul	collect samples				X
15-Jul	collect samples	X	X		X
22-Jul	collect samples				X
25-Jul	collect samples				
31-July	collect samples				
5 Aug	shut off irrigation	X	X		X
7-Aug	terminate test	X	X	X	X

10.0 Health and Safety

An excavation permit (No. DAN-1737) was obtained for work at this site in FY 2001 and has been revised (DAN-1946 and DAN-1958) for FY 2002 to accommodate the proposed work, and these are on file with the project manager. 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 A) 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 A. Briefings will be conducted with all site visitors to assure 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.

11.0 Waste and Residuals Management

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

Scope: This plan covers waste disposition for the waste generated from cone penetrometer installations 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**.

11.2 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 Clastic Dike study site.

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

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**.

12.0 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, 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/. 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.

13.0 References

Bond WJ and PJ Wierenga. 1990. "Immobile Water During Solute Transport in Unsaturated Sand Columns," *Water Resour. Res.* 26: 2475-2481.

Burr DT, EA Sudicky, and RL Naff. 1994. "Nonreactive And Reactive Solute Transport in 3-Dimensional Heterogeneous Porous-Media - Mean Displacement, Plume Spreading, and Uncertainty." *Water Resour. Res.* 30: 791-815.

Cassel DK and A Klute. 1986. "Water Potential: Tensiometry. pp. 563–596." *In: Methods of Soil Analysis, Part 1. Physical and Mineralogical Methods,* Agronomy Monograph 9, A. Klute (ed.), American Society of Agronomy, Madison, Wisconsin.

Clothier, BE, L Heng, GN Magesan, and I Vogeler. 1995. "The Measured Mobile-Water Content of an Unsaturated Soil as a Function of Hydraulic Regime." *Aust. J. of Soil Res*. 33 (3): 397-414.

Du S, and P Rummel. 1994. "Reconnaissance studies of moisture in the subsurface with GPR, Proceedings of the fifth international conference on Ground Penetrating Radar." GPR '94: 1241-1248.

Engelman RE, RE Lewis, and DC Stromswold. 1995a. *Calibration Models for Density Borehole Logging-Construction Report,* PNL-10800, Pacific Northwest Laboratory, Richland, Washington.

Engelman RE, RE Lewis, DC Stromswold, and JR Hurst. 1995b. *Calibration Models for Measuring Moisture in Unsaturated Formations by Neutron Logging,* PNL-10801, Pacific Northwest Laboratory, Richland, Washington.

Fayer MJ, EM Murphy, JL Downs, FO Khan, CW Lindenmeier, and BN Bjornstad. 1999. *Recharge Data Package for the Immobilized Low-Activity Waste 2001 Performance Assessment,* PNNL-13033, Pacific Northwest National Laboratory, Richland, Washington.

Fayer MJ, JB Sisson, WA Jordan, AH Lu, and PR Heller. 1993. *Subsurface Injection of Radioactive Tracers: Field Experiment for Model Validation Testing,* NUREG/CR-5996, U. S. Nuclear Regulatory Commission, Washington, D. C.

Fayer MJ, RE Lewis, RE Engleman, AL Pearson, CJ Murray, JL Smoot, RR Randall, WH Wegener, and AH Lu. 1995. *Re-Evaluation of a Subsurface Injection Experiment for Testing of Flow and Transport Models,* PNL-10860, Pacific Northwest National Laboratory, Richland, Washington.

Fecht KR, KA Lindsey, BN Bjornstad, DG Horton, GV Last, and SP Reidel. 1998. *Clastic Injection Dikes of the Pasco Basin and Vicinity*. BHI-01003, Draft A, Bechtel Hanford Inc., Richland, Washington.

Freeman EJ and R Bachrach. 2001. "Application of High Resolution Shallow Seismic Methods for Subsurface Characterization at the Hanford Site." Letter Report Submitted to ILAW.

