DOE/RL-2010-89
Revision 0

Long-Range Deep Vadose Zone Program Plan

Prepared for the U.S. Department of Energy
Assistant Secretary for Environmental Management

U.S. DEPARTMENT OF ENERGY | Richland Operations Office

P.O. Box 550
Richland, Washington 99352

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Executive Summary

This program plan summarizes our state-of-knowledge about the contaminant cleanup challenges facing the deep vadose zone (DVZ) beneath the Central Plateau of the Hanford Site and the U.S. Department of Energy's (DOE's) approach to solving those challenges. The Central Plateau was the location of Hanford's major uranium fuel reprocessing, waste management, and liquid disposal facilities.

Remediation of the DVZ is central to Hanford cleanup because it provides an ongoing source of contamination to the underlying aquifer and the Columbia River unless permanent solutions are developed and implemented.

For this plan, the DVZ is defined as that portion of the subsurface resting below the practical depth of surface excavation or surface engineered barrier influence and above the water table.

Past-waste disposal practices relied upon the DVZ as a containment buffer, based on the assumption that it would retain most radionuclides and hazardous chemicals released. Today, the vadose zone is recognized as a dynamic environment potentially impacting long-term human health and environmental risks at the Hanford Site.

Vadose zone remediation poses technical challenges—many of which are unique to DOE sites—that require advances in science and engineering. The challenges faced are the result of contaminant depth and spread, the presence of multiple contaminants and comingled waste chemistries, coupled geohydrologic/geochemical/microbial processes affecting contaminant transport, limited availability and effectiveness of cleanup remedies, uncertain contaminant behavior, and the efficacy of remediation performance over the periods and spatial scales needed for making decisions.

Magnitude of Problem: The Central Plateau contains nearly 800 waste disposal sites where 1.7 trillion L (450 billion gal) of water and various effluents were discharged underground. In addition, 67 single-shell tanks and their infrastructure leaked or are suspected to have leaked 3.8 million L (one million gal) or more of high-alkali and aluminate-rich cesium-bearing liquid into the sediment. Today, this contaminant inventory contains an estimated 550,000 curies of radioactivity and 150 million kg (165,000 tons) of metals and hazardous chemicals. A significant portion of these materials resides within the vadose zone.

Contaminants spreading through the vadose zone created plumes, some of which have migrated into the underlying aquifer. These groundwater plumes, covering nearly 170 km^2 (65 mi^2) of the Hanford Site, contain contaminants such as chromium, nitrate, carbon tetrachloride, tritium, iodine-129, and technetium-99 at concentrations above drinking-water standards. Smaller pockets of cobalt-60, cesium-137, strontium-90, and uranium also exist beneath some waste sites. The primary contaminants of concern at the Hanford Site that drive long-term risks are technetium-99 and uranium because of their potential biological hazard, high inventories in the vadose zone, mobility, difficulty in predicting subsurface behavior, and long-half life.

Need for Action: The overall need for improved science and technology can be summarized by stating that available technologies, including DOE Environmental Management baseline technologies, are not expected to provide effective solutions to remediate the Hanford Site's DVZ. As reported by the

National Research Council and other studies, available capabilities and approaches to characterizing, conceptually understanding, and modeling subsurface properties and contaminant-controlling processes are inefficient, insufficient, and can lead to incorrect predictions of contaminant behavior and remediation performance.

While contaminants in shallow sediments can be removed by excavation or hydraulically controlled by surface engineered barriers, contaminants in the DVZ rest beneath the influence of these technologies. Some of the vadose zone contaminant issues are urgent. Examples are summarized below:

- The leading edge of uranium contamination near the BX Tank Farm in the 200 East Area has reached groundwater at concentrations 150 times above drinking water standards. Another 2000 kg (2.2 tons) of relatively mobile uranium is now within 27 m (90 ft) of groundwater.
- Most of the 700 curies of technetium-99 released in the Central Plateau poses a long-term threat to groundwater, and continuing migrations of technetium-99 in vadose zone plumes near T Farm and SX Farm in the 200 West Area are now impacting groundwater quality at levels more than 100 times above drinking water standards.
- The long-term success of a large groundwater pump-and-treat system being constructed to target contaminant plumes beneath the 200 West Area depends on successful remediation of DVZ contamination to avoid recontamination of the aquifer during and after years of groundwater withdrawal.

DOE-Richland Operations (RL) recently negotiated new milestones for Central Plateau waste site cleanup and tank farm corrective action and closure. Initial decisions are planned for 2015, although some of the more difficult issues, including closure of the remaining tank farms, may span several decades. Near-term decisions will balance the need for taking actions based upon using the best available scientific and technical understanding under considerable uncertainty and deferring decisions pending the result of problem-targeted research and technology development.

Investment Targets and Opportunities: To support attaining remediation goals for the Hanford Site, progress is needed in the following four categories of scientific knowledge and technology development and application. Key areas of research emphasis are noted in each category.

Controlling Processes: Quantifying and establishing linkages between hydrologic, geochemical, and microbial processes functioning in the DVZ are critical to developing reliable, conceptual models of moisture flux and contaminant movement and successful remediation approaches. New, cost-effective technologies for remediating the DVZ must rely on processes such as chemical and biological reduction, physico-chemical sorption-precipitation, and natural attenuation. To implement *in situ* remedies, new knowledge regarding the subsurface processes controlling water movement and contaminant transport is needed. This will be obtained through new characterization methods, including noninvasive geophysics, as well as targeted field and laboratory studies.

Predictive Modeling and Data Integration: Creating validated predictive models depicting subsurface dynamics, contaminant behavior, and remedial performance at spatial and time scales of importance is critical to making defensible remedial decisions and meeting cleanup goals. Advanced coupled-process computing capabilities, such as under development in DOE's Advanced Simulation Capability for Environmental Management (ASCEM) project, will be relied upon to simultaneously model geohydrological, geochemical, and biogeochemical interactions and long-term contaminant behavior. The new models need to be linked with capabilities for simulating remediation processes and accounting for complicating factors and uncertainties associated with subsurface heterogeneities at scales pertinent to remediation, parameterization of vadose zone properties, non-linearity of transport properties, and quantitatively taking into consideration geochemical reactions between contaminants, reagents that are introduced, and host geologic materials.

Remedial Design: The purpose of DVZ contaminant remediation is to protect the underlying aquifer by reducing contaminant flux through the use of the natural system and/or engineered actions. Proposed remediation elements include methods supporting lower cost subsurface access, validating the depth of protection afforded by surface barriers, implementing test-bed facilities supporting remediation testing and design, and developing cost-effective *in situ* remedial technologies, including passive remedies that complement natural geochemical processes.

Monitoring: Direct DVZ measurements, acquired through monitoring, is required to ground truth subsurface data, remedial performance, and modeling results. Monitoring the long-term behavior of natural subsurface systems and the performance of remedial actions is critical to implementing and validating cleanup strategies. Monitoring components include methods and technologies for directly measuring moisture and contaminant flux to groundwater, improved biological indicators to examine potential impacts on the environment, and the development of early-warning monitoring “thresholds” of unexpected or unacceptable DVZ behaviors such as adverse changes in contaminant movement. Research into new approaches and tools for monitoring is needed to verify remedy performance and reduce future performance monitoring and life-cycle costs.

Organizational Strategy: DOE’s approach to solving DVZ challenges is designed to develop effective and economical solutions at the Hanford and other DOE sites while building upon available knowledge and capabilities. This approach will leverage investments from different DOE organizations, including sites across the DOE complex, working in basic science, applied research, and site engineering activities. DOE will use expertise from agency-wide activities, national laboratories, academia, and industry to work in collaboration with the Tri-Party Agreement signatories, site contractors, the public, and others to provide viable remedial technologies and strategies targeting baseline needs.

This approach will rely upon multi-project teams focusing on coordinated subsurface projects across the Hanford Site, plus facilitating research investments by implementing a DVZ Applied Field Research Center located at Hanford and relying upon scientific studies from other DOE sites. The Center will focus on understanding the subsurface processes affecting contaminant migration to predict the location, transport, and fate of contaminants. This knowledge will be used to transform science innovation into practical applications deployed by site contractors at Hanford and across the DOE complex. Carefully selecting investments will yield useful results within time frames supporting Tri-Party Agreement milestones, and documentation will need to be developed to strengthen cleanup decisions and make certain that resources are efficiently leveraged to obtain desired outcomes. Investments will support both time-critical decisions and long-term, non-time-critical objectives. Balancing these competing drivers will sustain both “bias for action” and “scientific sufficiency” priorities for program implementation.

Outcomes and Impacts: The risk posed by deep vadose contamination at the Hanford Site creates an enormous environmental liability. The impact of Applied Field Research Center investments is to develop remedies for the DVZ that can be deployed to meet cleanup goals. During FY 2011, treatability tests will continue to evaluate potential approaches to remediate deep contamination, and more closely integrated working relationships between user inspired research and field applied engineering will be established. In addition, a multiyear implementation plan will be developed to focus resource allocation on the most critical needs and opportunities.

Organization of Document

The following text briefly summarizes the topics covered in each section and appendix within this DVZ Program Plan.

Sections 1.0, 2.0 and 3.0 of the plan briefly summarize the background, remediation challenge, and DOE's defense-in-depth approach for cleanup of the DVZ to make certain that remediation protects the underlying groundwater aquifer and ultimately the Columbia River. Significantly expanded discussions on these topics are provided in Appendix A.

Although major advances have taken place in past years in developing technologies and approaches to characterize and remediate subsurface systems, most efforts have focused on groundwater systems—not the vadose zone, let alone the DVZ as beneath the Central Plateau of the Hanford Site.

Traditional cleanup remedies are expected to have limited effectiveness for meeting DVZ challenges. Key reasons include contaminant depth, distribution, and the presence of a complex geologic, geochemical, and microbial environment. Many of the challenges facing the Hanford Site are captured in **Section 4.0** and expanded upon in Appendices B and C.

DOE recognizes these challenges and is committed to a sustained, focused effort to apply existing technologies where possible while developing and investing in innovative, field-demonstrated capabilities. **Section 5.0** provides a program description and organizational approach to addressing these challenges, including the development of Multi-Project Team focusing on coordinating projects and activities across multiple DOE offices, programs, and site contractors. Facilitating timely linkages of basic and applied research investments will take place through an Applied Field Research Center (AFRC) and other scientific studies. The AFRC provides the framework for a coordinated research and technology development strategy to target the understanding and remediation of the DVZ.

Section 6.0 outlines DOE's approach to DVZ program implementation. It describes the interface between the deep vadose science and technology development activities as well as onsite remediation and closure projects that will implement solutions. This section also describes the project's approach to prioritization of program activities, implementation schedules, and critical insertion points into the baseline schedule for research applications.

As noted, **Appendix A** expands upon the background information contained in Sections 1.0 through 3.0. This appendix is recommended reading for those wanting a more thorough understanding of the waste management history and contaminant releases into the subsurface beneath the Central Plateau, examples of initial cleanup actions and vadose zone research underway, and DOE's planned approach and partnerships to remediate the DVZ.

Appendix B captures the knowledge and capability needs identified by participants attending a Deep Vadose Zone Technical Forum held in July 2010. That information is divided into three categories: Characterization and Monitoring, Subsurface Processes and Predictive Modeling, and Subsurface Access and Remediation.

An expanded list of the knowledge and capability needs extracted from published references and Hanford onsite meetings is provided in **Appendix C**. These challenges are organized into the same three categories around which the Deep Vadose Zone Technical Forum was established.

Appendix D provides a summary of how an integrated basic and applied research investment leveraging is already taking place at the BC Cribs and Trenches site located on the Central Plateau as well as the benefits gained through it. The distinct yet complimentary roles for DOE's basic science, applied research, and end users are discussed.

After participants in the Deep Vadose Zone Technical Forum (see Section 4.0 and Appendix B) identified DVZ challenges, an informal "resource" allocation exercise was conducted to gain audience views about potential investments targeting the highest priority needs. This exercise and its results are captured in **Appendix E**.

Acronyms and Abbreviations

AFRC	Applied Field Research Center
ASCEM	Advanced Simulation Capability for Environmental Management
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CHPRC	CH2M Hill Plateau Remediation Company
CMS	Corrective Measures Study
DOE	U.S. Department of Energy
DOE-HQ	U.S. Department of Energy Headquarters
DOE-RL	U.S. Department of Energy, Richland Operations Office
DVZ	Deep Vadose Zone
EMSL	Environmental Molecular Sciences Laboratory
EPA	U.S. Environmental Protection Agency
ES&H	environment, safety and health
IFRC	Integrated Field Research Challenge
MPT	Multi-Project Team
ORP	U.S. Department of Energy Office of River Protection
OTID	DOE EM-32 Office of Technology Innovation and Development
PCAD	Proposed Corrective Action Decision (RCRA)
PNSO	Pacific Northwest Site Office
PP	proposed plan (CERCLA)
PUREX	plutonium-uranium extraction
RCRA	Resource Conservation and Recovery Act of 1976
REDOX	reduction oxidation
RFI/CMS	RCRA Facility Investigation
RI/FS	Remedial Investigation/Feasibility Study
SC	U.S. Department of Energy Office of Science
SFA	Scientific Focus Area
SST	single-shell tanks
TPA	Tri-Party Agreement
WMA	Waste Management Area
WRPS	Washington River Protection Solutions

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1.0 Introduction

The introduction to this Program Plan provides a brief summary covering the background, remediation challenge, and (DOE's) defense-in-depth approach for cleanup of the deep vadose zone (DVZ) beneath the Central Plateau of the Hanford Site. Appendix A contains more detailed descriptions of these topics and the remediation challenges faced. This introduction also sets the context for Section 4.0 (Knowledge and Capability Needs), Section 5.0 (Program Description), and Section 6.0 (Program Implementation).

Reading Appendix A is recommended for those wanting a more thorough understanding of the waste management history and contaminant releases into the vadose zone and subsurface beneath the Central Plateau of the Hanford Site, the knowledge and capability challenges facing DVZ cleanup, examples of interim cleanup actions and research underway, and DOE's planned approach and partnerships to remediate the DVZ. The knowledge and technology developed at Hanford can also transfer to other DOE sites with DVZ contamiantion problems to promote expedited remedial actions.

1.1 Background

The Central Plateau of the Hanford Site (Figure A.1) contains more than 800 waste disposal sites, such as ponds, ditches, cribs, trenches, reverse wells, and landfills, contaminated with radioactive and hazardous chemicals. Most of these sites received liquid waste from reprocessing spent uranium fuel in the 200 Areas to recover plutonium. Contaminated liquids from tank leaks also remain in sediments beneath the 200 Area.

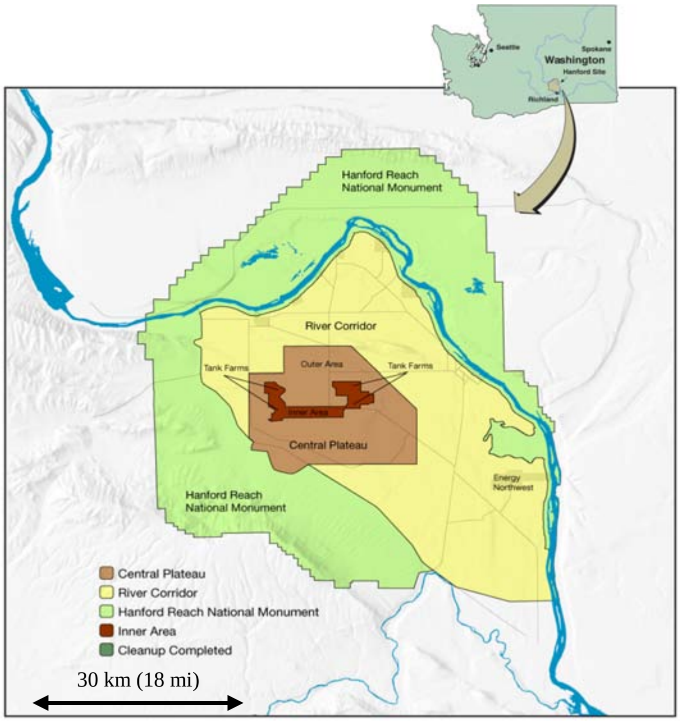


Figure A.1. Location of the Hanford Site and Central Plateau. The 200 Area is in the middle of the Central Plateau.

Broadly, the vadose zone is that portion of the subsurface lying between the land surface and the water table that marks the upper boundary of the underlying aquifer (Looney and Falta 2000). Throughout the vadose zone, pore spaces separating sediment grains are filled with a mixture of water and gas. Sometimes the vadose zone is called the unsaturated or partially saturated zone.

For this plan, the DVZ is defined as that region of the unsaturated sediment resting below the practical depth of surface excavation or surface engineered barrier influence and above the water table.

Subsurface geochemistry is strongly influenced by water interaction with sediment minerals and other subsurface constituents, including microorganisms. The behavior of contaminants released into the vadose zone is dominated by how those contaminants and their original liquid waste chemistry interacted with the subsurface environment.

During Hanford's plutonium production era, some 1.7 trillion L (450 billion gal) of water were discharged into the subsurface, mostly into ponds. Today, the Site's largest inventory of subsurface contamination lies beneath the Central Plateau. Liquid releases created large contaminated groundwater plumes that now cover nearly 170 km^2 (65 mi^2) beneath the Hanford Site (DOE-RL 2010). Downward-reaching contaminant plumes in the vadose zone created this groundwater contamination. Groundwater beneath the Hanford Site eventually flows to the Columbia River.

In Hanford's past, most subsurface studies focused on groundwater monitoring and characterization to support waste management decisions. The exceptions included tank farm vadose zone investigations and some shallow vadose zone studies assessing *in situ* moisture seepage and shallow contaminant migration. DVZ studies were not a priority because waste disposal practices relied upon that zone to buffer contaminant releases to the underlying aquifer, and it was difficult (and costly) to access. Remediating the DVZ is now central to Hanford Site cleanup because it has become clear that these sediments can provide an ongoing source of mobile contamination to the aquifer.

Characterization and remediation of the DVZ pose some unique challenges, including the following:

- low moisture content
- sediment thickness (~50 to 100 m)
- contaminant depth and spread in a complex and coupled geohydrologic, geochemical, and microbial environment
- presence of multiple contaminants (chemicals, metals, and radionuclides) and waste chemistries interacting with one another and the subsurface
- limited availability and effectiveness of traditional characterization tools and cleanup remedies
- contaminant behavior and remediation performance over long time periods and across large spatial scales (molecular-to-field).

1.2 Geohydrologic Background

The vadose zone beneath the Central Plateau consists of 50 m (160 ft) to 100 m (330 ft) of unsaturated, unconsolidated to semi-consolidated, stratified sediments of varied physical and geochemical character. It overlies an unconfined aquifer ranging in thickness from 10 (30 ft) to 120 m (390 ft).

Broadly, the major stratigraphic units comprising the vadose zone beneath the Hanford Site are shown in Figure A.1.

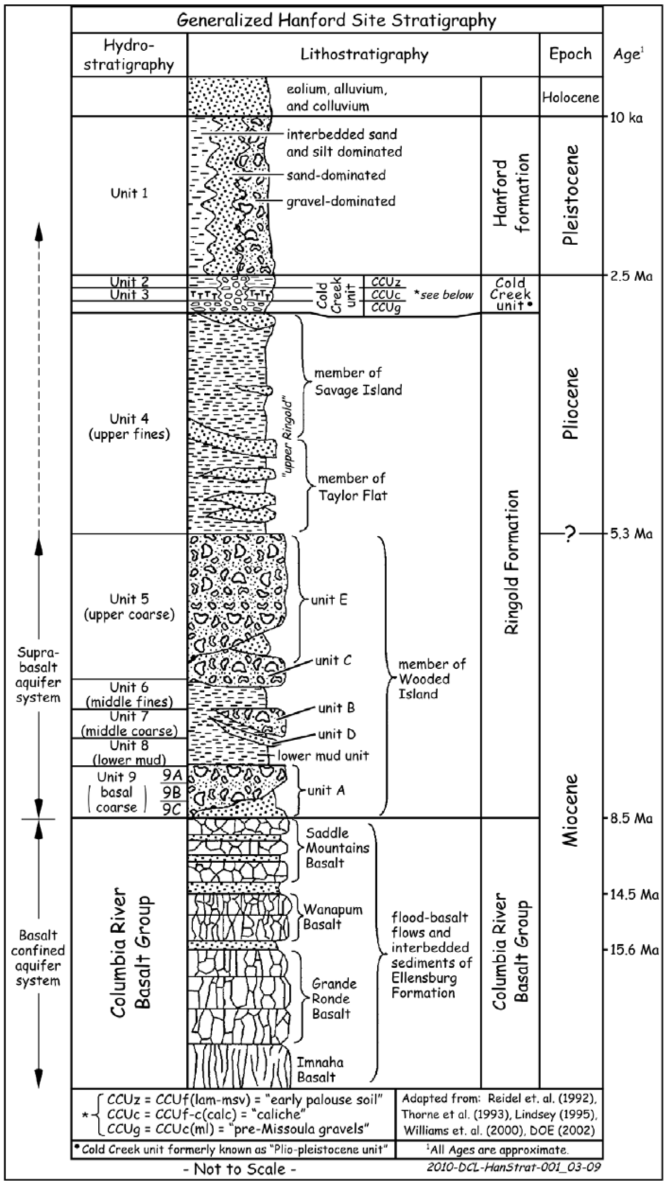


Figure A.1 General Stratigraphic Column Showing the Sedimentary Formations Underlying the Hanford Central Plateau

Those units are as follows:

- surface wind-deposited sand and silt deposits
- unconsolidated sand and gravel of the **Hanford formation**
- silt and carbonate-cemented layers of the **Cold Creek Unit**
- semi-consolidated sand, gravel, and mud units of the **Ringold Formation.**

Not all geologic units are present everywhere beneath the Central Plateau. Their thickness, distribution, and continuity depend upon site-specific sediment deposition and erosion histories.

The physical structure, layering of sediments, subsurface emplacement of wastes, geochemical characteristics, and biogeochemical properties of the geologic framework affect subsurface contaminant movement and distribution. A lack of knowledge quantifying key processes affecting contaminant migration challenges scientists' ability to reasonably predict the location and fate of contaminants under both natural and remediation conditions.

The geohydrologic contrast between sediment types plus crosscutting and discontinuous geologic features such as stratigraphic facies changes, sediment orientation, fractures, and clastic dikes can impact lateral and/or vertical contaminant movement. The degree of complexity may be pronounced on a local scale, such as near a waste site or beneath a tank farm, to far less influential on a broader field scale.

Perhaps the most significant stratigraphic feature beneath the 200 West Area affecting moisture flux and contaminant transport in the DVZ is the fine-grained, low-permeability, carbonate-cemented facies of the Cold Creek Unit sometimes found sandwiched between the Hanford and Ringold Formations.

A more thorough discussion of the Hanford Site geohydrologic background, with an emphasis on the DVZ underlying the Central Plateau, is captured within Section A.1.1 of Appendix A.

1.3 Vadose Zone Contaminants Released into Sediments Underlying the Central Plateau

Nearly 550,000 curies of radioactivity are estimated to exist in the Hanford Site's vadose zone and groundwater (Corbin et al. 2005; Kincaid et al. 2006); see Table 1.1. These radionuclides range from mobile and short-lived tritium to effectively immobilized ^{137}Cs, ^{241}Am, and plutonium. Half of this inventory is ^{137}Cs and ^{90}Sr; another 30% is tritium. While groundwater contamination has resulted from this inventory, a significant fraction of these radionuclides likely remain in the vadose zone beneath the Central Plateau.

Table 1.1. General Inventory Estimates for Select Radionuclides Released into the Central Plateau Subsurface. Numbers are approximated and rounded. Units listed in curies except for last column.

Radionuclides	Discharges to Soil	Tank Leaks to Soil*	Total (Curies)	Total (Kg)
Tritium	180,000	-	180,000	0.02
^{137}Cs	75,000	150,000	225,000	2.5
^{90}Sr	38,000	14,000	52,000	0.4
^{99}Tc	600	100	700	40
^{129}I	4.6	0.1	4.7	25
^{241}Am	28,700	-	28,700	8.4
U (total)	270	15	285	205,000
^{237}Np	55	-	55	80
$^{-239}$Pu, $^{-240}$Pu, $^{-241}$Pu	52,000	-	52,000	205

* Column includes waste leaks from tanks, overflow events, underground pipes, and other support infrastructure.

In addition, an estimated 150 million kg (165,000 tons) of metals and hazardous chemicals were released into the Central Plateau subsurface; see Table 1.2. Cribs, trenches, and ponds received the greatest inventory. Principal releases included nitrate, nitrite, sodium, chloride, phosphate, carbon tetrachloride, tributyl phosphate, and chromium. About 0.5 million kg (500 tons) of this inventory came from liquids leaked from single-shell tank (SST) operations.

Table 1.2. General Inventory Estimates for Select Metals and Hazardous Chemicals Released into the Central Plateau Subsurface. Numbers approximated and rounded from best estimate inventory values.

Chemical or Metal Released into Subsurface	Liquid Waste Release Sites (Kg)	Tank Leaks* (Kg)
Nitrate + Nitrite	9.8E+07	2.5E+05
Sodium	4.1E+07	2.0E+05
Chloride	4.0E+06	5.1E+03
Phosphate	3.6E+06	7.8E+03
Carbon tetrachloride	9.2E+05	0
Tributyl Phosphate	7.4E+05	0
Chromium	3.1E+05	2.0E+03
Lead	8.1E+04	1.0E+02
Iron	3.8E+05	4.6E+02
Bismuth	5.3 E+04	5.0E+01

* Column includes waste leaks from tanks, overflow events, underground pipes, and other support infrastructure.