Freeman EJ, RJ Knight, and JD Irving. 2000. "An Assessment of the Use of Ground Penetrating Radar to Obtain Information about Hydrostratigraphic Spatial Heterogeneity at the Hanford Site." Letter Report Submitted to ILAW, September 29, 2000.

Gee, GW, AL Ward, JC Ritter, JB Sisson, JM Hubbell, and H Sydnor. 2001. *Installation of a Hydrologic Characterization Network for Vadose Zone Monitoring of a Single-Shell Tank Farm at the U. S. Department of Energy Hanford Site*, PNNL-13712, Pacific Northwest National Laboratory, Richland, Washington.

Gee GW and AL Ward. 2001. *Vadose Zone Transport Field Study: Status Repor*t, PNNL-13679, Pacific Northwest National Laboratory, Richland, Washington.

Gephart RE. 2001. *A Short History of Hanford Waste Generation, Storage and Release*, PNNL-13605, Rev.1, Pacific Northwest National Laboratory, Richland, Washington.

Greaves, RJ, DP Lesmes, and MN Toksoz.. 1996. "Velocity variations and water content estimates from multi-offset, ground-penetrating radar." *Geophysics*, 61, 683-695.

Hubble JM and JB Sisson. 1996. "Portable Tensiometer Use in Deep Boreholes," *Soil Sci.* 161:376-381.

Hubble JM, and JB Sisson. 1998. "Advanced tensiometer for shallow or deep soil water potential measurements," *Soil Sci.* 163: 271-277.

Kabala ZK, and G Sposito. 1991. "A Stochastic Model of Reactive Solute Transport with Time-Varying Velocity in a Heterogeneous Aquifer," *Water Resour. Res.* 27:241-350.

Khaleel R. 1999. *Far-Field Hydrology Data Package for Immobilized Low-Activity Tank Waste Performance Assessmen*t. HNF-4769, Rev. 1, Fluor Daniel Northwest, Inc., Richland, Washington.

Leij FJ, TH Skaggs, and MTh van Genuchten. 1991. "*Analytical Solutions For Solute Transport In 3-Dimensional Semi-Infinite Porous-Media*." Water Resour. Res. 27: 2719-2733.

Lockheed Martin Hanford Company (LMHC). 1999b. *Statements of Work for FY 2000 to 2005 for the Hanford Low-Activity Tank Waste Performance Assessment Program,* HNF-SD-WM-PAP-062, Rev. 4, Richland, Washington.

Mann FM, RJ Puigh, II, PD Rittmann, NW Kline, JA Voogd, Y Chen, CR Eiholzer, CT Kincaid, BP McGrail, AH. Lu, GF Williamson, NR Brown, and PE LaMont. 1998. *Hanford Immobilized Low-Activity Tank Waste Performance Assessment*. DOE/RL-97-69, U. S. Department of Energy, Richland, Washington.

Meisner JE, RK Price, and RR Randall. 1996. *Radionuclide Logging System in situ Vadose Zone Moisture Measurement Calibration,* WHC-SD-EN-TI-306, Westinghouse Hanford Company, Richland, Washington.

Mishra S, JC Parker, and JL Zhu. 1990. "An Algorithm For Generating Spatially Autocorrelated Unsaturated Flow Properties." *Comput. Geosci.* 16: 697-703.

Murray CJ, AL Ward, JL Wilson, PE Long, BJ Lechler, WP Clement, PK Kannberg, and GW Gee. 2001. "The Effects of Clastic Dikes on Vadose Zone Transport at the Hanford Site, Southcentral Washington." *In: 2001 American Geophysical Union (AGU) Fall Meetings*.

National Academy of Science. 2000. Research Needs in Subsurface Science. National Academy Press, Washington, D.C.

Rabideau AJ and CT Miller. 1994. "Two-Dimensional Modeling of Aquifer Remediation Influenced b Sorption Nonequilibrium and Hydraulic Conductivity Heterogeneity," *Water Resour. Res.* 30: 1457-1470.