The primary contaminants of concern at the Hanford Site driving long-term risk are ^{99}Tc and uranium. Reasons include their potential biological risk, high inventory in the vadose zone, mobility, difficulty in predicting subsurface behavior, and long-half life. Two additional contaminants of long-term concern are ^{129}I and chromium.

A further discussion of contaminants released is provided in Section A.2.2 of Appendix A.

1.4 Central Plateau Cleanup Completion Strategy

The Central Plateau is a 195 km^2 (75 mi^2) elevated area near the center of the Hanford Site. It includes a rectangular Inner Area of about 25 km^2 (10 mi^2) containing the 200 East and 200 West Areas surrounded by adjoining land called the Outer Area (Figure A.1). DOE is focusing on a Central Plateau remediation strategy that is organized into the following components:

- **Inner Area**—The final footprint of the central Hanford Site dedicated to waste management and containment of residual contamination will remain under federal ownership and control.
- **Outer Area**—The Outer Area includes all of the Central Plateau outside the boundary of the Inner Area. DOE intends to clean up this portion of the Central Plateau to a level comparable with that achieved along the River Corridor.

- **Groundwater**—The goal is to restore the Central Plateau groundwater to beneficial uses, unless restoration is determined impractical. In such instances, programs will be implemented to prevent, or at least impede, further plume migration until new treatment technologies are developed and deployed.

Additional discussion of DOE's overall remediation strategy covering the Central Plateau is found in Sections 5.2 and 5.3 and Section A.1.2 of Appendix A. Specific organizational roles and responsibilities are addressed in Sections 5.0 and 6.0.

DOE has initiated a series of treatability tests to identify and evaluate potential approaches to DVZ contamination. These tests are focused on technologies for remediating deep ^{99}Tc and uranium. Initial test plans have been developed for field evaluation of soil desiccation to reduce the mobility of ^{99}Tc in the vadose zone located in the BC Crib Area found just south of the 200 East Area. Tests of potential uranium sequestration at the field scale using reactive gases, such as ammonia, were conducted. Examples of these and other subsurface remediation actions in the Central Plateau are summarized in Sections A.1.3 and A.1.4 of Appendix A.

DOE is committed to initiating other treatability tests to evaluate potential approaches to treat, recover, or stabilize DVZ contamination using new, advanced, or adapted technologies. DOE is also investing in the development of new technologies from which promising potential remediation capabilities will be demonstrated in future treatability tests.

2.0 Scope of Deep Vadose Zone Remediation Challenge

Contamination present in the DVZ beneath Hanford's Central Plateau is not believed to pose environmental or health risks through direct exposure or uptake by biota. However, the DVZ is a primary concern as a conduit and ongoing source of groundwater contamination by potentially exposing humans or other ecological receptors to radiological or hazardous chemical contaminants delivered through the groundwater pathway (DOE-RL 2010). Therefore, Central Plateau remediation and long-term stewardship requires close attention.

Remediation of DVZ contamination poses a long-term cleanup challenge. Traditional remedies are not expected to provide effective solutions. A number of previous efforts and reviews have identified science and technologies relevant to the DVZ challenge. Broadly, key knowledge and technology needs identified in publications and during meetings with Hanford Site contractor personnel are referenced and discussed in Appendix C. These are summarized in the following categories:

- **Characterization and Monitoring:** Locating and characterizing the concentrations, speciations, release rates, and movement of contaminants distributed within a heterogeneous sedimentary environment crosscut by discontinuities. Advancing subsurface monitoring technologies including novel sensors, detectors, and data transmission techniques tracking the long-term performance of the natural and engineered systems.
- **Subsurface Processes and Predictive Modeling:** Characterizing the coupled physical, geochemical, and microbiological properties/processes functioning within the subsurface that control contaminant transport over multiple time and spatial scales. Creating validated conceptual and predictive models to depict subsurface dynamics and contaminant behavior spanning the molecular-to field-scale. Accounting for uncertainty in model predictions. Quality modeling also requires preserving and enabling access to the extensive laboratory through field-generated data sets that support modeling, performance assessments, and decision making.
- **Subsurface Access and Remediation:** Developing improved subsurface access capabilities plus less costly and more effective contaminant treatment, recovery, containment, and stabilization techniques through coupled laboratory and intermediate scale testing before field tests and deployment programs.

Little is known about how DVZ characteristics interact over spatial scales (molecular to field) and extended times (present to thousands of years) critical to remediation decision-making nor how subsurface processes interplay to dominate contaminant movement and recovery (see Section A.2 of Appendix C). One the greatest limitations to the study of the DVZ is that very little reliable and accurate data have been obtained for characterization of the flow and transport state variables. After the National Research Council's review of DOE's cleanup technology roadmap, they wrote:

> "Currently, available technologies, including EM's baseline technologies, are insufficient to remediate many of DOE's groundwater and vadose zone contaminants….technologies and approaches to characterizing, conceptually understanding, and modeling subsurface properties and processes are both inefficient and insufficient, and can lead to unreliable predictions of subsurface contaminant behavior." (NRC 2009)

DOE recognizes that there are no immediate solutions to many Hanford DVZ contamination problems. This is why new capability investments are being targeted to yield usable results in both the near and long-term to achieve regulatory compliance, cleanup, and waste site closure.

Regulations exist to guide assessments of new remedial treatments and enhanced monitoring approaches when cleanup capabilities are limited. However, complicating decision-making is the fact that regulations are unclear as to the assessment process needed to secure alternative technology decisions.

Appendix B identifies a broader list of challenges facing the DVZ that was identified by participants attending a Deep Vadose Zone Technical Forum held in July 2010. A more detailed description of that meeting is introduced in Appendix B. Information from that appendix was also used to build the knowledge and capability needs addressed in Section 4.0.

3.0 Defense-in-Depth Approach for Remediation of the Central Plateau

DOE is using a defense-in-depth approach to bring new understanding and technologies to Hanford Site subsurface remediation. This will be accomplished by integrating the DVZ project into the Site's subsurface baseline program and solving targeted problems hindering progress. A cornerstone of this strategy is applying existing knowledge and technology where they work and targeting new knowledge and capabilities where opportunities exist to more effectively remediate contaminants, reduce costs, accelerate schedules, and minimize risks.

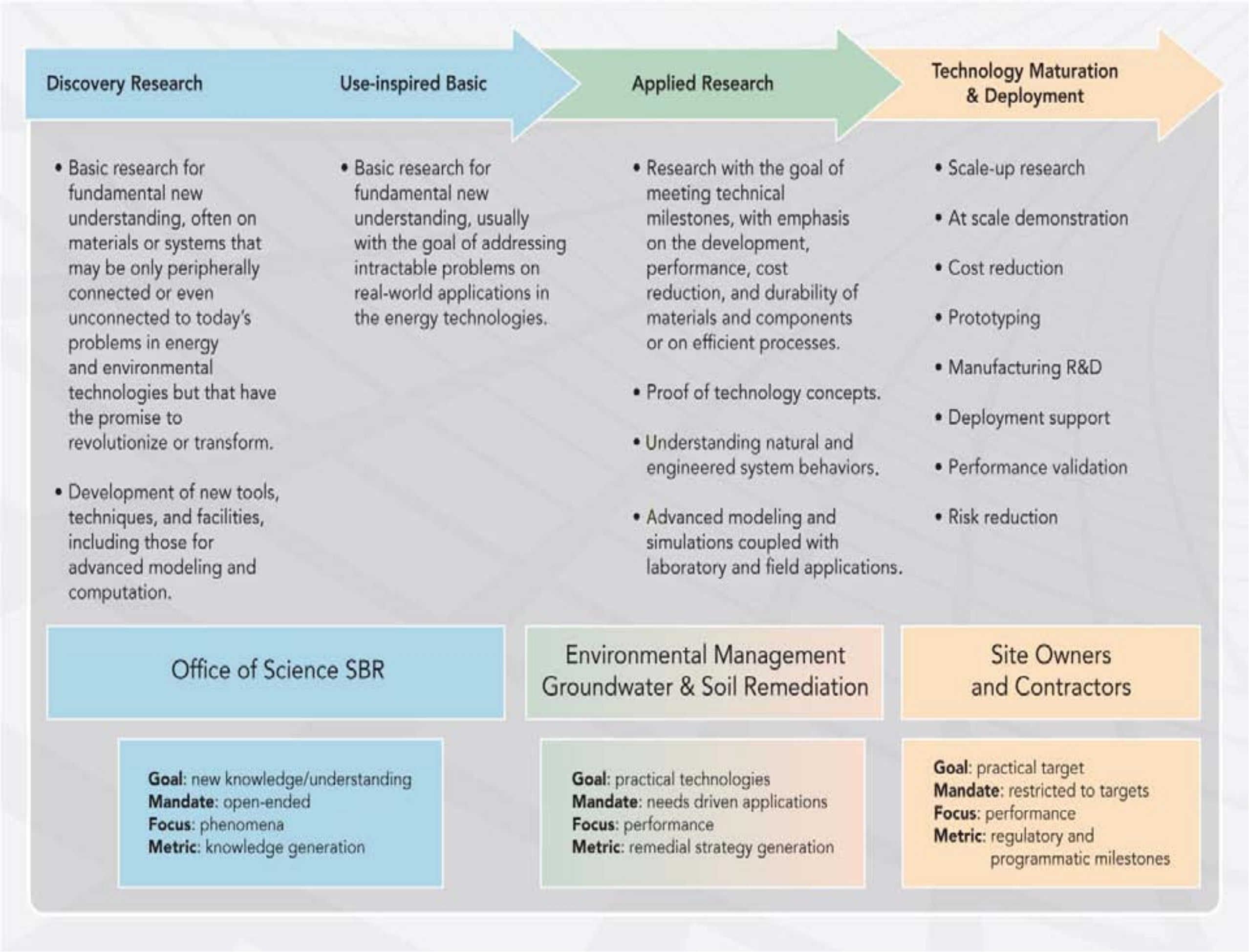
This approach to remediate the DVZ will be framed upon the following components that are further discussed in Section A.3 of Appendix A:

- Rely upon a bias-for-action by first using **best available knowledge and capabilities**
- Invest in problem-targeted **technology innovation** and field **treatability tests**
- Sustain investments in **integrated research and field-scale testing/engineering** focused on the most intractable problems
- Focus **science infrastructure** (instruments, laboratories, staff, and resources) on critical cleanup problems
- Sustain integrated **laboratory and intermediate-scale testing** to advance the most promising remediation ideas to field-scale evaluation by bridging the gap between fundamental research and needs-driven technology development
- **Combine treatment approaches**, such as select surface and subsurface remedial actions, to overcome limitations of individual techniques
- Integrate **groundwater and vadose zone monitoring** to provide an early warning of significant contaminant movement or impacts to groundwater
- Deploy **groundwater treatment systems** that can be expanded or redesigned to address emerging plumes
- Periodically revisit the **effectiveness of remedies** and possible changes in environmental conditions
- **Leverage** knowledge, capabilities, and funding sources across multiple programs.

Bridging the gap between basic science and "needs-driven" research is a universal challenge for all areas of technology development. It is particularly challenging when confronting intractable problems, such as environmental cleanup of the DOE complex, for which well-established economic incentives for translating basic scientific advances into commercial products and services do not exist. Therefore, DOE is facilitating this transition of scientific results into applied solutions.

Broadly, the motivation and goals for DOE's use-inspired basic science and applied research programs in subsurface science are summarized in Figure A.1. The motivation of much discovery research is to develop a deeper understating of fundamental processes, such as those controlling contaminant fate and transport, and to continually advance the state of the science. Complementary to these efforts, applied research advances the use of existing scientific principles and discoveries obtained through basic science to solve site-specific problems and guides remediation and management strategies across a range of contaminated sites.

The proposed roles and responsibilities for these activities applied to the DVZ at the Hanford Site are discussed in Section 5.0. Appendix D summarizes how integrated investments in basic and applied research programs, being applied at the BC Cribs and Trenches site located in the Central Plateau, have benefited the study and development of remediation approaches for that site.



- Basic research for fundamental new understanding, often on materials or systems that may be only peripherally connected or even unconnected to today's problems in energy and environmental technologies but that have the promise to revolutionize or transform.
- Development of new tools, techniques, and facilities, including those for advanced modeling and computation.

- Basic research for fundamental new understanding, usually with the goal of addressing intractable problems on real-world applications in the energy technologies.

- Research with the goal of meeting technical milestones, with emphasis on the development, performance, cost reduction, and durability of materials and components or on efficient processes.
- Proof of technology concepts.
- Understanding natural and engineered system behaviors.
- Advanced modeling and simulations coupled with laboratory and field applications.

- Scale-up research
- At scale demonstration
- Cost reduction
- Prototyping
- Manufacturing R&D
- Deployment support
- Performance validation
- Risk reduction

Goal: new knowledge/understanding
Mandate: open-ended
Focus: phenomena
Metric: knowledge generation

Goal: practical technologies
Mandate: needs driven applications
Focus: performance
Metric: remedial strategy generation

Goal: practical target
Mandate: restricted to targets
Focus: performance
Metric: regulatory and programmatic milestones

Figure A.1. Linkage of Use-Inspired Basic Research and Applied Science to Support Technology Deployment

4.0 Technology, Information, and Scientific Understanding Needed to Obtain Desired Outcomes

As noted in Section 2.0, existing remediation technologies are expected to have limited effectiveness for solving many DVZ contamination problems. In recognition of this challenge, DOE is committing to a focused effort to develop and invest in new, innovative, field-demonstrated technologies and directed research to solve presently intractable DVZ challenges while also reducing remediation costs and risks to human health and the environment.

A more detailed discussion of previously published knowledge and capability needs required to characterize, model, monitor, access, and remediate the DVZ is found in Appendix C.

A Deep Vadose Zone Technical Forum held on July 20-21, 2010, in Richland, Washington, had broad participation from a variety of organizations. Approximately 80 participants attended, including, but not limited to, the public, interest groups, the Hanford Advisory Board, state agencies, DOE, representatives from Tribal Nations, Hanford contractors, national laboratories, universities, and the regulatory community. One of the Forum's principal goals was to have participants identify the knowledge and capability challenges they believe DOE will face during remediation of the DVZ; that information is in Appendix B.

The following text draws upon the above information and identifies areas of research emphasis organized into the four research and technology development categories. These categories will be translated into an organizational construct for the Hanford Site's new Applied Field Research Center discussed in Section 5.0 (see Figure A.1). The four categories are as follows:

- Controlling Processes: Characterize, quantify, and conceptually model the physical, chemical, and microbial properties controlling contaminant fate and transport.
- Predictive Modeling and Data Integration: Simulate the integrated processes controlling moisture flux, contaminant transport, and remediation performance.
- Remedial Design: Perform fundamental and applied research supporting the design of surface and subsurface techniques to access and remediate DVZ contamination.
- Monitoring: Monitor subsurface behavior, contaminant movement, and remediation performance.

4.1 Controlling Processes

Quantifying coupled hydrologic, geochemical, and microbial processes functioning in the DVZ is key to developing reliable conceptual models of moisture flux and contaminant movement.

4.1.1 Hydrogeologic and Contaminant Characterization

Topics identified as important for hydrogeologic (physical) and contaminant (plume) characterization include the following:

Contaminant Identification. Create high resolution, field-deployable methods to identify the location and distribution of subsurface contaminants.

Three-Dimensional Stratigraphic Imaging. Develop less-invasive natural isotope and subsurface tools to characterize subsurface properties.

Geophysical Approaches to Three-Dimensional Contaminant Plume Imaging. Couple new, low-invasive geophysical tools with controlled laboratory/field test bed experiments to identify the fundamental relationships between geophysical responses of differing contaminant plume distributions and moisture content.

***In Situ* Measurements of Migration Velocities and Moisture Flux**. Develop methods to directly measure and validate deep contaminant migration rates and moisture fluxes beneath waste sites and undisturbed locations.

Discontinuity Impacts on Lateral Flow. Develop field-testing and modeling approaches to quantify the impact that subsurface heterogeneities and anisotropic conditions have on moisture flow and contaminant transport.

Subsurface Sample Collection and Preservation. Maximize sample collection opportunities and initiate long-term preservation of samples for research and technology development use.

4.1.2 Geochemical and Biochemical Characterization

Key areas of interest for geochemical and biogeochemical characterization include the following:

Geochemical and Biogeochemical Processes. Examine contaminated sediments beneath waste sites to quantify geochemical and biogeochemical processes that control contaminant behavior.

Isotopic Studies. Examine the isotopic compositon of shallow to DVZ pore water for insight into contaminant sources, behavior, and processes that affect radionuclude transport and mobility.

Microbiologic Transformations and Reactions. Identify prominent organism types, evaluate microbiologic subsurface activities, and assess the potential of biologic-induced transformation and reactions that influence, enhance, or sequester contaminants.

Coupled Ion Exchange and Precipitation/Dissolution Reactions. Quantify predictions of ion exchange and precipitation fronts required to describe geochemical reactions between contaminants and in-earth materials to factor reactive transport analyses into predictive models.

Mass Transfer and Slow Reactions. Study the roles of mass transfer and slow reactions to develop mass transfer models addressing contaminant movement resulting from slow sediment-waste geochemical reactions in inaccessible sediment micro-pores and micro-fractures.

Contaminant Sequestration and Release. Identify subsurface host mineral phases that control contaminant release and uptake.

Kinetic Database. Develop an experimental, scientifically defensible kinetics database used to determine first-order reactions controlling source-term contaminant behavior.

Chemical and Biological Kinetics. Research mechanisms and kinetics of chemically and biologically controlled reactions that can be innovatively applied to new remediation capabilities.

4.1.3 Conceptual Model

Critical topics identified for conceptual model development and evaluation include the following:

Systems-Level Simulation Framework. Develop an integrated systems-level (micro- to field-scale) conceptual simulation framework that integrates best available information describing vadose zone characteristics, contaminants, and reactive transport processes encompassing waste sites to Central Plateau scales.

Dominant Contaminant Transport Pathways Identification. Identify key geostratigraphic-controlled contaminant flow pathways that control moisture/contaminant flux and remediation amendment movement in the subsurface at waste sites.

4.2 Predictive Modeling and Data Integration

Predictive modeling and data bases are useful for integrating site characterization information, evaluating conceptual models, and supporting site remediation. Topics identified as important for predictive modeling and data integration include the following:

Advanced Computing Capabilities. Develop an advanced coupled process computing capability to simultaneously support modeling DVZ site geohydrological, geochemical, and biogeochemical interactions, contaminant fate/transport, and remedial performance using large data sets and across multiscales.

Heterogeneity Incorporation into Predictive Models. Create new approaches for incorporating subsurface heterogeneities into models at realistic field scales to examine the impact of potential contaminant flow and transport behavior.

Contaminant Mobility and Transport Modeling. Develop calibrated and validated models to predict the mobility of risk-driving contaminants and their reactive transport for the range of waste, geochemical, and hydrological conditions prominent to DVZ natural attenuation or engineered remediation.

***In-situ* Remediation Technology Performance Modeling**. Develop modeling approaches to support the design and evaluation of *in situ* technologies at waste site scales. This includes validating characteristics and processes needed to model the performance of remediation systems under current and potential future conditions.

Integrated Databases and Preserved Information Archives. Maintain data and synthesize into integrated, accessible, and searchable databases for existing knowledge pertinent to scientific, engineering, and regulatory decision-making as well as future knowledge to be generated.

Computing Capabilities Supporting Geophysics Interpretation: Advance computing capabilities to enable faster processing of large characterization data sets, such those acquired through surface and subsurface geophysics, to support defining three-dimensional subsurface properties and contaminant plume distributions.

4.3 Remedial Design

The purpose of DVZ contaminant remediation is to protect the underlying aquifer by reducing contaminant flux. Reducing contaminant flux involves implementing fixes that reduce or match the lifetimes of the contaminants. This places a significant burden on using effective models, knowledge, scientific understanding, and engineering tailored to the challenges faced. A general recommendation is to establish field research and test facilities. Remediation elements for the DVZ include subsurface access, surface barrier technologies, and subsurface remedial technologies. These are described in the following sections.

4.3.1 Field Research Facilities

Field Research and Test Facilities. Establish field-scale analog test facilities at uncontaminated locations that are analogous to contaminated sites for investigators to test advanced characterization approaches and remedial technologies.

4.3.2 Subsurface Access

Subsurface Access. Develop and test new, improved, more cost-effective methods to access the subsurface for sediment/contaminant sampling, characterization, and amendment delivery.

4.3.3 Surface Barrier Technology Development

Methods for Application of Surface Barriers. Develop methodology for predicting the effect of surface barriers on shielding deep contamination from moisture flux.

Surface Barrier Components. Study the mechanisms and kinetics of chemically and biologically mediated reactions occurring between contaminants, sediment, and surface barrier components to increase longer term, barrier-induced, contaminant containment and stabilization.

Surface Engineered Barrier Design. Field test and model new surface barrier designs and materials for improved isolation and long-term durability in reducing moisture flux and contaminant movement.

4.3.4 Subsurface Remedial Technology Development

Desiccation Barrier. Scale up current treatability field tests underway in the BC Crib/Trench area to larger waste site scales. Model and field test the extent that desiccation of pore water reduces contaminant flux.

Passive Remediation. Advance passive remediation techniques that work with natural geochemical processes.

Gas Phase Remediation. Examine sequestration effects from geochemical manipulation using reactive gas injection on various soil types, contaminants such as ^{99}Tc and ^{129}I, and leaked tank waste.

Advanced Amendment Delivery. Research advanced and minimally invasive delivery mechanisms, such as foams, to more effectively deliver reactive agents into the deep subsurface.

Advanced Amendment and Remediation Tracking. Develop advanced sensing methods that are needed to quantify the distribution of injected amendments, remediation treatment, and induced transformations *in situ* and over field-relevant scales.

Reductants. Increase the number and variety of reductants used for *in situ* vadose zone remediation. The goal is to provide preferential reaction with target constituents or to produce reduced phases with greater stability.

Subsurface Permeability Alteration. Research chemical, electrochemical, or biochemical manipulations that alter subsurface permeability to allow greater targeted sequestration.

Bioremediation. Study the viability of bioremediation and gene expression monitoring to examine the *in situ* physiological basis for bioremediation technology where other remediation options are not feasible.

Long-Term Effectiveness of Potential Remedies. Develop technically defensible data and methodologies to evaluate how potential technologies will perform over long periods, particularly for technologies that leave contaminants in place.

4.4 Monitoring

Monitoring is a key component for successfully implementing remediation strategies and is necessary for evaluating long-term performance. Both direct point measurements (e.g., from water content sensors or fluid chemical data) and indirect (geohysical) data can be relied upon to monitor the subsurface. However, ground proofing data typically requires direct samples and measurements. Topics in this section include a broad spectrum of sensors and measurements that can be applied to the DVZ, including the following:

Field Tests at Former Contaminant Release Sites. Develop advanced sensing and subsurface monitoring technologies and strategies to monitor long-term moisture and contaminant plume behavior at contaminant release sites.

Monitoring Remedial Performance. Develop advanced sensing and subsurface monitoring technologies and methods to evaluate remedial performance, including distribution of injected amendments.

Monitoring for Surface Barrier Applications. Develop monitoring technologies and methods capable of resolving deep yet subtle and transient (episodic) changes in moisture flow and contaminant movement in the DVZ beneath surface barriers—and other Central Plateau locations criticial to remediation.

Early-Warning Thresholds of Unexpected Performance. Test and establish the basis for early-warning monitoring "thresholds" of unexpected or unacceptable DVZ behaviors such as changes in moisture flow and contaminant movement. Possibilities include buried sensors, surface surveillance, microbial community profiles, tracer detection, and performance-modeling indicators.

Natural Microbial Profiling. Characterize and monitor changes in microbial community composition as an indicator of chemical flux that can be integrated with measurements of subsurface system performance and potential contaminant impacts on the environment.

Transitional Monitoring Techniques. Develop, demonstrate, and validate monitoring techniques that transition from point measurements to integrated waste-site and landscape-scale measures.

Monitor Fluid and Gaseous Flux. Develop novel methods for monitoring fluid and gaseous fluxes through vadose zones in response to diurnal and seasonal changes that can be extrapolated to the longer term (e.g., decades).

Real-Time Monitoring. Develop real-time monitoring instruments for field use and remote/automated data collection covering a range of chemical/radiological species relevant to DOE. Includes advanced, long-term, reliable geophysical sensors, detectors, and data-transmission (e.g., wireless) technology for subsurface monitoring.

Time-Elapse Geophysical Imaging of Plumes. Research the potential of using isotopes and time-lapse geophysical "imaging" to monitor remediation-induced processes.

4.5 Summary of Deep Vadose Zone Technical Forum Resource Allocation Exercise

At the end of the Deep Vadose Zone Technical Forum (see Appendix B), attendees were given the opportunity to participate in a resource "prioritization" exercise. In this exercise, they were asked to invest surrogate money, or "Vadose Bucks," in nine investment categories that were derived from the breakout group discussions. The specific objectives of the allocation exercise were to 1) elicit information from the participants using a simulated portfolio investment exercise; 2) provide insight into the participants' values and preferences; and 3) generate information to assist DOE and Hanford as they plan future DVZ applied research activities.

Participants were then able to allocate their "Vadose Bucks" to a portfolio of investments of their own choosing. Demographic information, such as organizational affiliation, was anonymously collected to facilitate the analysis of possible differences in investment preferences across subgroups of participants.

The nine investment categories were broken into three broad categories corresponding to the three topical breakout sessions from the Forum (see Appendix B). Each category contains three investments.

Characterization and Monitoring

1. Improved conceptual models for vadose systems and vadose contaminant behavior and better use of available data
2. New characterization tools and techniques
3. Systemic changes to implement best practices for monitoring

Processes and Predictive Modeling

1. Develop models for coupled reactive flow and transport in the vadose zone
2. Analyze long-term system scale response to changes in water input to the vadose zone
3. Quantify uncertainty in vadose zone models

Access and Remediation

1. Perform pilot scale testing of potential vadose zone treatment methods
2. Develop improved access and delivery methods
3. Resolve technical, process, and predictive modeling issues associated with reactive gas and foam delivery in the vadose zone

There was a general consensus that investment in all of the overarching topics—characterization and monitoring, processes and predictive modeling, and access and remediation—are important, but there was significant variation in investments among the Forum participants and even within identified demographic subgroups. The investment allocations and assoicated comments provide insights that enhance the value of the Deep Vadose Zone Technical Forum for DOE. A summary of the results from this exercise is provided in Appendix E.

5.0 Deep Vadose Zone Program Description

Previous subsurface research carried out through the Groundwater/Vadose Zone Integration Project (Integration Project) focused on understanding the fate and transport of contaminants in the vadose zone and predicting potential impacts on people and ecological systems. The current focus of the DVZ program is similar to that of the Integration Project, but emphasis has shifted to remediating contamination and closing waste sites on the Central Plateau.

A number of organizations and projects are involved in remediation activities that comprise the DVZ Program. These are as follows:

- DOE Richland Operations (RL) and CH2M HILL Plateau Remediation Company (CHPRC) are responsible for soil and groundwater remediation activities at the Hanford Site. The projects that are part of or related to the DVZ Program include operable unit investigations for 200-WA-1, 200-EA-1, and 200-DV-1, the DVZ Treatability Test Plan, and groundwater operable unit remediation activities (see Figure A.1 and Figure A.2 in Section 6.0).
- The DOE Office of River Protection (ORP) and contractor Washington River Protection Solutions (WRPS) are focused on tank-farm closure and corrective action activities, currently for Waste Management Area (WMA) C. A summary of WMA C activities is captured in Section 5.3. Discussion of surface infiltration reduction and interim surface barrier demonstrations in and around tank farms is found in Sections A.1.3.2.2 and A.1.4.3.

In addition to activities by the site contractors, a number of science and technology activities are underway that will be leveraged to provide support for remediation. These activities are as follows:

- The DOE EM-32 (Office of Groundwater and Soil Remediation within the Office of Technology Innovation and Development [OTID]) has initiated a DVZ Applied Field Research Center (AFRC), which leverages field investigations and treatability testing done by the site contractors. The AFRC provides the framework for coordinated and integrated research and technology development to provide the scientific and technical underpinning for remedial strategies. This approach advances efforts from DOE Office of Science (SC) scientific focus areas (SFAs) to enhance a fundamental understanding of the DVZ challenges and infuse investments from DOE EM to develop more cost-effective characterization, monitoring, and remedial approaches.
- The AFRC is closely linked with a DOE SC SFA that is directed at researching subsurface controls on reactive transport of contaminants. The SFA is linked with an SC field research project focused on the 300 Area, but a component is enabling project staff to investigate the transport behavior of uranium at several cribs in the Central Plateau. The DVZ Program provides a scientific framework for additional DOE SC investment.

Contractor activities, along with scientific knowledge and data in the Hanford Site baseline, will be integrated through a Multi-Project Team (MPT) approach currently used at the Hanford Site. The MPT for the DVZ will primarily focus on projects and activities of the site contractors while leveraging OTID and SC investments through the AFRC and focused scientific studies. The AFRC and PNNL SFA projects also will participate in the MPT meetings to provide updates on progress and seek opportunities for leveraging laboratory and field investigations with ongoing site activities.

5.1 Multi-Project Team Integration

The MPT will focus on integrating laboratory, field, and remediation activities to verify that a realistic and representative understanding of the nature and extent of contamination in the DVZ is obtained, the potential threat to groundwater posed by this contamination is understood, and remedies are identified that can be applied to mitigate that threat. The MPT will provide input to DOE-RL and DOE-ORP to help inform their decisions related to managing the DVZ at Hanford.

The MPT will maintain an integrated schedule for DVZ investigations, research activities, reports, and actions across multiple DOE offices and programs to facilitate timely linkage of activities and contributions from DOE EM-32 and SC. The field activities will be centered at sites within the 200-DV-1 operable unit as well as at sites within 200-WA-1 and 200-EA-1, and the tank farms. These locations are identified in Section 6.0.

The overall objectives of the DVZ within the MPT will be to maintain a forum for:

- Reviewing the status of field and laboratory activities to meet the needs of multiple projects characterizing and remediating the DVZ
- Identifying and recommending prioritized knowledge and capability gaps targeted for investments
- Recommending prioritized field studies to be undertaken
- Supporting the development of the integrated schedules, priorities, and maps to define the actions taken to address DVZ characterization, documentation, and remediation
- Making sure that the suite of DVZ treatability test plans adequately addresses the needs of multiple projects
- Highlighting and communicating emergent characterization data, scientific results, and technology-development advancements
- Jointly developing and communicating alternative conceptual and predictive models of subsurface transport and contaminant fate.

5.2 Hanford Site Soil and Groundwater Remediation

As noted in Section 1.0 and Appendix A, the Central Plateau component of cleanup includes approximately 195 km^2 (75 mi^2) in the central portion of the Hanford Site (see Figure A.1). This component includes the Inner Area covering about 25 km^2 (10 mi^2) and containing the 200 East and 200 West Areas where the major nuclear fuel processing, waste management, and disposal facilities are located. This Inner Area is anticipated to be the final footprint of the Hanford Site and will be dedicated to long-term waste management and containment of residual contamination.

The larger Outer Area is that portion of the Central Plateau outside the boundary of the Inner Area. Waste sites in the Outer Area are being remediated to a level comparable to that achieved for waste sites in the River Corridor. Cleanup of the Outer Area is planned to be completed in the 2015 to 2020 time period, leaving remediation focused on the Inner Area.

For areas of groundwater contamination in the Central Plateau (see Figure A.23), the goal is to restore the aquifer to drinking water standards. In those instances where remediation goals are not achievable in a reasonable time frame, programs will be implemented to contain the plumes, prevent exposure to contaminated groundwater, and evaluate further risk-reduction opportunities as new technologies become available. Near-term actions will be taken to control plume migration until remediation goals are achieved.

At the completion of cleanup efforts, residual hazardous and radioactive contamination will remain, both in surface disposal facilities and in the subsurface within portions of the Central Plateau. DOE intends to minimize the area requiring long-term institutional controls for protection of human health and the environment. However, portions of the Central Plateau will require long-term waste management. For the foreseeable future, it is expected the Inner Area of the plateau will require this approach.

Additional discussion of the approach and schedule for implementing DOE's remediation strategy covering the Central Plateau is found in Section 6.0 and discussed in Sections A.1.2.3 and A.1.2.4.

As part of the cleanup strategy, DOE, the U.S. Environmental Protection Agency (EPA), and the Washington State Department of Ecology have established the DVZ Operable Unit (200-DV-1) to bring a centralized focus and systematic approach to the challenges presented by contamination in the DVZ (see Figure A.1). This operable unit will address the waste sites that require specialized remediation approaches to deal with vadose zone contamination that cannot be remediated using typical surface techniques. A common approach will be applied through the DVZ operable unit to make certain that consistent and protective remedies are developed.

The 44 waste sites now included in the 200-DV-1 operable unit were selected from the previous Tank Waste (200-TW-1/2) and Process Waste (200-PW-5) operable units (see Figure A.1 and Figure A.2 in Section 6.0 for location of these operable units). These waste sites have been grouped together for investigation and decision-making purposes because they are estimated to have similar contaminant characteristics and groundwater risk drivers that require specialized remediation approaches to deal with DVZ contamination. There are some differences in site characteristics and in the nature and extent of contamination; however, these sites represent a logical grouping for the DVZ Operable Unit.

DOE is developing the plans necessary to meet the DVZ technology development/deployment, characterization, testing, and remedial needs. The legal commitments established by existing and new Tri-Party Agreement (TPA) milestones set an aggressive schedule.

The first milestone in the TPA process for the DVZ operable unit is for completing the Resource Conservation and Recovery Act of 1976 (RCRA) Facility Investigation/Corrective Measures Study (RFI/CMS) and Remedial Investigation/Feasibility Study (RI/FS) work plan due September 30, 2012 (see Figure A.1). In accordance with this milestone, the work plan will include a screening of applicable characterization, monitoring, and remediation technologies from both the DOE complex and non-DOE sources and vendors. The work plan will describe the strategy for the DVZ operable unit and identify the activities and schedule for additional characterization, testing, and selection of remediation technologies. The results from this effort will be described in follow-on TPA milestones, such as the corrective measures study and feasibility study report and proposed plan/proposed corrective action decision, which is due September 30, 2015.

For waste sites that are part of other geographic operable units (e.g., 200 West Inner Area and 200 East Inner Area), it is anticipated that DVZ sites will be identified for which remedies protective of groundwater cannot be verified and for which further technology development and treatability testing will be needed. In this situation, these sites will be evaluated first for the need to apply interim actions (e.g., soil removal or interim barriers). Next, these sites will be assigned to the DVZ operable unit for selecting final remedies.

These final remedies will be supported by ongoing treatability testing and science and technology development efforts that DOE has initiated for the DVZ portion of the Central Plateau. It is expected that some final remedies may not be implemented until adjacent tank farms are ready for closure. By bringing about a centralized focus on technologies and remedies, establishing the DVZ operable unit is expected to enhance coordination with the cleanup activities for other waste sites that have groundwater protection concerns, including the contaminated vadose zone underlying the tank farms.

The DVZ operable unit will use a comprehensive, defense-in-depth approach (see Figure A.1) for remedy selection and long-term monitoring for the waste sites where soil contamination remains (e.g., under caps or very deep contaminants) after completing the Central Plateau remediation activities. This approach will help mitigate the potential threat of release and, at the same time, provide an early warning of any significant contaminant movement or impacts to groundwater as part of the long-term institutional controls. This defense-in-depth approach is discussed in Section A.3 of Appendix A.

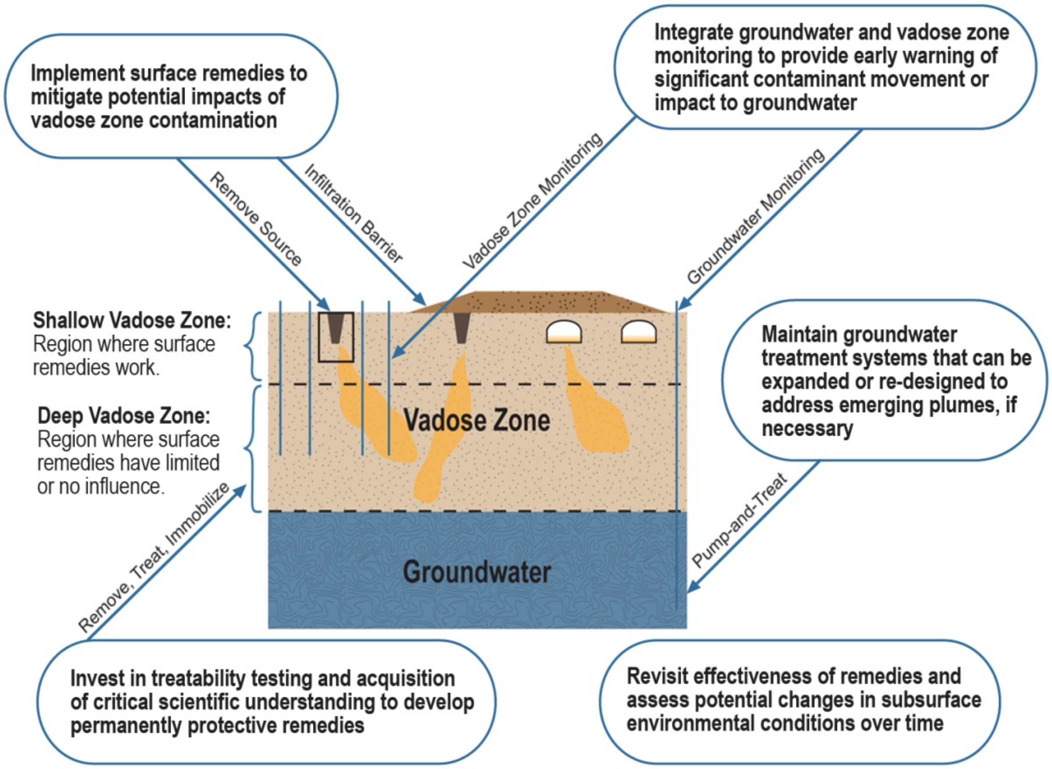


Figure A.1. Defense-in-Depth Strategy for the DVZ

As part of the defense-in-depth strategy for the DVZ, a series of treatability tests has been initiated to evaluate potential approaches to remediate the deeper contamination (see Section A.1.4). If viable technology remedies are developed here or elsewhere, those remedies could be selected and implemented across broad regions of the Central Plateau in a manner analogous to selecting groundwater remediation technologies. If viable technologies are not available, then long-term institutional controls focused on integrated vadose zone and groundwater monitoring will provide an early warning of potential contamination entering the groundwater below the Central Plateau and contribute lead time to implement existing remedies such as groundwater pump-and-treat systems.

The DVZ plumes within the Central Plateau originated beneath specific waste sites and tank farms where liquid releases were of sufficient volume and held enough contaminant mass to reach deep underground. Many of these plumes have spread outward. The distribution and characteristics of the DVZ plumes will depend upon their location, waste receipt history, and antecedent subsurface setting.

Given the large number of expected DVZ plumes beneath the 200 Area, it is clear that a holistic understanding of water, gas, and chemical reactions within this region is needed to improve long-term predictions of contaminant movement and flux into the groundwater. Through this understanding of the DVZ, DOE intends to devise and demonstrate remedial actions that control the migration of deep subsurface contaminants.

The defense-in-depth approach relies on leveraged investments from different organizations working in basic science, applied research, and site cleanup activities. While the full scope of the activity and the available resources are still under development, DOE is committed to utilizing expertise from agency-wide science and technology activities, the national laboratories, universities, and private companies to work in collaboration with the TPA signatories, site contractors, and the public to address the DVZ contamination. Integrating these activities is directed towards bringing resources of many organizations together to provide viable remedial technologies and strategies (see Section 6.0).

5.3 Tank Farm Closure

The SSTs and support facilities will undergo closure by WMA. Each WMA consists of one or more tank farms, including the tanks, ancillary equipment, and soil (see Figure A.1). The tank farms, which consist of treatment, storage, and disposal units, will be closed under RCRA. Appendix I of the Action Plan within the Tri-Party Agreement addresses the regulatory process for closing the Hanford’s single-shell tanks including their waste transfer piping, value pits, contaminted soils, and contamianted groundwater (Washington State Department of Ecology et al 2010). That agreement states that “final WMA closure decisions will be made after all components are retrieved and/or characterized, and all other component closure activities have been completed and a final WMA PA (Performance Assessment) is completed.”

A RCRA RFI/CMS will be prepared to support the soil corrective measure decisions for each WMA. The scope of the RFI/CMS will include both the shallow and DVZs. Each RFI/CMS will also address the requirements of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) (principally associated with remediation of radiological contamination). The decisions made regarding the soil in the RCRA site-wide permit will also be used to support CERCLA decisions.

The first waste management area to be closed is WMA C. The proposed TPA milestone M-45-83 requires that the closure of WMA C be completed by June 30, 2019 (see Figure A.1). To support this milestone, retrieval of the tanks in WMA C is underway, closure planning has begun, and characterization of the contaminated soil is being performed per an RFI/CMS work plan. Proposed TPA milestone M-45-61 requires completion of the WMA C RFI/CMS by 2014, and proposed milestone M-45-82 requires completion of all closure plans associated with WMA C by 2015.

The detailed schedule for closure of the remaining SST WMAs has not yet been determined. However, closure of all SST farms is required by 2043, per proposed TPA milestone M-45-00. For each future WMA closure, an RFI/CMS work plan will be developed, soil characterization performed, and an RFI/CMS delivered to support decisions on soil remediation. As information from the DVZ Project becomes available, it will be integrated into the RFI/CMS process.

In addition to closure activities, the tank operations contractor is performing vadose zone characterization in other tank WMAs to define and perform interim corrective measures. For example, interim surface barriers have been installed in two tank farms (241-T and 241-TY) to limit recharge from precipitation that could drive existing soil contamination deeper into the vadose zone. This action is further discussed in Section A.1.4.3. It is anticipated that up to four more interim surface barriers will be constructed in the 2011 and 2015 time frame. Vadose zone characterization is being performed or is planned in S, SX, and BY tank farms to identify areas that would benefit from an interim surface barrier (see Figure A.1). Examples of existing interim barriers constructed atop tank farms are addressed in Section A.1.4.3). Technologies developed that support characterizing the vadose zone or monitoring the effectiveness of interim measures (such as surface barriers) would be particularly useful in supporting tank farm remediation activities.

5.4 Applied Field Research Center

The mission of the DOE OTID is to transform science and innovation into practical applications for environmental cleanup. DOE EM has made progress during the last 20 years to reduce the overall risk of the cold war legacy by completing cleanup of more than 80% of the DOE waste sites. However, the remaining challenges are far more complex than those addressed to date and require significant advances in science and engineering to solve both short- and long-term challenges.

OTID works at the intersection of basic science and needs-driven applied science and technology. This linkage facilitates the development and incorporation of innovative technologies and remedial strategies into the DOE EM cleanup operations to meet these challenges.

Because of the difficulty addressing the remaining subsurface challenges, OTID identified four strategic groundwater and soil remediation initiatives that provide the opportunity for DOE to complete its legacy waste mission successfully and link all stages of basic science and discovery and technology deployment and implementation to produce solutions that reduce the risk, time, and cost for site closure. Those four initiatives are as follows:

1. Improved sampling and characterization

2. Advanced predictive capabilities

3. Enhanced remediation methods
4. Enhanced long-term performance evaluation and monitoring.

These initiatives are being implemented through significant, long-term investments in three integrated AFRCs located across the DOE-EM complex. These centers will provide the following:

- Technologies to access and deliver remedial amendments, monitor contaminant flux, and assess remedial performance in deep subsurface environments at the DVZ AFRC.
- Transition technologies to enable sites to discontinue the use of active remediation technologies and shorten time frames to reach remediation goals at the Biogeochemical Processes for Applied Subsurface Science Center at the DOE Savannah River Site in South Carolina.
- Remediation strategies for mercury contamination in shallow soils, surface water, and groundwater at the Mercury Remediation and Characterization Center at Oak Ridge, Tennessee.

The AFRC located at the Hanford Site will focus on the following:

- Developing and demonstrating minimally invasive access and delivery methods to emplace remedial amendments in DVZ environments.
- Developing and demonstrating innovative strategies and *in situ* technologies that attenuate and achieve sustainable immobilization in the vadose zone to control contaminant fluxes to water resources.
- Providing the scientific and technical understanding necessary for Advanced Simulation Capability for Environmental Management (ASCEM) to predict the location, transport, and fate of contaminant sources and support remedial selection, implementation, and performance to gain regulatory approval for integrated remedial strategies.
- Developing and demonstrating innovative approaches to measure, predict, and monitor the long-term impacts of remedial strategies in the vadose zone.
- Understanding subsurface heterogeneities to minimize sampling and analysis costs, improve remedial amendment emplacement, and develop *in situ* and geophysical measurement techniques for characterizing key subsurface features that control contaminant fate and transport.

The AFRC will establish a management infrastructure based on close collaboration and communication between participants within the AFRC and with other OTID investigators, SC investigators, industry, academia, and remediation activities underway by DOE contractors.

The organizational structure for the AFRC located at the Hanford Site is shown in Figure A.1. The project includes a management and integration team, including technical program management, site coordination activities, and communications. The management and integration team receives input from a steering committee that includes input from national laboratories, private industry, basic sciences within DOE, OTID, ASCEM, and site contractors. Tasks are organized around technical targets defined in Section 4.0. Associated lines of inquiry describe the scientific and technical issues that need to be addressed.

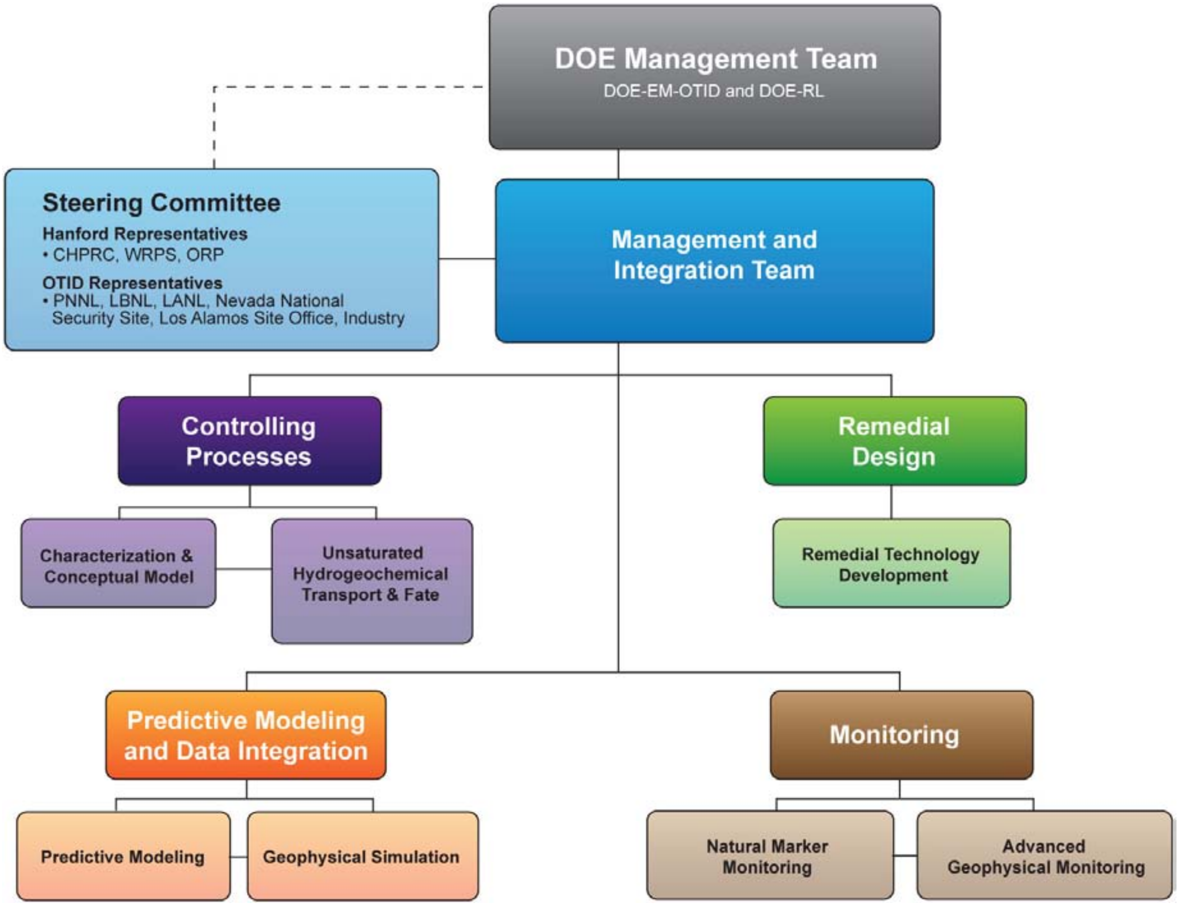


Figure A.1. Organization Chart for the Applied Field Research Center

Several offices within DOE are involved in the Hanford AFRC. DOE EM-32 and RL provide funding for the project and oversight of research. Pacific Northwest National Laboratory (PNNL) reports to the DOE SC as a multi-program national laboratory. PNNL research operations are overseen by the DOE SC Pacific Northwest Site Office (PNSO). DOE-RL also provides general project support and an interface to remediation activities that are underway, is responsible for operation and remediation of the Hanford Site Central Plateau and provides permission for PNNL and other researchers to operate in the Central Plateau.

The management approach for the DVZ AFRC requires close collaboration and communication between participants on the project, other EM-32 investigators, DOE SC, academia, industry, and field activities funded by DOE-RL and CHPRC. The AFRC team members will collaborate with basic science, applied research, and site operation to conduct field and laboratory experiments, share information and data, and publish results. AFRC researchers will have access to the site and associated resources to perform work overseen by CHPRC. All AFRC staff and other investigators accessing the field site are required to be trained on CHPRC procedures for conducting field work. Similarly, if AFRC investigators work inside tank farms, they will be trained on WRPS work procedures.

The AFRC Management and Integration Team includes a DVZ Technical Program Manager and co-Manager, a Program and Site Coordination Manager, and a core research team. All members of the core research team for the AFRC report to the DVZ Technical Program Manager. The Program and Site Coordination Manager reports directly to the DVZ Technical Program Manager and is responsible for managing and coordinating field activities, ensuring compliance with environment, safety and health (ES&H) requirements, managing field staff and infrastructure, obtaining and maintaining appropriate permits for conducting field work at the site, and coordinating with other ongoing field research activities.

An executive steering committee is responsible for reviewing and evaluating opportunities for enhancing investigations, laboratory research and technology development efforts, and efforts to integrate basic science and applied research and providing guidance on these activities to better meet the DVZ characterization, remediation, and monitoring needs of DOE. The steering committee is responsible for the following activities:

- Develop recommended resource allocation priorities to verify that AFRC efforts lead to tangible and field-deployable results
- Verify AFRC integration with DOE SC research, CHPRC treatability testing, and other laboratory to field related research activities supporting the characterization, modeling, monitoring, and remediation of the DVZ
- Provide guidance to make sure that a comprehensive understanding of the nature and extent of the contamination in the DVZ and appropriate remedial strategies is identified, developed, and demonstrated to mitigate subsurface contaminant migration and any potential flux to groundwater.