Reidel SP and DG Horton. 1999. *Geologic Data Package for Immobilized Low-Activity Waste 2001 Performance Assessment,* PNNL-12257, Pacific Northwest National Laboratory, Richland, Washington.

Robin MJL, EA Sudicky, RW Gillham, and RG Kachanoski. 1991. "Spatial Variability of Strontium Distribution Coefficients and their Correlation with Hydraulic Conductivity in the Canadian Forces Base Borden Aquifer." *Water Resour. Res.* 27:2619-2632.

Rockhold ML, CJ Murray, and MJ Fayer. 1999. "Conditional simulation and upscaling of soil properties." pp. 1391-1402. *In: Proceedings of the International Workshop on Characterization and Measurement of the Hydraulic Properties of Unsaturated Porous Media.* M. Th. van Genuchten, F. J. Leif, and L Wu (eds.). University of California, Riverside.

Russo D and G Dagan. 1991. "On Solute Transport in a Heterogeneous Porous Formation Under Saturated and Unsaturated Water Flows." Water Resour. Res. 27: 285-292.

Sisson JB and AH Lu. 1984. *Field Calibration of Computer Models for Application to Buried Liquid Discharges: A Status Report,* RHO-ST-46 P, Rockwell Hanford Operations, Richland, Washington.

Smith L and FW Schwartz. 1981. "Mass Transport. III. Role of Hydraulic Conductivity Data in Prediction," *Water Resour Res.* 17: 1463.

Topp GC, JL Davis, and AP Annan. 1980. "Electromagnetic determination of soil water content: Measurements in coaxial transmission lines." *Water Resour. Res*. 16: 574-582.

Tyler SW. 1988. "Neutron Moisture Meter Calibration in Large Diameter Boreholes," *Soil Sci. Soc. Am. J.* 53: 890-893.

United States Department of Energy (DOE). 1998a. *Groundwater/Vadose Zone Integration Project Specification,* DOE/RL-98-48, Richland Operations, Richland, Washington.

United States Department of Energy (DOE). 1998b. *Removal Performance Evaluation for the AX Tank Farm*. DOE/RL-98-72, Draft A, Richland Operations, Richland Washington.

United States Department of Energy (DOE). 1999. *200-BP-1 Prototype Barrier Treatability Test Report,* DOE/RL-99-11, Richland, Washington.

United States Department of Energy-Grand Junction Projects Office (DOE-GJPO). 1998. *BX Tank Farm Report,* GJO-98-40-TAR (GJPO-HAN-19), Grand Junction, Colorado.

van Genuchten MTh. 1980. "A closed form equation for predicting the hydraulic conductivity of unsaturated soils." *Soil Sci. Soc. Am. J*. 44: 892-898.

Ward AL and GW Gee. 1997. "Performance Evaluation of a Field-Scale Surface Barrier," *J. Environ. Qual.* 26:694-705.

Ward AL and GW Gee. 2000. *Vadose Transport Field Study: Detail Test Plan for Simulated Leak Tests*, PNNL-13263, Pacific Northwest National Laboratory, Richland, Washington.

Ward AL, RE Clayton, and JC Ritter. 1998. *Hanford Low-Activity Tank Waste Performance Assessment Activity: Determination of In Situ Hydraulic Parameters of the Hanford Surface Sediments*. A letter report for activity S1W03490 submitted to the Lockheed Martin Hanford Company.

Wessolek G, R Plagge, FJ Liej, and MT van Genuchten. 1994. "Analysing Problems in Describing Field and Laboratory Measured Soil Hydraulic Properties," *Geoderma,* 64:93-110.

White MD, M Oostrom, MD Williams. 2001. *Initial Assessments for S–SX Field Investigation Report FIR): Simulations of Contaminant Migration with Surface Barriers,* PNWD-3111, Pacific Northwest National Laboratory, Richland, Washington.