The four major tasks for the DVZ (Controlling Processes, Predictive Modeling and Data Integration, Remedial Design, and Monitoring) parallel the categories defined below and in Section 4.0.

5.4.1 Controlling Processes

Hydrologic conditions and biogeochemical transformations are subsurface controlling mechanisms that depend upon the physical and chemical setting of the site and contaminants. Understanding these controlling processes is critical to the development of new and cost-effective in-situ remediation technologies such as chemical and biological reduction, physico-chemical sorption-precipitation, and monitored natural attenuation. This knowledge enables better definition of the level of remediation and design of remedial strategies for remediation and long-term stewardship of contaminated sites.

More specifically, research in this area of interest provides 1) better design of remedial strategies; 2) reduction of unintended consequences from treatment processes; 3) technical basis for transitioning from active remediation to monitored natural attenuation; and 4) improved predictive capabilities for contaminant fate and transport. These outcomes will provide information to help Hanford Site and other DOE sites that have DVZ s meet specific regulatory milestones associated with the CERCLA and RI/FS processes and impact site milestones. Activities conducted to address this need include the following:

- Develop cost-effective characterization techniques or approaches that will track the movement of contaminants and permit identifying subsurface physical and hydrological heterogeneities (e.g., advanced geophysical methods)

- Develop cost-effective characterization techniques or approaches that will permit identifying subsurface microbial, aqueous chemical, and mineralogical properties that influence redox, sorption, and (co)precipitation of the contaminant of concern
- Quantify hydrogeophysical and biogeochemical heterogeneous controls on contaminant and water flux to support remedy selection, implementation, and long-term monitoring
- Determine the effect of co-disposed contaminants on contaminant behavior and fate to support remedy selection, implementation, and long-term monitoring
- Evaluate and quantify the contaminant mass flux from the vadose zone to the groundwater to support remedy selection, implementation, and long-term monitoring.

5.4.2 Predictive Modeling and Data Integration

The DVZ AFRC will use predictive models to integrate science and technology information on site-specific hydrogeology and biogeochemistry defining contaminant source characteristics and controlling processes and remedial strategies. Predictive models will be used to access this information and evaluate the performance of remedial strategies and facilitate development of the scientific foundation, applied technologies, and remedial strategies necessary to make defensible remedial decisions that will meet targeted cleanup goals in a manner acceptable by regulators. The following activities will be conducted to address this need:

- Develop a method to evaluate and quantify (e.g., through characterization and/or modeling) the persistence of contaminant sources in the vadose zone to support remedy selection, implementation, and monitoring
- Establish the technical basis for treatability testing
- Develop methods to model, assess, and predict system and remediation performance (linked with ASCEM) and monitor their long-term performance
- Translate the scientific basis for performance into a remediation strategy(s) to meet regulatory goals
- Evaluate the utility of predictive models in the design of efficient delivery systems and for prediction of impacts on hydrogeologic conditions.

As noted in Section A.2.1 and illustrated in Figure A.29, little is known about how DVZ characteristics and processes interact over the spatial and time scales critical to DOE decision-making nor how subsurface processes interplay to dominate contaminant movement and recovery. Identifying, investigating, and modeling these features will be challenging.

OTID is supporting development of a simulation approach and framework (ASCEM) to address these challenges. ASCEM will be a modular, open-source, high-performance-computing tool to facilitate integrated approaches to modeling and site characterization. As part of the initial development process, a series of demonstrations are being defined to test several ASCEM components and provide feedback to the developers, engage end users in applications, and lead to an outcome that would benefit the sites. These demonstrations are being used to form working groups focused on key aspects of DOE problems. The Hanford Site BC Cribs and Trenches area (see Section A.1.4.4 and Appendix D) was selected for one of these working groups and will be used to link ASCEM with the DVZ AFRC.

5.4.3 Remedial Design

Numerous in situ technologies have been developed and demonstrated in field pilot tests to treat large plume volumes. However, subsurface heterogeneities, which largely control the location and transport of contaminants and treatment media, significantly impacted remedial performance. Frequently, the performance of in situ remedial methods is limited by the ability to effectively deliver the treatment media to targeted regions in the subsurface. Significant research and development addressing aquifer systems has ensued, but research and development of effective delivery of treatment media in variably saturated media, where the sources that require treatment are located, is critically needed. Moreover, DVZ environments provide unique challenges (i.e., depth of contamination, mobile contaminants in water unsaturated source zones overlying groundwater) for subsurface access and delivery of remedial amendments (see Section A.1). Subsurface access and delivery are critical technology needs for remediating persistent contamination in the DVZ. The following initial project activities will be conducted to address this need:

- Identify the scientific or technical uncertainties preventing implementation of technologies and means to maintain and monitor remedies over long time periods
- Identify enhancements of existing technologies that can be used in combination to provide alternative remedial strategies to current baseline approaches, including cost-effective access and delivery of remedial materials
- Improve understanding of vadose zone transport of multiphase fluid systems and gaseous phases in heterogeneous porous media to enable design of effective systems to deliver treatment media to the subsurface
- Identify and evaluate innovative methods to efficiently and effectively deliver amendments to the DVZ.
- Determine the effect of heterogeneous hydrogeologic and biogeochemical conditions on amendment distribution and whether delivery methods can be adapted to account for heterogeneities.

5.4.4 Monitoring

At many DOE sites, long-term monitoring costs are projected to exceed cleanup costs. There is a need to steer away from adapting, by default, the “detection monitoring well” networks as the long-term performance-monitoring network, and promote the development of new strategies and approaches to performance monitoring networks.

Developing monitoring techniques for the vadose zone to characterize persistent contaminants is critical to develop defensible conceptual site models, quantify contamination and moisture flux, reasonably estimate future contaminant flux to the groundwater, and implement effective monitoring strategies. The ability to monitor remedy emplacement and performance will allow remediation approaches to be optimized during application, lead to better selection of appropriate technologies and application methods, and provide an independent validation of predictive model simulations. Research into new approaches and tools for monitoring is needed to verify the remedy performance over time and reduce future performance monitoring and life-cycle costs.

Contaminant mass flux from the vadose zone to the groundwater will be evaluated and quantified to support remedy selection, implementation, and long-term monitoring. The focus will be on developing approaches for characterization; investigation of controls on contaminants and water flux including hydrologic/biogeochemical heterogeneities and microbial community composition assessment; methods to monitor emplacement of reagents; and effective noninvasive, long-term monitoring strategies. The following initial activities will be conducted to address this need:

- Develop methods to monitor remedial performance and/or amendment emplacement, injection, and effectiveness (e.g., advanced geophysical methods)
- Develop non-intrusive monitoring techniques of flux and remediation performance (e.g., microbial community profiling)
- Develop long-term monitoring strategies.

5.5 Office of Science Linkages

The PNNL SFA is investigating fundamental Hanford Site subsurface science issues through integrated, multidisciplinary, science-theme focused research on the role of microenvironments and transition zones in the reactive transport of technetium, uranium, and plutonium (see Section A.3.4).

The overall goals of the SFA are to develop the following:

- An integrated conceptual model for microbial ecology in the Hanford Site subsurface and its influence on contaminant migration
- A fundamental understanding of chemical reaction, biotransformation, and physical transport processes in microenvironments and transition zones
- Quantitative biogeochemical reactive transport models for technetium, uranium, and plutonium that integrate multiprocess coupling at different spatial scales for field-scale application.

Targeted contaminant chemical reaction and biotransformation processes include heterogeneous/biologic electron transfer, precipitation and dissolution, and surface complexation. The SFA is emphasizing laboratory-based, coupled computational and experimental research using physical/biological models, and sediments and microbial consortia and isolates from multiple Hanford Site settings to explore molecular, microscopic, and macroscopic processes underlying field-scale contaminant migration. It also will pursue the refinement of geophysical and geo-statistical techniques to define, characterize, and map spatial structures, sediment facies distributions, and reactive transport properties of microenvironments and transition zones in the field.

The SFA is using capabilities in the Environmental Molecular Sciences Laboratory (EMSL) to develop molecular understandings of key processes, and the 300 Area Integrated Field Research Challenge (IFRC) access to and samples from subsurface environments where these microenvironments exist and are important to understanding contaminant movement and remediation performance. The research program builds on established areas of PNNL expertise in geochemistry, microbiology, and multi-scale modeling. Individual, but highly collaborative research projects, are focused on different scales, coupled processes, and/or contaminants.

5.6 Communication and External Outreach

The Deep Vadose Zone Program will conduct its activities in an open and transparent manner. It will work with the staff of the DOE-RL Office of Communications and External Affairs to provide timely information and opportunities for involvement to regulatory agencies, Tribal Nations, and stakeholders. Methods for communication will include:

- Inviting regulatory agencies to participate in monthly Deep Vadose Zone Multi-Project Team meetings.
- Inviting Tribal Nations to participate in monthly Deep Vadose Zone Multi-Project Team meetings. In addition, the Tribal Nations will be provided regular briefings, coordinated through the DOE-RL tribal liaison. The program will work with the tribal liaison to identify opportunities to brief the cultural resources group.
- Providing periodic updates to the Hanford Natural Resources Trustee Council, the Hanford Advisory Board and/or its committees, the Oregon Hanford Cleanup Board, the Hanford Communities, and other stakeholder groups.
- Coordinating all interactions with the media with the DOE-RL media relations point of contact. Information will be shared through press releases, interviews, and other appropriate venues.

6.0 Program Implementation

The purpose of this section is to describe the interface between science and technology development activities and the remediation and closure projects that are responsible for implementing solutions to DVZ issues at the Hanford Site. The section describes the project implementation schedules and critical "insertion" points and "decision" points relative to research and technology development outcomes and applications.

It is recognized that TPA milestones drive cleanup schedules, and the development of documentation to support cleanup decisions requires timely inputs from AFRC activities (see Section 5.0). The most current scientific and technical information will be needed to support the testing, selection, design, and implementation of DVZ remedies at each step in the process.

A tension will remain between the drive to meet decision milestones using available information and technology versus the desire to defer decisions to allow better information and technology to emerge. There is no simple answer to this dynamic. Both driving forces need to actively work to accommodate the requirements and realities of the other. Therefore, the regulatory framework and remediation efforts will be managed to support both near-term decisions and the longer term remedy implementation and, as needed, the remedy revision process. For example, available resources and the practicalities of technology research and development will mean that, at the time of remedy selection, there will always be uncertainty regarding potential solutions that are unproven.

Nonetheless, the CERCLA process is aware that remedy selection may not be absolute and final. This recognizes that a remedy can be selected with the details of implementation still needing work. For example, treatability studies can be conducted to gain site-specific design parameters after the proposed remedy is selected. In addition, the CERCLA strategy of remedial implementation is supported by maturing technology performance and monitoring results.

The CERCLA 5-Year review requires periodic re-examination of remedy performance and, in some cases, evaluates the availability of improved solutions that were not known or mature at the time of remedy selection. This process has been successfully used at Hanford to revisit initial remedies that did not perform as expected or whose performance was significantly improved by new capabilities.

The AFRC development process also must adapt to the requirements of the regulatory decision processes. There must be a careful selection of the investments expected to yield useful results within the time frame of the regulatory decision process versus those investments that will not be ready to implement. Thus, AFRC investments need to simultaneously support both short-term critical decisions and longer-term objectives. Balancing the competing drivers for a "bias for action" and "scientific sufficiency" will remain a challenge and a high priority for program implementation and investment strategies.

Section 4.0 identified potential high-priority research and development activities to be pursued by AFRC. The following items identify the end user projects that the AFRC activities will support. Figure A.1 shows the location of many of the waste site operable units within the Inner Area of the Hanford Site Central Plateau, and Figure A.2 shows the location of the groundwater operable units. (For the purpose of discussion in this section, these two figures are reproduced from Appendix A).

- Central Plateau Soil/Vadose Zone Operable Units
  - 200-WA-1 – includes BC cribs and trenches and U cribs
  - 200-EA-1 – includes plutonium-uranium extraction (PUREX) cribs
  - 200-DV-1 – includes cribs and trenches associated with WMAs B-BX-BY, T, and TX-TY along with several reduction oxidation (REDOX) cribs.
- Central Plateau Groundwater Operable Units
  - 200-ZP-1 – northern portion of 200 West Area
  - 200-UP-1 – southern portion of 200 West Area
  - 200-BP-5 – northern portion of 200 East Area
  - 200-PO-1 – southern and eastern portion of 200 East Area.
- Deep Vadose Zone Treatability Testing Project
  - ^{99}Tc treatability testing
  - Uranium treatability testing.
- Tank Farm WMAs
  - WMA A-AX
  - WMA B-BX-BY
  - WMA C
  - WMA S-SX
  - WMA T
  - WMA TX-TY
  - WMA U.

For each project area, the following information is relevant to defining the interface with the AFRC:

- Regulatory milestones, timetable for enabling documents (e.g., work plans, remedial investigations, feasibility studies, corrective measures studies, etc.)
- State of knowledge. Overview of contaminant threat plus nature and extent. What is the problem to be remediated?
- Remediation goals (measured or model predicted)
- State of uncertainty. Critical information gaps and uncertainties. What do we need to know?
- Overview of field activities and opportunities for “leveraging”
- Focal points/priorities for basic science
- Focal points/priorities for applied science and engineering
- Focal points/priorities for field treatability testing and demonstration.

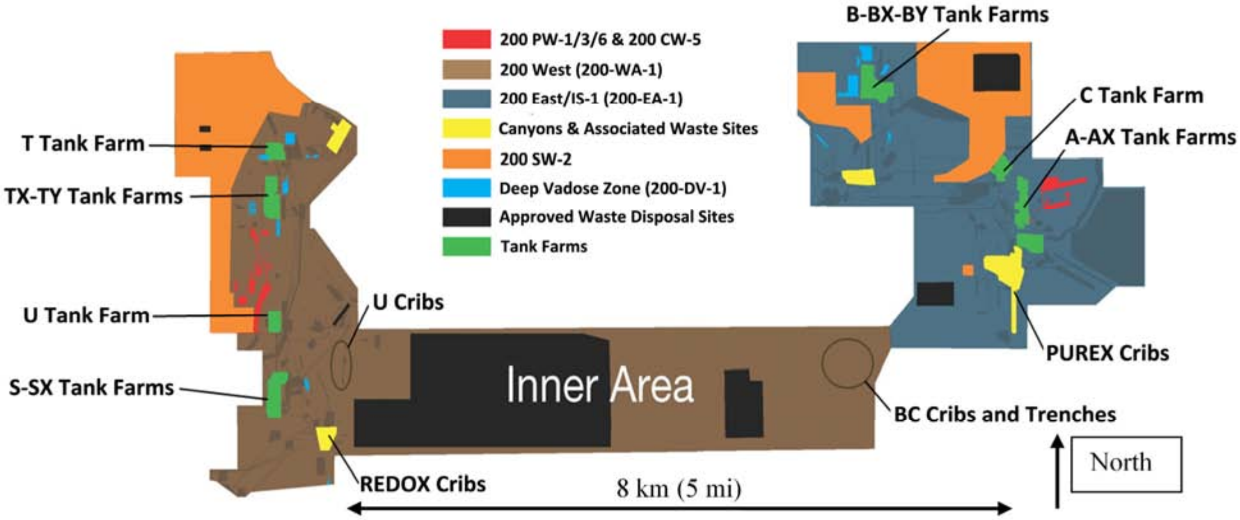


Figure A.1. Inner Area Operable Units, Tank Farms, and Other Potential DVZ Sites

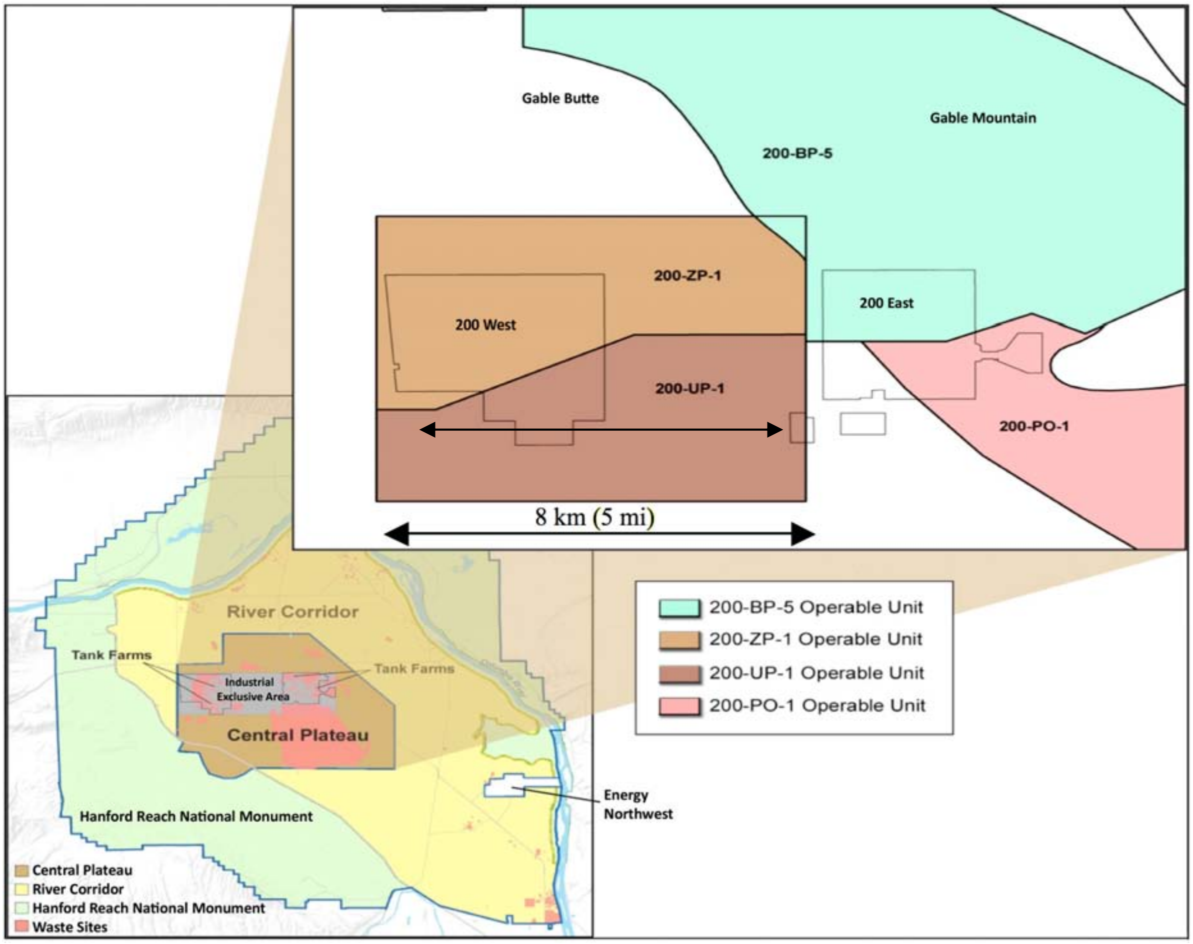


Figure A.2. Central Plateau Groundwater Operable Units

6.1 Planned Outcomes for the Deep Vadose Zone Applied Field Research Center

This section describes the expected outcomes and success indicators for AFRC covering the time frame of approximately FY 2011 through FY 2012. These outcomes will be further refined along with a more detailed description of supporting research activities in an Implementation Plan that will be prepared during FY 2011. The following outcomes and success indicators are intended to communicate the higher-level expectations for AFRC as it begins operations in FY 2011. These outcomes are organized into four topical areas:

1. Establish the AFRC management infrastructure.
2. Establish effective working interfaces with Hanford Site field projects (in both Central Plateau and tank farms) including DVZ and groundwater activities at Hanford.
3. Establish working interface with DOE's Office of Technology Innovation and Development funded efforts including AFRC research and ASCEM activities to identify and develop the next phase of remediation technology and supporting capabilities. Establish collaborative research and development partnerships with national laboratories, universities and private industry.
4. Establish an effective working interface with the SC SFA initiatives to improve alignment with DVZ needs at Hanford.

Specific outcomes and success indicators for each of these topical areas are described below. The key elements of these outcomes will be included in the Hanford Site's annual listing of priorities for groundwater and vadose zone integration activities.

1. Establish the AFRC management infrastructure

- Coordinate science and technology integration ties with the Multi-Project Team
- Gain endorsement from the Hanford Site Groundwater/Vadose Zone Executive Council
- Gain U.S. Department of Energy Headquarters (DOE-HQ) endorsement through peer review of the DVZ Long-Range Plan
- Obtain feedback on the DVZ Long-Range Plan from regulators, Tribal Nations, and stakeholders
- Officially "launch" AFRC
- Formally implement the management structure, thus establishing the decision-making authority
- Develop and issue a detailed implementation plan and a multi-year funding projection.

2. Establish effective working interfaces with Hanford Site field projects

- Integrate next ~3-year supplemental characterization and wrap-around science activities with Office of Environmental Management/SC priorities
- Establish onsite radiological and non-radiological subsurface sample archive capability
- Provide broad technical and scientific expertise to support development of the T Complex Conceptual Model Report (200-DV-1)

- Leverage and develop tangible, multi-use field test sites for deploying/testing new characterization, remediation, and monitoring technologies
- Foster improved understanding across Hanford of the state-of-the-art DVZ characterization and monitoring methods and technology development efforts
- Support integrated data management to establish a comprehensive resource for Hanford DVZ studies
- Increase science and technology support to Hanford's DVZ treatability testing activities.

3. **Establish working interface with DOE's Office of Technology Innovation and Development funded efforts**
   - Complete development of foam delivery technology to assess its potential for field testing at Hanford. Evaluate cost and performance attributes.
   - Complete the development of a capability to monitor complex resistivity with high spatial-temporal resolution and to understand how three-dimensional changes in complex resistivity are diagnostic of three-dimensional foam amendment delivery and remedial performance
   - Couple geochemical and geophysical characterization data with microbial community composition information to assess and predict changes in the vadose zone
   - Develop geophysical monitoring techniques to provide spatially extensive information about hydrogeological heterogeneity, the distribution of injected materials, and induced (bio) geochemical transformations. Continue developing the modeling capability to predict mobility and migration of foam in unsaturated porous media.
   - Continue development of improved methods to quantify and control the mass flux of persistent contamination from the vadose zone to the groundwater and validate with laboratory experiments and site field data
   - Create incentives for Hanford contractors, private industry, universities, and national laboratories to collaborate on developing and testing new capabilities onsite
   - Establish a working interface with the ASCEM initiative
     - Establish a DVZ Working Group
     - Apply the Phase-I demonstration at the BC cribs and trenches site.

4. **Establish an effective working interface with the SC SFA initiatives**
   - Complete analytical studies of U-8/12 borehole samples
   - Establish formal linkage to SC and the SFA to align priorities with DVZ needs, to support additional opportunistic sampling activities, and to leverage additional SC resources/activities.
   - Improve understanding of redox chemistry of ^{99}Tc in 200 Area sediments
   - Characterize the intra-grain microscopic transport processes of U and ^{99}Tc in different Hanford sediment facies
   - Transfer applicable 300 Area IFRC lessons learned, results, and technologies to the AFRC or entire DVZ project

- Compile a retrospective (state-of-knowledge) report on past studies related to technetium mobility at Hanford (analogous to the uranium state-of-knowledge report published in Zachara et al. 2007).

6.2 Linkages to Hanford's Groundwater and Vadose Zone Projects

This section describes Central Plateau operable units and tank farm WMAs at the Hanford Site. The intent is to single out the principal actions underway and identify opportunities or potential interface points with Hanford cleanup projects. For each operable unit and tank farm WMA, Table 6.1 summarizes key milestones, relevant characterization, treatability testing, and remediation activities. The last column highlights specific interface or linkage points that define opportunities for AFRC activities to influence planned DVZ project activities.

6.3 Implementation Schedule

An initial implementation schedule showing the principal activities and milestones for Hanford's end user projects (tank farm and non-tank-farm sites), DVZ treatability testing activities, the DVZ AFRC, and SC-funded activities is outlined in Figure A.1. This figure lists the principal activities and milestones along with key interface or collaborative opportunities between these efforts. This implementation schedule represents the current point in time. These activities will be updated as the definition of the lower half of the figure improves. In addition, a revised implementation plan that will define these linkages and collaborative opportunities to a greater level of detail is scheduled to be prepared during FY 2011.

6.3.1 Hanford Deep Vadose Zone Program

The upper portion of Figure A.1 shows the primary milestones and activities for Hanford's end-user projects. The 200-WA-1 is a new operable unit that includes the following:

- Most of the 200 West Area of the Central Plateau plus the BC cribs and trenches where most DVZ project activities currently are being conducted.
- 216-U-8 and 216-U-12 cribs where supplemental characterization work will be supported by analytical resources from the SC through Hanford's SFA. The 200-EA-1 operable unit includes most of the waste sites in the 200 East Area of the Central Plateau.

The 200-DV-1 operable unit includes the following:

- DVZ sites associated with the B and T cribs and trenches surrounding tank farms in both the 200 East and 200 West Areas
- Several additional DVZ sites near the REDOX facility and the S-SX tank farms.

A feasibility study and proposed plan are due in 2015 for the sites identified above. In establishing the DVZ operable unit, the TPA signatories recognized the potential for additional waste sites being added to this operable unit as site investigations and remedy selection continues.