Wood MI, R Khaleel, PD Rittmann, SH Finfrock, TH DeLorenzo, and DY Barbrick. 1996. *Performance Assessment For The Disposal Of Low-Level Waste In The 200 West Area Burial Grounds*, WHC-EP-0645, Westinghouse Hanford Company, Richland, Washington.

Zhang ZF, RG Kachanoski, GW Parkin, and B Si. 2000. "Measuring hydraulic properties using a line source: II. Field test." Soil Sci. Soc. Am. J. 64:1563-4569.

Zhang ZF, AL Ward, and GW Gee. 2002a. "A Parameter Scaling Concept For Estimating Field-Scale Hydraulic Properties for Layered Soils." Vadose Zone J. (In Review)

Zhang ZF, AL Ward, GW Gee, and MD White. 2002b. "Parameter Estimation for Unsaturated Layered Soils Through a Combination of Non-similar Media Scaling and Inverse Flow Modeling." In: IAHR International Groundwater Symposium "Bridging the Gap between Measurement and Modeling in Heterogeneous Media," International Groundwater Symposium, Berkeley, California, March 25-28 (In Press).

Appendix A

Clastic Dike: Antiaircraft Site H-42-Army Loop Road Site Access and Conduct Requirements Health and Safety Plan and Site Briefing

Appendix A: Clastic Dike: Antiaircraft Site H-42-Army Loop Road Site Access and Conduct Requirements Health and Safety Plan and Site Briefing

A.1.0 Application and Scope

This document controls Pacific Northwest National Laboratory (PNNL) Science and Technology Project safety and conduct activities related to the Army Loop Road Clastic Dike Site.

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 Army Loop Road Clastic Dike Site. The site is located near Antiaircraft Site H-42. The Washington State Plane coordinates are approximately 128500 N and 573500 E. Figure A.1 shows the location of the Army Loop Road site as being just off the Army Loop Road due south of the 200 East Area