Table 6.1. Decisions and Actions Related to DVZ and Groundwater Protection

Decision Unit	Key Milestones	Characterization, Testing, and Remediation	DVZ Project Research Linkages
200-DV-1* (includes B, T, and S-SX cribs and trenches plus REDOX cribs)	• Submit RI/FS Work Plan (with technology screening report)—9/30/2012 (M-015-110A) • Submit FS/PP—9/30/2015 (M-015-110B)	• B Complex Conceptual Model Report (July 2010) • Supplemental Characterization (TBD) • T Complex and S-SX Complex Conceptual Model Reports • Technology screening • Predictive modeling for risk determination and remedy evaluation	• Technology screening report (input to work plan) • Supplemental characterization boreholes – opportunity for enhanced analyses • Develop T Complex Conceptual model report to integrate available data and prioritize data needs. • Characterization of extracted "perched" water and uranium from BX-102 overfill event.
200-WA-1 (includes BC Cribs and trenches, U-8, U-12)	• Submit RI/FS Work Plan – 12/31/2011 (M-015-91A) • Submit FS/PP – 6/30/2013 (M-015-91B) • Submit uranium treatability test plan—12/31/2010 (M-015-110C) • Submit ^{99}Tc pilot treatability test report – 6/30/2012 (M-015-110D)	• 216-U-8 and 216-U-12 new boreholes with SC-funded analyses; with electrical resistivity survey • Additional Supplemental Characterization (TBD)	• BC Cribs pilot scale treatability test report (6/30/2012); monitoring using electrical resistivity • High-air-flow test for ^{99}Tc extraction at BC Cribs and/or other locations • Uranium sequestration test at 216-U-8 • 216-U-8 and U-12 boreholes and SFA-funded analyses • Foam Delivery Technology test at BC Cribs, including innovative monitoring methods • Apply ASCEM Phase-I demonstration to BC cribs and trenches site
200-PW-1/3/6 (soil vapor extraction for CCl_4)	• Submit revised FS with PP – Spring 2011	• Soil vapor extraction (ongoing)	• EM-32 funding project addressing chlorinated organics in the vadose zone.
200-EA-1 and 200-IS-1 (includes all of 200-IS-1)	• Submit RI/FS Work Plan – 12/31/2012 (M-015-92A) • Submit FS/PP—6/30/2014 (M-015-92B)	• Supplemental characterization (TBD)	• Potential DVZ uranium sites associated with PUREX waste sites. Need to evaluate uranium mobility at these high inventory sites.
200-ZP-1/UP-1 (200-West Area groundwater operable units)	• Submit UP-1 RI/FS/PP – 9/30/2010 (M-015-17A)	• Initiate full-scale ZP-1 (and UP-1) groundwater treatment system (12/31/2011, M-016-122) • Initiate ^{99}Tc groundwater pump-and-treat system at S-SX (12/31/2011, M-016-120)	• S-SX extraction boreholes—opportunity for enhanced analyses and DVZ characterization • Long-term monitoring opportunity for DVZ response to 200 West Area Treatment System.
200-BP-5/PO-1 (200-East Area groundwater operable units)	• Submit RI/FS /PP – 12/31/2012 (M-015-21A)	• Submit treatability test plan for B Complex uranium and ^{99}Tc in groundwater (12/31/2011, M-015-82) • Install new monitoring wells (TBD)	• Conduct treatability test for B Complex uranium in groundwater—potential opportunity for DVZ uranium treatability test.

Table 6.1. (cont'd)

Decision Unit	Key Milestones	Characterization, Testing, and Remediation	DVZ Project Research Linkages
WMA C	• Submit RFI/CMS – 12/31/2014 (9/30/2013 baseline date) • Submit permit modification to support WMA C closure – 9/30/2015	• Conduct vadose zone characterization at WMA C per approved work plan (ongoing)	• Key interface with B Complex conceptual models and BP-5 conceptual models • Application of enhanced vertical resolution electrical resistivity characterization methods to locate vadose zone plumes • Reconcile performance assessment approach with ASCEM modeling methods
WMA A-AX	• TBD	• Likely to be the next tank farm in sequence for corrective action, retrieval, and closure	• Key interface with B Complex conceptual models and BP-5/PO-1 conceptual models • Retrieval challenges in A could force revisit of retrieval specification that could require support from risk assessment
WMA B-BX-BY	• TBD	• Evaluate potential for interim barrier (TBD)	• Interim barrier design and coordination with BY Cribs (potential joint interim action) • Characterization to support barrier design/placement provides opportunity for opportunistic characterization of BY Cribs and DVZ • B-BX-BY leak assessment updates will require inclusion in Soil Inventory Model updates (i.e., inventory estimates)
WMA S-SX	• TBD	• Evaluate potential for interim barrier (TBD)	• Design of interim barrier in 2011—opportunity for additional vadose zone characterization and additional barriers • Incorporate advanced DVZ monitoring capabilities • Potential to incorporate desiccation or high-air-flow remedy in conjunction with an interim surface barrier • S-Tank Farm could be used for waste staging, which could require additional risk assessment • Need to assess Cold Creek Unit permeability
WMA T	• TBD	• Interim barrier monitoring (ongoing)	• Continued monitoring of barrier performance • T leak assessment required to support T area conceptual model and Soil Inventory Model update • Need to assess Cold Creek Unit permeability
WMA TX-TY	• TBD	• Interim barrier monitoring (TBD)	• Continued monitoring of barrier performance • TX leak assessment required to support TX-TY area conceptual model and Soil Inventory Model update • Need to assess Cold Creek Unit permeability

Table 6.1. (cont'd)

Decision Unit	**Key Milestones**	**Characterization, Testing, and Remediation**	DVZ **Project Research Linkages**
WMA U	• TBD	• Evaluate potential for interim barrier (TBD)	• U leak assessment required to support Soil Inventory Model update • Need to assess Cold Creek Unit permeability

Notes:

* For both 200-DV-1 and 200-EA-1, the regulatory documentation is intended to meet RCRA corrective action and CERCLA cleanup requirements. Where an "RI/FS Work Plan" is listed in this table, it is assumed that the document will also meet the needs of a RCRA "RFI/CMS work plan." Similarly, an "FS" will meet the requirements of a "RCRA CMS," and a "PP" will meet the needs of a "RCRA Proposed Corrective Action Decision." Both RCRA and CERCLA designations are implied for the documentation supporting these two operable units.

Nomenclature:

ASCEM – Advanced Simulation Capability for Environmental Management
CMS – Corrective Measures Study
DVZ – Deep vadose zone
FS – Feasibility Study
PCAD – Proposed Corrective Action Decision (RCRA)
PP – Proposed Plan (CERCLA)
RFI – RCRA Facility Investigation
RI –Remedial Investigation
SFA – Scientific Focus Area
WMA – Waste Management Area

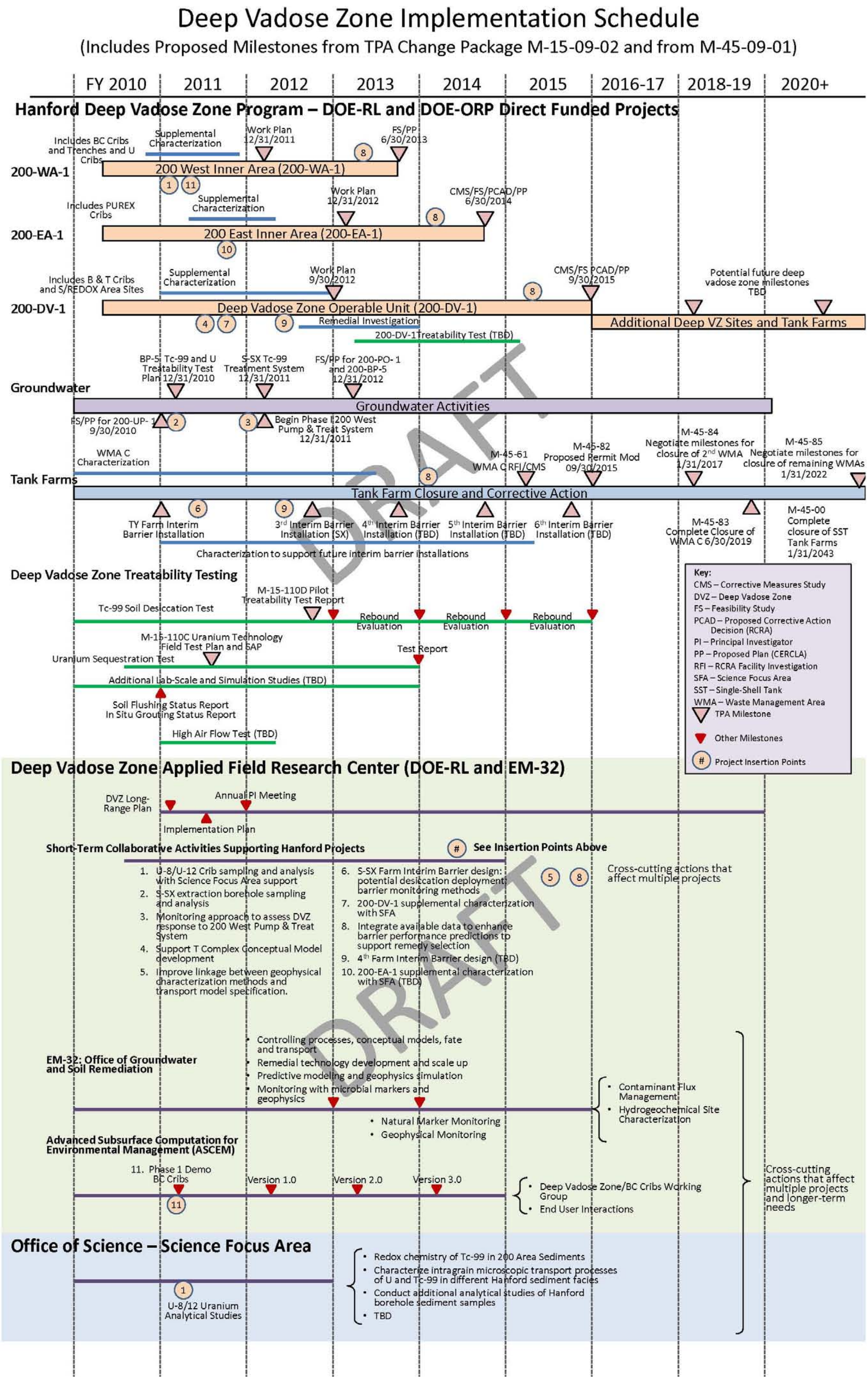


Figure A.1. DVZ Program Implementation Schedule

In addition, DOE-RL and ORP intend to apply a consistent set of remedy evaluations for past releases from tank farms that reside in the DVZ. Tank farm closure and corrective action decisions are planned in a sequential fashion with the first tank farm decisions occurring for WMA C in 2015. Subsequent tank farm decisions will occur following WMA C with closure of all SST farms expected by 2043. Consequently, there may be challenging remedy decisions for several decades to come.

The top portion of Figure A.1 also shows the key milestones for the Central Plateau groundwater operable units. These include treatability tests or small-scale treatment systems for localized ^{99}Tc and uranium contamination that currently is being released from the DVZ and is impacting groundwater at concentration levels significantly above drinking water standards. These localized treatment systems and tests provide opportunities for gaining additional information on high-priority DVZ plumes.

A record of decision is already in place for the 200-ZP-1 groundwater operable unit in the northern half of 200 West Area. A large treatment system pumping up to 9500 L per minute (2500 gpm) is being constructed to remediate this plume. That treatment system will have the capacity to also treat contaminants from the 200-UP-1 groundwater operable unit, which is located in the southern half of the 200 West Area. This system is being designed to remove 95 percent of the mass of contaminants presently in the groundwater in this area within 25 years.

To complement this groundwater treatment system, DOE also will need to implement effective remedies to provide long-term protection of the groundwater by preventing DVZ contamination entering and re-contaminating the underlying groundwater.

6.3.2 Deep Vadose Zone Applied Field Research Center

The lower portion of Figure A.1 shows the primary elements of the AFRC. During FY 2011, an implementation plan will be written to provide more detail and resolution regarding the science and technology activities associated with the AFRC. As described in Section 5.0, the AFRC interface with Hanford Site projects will be supported by a Multi-Project Team that will meet approximately once each month.

6.3.2.1 Collaborative Activities Supporting Hanford Projects

Figure A.1 shows an initial set of collaborative activities between Hanford projects and the AFRC. These collaborative activities identify key opportunities for AFRC research activities to provide direct input into Hanford field projects. These activities are numbered, and the insertion points also are shown along the schedule bars for the associated Hanford field project.

This initial set of activities will be refined as AFRC efforts evolve and as needs and opportunities for Hanford field projects change over time. Such activities include both project-specific actions (e.g., Action #1—U-8/U-12 Sampling and Analysis) and crosscutting efforts (e.g., Action #8—Integrate Available Data to Enhance Barrier Performance Predictions to Support Remedy Selection) that influence multiple projects. The status of these collaborative activities will be discussed and monitored by the Multi-Project Team.

6.3.2.2 DOE Activities

The detailed schedule for AFRC activities is under development.

6.3.2.3 SC and SFA Contributions

Contributions and collaborations involving the SC and subsurface SFAs are summarized in Sections 5.4 and 5.5 plus the BC Cribs and Trenches integration example found in Appendix D.

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Appendix A

Background Information Supporting Sections 1.0 Through 3.0 of the *Deep Vadose Zone Program Plan*

Appendix A

Background Information Supporting Sections 1.0 Through 3.0 of the *Deep Vadose Zone Program Plan*

Acronyms and Abbreviations

ARAR	Applicable or Relevant and Appropriate Requirements
ASCEM	Advanced Simulation Capability for Environmental Management
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
DNAPL	dense, nonaqueous phase liquid
DOE	U.S. Department of Energy
DVZ	deep vadose zone
EMSP	Environmental Management Sciences Program
ERDF	Environmental Restoration Disposal Facility
FS	feasibility study
FY	fiscal year
GAO	U.S. General Accounting Office
NABIR	Natural and Accelerated Bioremediation Research
PNNL	Pacific Northwest National Laboratory
PUREX	Plutonium Uranium Extraction (Plant)
RCRA	Resource Conservation and Recovery Act
REDOX	Reduction-Oxidation (S Plant)
RI	remedial investigation
RL	Richland Operations (U.S. Department of Energy)
SC	Office of Science (U.S. Department of Energy)
SFA	Scientific Focus Area
SIM	Site Inventory Model
SST	single-shell tank
STOMP	Subsurface Transport Over Multiple Phases

Contents of Appendix A

Figures

Tables

A.1 Background

> "Historically, scientists, regulators, managers, and decision makers concerned with subsurface contamination have focused on groundwater and contaminant movement below the water table. This focus seemed warranted because groundwater is the principal system for moving contaminants away from a disposal site…In contrast, the vadose zone has been looked upon as a natural contaminant buffer, and not as an important, and dynamic part of the contaminant 'delivery system.' Today, the vadose zone is recognized as a key player in determining the long-term impacts of contamination."
> (Looney and Falta 2000)

This section of the deep vadose plan summarizes the geologic and waste management history of the Hanford Site, the cleanup strategy covering the subsurface environment beneath the site's Central Plateau (Figure A.1), and remediation activities and treatability testing.

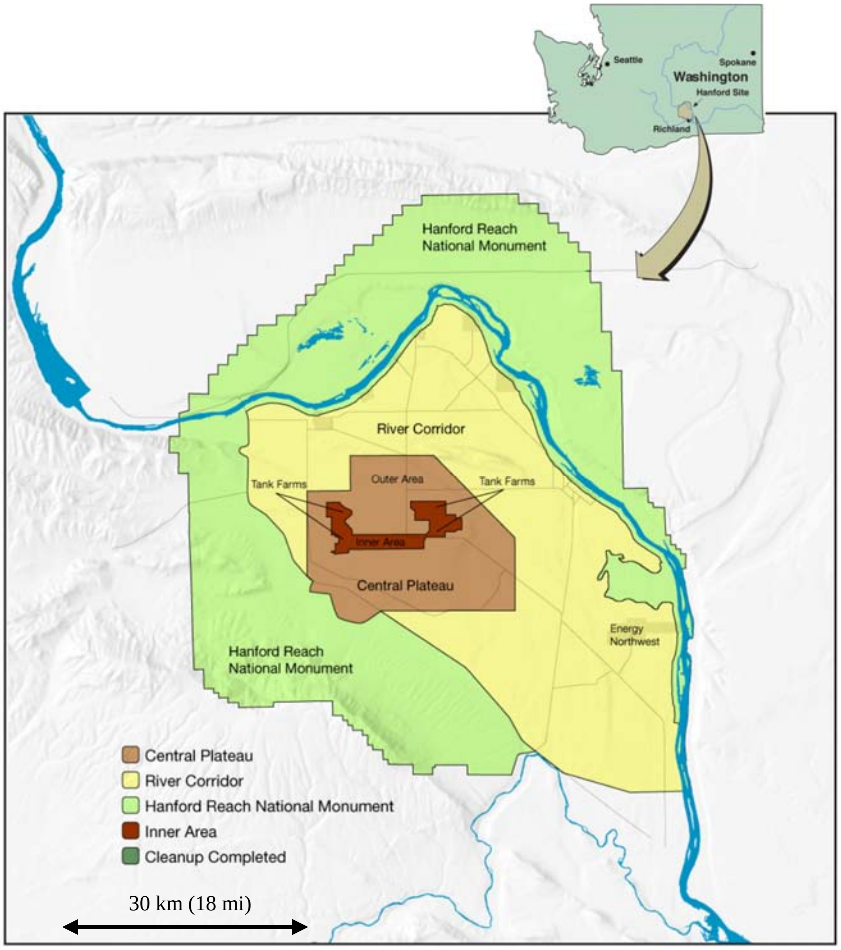

Figure A.1. Location of the Hanford Site and Central Plateau

Broadly, the vadose zone is that portion of the subsurface geologic media between the land surface and the water table (Figure A.2). Throughout the vadose zone, pores separating sediment are filled with a mixture of water and gas; this is why the vadose zone is sometimes called the unsaturated zone.

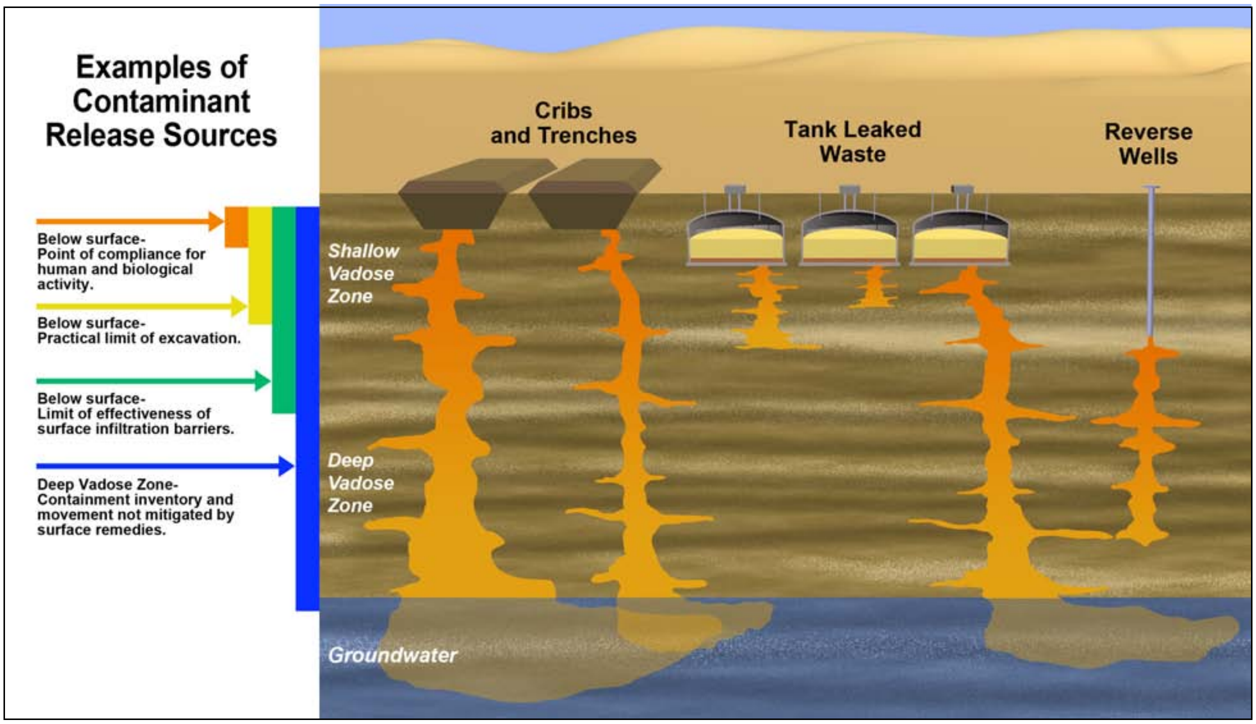

Figure A.2. Some Vadose Zone Terminology. (Modified after DOE-RL 2008b)

In this plan, the deep vadose zone (DVZ) is defined as that region of the unsaturated sediment resting below the practical depth of surface excavation or surface barrier influence and above the upper boundary (water table) of the underlying aquifer.

On the most basic level, two processes control water movement in the vadose zone: gravity and capillary forces (Looney and Falta 2000). Gravity tends to move water downward from regions of high to lower energy—like water flowing down a hill. Capillary forces are created by the surface tension between water molecules and the outer surface of sediment grains and narrow fractures. Capillary forces cause the vadose zone to act like a sponge, potentially moving water in all directions as water is stored and released. Broadly, gravity flow dominates in coarse-grained sediment such as gravels and large fractures while capillary flow dominates finer-grained silts and clays. Other geochemical, biological, and atmospheric forces add more complexities to understanding and predicting water flow in the vadose zone.

Water chemistry is strongly influenced by its geochemical interaction with sediment minerals and other subsurface constituents, including microorganisms. Similarly, the behavior of contaminants released into the vadose zone is dominated by how those contaminants and their associated waste chemistry interact with the subsurface environment.

The DVZ poses some unique challenges, including:

- low moisture content
- sediment thickness (~50 to 100 meters)
- contaminant depth and spread in a complex geohydrologic, geochemical, and microbial environment
- presence of mixed contaminants (chemical, metals, and radionuclides) interacting with one another and the subsurface environment
- limited availability and effectiveness of traditional characterization tools and cleanup remedies
- Understanding contaminant behavior and remediation performance over long time frames and across molecular- to field-scales.

While multiple remediation approaches, such as groundwater pump-and-treat and sequestration barrier testing, have been underway at the Hanford Site—some for nearly 20 years—most field-scale efforts to date addressing vadose zone contamination have focused on minimizing water releases and soil vapor extraction targeting carbon tetrachloride recovery. For nearly a decade, research into subsurface contaminant movement, surface barrier performance, and treatability tests has been underway.

Remediation of the DVZ is central to Hanford Site cleanup because the vadose zone can provide an ongoing source of contamination to the underlying aquifer and therefore, perhaps later, to the Columbia River. Contaminant recovery, long-term fixation/sequestration, control, and monitoring in the cubic kilometers of sediment beneath the central Hanford Site will be required.

While contamination in the shallow vadose zone can be removed by excavation or hydraulically controlled by surface engineered barriers, contamination in the DVZ rests beneath the influence of these remediation techniques. In addition, while many of the environmental processes controlling fluid flux and contaminant movement in the DVZ are identified, they are not well quantified. This underscores the need for a far-reaching characterization, modeling, remediation, and monitoring strategy that not only defines the key characteristics and processes controlling contaminant behavior but also the short- to long-term impact remediation applications have on the subsurface.

A.1.1 Site Geohydrologic Background

This section describes the geologic history of the Hanford Central Plateau with emphasis upon the DVZ (Figure A.3). Key subsurface characteristics, features, events, and processes important to explaining water and contaminant movement plus impacting the effectiveness of remediation approaches are summarized. More detailed information and descriptions are summarized in Last et al. (2006, 2009a, 2009b) and DOE-RL (2008b).Introduction

During most of the Hanford Site's history, subsurface studies primarily focused upon groundwater monitoring and characterization supporting waste management operations and environmental assessments. Some shallow vadose zone studies assessed *in situ* moisture seepage and shallow contaminant migration. DVZ studies were not a priority. Waste disposal practices relied upon the vadose zone as a contaminant-retaining buffer sited between ground level and the underlying groundwater aquifer. Groundwater monitoring wells drilled near liquid waste disposal sites— such as cribs and trenches—made sure that the vadose zone retained at least 90% of the contaminant releases. Operating guidelines permitted the remaining 10% to reach groundwater.

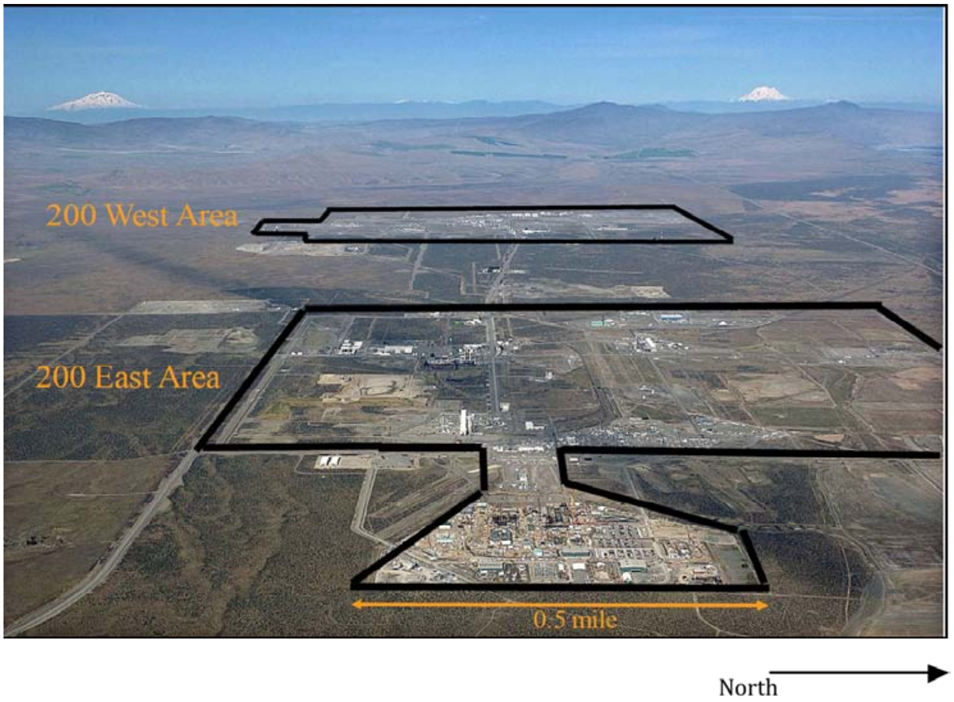

Figure A.3. Aerial Photograph Facing West Across the 200 East and 200 West Areas. This photograph covers a large portion of the Central Plateau where most of the contaminated liquids from reprocessing spent uranium fuel were intentionally or accidentally released into the subsurface.