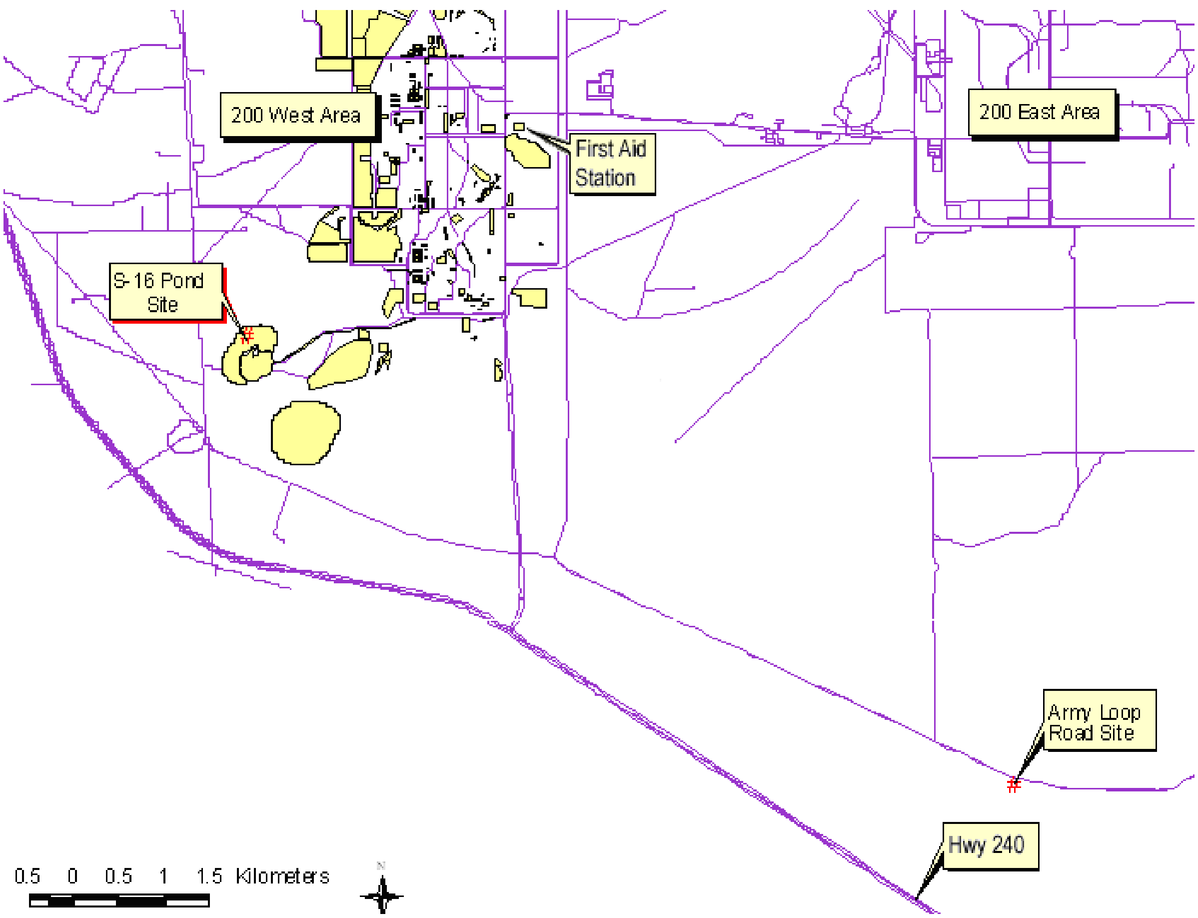

Figure A.1. Location of the Army Loop Road Clastic Dike Site

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 prior to that person's continued work at the site.

A.2.0 Responsible Staff

The person responsible for this document is the PNNL project manager, Glendon W. Gee, who can be reached at (509) 372-6096. In his absence, the contact person is Andy Ward, co-project manager, who can be reached at (509) 372-6114.

A.3.0 Testing and Monitoring Goals

The goals of the tests at the Clastic Dike 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 that are 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 assure that his or her activities do not jeopardize the integrity of the other monitoring activities that are ongoing at the site.

A.4.0 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]). A first-aid station (H2W Medical Building) that operates Monday through Friday (7:00 a.m. to 4:00 p.m.) is located in the 200 West Area (immediately inside the 200 West Area on 20th Street as indicated in Figure A.1) (Phone: 373-2714). For all other emergency medical assistance, contact Hanford Patrol-Fire-Ambulance at 811.

Site access and safety requirements refer only to the area within and immediately adjacent to the Clastic Dike Site . Staff should be aware that radiological hazards potentially exist at the site.

EMERGENCY TELEPHONE NUMBERS

PNNL Emergency	375-2154
Hanford Emergency Response	811
Hanford Patrol/Fire/Ambulance	811

WARNING SIRENS:

The following action should be taken relative to warning sirens:

- For all gongs and horns, go to the staging area located near the nearest power pole adjacent to the Army Loop Road. The supervisor should call 375-2154 and follow directions.
- Wavering Siren (Get in vehicle, call emergency phone #, and follow directions)
- Howler (AH-OO-GAH). Get in vehicle, drive off the Clastic Dike Site, and leave area—preferably away from the criticality area.

Planned siren tests are frequent. Call Dyncorp Emergency Prep. (373-4308) if questions arise regarding specific siren tests.

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 prior to 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 4th Street (Building 2719EA). Notify your line manager and the project manager (Glendon W. Gee, 372-6096).

For General Work:

When drill rigs are on the site and workers and collaborators are on the site, workers shall use hard hats and 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 requirements 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 onsite.