The vadose zone extends from ground level to the water table. Beneath the Central Plateau, the vadose zone ranges in thickness from about 50 m (160 ft) in the western portion of the 200 West Area to 100 m (330 ft) in the southern part of the 200 East Area (Last et al. 2006).

Broadly, the major stratigraphic units comprising the Hanford vadose zone are as follows:

- Surface wind-deposited sand and silt deposits
- Unconsolidated sand and gravel of the Hanford formation
- Silt and carbonate-cemented layers of the Cold Creek Unit
- Semi-consolidated sand, gravel, and mud units of the Ringold Formation.

As Figure A.4 depicts, these sediments are deposited upon basalt.

Geologic stratigraphy varies significantly across the Central Plateau. As generalized in an east-west geologic cross-section shown in Figure A.5, the vadose zone beneath 200 West Area consists of the Hanford formation, Cold Creek Unit, and Ringold Formation, whereas the vadose zone beneath the 200 East Area consists almost entirely of the younger Hanford formation. Ancestral rivers eroded away most of the Ringold Formation from beneath the 200 East Area.

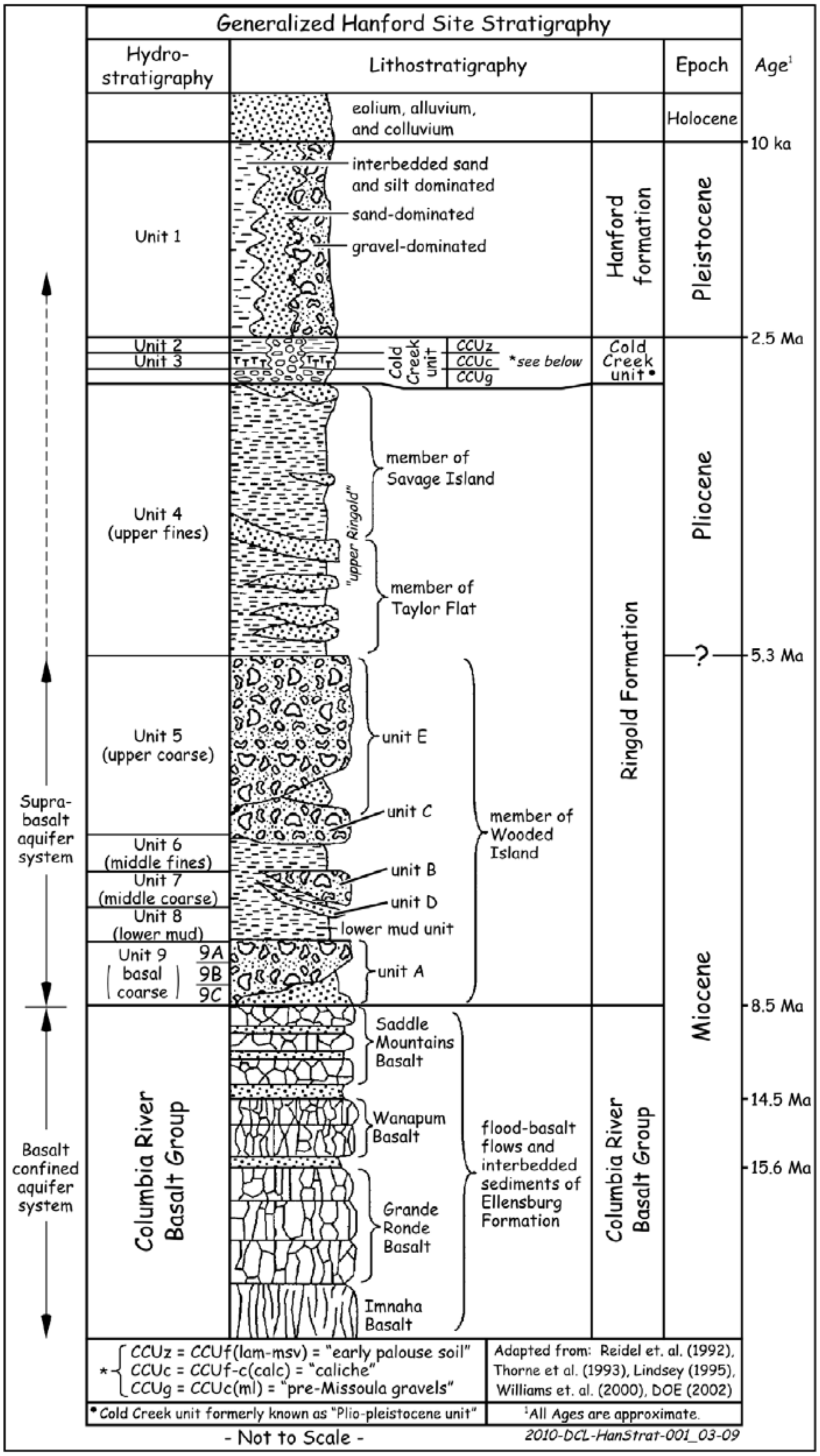

Figure A.4. General Stratigraphic Column Showing Commonly Used Geologic Names for the Sedimentary Formations Underlying the Hanford Central Plateau

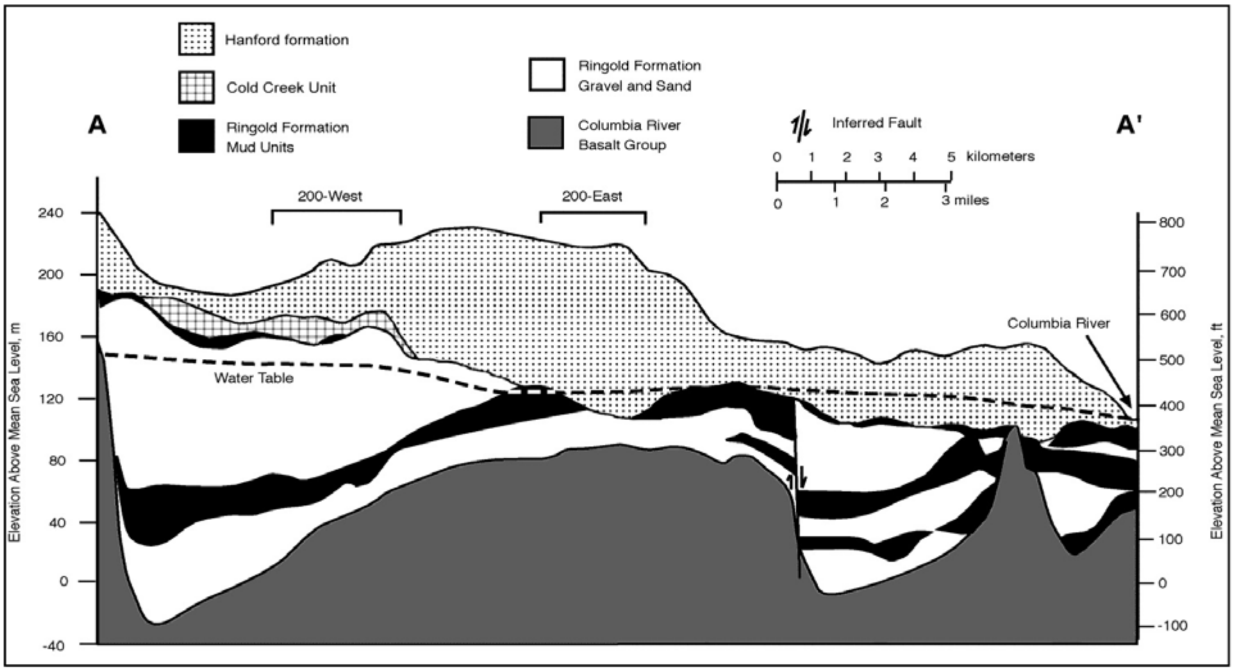

Figure A.5. Generalized East-to-West Geologic Cross Section Through the Hanford Site. The Central Plateau encloses the 200 East and 200 West Areas. (Source: Hartman 2000)

The physical structure, geochemical characteristics, and biogeochemical properties of the geologic framework affect contaminant movement and distribution within the vadose zone. Examples include the geohydrologic contrast between sediment types and sedimentary features, as well as crosscutting and discontinuous geologic features such as stratigraphic facies changes, sediment orientation, fractures, and clastic dikes (see Section A.1.1.2.2). Thin, fine-grained sedimentary lenses as well as more dominant stratigraphic changes can provide capillary breaks that promote horizontal spreading of liquids, including natural recharge water. The degree of complexity can be pronounced on a local scale such as near a waste release site or beneath a tank farm.

The Central Plateau is underlain by discontinuities that not only complicate subsurface characterization and monitoring, but also affect the development of reliable models created to mimic the natural environment and impacts of remediation efforts. Figure A.6 illustrates some of the potential impacts these features have on contaminant flow.

Contaminants entered the vadose zone through a variety of planned and accidental liquid waste sources. The nature and extent of contamination is also affected by the original waste chemistry, interaction with sediment minerals, and subsurface emplacement of the release. Deciphering the migration of some metals, such as uranium, is difficult because of metal’s interactions with sediment and the formation of previously non-existing precipitates or even new soluble compounds.

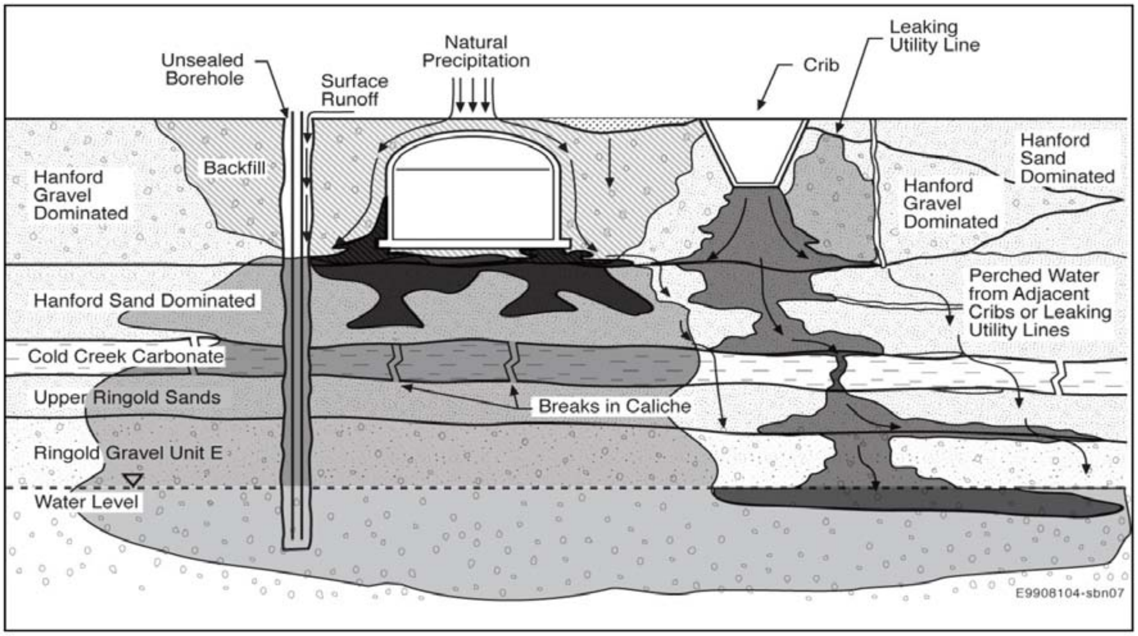

Figure A.6. General Vadose Zone Conceptual Model Illustrating Examples of Subsurface Features Potentially Impacting Groundwater Flow and Contaminant Movement. (Source: Last et al. 2006)

Geochemical reactions with Hanford Site sediments retain some contaminants, such as ^{137}Cs, ^{90}Sr, and ^{60}Co, effectively immobilizing them except under conditions of extreme saline or acidic conditions existing near some liquid release sites (Gee et al. 2007). However, tritium, ^{99}Tc, ^{129}I, and nitrate are mobile, enabling them to potentially move deep into the vadose zone and pose a long-term threat to groundwater. Certain other radionuclides, such as the transuranic elements, can undergo chemical sorption onto the surface or into the crystalline structure of sedimentary minerals.

Section A.2.2 contains a summary of select radionuclides and hazardous chemicals released into the subsurface from liquid discharges and tank leaks. Most releases took place in the 200 East and 200 West Areas.

Beneath the southwest corner of the 200 West Area, water discharges to U Pond raised the waste table 25 m (80 ft) into the overlying vadose zone. Water releases to B-Pond, located just east of the 200 East Area, raised groundwater levels 10 m (30 ft). By the mid-1990s, these large water discharges ceased, the ponds were filled with sediment, and the water table levels began to decline, leaving contaminants in the previously water-saturated sediment.

Today, the long-term natural driving force for liquid flux into and through the vadose zone is natural water infiltration from precipitation.

A.1.1.1 General Description of Deep Vadose Zone Beneath the Central Plateau

Key components of the subsurface geohydrologic setting are summarized below to provide context for describing the subsurface conditions influencing contaminant movement, selection of treatability test sites, success of various remedial approaches, and research undertaken to fill knowledge and capability gaps critical to achieving DOE’s vadose zone remediation goals.

Photographs and illustrations of the sediments underlying the Central Plateau are provided to demonstrate the sometime physical complexity of the geologic layers through which contaminants have migrated and the challenges facing contaminant recovery, fixation, stabilization, or monitoring.

A.1.1.2.1 Overview of Sediment Deposition and Erosion

Over the past 10 million years, rivers, streams, lakes, swamps, and other surface environments have progressively and repeatedly shifted back and forth across the land now known as the Hanford Site. Sediments were deposited, then sometimes reworked, and then redeposited by different paleo-environments. The result is a vertically and laterally inter-layered sequence of sediments varying in geohydrologic properties over time and spatial scales. A general stratigraphic column depicting these sediments and the underlying basalt is shown in Figure A.4.

Ringold Formation

Between 6 and 17 million years ago, vast quantities of Columbia River Basalt erupted and covered 230,000 km^2 (89,000 mi^2) of the Pacific Northwest. The Hanford Site lies atop the thickest accumulation of these basalts.

The earliest sequences of inter-fingered gravel, sand, silt, and clay deposited atop these basalts are collectively called the Ringold Formation (Newcomb et al. 1972). Ringold Formation sediments were deposited within a subsiding Pasco Basin, when rising east-west linear trending ridges of basalt—such as the Rattlesnake Hills, Saddle Mountains, and the Horse Heaven Hills—controlled the rivers’ flow direction and hydraulic base levels.

The first record of the Columbia River at the Hanford Site, after cessation of basalt volcanism, is the gravelly plain and paleosol system deposited as the river meandered across the Hanford Site.

About 6.7 million years ago, the depositional environment changed to one of a sandy alluvial system with extensive fine-grained lacustrine (lake) and over-bank deposits. A widespread lacustrine-overbank deposit called the lower mud (unit 8 in Figure A.4) was deposited over portions of the Hanford Site. The lower mud was covered by another sequence of fluvial gravels and sands. The most extensive of these is called Unit E, which is a Ringold Formation member of Wooded Island that underlies the Central Plateau (Figure A.4).

Five million years ago, the Columbia River sediments became more sand-dominated, and more than 90 m (300 ft) of interbedded fluvial sand and overbank deposits accumulated at the Hanford Site. These deposits are collectively called the Taylor Flat member of the Ringold Formation.

Between 4.8 and 3.4 million years ago, lacustrine deposits again dominated Ringold Formation deposition. A series of three successive lakes are recognized in the geologic record, likely forming from the downstream damming of the Columbia River. In the Pasco Basin, these deposits are collectively called the Savage Island member of the Ringold Formation (Figure A.4).

Figure A.7. Portions of the Wooded Island E Unit of the Ringold Formation. This unit contains a well-rounded gravel mixed in a sand and silt matrix deposited by a high-energy fluvial environment. Cementation varies from well to poor. Geology hammer shown for scale.

At the Hanford Site, the Ringold Formation is almost exclusively restricted to the subsurface. However, extensive outcrops of the upper Ringold Formation are found in the White Bluffs exposed along the eastern and northern shores of the Columbia River as it passes through the Hanford Site (Reidel et al. 1992).

At its thickest on the Hanford Site, Ringold strata are some 200 m (650 ft) thick within both the Cold Creek Syncline south of the Central Plateau and the Wahluke Syncline north of Gable Mountain.

Ringold Formation sediment is generally higher in quartz but lower in plagioclase and pyroxene than the younger, overlying Hanford formation. This reflects a higher percentage of basalt contained in the Hanford formation compared to the Ringold Formation. Deep within the Ringold Formation, calcic/ferric oxide cements are often present. This cementation can significantly decrease the permeability of Ringold Formation sediment.

Cold Creek Unit

Some 3.4 million years ago, western North America underwent a regional uplift, resulting in the ancestral Columbia River system eroding more land than in the past and cutting deep into the previously deposited Ringold Formation sediments. Nearly 100 m (330 ft) of the Ringold Formation was removed. In some places, erosion cut completely through the Ringold Formation and into the underlying basalt.

During and immediately following this period of erosion, river laid sediments and fine windblown material deposited in the basin’s lower valleys. Thick calcium carbonate-rich paleosols developed across extensive parts of the area because of the beginning of a drier climate. These sediments were deposited atop the eroded surface of the underlying Ringold Formation. Gravel, sand, and silt deposits accumulated along the high-energy stream and river pathway. The deposits, now sandwiched between the Ringold Formation and the overlying Hanford formation, are locally referred to as the Cold Creek Unit (DOE-RL 2002). Figure A.8 is a photograph of an outcrop of this unit.

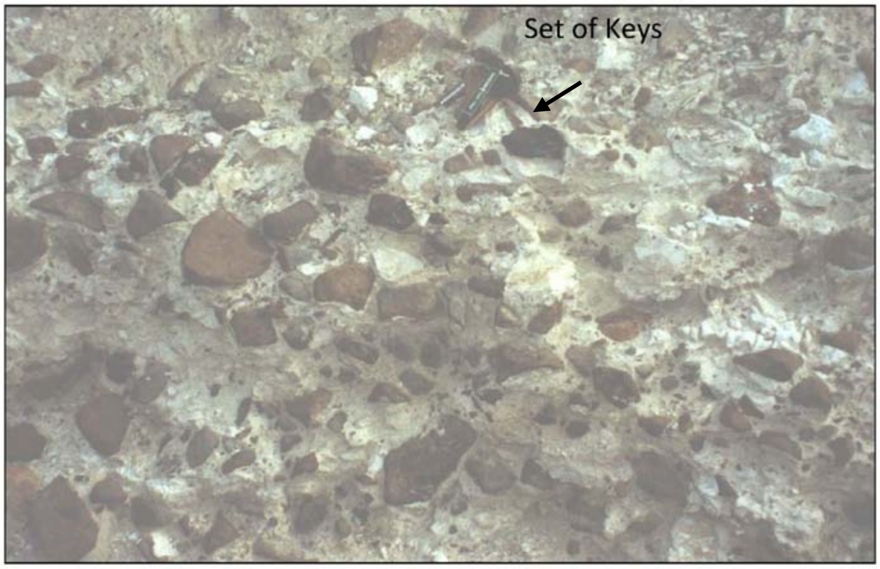

Figure A.8. Photograph of an Outcrop of the Cold Creek Unit. Image shows angular basaltic gravel mixed with sand and silt cemented with calcium carbonate. Keys given for scale. (Source: DOE-RL 2002)

The mineralogy of the Cold Creek Unit resembles that found in the overlying Hanford formation. Tallman et al. (1979) reported that the sediment contained high percentages of quartz, plagioclase, microcline, and amphiboles, but are generally higher in calcite than the Hanford formation. Bjornstad (1990) also found abundant carbonate-rich facies. Thin beds of caliche with calcite predominate, and variable amounts of ferric oxide exist beneath the 200 West Area in the Cold Creek Unit.

Hanford Formation

With the onset of the last major Ice Age some 2.6 million years ago, cataclysmic floods repeatedly inundated the Pasco Basin, depositing a thick sequence of sediment informally called the Hanford formation (Baker et al. 1991, DOE-RL 2002, Bjornstad 2006).

These floods occurred when ice dams failed, releasing large volumes of water. Repeated episodes of flooding took place during this glacial period.

In addition to major flood episodes, numerous smaller floods occurred. As many as 100 separate flood events have been postulated during the last glacial cycle alone, approximately 15,000 to 20,000 years ago (Waitt 1994).

Deciphering the history of cataclysmic flooding in the Pasco Basin is complicated, not only because of floods that originated from multiple sources, but also because the paths of Missoula floodwaters migrated and changed course with each advance and retreat of the northern ice sheets. Each succeeding flood would re-erode previously deposited sediments and then deposit new sediments, plus earlier laid sediments (Figure A.9 and Figure A.10).

Figure A.9. Gravel-Dominated Sediments of the Hanford Formation Exposed in Pit #30. This exposure, located between the 200 East and 200 West Areas, displayed a mixture of repeated channel-cut scour and fill features deposited along various angles. (Source: DOE-RL 2008b)

Figure A.10. Sand-Dominated Sediments of the Hanford Formation. This photograph is of a freshly cut sediment exposure at the Integrated Disposal Facility sited along the southern edge of the 200 East Area. (Source: DOE-RL 2008b)

Gravel-dominated sediments are generally confined to relatively narrow tracts within or near previous flood channels. Sand-dominated sediments, commonly called the Touchet Beds, occur primarily around the edges of the Pasco Basin when the calm backwaters from catastrophic floods deposited their finer sediment.

Hanford formation sediment mineralogy is highly variable, depending on grain size. Gravel-dominated sediment contains a high abundance of rock fragments (mostly basalt) (DOE-RL 2002). Finer-grained facies have fewer fragments and more quartz, feldspar, and mica grains. Smectite clays represent a few weight percent of the bulk sand fraction (Serne et al. 1993) and generally dominate the clay fraction (Tallman et al. 1979).

A.1.1.2.2 Vadose Zone Beneath the 200 West Area

The vadose zone beneath the 200 West Area ranges from 50 to 80 m (160 to 260 ft) thick. Generally, it can be subdivided into six principal hydro-stratigraphic units (Lindsey et al. 1992a, Connelly et al. 1992a, Thorne et al. 1993, Williams et al. 2002, Reidel and Chamness 2007). These include the following:

- Two facies associations with the Hanford formation:
  - Gravel-dominated
  - Sand-dominated
- Two lithofacies of the Cold Creek Unit:
  - Fine-grained, laminated to massive facies
  - Coarse to fine-grained carbonate-cemented facies
- Two members of the Ringold Formation:
  - Taylor Flat
  - Wooded Island, Unit E.

Not all units are present everywhere beneath the 200 West Area or the Central Plateau. As in any depositional environment, the thickness, distribution, and continuity of geologic units vary depending upon site sediment deposition and erosion histories.

Clastic dikes (Figure A.11 and Figure A.12) are common to the Hanford Site, primarily in the finer-grained Hanford formation sediments in the southern portions of 200 East and 200 West Areas. They have also been reported within the Cold Creek Unit and Ringold Formation (Fecht et al. 1999, Reidel and Chamness 2007, Murray et al. 2003, 2007).

Clastic dikes occur as vertical to sub-vertical, sediment-filled structures that crosscut normal sedimentary layering. They have been observed to form multisided polygonal cells (up to 150 m—or 500 ft—across) enclosing the host sediment.

Price and Fecht (1976) observed clastic dikes beneath most of the single-shell tank (SST) farms and throughout the waste management areas of the Central Plateau. Fecht et al. (1998) and Reidel and Fecht (2005) documented clastic dikes at the Fast Flux Test Facility, the U.S. Ecology Site, the Environmental Restoration Disposal Facility, the Waste Treatment Plant, and the Integrated Disposal Facility.

Clastic dikes range in widths, lengths, and depths. Their vertical range is less than 1 m (3 ft) to greater than 55 m (180 ft); length varies from less than 1 m (3 ft) to greater than 100 m (330 ft); width ranges from 1 mm (<<1 inch) to greater than 2 m (6 ft) (Murray et al. 2007). Generally, clastic dikes are composed of an outer skin of clay with coarser infilling sediment made of sand, silt, clay, and gravel. The internal structure of clastic dikes is complex, inhomogeneous, and frequently cross-cut by shear zones, inhibiting their forming a locale of enhanced vertical moisture movement compared to the surrounding sediment.

While their effect on the water movement, moisture flux, and contaminant transport on a regional scale is likely minimal, on a local or waste site scale, clastic dikes and other geologic discontinuities may impact flow paths (Murray et al. 2007). This topic is further discussed in Section A.1.1.2.5.