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 the following:

- 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 PNL-MA-43 and applicable SBMS subject areas (e.g., working with chemicals, electrical safety, machine guarding). In this study, the operation of neutron probes is the only task requiring a procedure and is governed by PNL-PSB-10-0. Workers performing these jobs must demonstrate a knowledge of hazards associated with the work prior to commencing work.

A.5.0 Site Access Requirements

There are no formal site-access requirements. Access is gained via gravel roads from the Army Loop Road (Figure A.1), and vehicular traffic is encouraged to travel only on the gravel roadways. Parking of vehicles adjacent to the roads is permitted, but the vehicle parking is restricted to the disturbed areas that are adjacent to the roadway into the site from Army Loop Road. Vehicles can be turned around by driving on the disturbed area that is immediately adjacent to the access road. 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 remote possibility that radioactive contamination may migrate onto the site, it is recommended that staff walking on the vegetation because of requirements to conduct civil and biological surveys should be aware of the potential for surface contamination via biotic pathways biologic activity. For this reason, no animal droppings (feces) are to be removed from the surface without first contacting radiation safety and the project manager. In general, the staff are encouraged to walk only in the disturbed areas.

A.6.0 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 and 2) driving vehicles onto the Clastic Dike site when monitoring is ongoing unless a drill rig or similar vehicle is scheduled and has been authorized for access onto the site. 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 any 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. Prior to work, resolve with the project manager any uncertainty about the potential to cause a significant impact. Guidelines are as outlined in PNL-MA-26 (Radiological Control Procedures) and PNL-MA-50 (Facilities Management Department PNL Operations Manual).

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 A.2.0)

A.7.0 Training Requirements

Signing this document provides the authority to access the site and perform monitoring work at the Army Loop Road Clastic Dike Site

Radiation Worker I 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.

A.8.0 References

PNL-MA-26 Radiological Control Procedures
PNL-MA-43 Industrial Hygiene, Occupational Safety and Fire Protection Programs
PNL-MA-50 Facilities Management Department PNL Operations Manual
SBMS Standards Based Management Systems-Subject Areas.

Distribution

No. of Copies

OFFSITE

Wesley L. Bratton
Vista Engineering
8203 W. Quinault Ave
Kennewick, WA., 99336

2 Lawrence Livermore National Laboratory
L-130
Livermore, California 94550
Attn: William D. Daily
Abe Ramirez

2 Lawrence Berkley National Laboratory
Department of Earth and Planetary Sciences
MS 4767
1 Cyclotron Road
Berkeley, California 94720-4767
Attn: Donald J. DePaolo
Mark Conrad

James B. Fink
HydroGEOPHYSICS, Inc.
5865 South Old Spanish Trail
Tucson, Arizona 85747

Sandra Lilligren
Nez Perce Tribe, ERWM
P.O. Box 365
Lapwai, Idaho 83450

Michael Hoversten
Lawrence Berkeley National Laboratory
One Cyclotron Road
MSIN 90-1116
Berkeley, California 94720

No. of Copies

OFFSITE

Rosemary J. Knight
Stanford University Mitchell Bldg
Satnford, CA., 94305-2215

Peter C. Lichtner
Los Alamos National Laboratory
Environmental Sciences Division (EES-5)
MS F-649
Los Alamos, New Mexico 87545

Ernest L. Majer
Lawrence Berkeley National Laboratory
1 Cyclotron Road (MS 90-116)
Berkeley, California 94720

Earl D. Mattson
Idaho National Engineering and Environmental Laboratory
P.O. Box 1625
2251 N. Boulevard
Idaho Falls, Idaho 83415-2107

Gregory A. Newman
Sandia National Laboratories
P.O. Box 5800
MS-0750
Albuquerque, New Mexico 87185-0750

Wade Riggsbee
Yakima Nation
1933 Jadwin
Richland, Washington 99352

No. of Copies

OFFSITE

James B. Sisson
Idaho National Engineering and Environmental Laboratory, BBWI
P.O. Box 1625, MS-2107
Idaho Falls, Idaho 83415-2107

2 Los Alamos National Laboratory
Environmental Science Group
MSJ495
Los Alamos, New Mexico 87545
Attn: Everett P. Springer
Brent Neuman

Carl. I. Steefel
Lawrence Livermore National Laboratory
L-204
P.O. Box 808
Livermore, California 94551

P. J. Wierenga
Soil, Water, and Environmental Science
University of Arizona
Tucson, Arizona 85721

Michael Wilt
EMI
1301 S. 46th St.
UCRFS Bldg. 300
Richmond, California 94804

Ivana Witt
Yakima Nation
1933 Jadwin
Richland, Washington 99352

T.C. Jim Yeh
University of Arizona
Department of Hydrology and Water Resources
The University of Arizona, Bldg. 11
Tucson, Arizona 85721

No. of Copies

ONSITE

2 **DOE Office of River Protection**

C. A. Babel	H6-60
R. M. Yasek	H6-60

9 **DOE Richland Operations Office**

B. L. Foley	P7-62
J. P. Hanson	K8-50
R. D. Hildebrand	A5-13
K. A. Kapsi	K8-50
R. W. Lober	H6-60
J. G. Morse	A5-13
D. Tano	A7-75
K. M. Thompson	A5-113
R. M. Yasek	H6-60

8 **Bechtel Hanford Inc.**

R. L. Biggerstaff	H0-02
L. R. Curry	H0-19
A. G. Dada	H0-02
R. J. Fabre	X5-50
K. R. Fecht	H0-02
B. H. Ford	H0-19
M. J. Graham	H0-09
R. L. Jackson	H0-19

8 **CH2M Hill Hanford Group**

J. W. Cammann	T4-08
R. Khaleel	B4-43
A. J. Knepp	H0-22
F. M. Mann	H-022
D. A. Myers	H0-22
V. J. Rohay	H0-19
L. C. Swanson	H9-02
C. D. Wittreich	H9-03

2 **MACTER-ERS**

J. F. Bertsch	B1-42
R. G. McCain	B1-42

No. of Copies		
ONSITE		
3	**Waste Management Technical Services**	
	M. G. Gardner	H1-11
	J. E. Meisner	H1-11
	R. K. Price	H1-11
6	**Washington Department of Ecology**	
	F. W. Bond	B5-18
	J. Caggiano	B5-18
	D. Goswami	B5-18
	A. Huckaby	B5-18
	S. Leja	B5-18
	N. H. Uziemblo	B5-18
1	**U.S. Environmental Protection Agency**	
	D. A. Faulk	B5-01

No. of Copies		
ONSITE		
61	**Pacific Northwest National Laboratory**	
	B. Barnett	K6-81
	W. F. Bonner	K9-14
	R. E. Clayton	P8-37
	M. J. Fayer	K3-33
	M. D. Freshley (2)	H0-21
	G. W. Gee (20)	K9-33
	J. O. Goreham	K9-33
	T. J. Gilmore	K6-81
	D. G. Horton	K6-81
	G. V. Last	K6-81
	P. E. Long	K9-33
	W. J. Martin	K3-54
	P. D. Meyer	BPO
	C. J. Murray	K6-81
	S. M. Narbutovskih	K6-96
	S. P. Reidel	K6-81
	K. A. Rod	K9-33
	M. L. Rockhold	K9-33
	R. J. Serne	K6-81
	C. E. Strickland	K9-36
	M. D. Sweeney	K6-81
	M. J. Truex	K2-10
	A. L. Ward (10)	K9-33
	K. Waters-Husted	K9-33
	M. White	K9-36
	B. A. Williams	K6-81
	M. D. Williams	K9-36
	S. B. Yabusaki	K9-36
	J. M. Zachara	K8-96
	F. Zhang	K9-33
	Technical Report Files (2)	