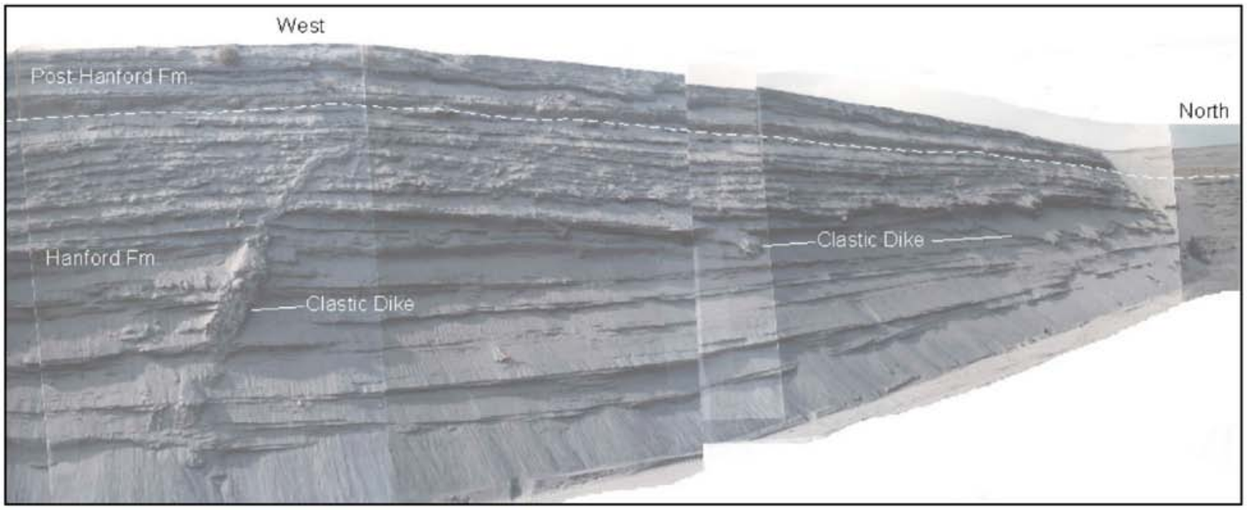

Figure A.11. 1984 Photograph Shows Clastic Dikes Crosscutting a 10 m (~35-ft) High Exposure of Sand-Dominated Sedimentary Sequence of the Hanford Formation. This exposure was located at the U.S. Ecology site built south of the 200 East Area. (Source: DOE-RL 2002)

Figure A.12. Close-up Photograph of a Typical Clastic Dike. This dike was found crosscutting sand-dominated strata at the U.S. Ecology site located in the Central Plateau along the southwest edge of the 200 East Area. (Source: Fecht et al. 1999)

Perhaps the most significant feature beneath the 200 West Area affecting moisture flux and contaminant transport in the vadose zone is the fine-grained siliciclastic and carbonate-cemented facies of the Cold Creek Unit. This unit represents an ancient buried calcic paleosol sequence (Slate 1996, 2000). This unit is encountered about midway between the ground surface and the water table where perched water has been encountered (CHG 2007). Because of the cemented nature of this unit, the layer is often considered impervious; however, it can also be structurally brittle and may contain fractures enabling fluids to more readily move through those discontinuities. Also, the cemented nature of the Cold Creek Unit may be discontinuous. Any unsealed boreholes drilled through the unit may also provide a conduit for increased vertical leakage.

The Cold Creek Unit contains abundant weathering products (e.g., oxides and carbonates) and may chemically react on contact with contaminants. Immediately overlying this carbonate-cemented facies is the fine-grained, laminated to massive facies that has a high moisture-retention capacity with a corresponding low permeability that retards the downward movement of moisture.

Geologic Cross Sections for the 200 West Area

Two geologic cross sections, one orientated east-west, and the other north-south, were reported by Last et al. (2009a) to illustrate the sedimentary geology beneath the 200 West Area including lateral and vertical changes in the subsurface sediments (see Figure A.13 through Figure A.15). The major units shown include the Hanford formation, the Cold Creek Unit, and the Ringold Formation. The stratigraphic location of the local water table is also noted.

Figure A.14 and Figure A.15 show the Ringold Formation with an average thickness of about 100 m (330 ft) reaching a maximum thickness of 120 m (390 ft) beneath the southern portion of the 200 Area (Last et al. 2009a). The near absence of Ringold Formation strata along the northern part of Figure A.14 results from the erosion of the originally deposited Ringold Formation and re-deposition of younger Hanford formation sediments. The same figure shows the Ringold Formation thinning eastward as the underlying basalt rises in elevation (Last et al. 2009a).

Both Figure A.14 and Figure A.15 show the Cold Creek Unit as mostly continuous, though of varying thicknesses, beneath much of the 200 West Area.

Underneath nearly all of the 200 West Area, the water table rests in the low permeability sediments of the Ringold Formation compared to the more water transmissive, overlying Hanford formation.

These cross-sections display generalized two-dimensional representations of the thickness, depths, and trends of the major sedimentary layers crossing two slices of the 200 West Area. Based upon available data, researchers use sediment thickness (isopach) maps to build three-dimensional depictions of geologic features controlling contaminant movement and impacting remediation applications.

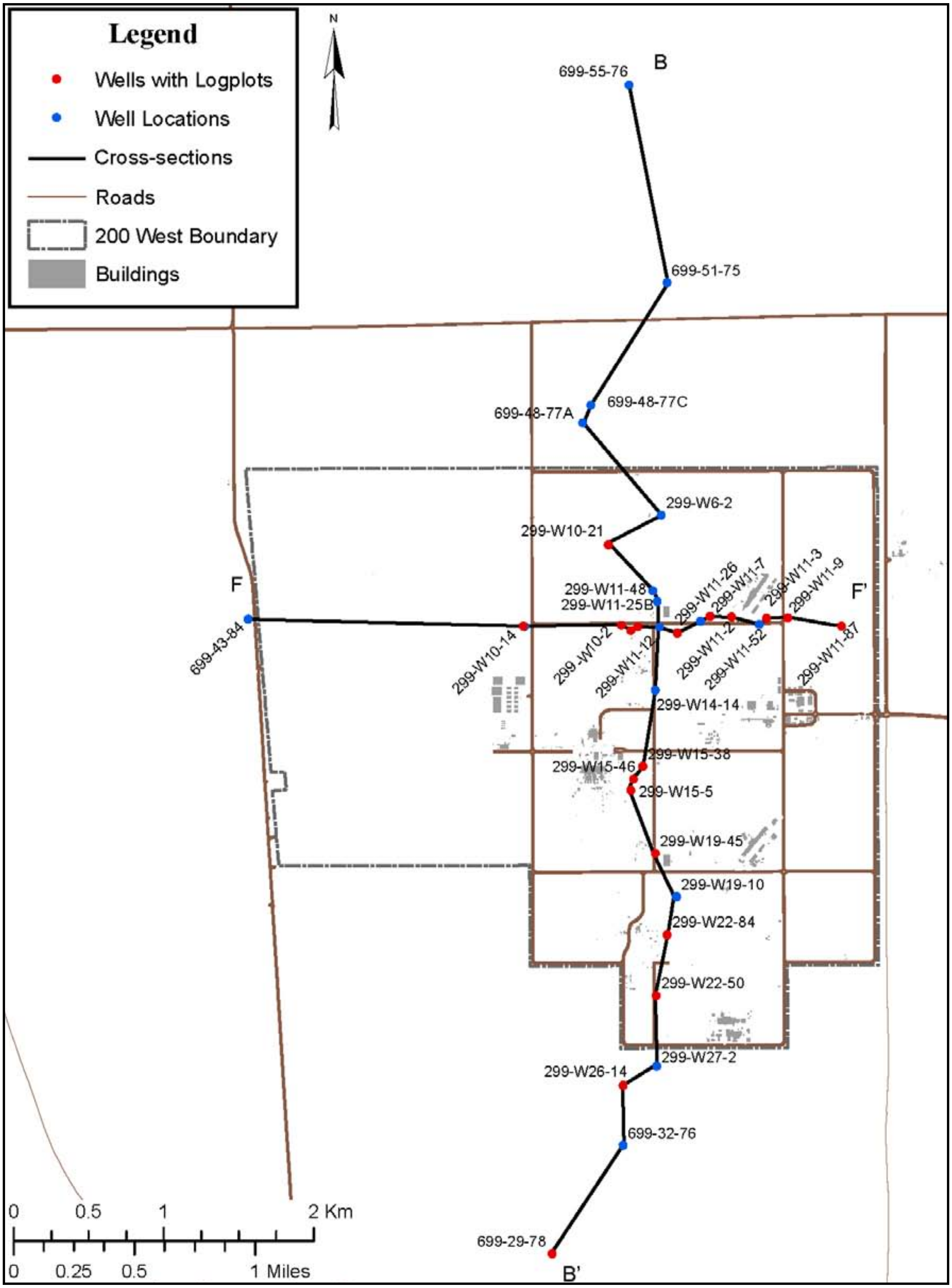

Figure A.13. Location of 200 West Area Cross-Sections. (Source: Last et al. 2009a)

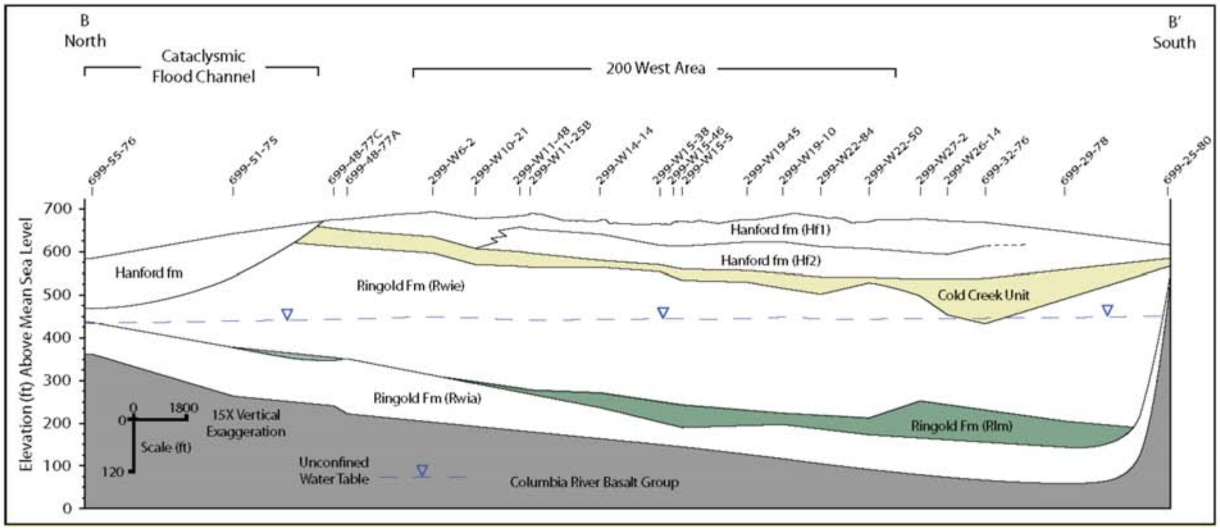

Figure A.14. 200 West Area North-South Cross-Section (B-B'). See Figure A.13 for location of cross-section. (Source: Last et al. 2009a)

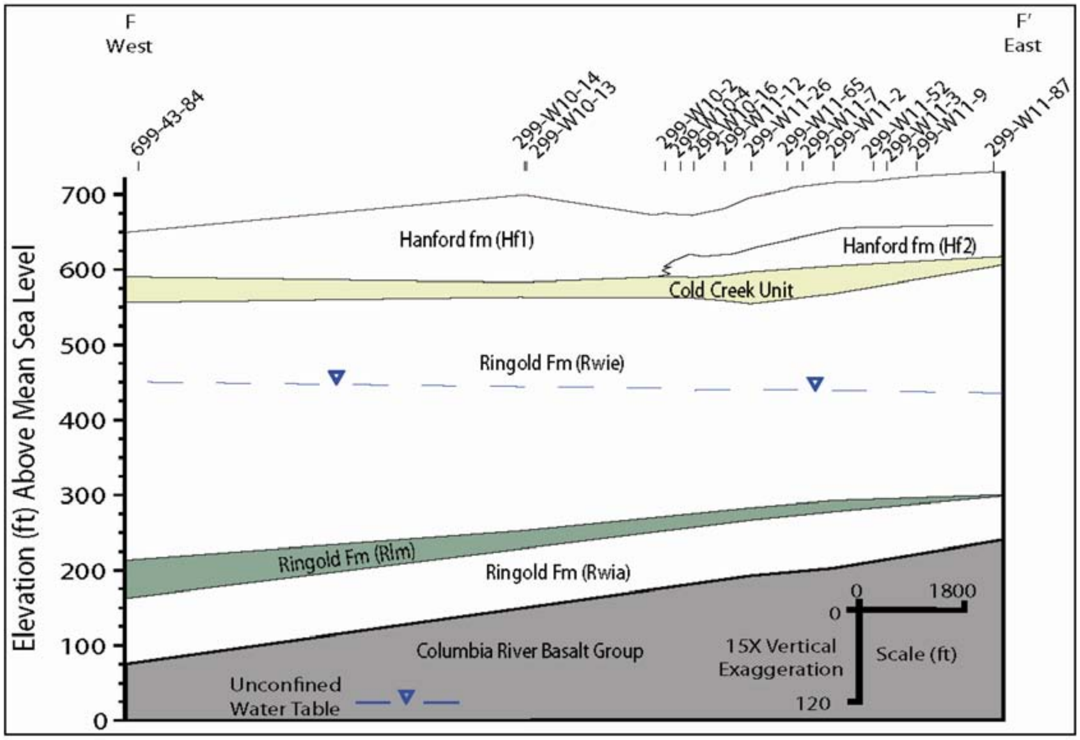

Figure A.15. 200 West Area East-West Cross-Section (F-F'). See Figure A.13 for location of cross-section. (Source: Last et al. 2009a)

A.1.1.2.3 Vadose Zone Beneath the 200 East Area

The vadose zone beneath the 200 East Area ranges from 50 m (165 ft) to 100 m (330 ft) thick. The zone is subdivided into six principal hydrostratigraphic units (Last et al. 2006, Reidel and Chamness 2007):

- Three units within the Hanford formation:
  - An upper gravel-dominated facies
  - A sand-dominated facies
  - A lower gravel-dominated facies
- Fluvial gravel to finer grained facies of the Cold Creek Unit
- Two units belonging to the Ringold Formation:
  - Member of Wooded Island, Unit A gravels
  - Member of Wooded Island, Unit E gravels.

Beneath most of the 200 East Area, the Hanford formation sand-dominated facies lies between the upper and lower gravel-dominated facies (Lindsey et al. 1992b, Connelly et al. 1992b). The Ringold Formation is mostly eroded away by the ancestral Columbia River in the northern half of the 200 East Area. Here, the Hanford formation lies directly atop the basalt bedrock. As the water table has continued to drop in response to the cessation of water discharges in the Gable Mountain and B-Ponds starting in the mid-1990s, some water levels are falling below the top of underlying basalt beneath the northeastern portion of the 200 East Area. Just south of the 200 East Area, the top of the unconfined aquifer lies within the Ringold Formation. Otherwise, the water table rests mostly in the permeable Hanford formation.

Channel-cut and fill features occur within the Hanford formation. These may act as preferential flow and contaminant transport pathways in the horizontal direction. Other types of heterogeneity are associated with stratigraphic pinch out or off-lapping of different sedimentary facies. Both the Ringold and the Hanford formations often contain thin fine-grained stringers that can result in lateral spreading of moisture and may slow the vertical movement of contaminants within the vadose zone. Low-permeable layers within the Hanford formation frequently are thin and laterally discontinuous. These discontinuities occur more frequently in the sand-dominated facies than in predominantly gravel-dominated layers.

Beneath the 200 East Area, Ringold Formation strata are as much as 75 m (250 ft) thick and then thin to the north where the formation was eroded away by glacial flooding.

Also, beneath the 200 East Area, the Cold Creek Unit is frequently absent except for a few isolated locales where it thickens to 60 m (200 ft). Glacial flooding and the resultant deep erosion removed large sections of the Cold Creek Unit in this portion of the Central Plateau. Where present, the unit lies either above or below the water table.

The Hanford formation is 90 m (300 ft) thick beneath portions of the 200 East Area.

Geologic Cross-Sections for the 200 East Area

The location of two geologic cross-sections spanning the 200 East Area is shown in Figure A.16 (Last et al. 2009b). The cross sections, running southwest-northeast and southeast to northwest are shown in Figure A.17 and Figure A.18. These illustrations show the current interpretation of the lateral and vertical extent of the major stratigraphic units beneath 200 East Area used to develop models of the subsurface.

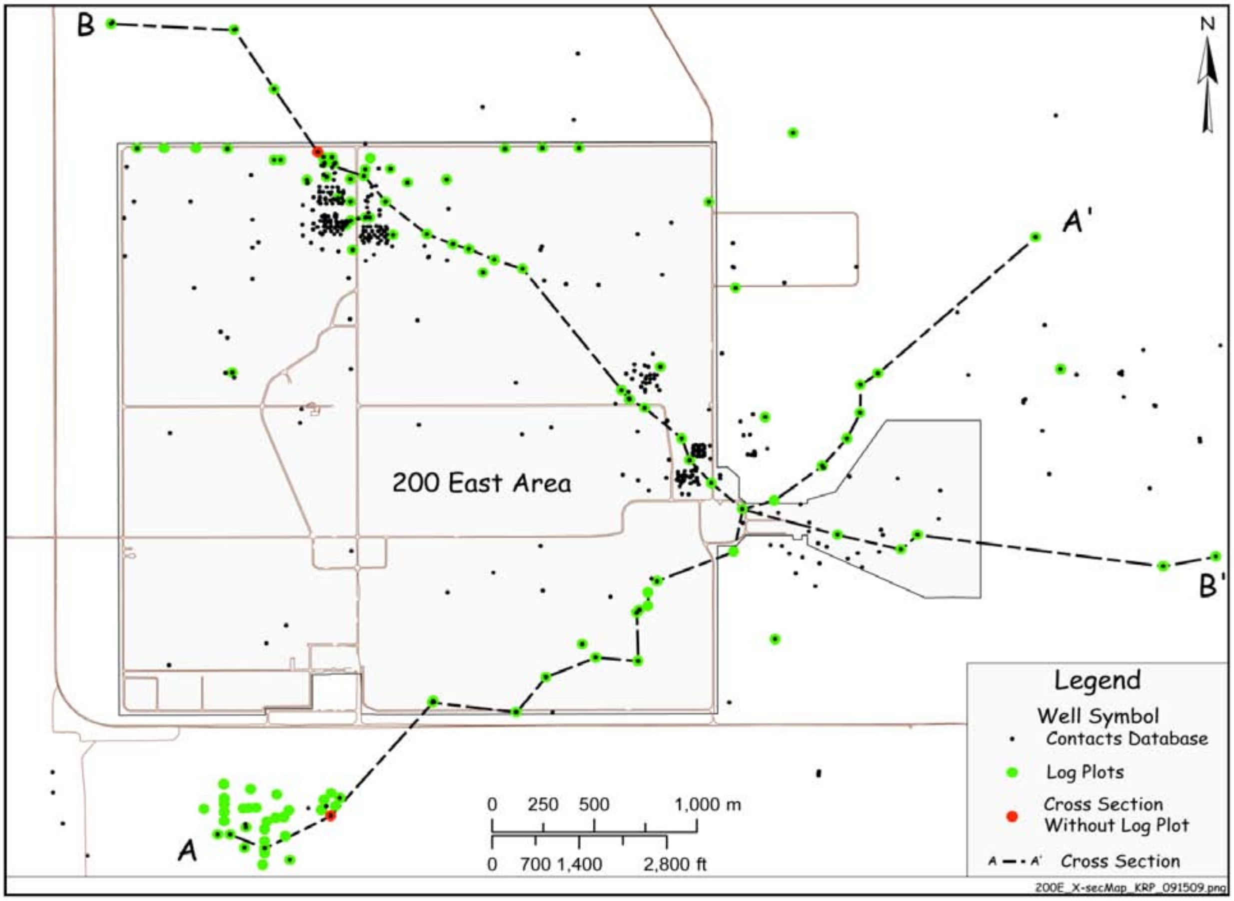

Figure A.16. Location of 200 East Area Cross-Sections. (Source: Last et al. 2009b)

Across the 200 East Area, the vadose zone consists of mostly sedimentary units found in the Hanford formation. Some Cold Creek Unit and Ringold Formation sediments rise above the water table but only in the western portion of the 200 East Area.

Figure A.18 illustrates sedimentary units thinning northward, especially the Ringold Formation, as a buried basalt ridge is approached.

A.1.1.2.4 Water Infiltration

Contamination residing in the DVZ was, in many cases, driven deeper underground by water and liquid waste discharges from Hanford Site operations than would have occurred by just natural infiltration of meteoric water. As noted in Section A.1.3.2.2., 1.7 trillion L (450 billion gal) of water were disposed to the subsurface through ditches, ponds, cribs, and trenches. Most wastewater disposal ceased by the mid-1990s. The long-term natural driving force for moisture flux and transport through the vadose zone is now that fraction of the precipitation infiltrating below the zones of evaporation and plant root uptake.

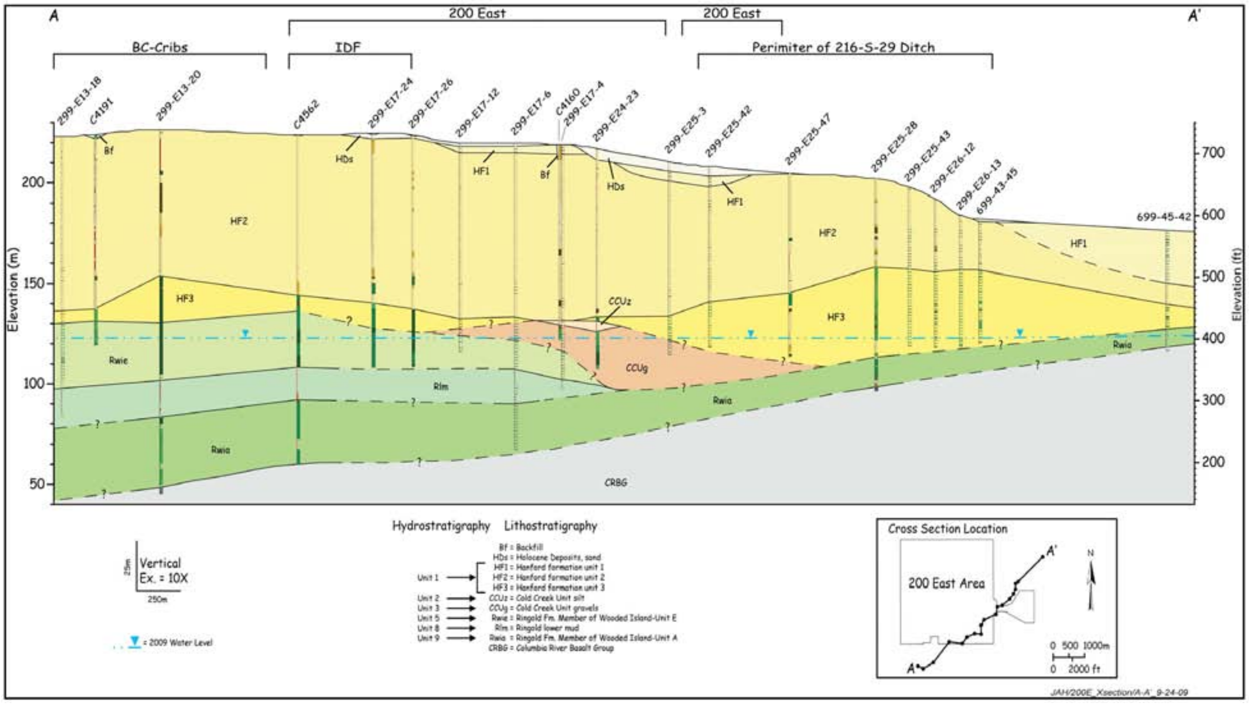

Figure A.17. 200 East Area Southwest to Northeast Cross-Section (A-A'). See Figure A.16 for location of cross-section. (Source: Last et al. 2009b)

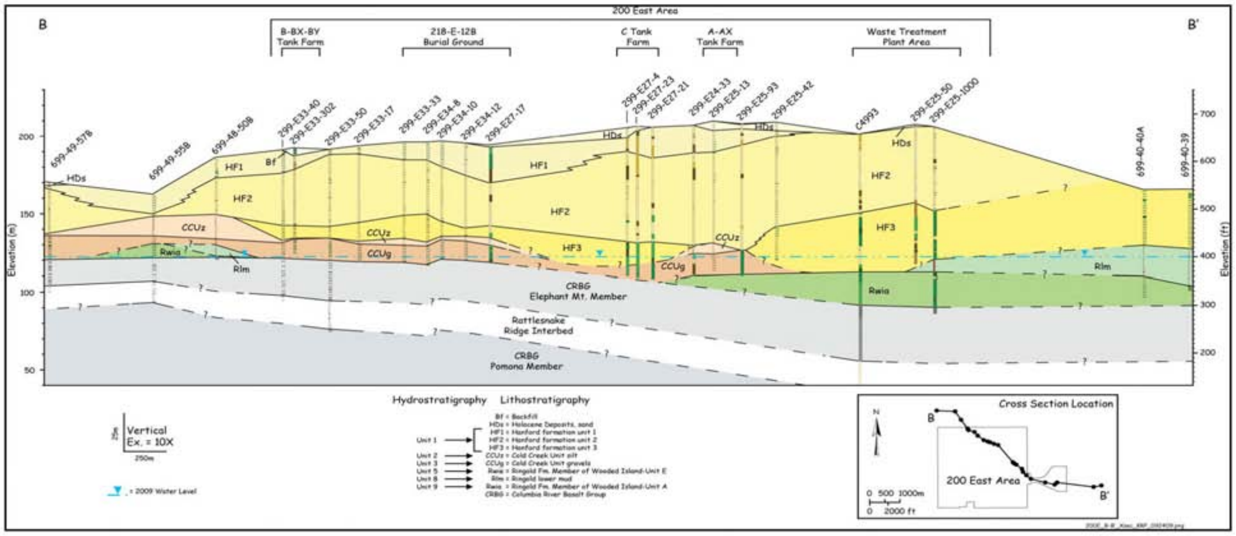

Figure A.18. 200 East Area Northwest to Southeast Cross-Section (B-B'). See Figure A.16 for location of cross-section. (Source: Last et al. 2009b)

Gee et al. (1992) presented evidence showing that measurable diffuse natural infiltration occurs across the lower elevations of the Hanford Site, with rates ranging from near zero in undisturbed plant dominated communities to more than 100 mm/year (4 inches/year) beneath the un-vegetated gravel surfaces. Fayer and Walters (1995) presented a recharge distribution map for the Hanford Site suggesting that recharge rates could range from over 50 mm/year (2 inches/year) for un-vegetated sand to about 25 mm/year (1 inch/year) for cheat-grass covered sand. Last et al. (2006) presented a number of recharge classes for individual waste sites, based on soil or surface barrier conditions and the degree of vegetation coverage. In addition, Fayer and Keller (2007) compiled recharge data targeting the Hanford Site's SST waste management areas while Fayer and Gee (2006) reported on multiyear water balances for soil covers in the semiarid setting of the site.

A.1.1.2.5 Subsurface Water Movement

As noted in Section A.1, pore spaces and fractures in the vadose zone are partially filled with water. On the most basic level, two processes control water movement in the vadose zone: gravity and capillary forces. Other geochemical, biological, stratigraphic, hydrologic, and atmospheric forces, plus past water and contaminant disposal releases, also impact water movement in the vadose zone. These influences can be temporally and spatially variable, especially beneath the Central Plateau where significant liquid disposal occurred from the mid-1940s to the mid-1990s.

Although the direction of water movement is normally of interest, it is not always easily determined because water fluxes in arid environments are low, sometimes having a magnitude close to the errors inherent in measuring and calculating the fluxes themselves.

The dominant direction for fluid and mobile contaminant movement in the vadose zone is downward because of gravity-driven drainage. Nonetheless, fine-grained sedimentary lenses as well as dominant stratigraphic changes in the subsurface geology can provide capillary breaks that promote horizontal spreading of discharged liquids and natural recharge water.

Scanlon et al. (1997) reported that uniform flow through the unsaturated vadose zone is the dominant flow mechanism at arid sites within unconsolidated sediments. Scanlon et al. (1997) also reported that inclined sedimentary units and capillary barriers can cause lateral flow.

Other potential preferred flow paths created by cross-cutting geologic features are not considered dominant over the large regional scales. Nonetheless, their impact on a smaller scale—for example, across a waste site or beneath a tank farm—may be important. The critical question centers not upon whether geologic discontinuities exist, but rather understanding the degree to which they may, under the right conditions, impact contaminant movement and complicate remediation performance, amendment placement, modeling, and monitoring.

Figure A.19 shows a simple demonstration of the lateral movement of water released atop a set of cross-bedded Hanford formation sediments. Section A.1.1.2.2 summarizes information about the physical properties and occurrence of geologic discontinuities, such as clastic dikes (Figure A.11 and Figure A.12).

Structurally controlled flow occurs when the bedding of a porous media or the presence of buried structures (such as tanks) route infiltrating water along a preferred path rather than being more uniformly distributed.

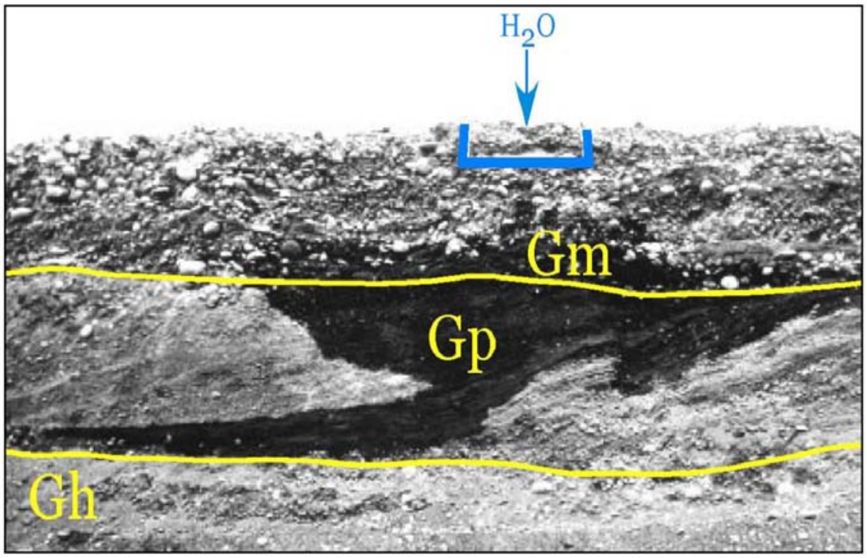

Figure A.19. Water Released Atop This Cross-Cutting Set of Hanford Formation Intermixed Layers. Water Redirected by Sedimentary Cross-Bedding. The open box is 1 m (3 ft) wide and shows where water was poured atop the land surface adjacent to a gravel pit located in the 200 West Area. (Gm = gravel massive; Gp = gravel planer; Gh = gravel horizontal)

Whenever there are variations in sediment properties, such as textural breaks of fine sediment overlying coarse sediment, the potential exists for water flow to be affected. When textural breaks occur along a slope, the water retained by fine sediments can move laterally rather than just downward. This is illustrated in Figure A.6 where various waste fluids are shown migrating through a sequence of sandwiched sedimentary layers of varying properties—from low permeability clays to coarse gravels.

Last et al. (2006) reported that clastic dikes may act as preferential flow paths for saturated flow when they provide large amounts of connected pore spaces. The actual influence of clastic dikes on water flow remains uncertain, although some portions of the dikes have large connected pore spaces while others have fine grain shears that would greatly hinder vertical flow and/or fine-grained clay outer skins that limit lateral flow (Murray et al. 2002).

Wood et al. (1995) and Jacobs (1999) indicate that clastic dikes (and unsealed boreholes) are not sufficiently large or continuous to play a significant role in water or contaminant flux through the vadose zone. Murray et al. (2003) also report from a field study that clastic dikes are not an important preferred pathway when drainage flux was less than 100 mm/year (4 in./year). This is why such pathways may not dominate in large-scale modeling assessments.

Several studies indicate that contaminants have moved to greater depths beneath the Hanford Site than expected (Murray et al. 2007). This includes ^{137}Cs in the DVZ beneath the S-SX Tank Farms in the 200 West Area plus the presence of technetium, carbon tetrachloride, and other mobile contaminants now found in groundwater (see Section A.1.4.8). Discrepancies between observed and predicted travel times could result from not understanding the contaminant-geochemical dynamics occurring in the subsurface and/or contaminants flowing along preferred geologic features or once enhanced surface water infiltration (e.g., from leaky water lines or surface flooding adjoining waste tanks).

In the past, flow and contaminant flow modeling of the vadose zone beneath the 200 Areas was commonly based on relatively simple models that assumed horizontally layered sediments without potential preferential vertical flow paths or impediments. Caution must be used when such screening models are relied upon for waste retrieval performance evaluations because they do not incorporate the naturally occurring heterogeneities, crosscutting features, coupled geochemical, and biogeochemcial influences found in the subsurface that will impact contaminant movement and remediation performance. The simplicity or sophistication of the models should match the problem addressed.

Murray et al. (2007) excavated a 2-m (6-ft) wide clastic dike south of the 200 Area on the Hanford Site and characterized it and the surrounding sedimentary matrix. A conceptual model was developed, and the unsaturated flow was modeled.

That study (Murray et al. 2007) suggests that clastic dikes may serve as preferred pathways in the vadose zone—on a limited spatial scale. This potentially enhanced flux rate, compared to the surrounding sediment, is highly dependent on the imposed infiltration. Such saturation-dependence suggests that the contaminant release history of a site may be critical in choosing the correct remedial action and modeling approach. Such behavior may also explain the occurrence of contaminant breakthroughs.

Dresel et al. (2008) reported that inter-fingered coarse and fine-grained sediments, common beneath the Central Plateau, form capillary breaks impacting fluid flow and perhaps the targeted delivery of remediation amendments. Slanted sedimentary beds and crosscutting features can alter emplaced reactive fronts and locally redirect flow paths. They also noted that reactive amendments may also mobilize dissolved or soluble contaminants, increasing contaminant transport rather than fixing it in place.

Chemicals move through the vadose zone by a variety of mechanisms, including advection, diffusion and dispersion, solubility, mass transfer between liquid/gas phases, and interactions between released chemicals. The specific gravity, viscosity, and contaminant speciation of released wastes influence chemical mobility and residence time. Contaminant-microbial activity is also present.

The flow of water through unsaturated soils depends on interactions between the rate of water infiltration, soil moisture content, soil texture, sediment textural heterogeneity, and soil hydraulic properties. Infiltrating water provides the primary driving force for downward migration of contaminants.

Data on particle-size distribution, moisture retention, and saturated hydraulic conductivity have been cataloged for over 284 sediment samples from across the Hanford Site, including 12 locations in the 200 East and 200 West Areas (Khaleel and Freeman 1995, Khaleel et al. 1995, Khaleel and Relyea 1997, Freeman et al. 2001, 2002; Freeman and Last 2003, Khaleel and Heller 2003, Brown and Serne 2008, and Um et al. 2009). The Freeman et al. (2001) report summarizes vadose zone hydraulic properties, collected from laboratory and field experiments, for the Hanford Site. No field data exist on large-scale dispersivities for the vadose zone beneath the Hanford Site.

Local, preferential flow has also been documented along poorly sealed well casings (Baker et al. 1988).

Perched water zones and lateral spreading may develop when vadose water accumulates atop low-permeability sedimentary units, highly cemented horizons (such as the calcic rich portion of the Cold Creek Unit), or along contacts separating fine-grained horizons and underlying coarse-grained sediment. For years, well drillers encountered regions of perched water lying beneath the Central Plateau.

Geochemical processes dominate contaminant migration and mineral alteration within the vadose zone sediment beneath both the 200 East and the 200 West Areas. Section A.1.4.8 gives examples of geochemical research on contaminant reactivity in vadose zone sediments.

Some contaminants are volatile and move in the gas phase. Carbon tetrachloride is a prime example (see Section A.1.3.1). The bulk of this movement is diffusional, but convective flow can occur near the soil surface and along open boreholes in response to barometric changes.

The formation of colloids and the occurrence of colloid-facilitated transport of contaminants were identified as potentially important processes affecting vadose zone transport (DOE-RL 1997). At sites that received highly concentrated waste, such as from leaking tanks or tank farm infrastructure, conditions may have existed for colloid formation (Mashal et al. 2004). Research performed by Flury et al. (2002) addressed this issue. Results indicate that mobile colloidal particles may exist in sediments below waste tanks that once leaked waste and that these particles may enhance the movement of a small fraction of the cesium residing below the tanks. However, the researchers also reported that it is unlikely that a significant amount of cesium can be mobilized with the colloids unless present geochemical and hydrological conditions change. Large amounts of colloids could be re-mobilized through artificial recharge of low ionic strength water from, for example, surface flooding. Under present conditions, however, it appears that the main mass of cesium located in the vadose zone will not migrate much farther. This suggests that the current depth of cesium beneath Hanford waste tanks can be explained by ion exchange reactions, and further downward movement of cesium is unlikely.

A.1.2 Central Plateau Cleanup Completion Strategy

> “Waste site remediation is appropriately left to future generations if risks are low, if it is impractical with currently available technology, or if it would impose unacceptable costs on society were it to be undertaken today. Remediation is inappropriately left to future generations if the risks are such that what is a tractable remediation problem today becomes much less so in the future as a result of events or changes in conditions that could reasonably have been foreseen.” (National Research Council 2000)

The Central Plateau is a 195 km^2 (75 mi^2) elevated area near the center of the Hanford Site overlooking the surrounding terrain. It includes a rectangular Inner Area of about 25 km^2 (10 mi^2) containing the 200 East and 200 West Areas surrounded by adjoining land called the Outer Area (Figure A.1).

During the Hanford Site’s plutonium production era, nuclear fuel processing and management of the resulting waste and nuclear materials took place inside the 200 Areas.

Today, these areas contain Hanford Site reprocessing plants and support facilities, all underground waste storage tanks, and about 800 sites used for liquid and solid waste disposal and storage. Because of past contaminant releases, the Site’s largest inventory of subsurface contamination is beneath the Central

Plateau. Waste releases have also created the Site's largest groundwater contamination plumes covering nearly 170 km^2 (65 mi^2) flowing toward the Columbia River (DOE-RL 2010).

For decades to come, the Hanford Site's active waste treatment and storage facilities will be located in the Inner Area (Figure A.20). These include liquid effluent treatment, solid waste packaging and handling, solid waste disposal, spent fuel storage, analytical laboratories, tank waste management, and eventually the Waste Treatment Plant for handling tank waste.

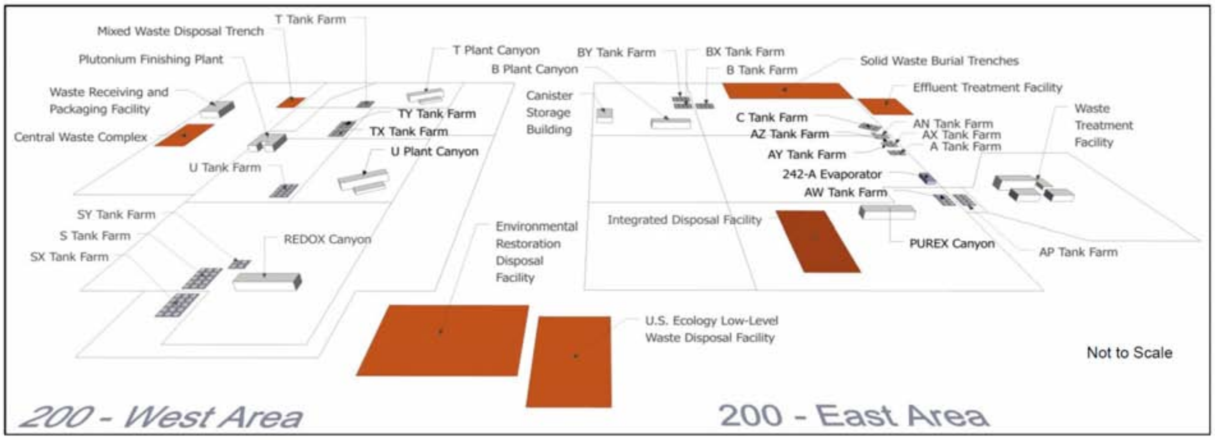

Figure A.20. Major Facilities in 200 Areas of the Hanford Site's Central Plateau

A significant portion of the previously released contamination remains above the water table, in the vadose zone, posing a future threat to groundwater and the Columbia River. As discussed in Section A.1.1.2.1, considerable past released contamination likely rests atop the low permeability Cold Creek Unit, sandwiched, in places between the Ringold and Hanford formations. This is particularly true beneath the 200 West Area. Characterizing and monitoring the vadose zone, including remediating and confirming that remediation, presents a daunting scientific and technical challenge.

The major elements of the U.S. Department of Energy's (DOE's) Central Plateau cleanup strategy include the following:

1. Containing and remediating contaminated groundwater
2. Developing and implementing a cleanup strategy guiding remedy selection from a plateau-wide perspective
3. Identifying, evaluating, and deploying viable remediation methods for the DVZ to provide long-term protection of the groundwater
4. Conducting critical waste management operations in coordination with cleanup actions and regulations.

This strategy is organized into the following components:

- **Inner Area**—The final footprint of the central Hanford Site dedicated to waste management and containment of residual contamination will remain under federal ownership and control. The boundary of the Inner Area is defined by waste disposal facilities already built plus future decisions for continued waste management and containment of residual contamination.

- **Outer Area**—The Outer Area includes all areas of the Central Plateau outside the boundary of the Inner Area. It is DOE's intent to clean up this portion of the Central Plateau to a level comparable with that achieved along the River Corridor. Contaminated soil and debris removed from the Outer Area will be placed in the Environmental Restoration Disposal Facility (ERDF) within the Inner Area for final disposal. Completion of cleanup of the Outer Area will shrink the final footprint to the land covered by the Inner Area.
- **Groundwater**—The goal is to restore Central Plateau groundwater to its beneficial uses, unless restoration is determined to be impracticable. This includes groundwater underlying the 200 West and 200 East Areas.

To achieve consistent and protective cleanup decisions for the Inner Area, DOE intends to develop cleanup levels that 1) satisfy applicable or relevant and appropriate regulatory requirements and 2) verify that the selected remedies are protective of groundwater, ecological resources, and human health for future surface users consistent with designated land uses.

Remediation up to a depth of about 5 m (15 ft) is planned across the Outer Area to be consistent with the River Corridor and to enable authorized surface uses. Institutional controls will be required in limited areas as there may be restrictions on subsurface use in portions of the Outer Area. Monitoring and continued institutional control will likely be required in select portions of the Outer Area to allow radioactive contaminants to decay to levels suitable for unrestricted surface use, consistent with anticipated future land use of conservation/mining.

A.1.2.1 Types of Waste Sites and Surplus Facilities Located in the Central Plateau

The Central Plateau contains more than 800 sites contaminated with radioactive and hazardous chemicals. Most sites received liquids or solids from 200 Area operations. Examples include ponds, ditches, cribs, trenches, and injection or reverse wells. Most solid waste was dumped into landfills. Septic tanks and drain fields, pipelines, pits, diversion boxes, and underground waste storage tanks also exist in the Central Plateau.

More than 900 surface facilities and support structures are also found in the Central Plateau. Examples include offices, shops, and trailers as well as large processing, storage, or nuclear material handling facilities such as the Plutonium Finishing Plant and the five chemical reprocessing plants (T, B, U, Reduction-Oxidation Plant [REDOX], and the Plutonium Uranium Extraction Plant [PUREX]) built for recovering plutonium and other valuable elements from spent fuel. (U Plant was only used to recover uranium from tank waste.)

Today, four of the five canyons (U, PUREX, B, and REDOX) are in an inactive surveillance and maintenance mode. The fifth canyon, T Plant, is still part of active waste management operations.

A.1.2.2 Challenges for Central Plateau Cleanup

Challenges for cleanup of the Central Plateau differ from those in the adjoining River Corridor. Most remediation efforts along the River Corridor focus on removing shallow demolition debris and shallow soil contamination and placing them inside regulated disposal facilities, such as ERDF, constructed inside the Central Plateau.

A portion of the plateau, however, will retain significant radiological and hazardous contamination inventories requiring long-term vigilance. In addition, a number of facilities have been built, are under construction, or will be constructed in the Central Plateau for future waste treatment and management.

The number and variety of waste sites, facilities, and contaminant inventories to be remediated in the Central Plateau are far greater than other portions of the Hanford Site. Some of the broad challenges facing subsurface cleanup of the Central Plateau include the following:

- Identifying agreed-upon and verifiable cleanup goals protective of groundwater, ecological resources, and human health
- Characterizing, modeling, remediating, and monitoring the deep subsurface
- Validating contamination behavior under both natural and anthropogenic conditions to support decision-making
- Developing the scientific knowledge and remediation capabilities to effectively and efficiently remediate the subsurface when existing techniques prove inadequate
- Developing a credible basis for comparing the merits of alternative cleanup strategies.

A.1.2.2.1 Remediation Strategy for Inner Area Cleanup

The Inner Area of the Central Plateau (Figure A.21) is defined as the final footprint of the Hanford Site, resting in the Central Plateau, remaining after active cleanup completion. The area's size will depend upon existing and future waste management decisions affecting remediation options used, facilities built to support cleanup, and the nature of post-closure residual waste and nuclear materials remaining onsite. This land includes regions underlain by DVZ contamination. Therefore, DOE's defense-in-depth approach to DVZ cleanup, as described in Section 3.0, will focus on the Inner Area.

Expectations are that the Inner Area will cover approximately 25 km^2 (10 mi^2). The Inner Area will remain under federal ownership and control.

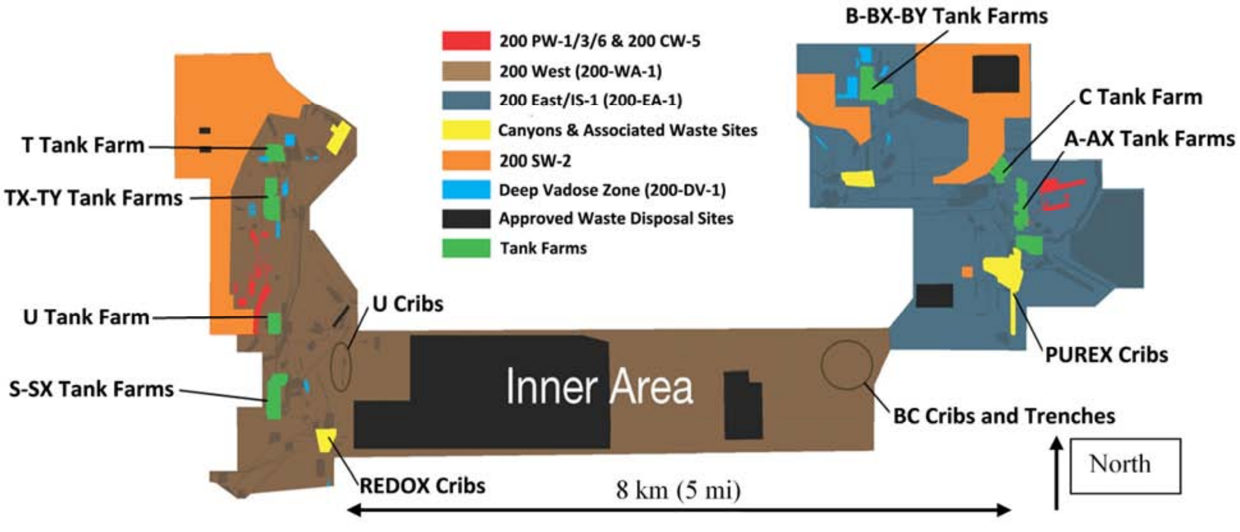

Figure A.21. Inner Area of the Central Plateau

DOE’s goal is to make the final Inner Area’s footprint as small as possible. Examples of existing facilities or waste management capabilities included within the Inner Area include the following:

- ERDF (Environmental Restoration Disposal Facility)
- Integrated Disposal Facility
- Naval Reactor Compartment Disposal trench
- Reprocessing canyons
- U.S. Ecology Washington Low-Level Radioactive Waste facility
- BC Crib and Trench Area
- Waste Treatment Plant
- Canister Storage Building
- Waste Receiving and Processing Facility
- Areas where DVZ contamination likely exist requiring long-term remediation, surface controls, and/or monitoring.

A.1.2.2.2 Remediation Strategy for Outer Area Cleanup

The Outer Area covers approximately 170 km^2 (65 mi^2) and contains more than 100 waste sites and structures. Most waste sites are small near-surface locations that will be removed for treatment as needed for onsite disposal or sampled to confirm whether additional action is required. Some of the largest past waste management components in the Outer Area are where surface ponds once existed.

The Outer Area will be remediated to unrestricted surface levels comparable to the adjacent River Corridor to support the future land use of conservation and mining. This will be done by soil excavation and removal to ERDF. The remediation depth in the River Corridor was about 5 m (15 ft), unless sediment sampling specified great depths. Any portions of the Outer Area found containing significant deep chemical or radiological inventories will be monitored and/or remediated.

Most of the Outer Area is reserved for managing and protecting archeological, cultural, ecological, and natural resources and related uses.

Cleanup of the Outer Area is biased to removal for treatment and disposal in ERDF or other approved disposal locations. Monitoring and continued institutional control will likely be required at the large pond sites to allow radioactive contaminants to decay to levels suitable for unrestricted surface use or consistent with anticipated future land use.

A.1.2.3 Remediation Strategy for Central Plateau Groundwater Cleanup

A key element of the Central Plateau cleanup strategy is groundwater remediation and protection. To be successful, groundwater protection requires DVZ remediation.

Nearly all aquifer contamination underlying the Central Plateau once seeped through the overlying vadose zone. In a few instances, contaminants were injected deep into the vadose zone or directly into the aquifer, bypassing the sorptive capability of the overlying sediments.

DOE's goal is to restore the groundwater underlying the Central Plateau to beneficial uses, unless technically impracticable in a reasonable time. This includes groundwater underlying the 200 East and 200 West Areas. In such instances, programs will be implemented to prevent, or at least impede, further contaminant plume migration until new groundwater treatment technologies are developed and deployed. A new groundwater treatment system is being designed and constructed to remove 95% of the mass of key contaminants from beneath the 200 West Area within 25 years (Triplett et al. 2010).

Groundwater beneath the Central Plateau is currently divided into the following four operable units (Figure A.22):

- 200-PO-1 Operable Unit is located in the southern half of the 200 East Area and includes extensive plumes of tritium, ^{129}I, and nitrate.
- 200-BP-5 Operable Unit lies in the northern half of the 200 East Area, extending northwest toward the Columbia River. It includes contaminant plumes of nitrate, uranium, and ^{99}Tc.
- 200-UP-1 Operable Unit is found in the southern half of the 200 West Area and includes contaminant plumes of ^{99}Tc, nitrate, and uranium.
- 200-ZP-1 Operable Unit is located in the northern half of the 200 West Area and includes a large plume of carbon tetrachloride and smaller plumes of ^{99}Tc, chromium, nitrate, trichloroethylene, and ^{129}I.

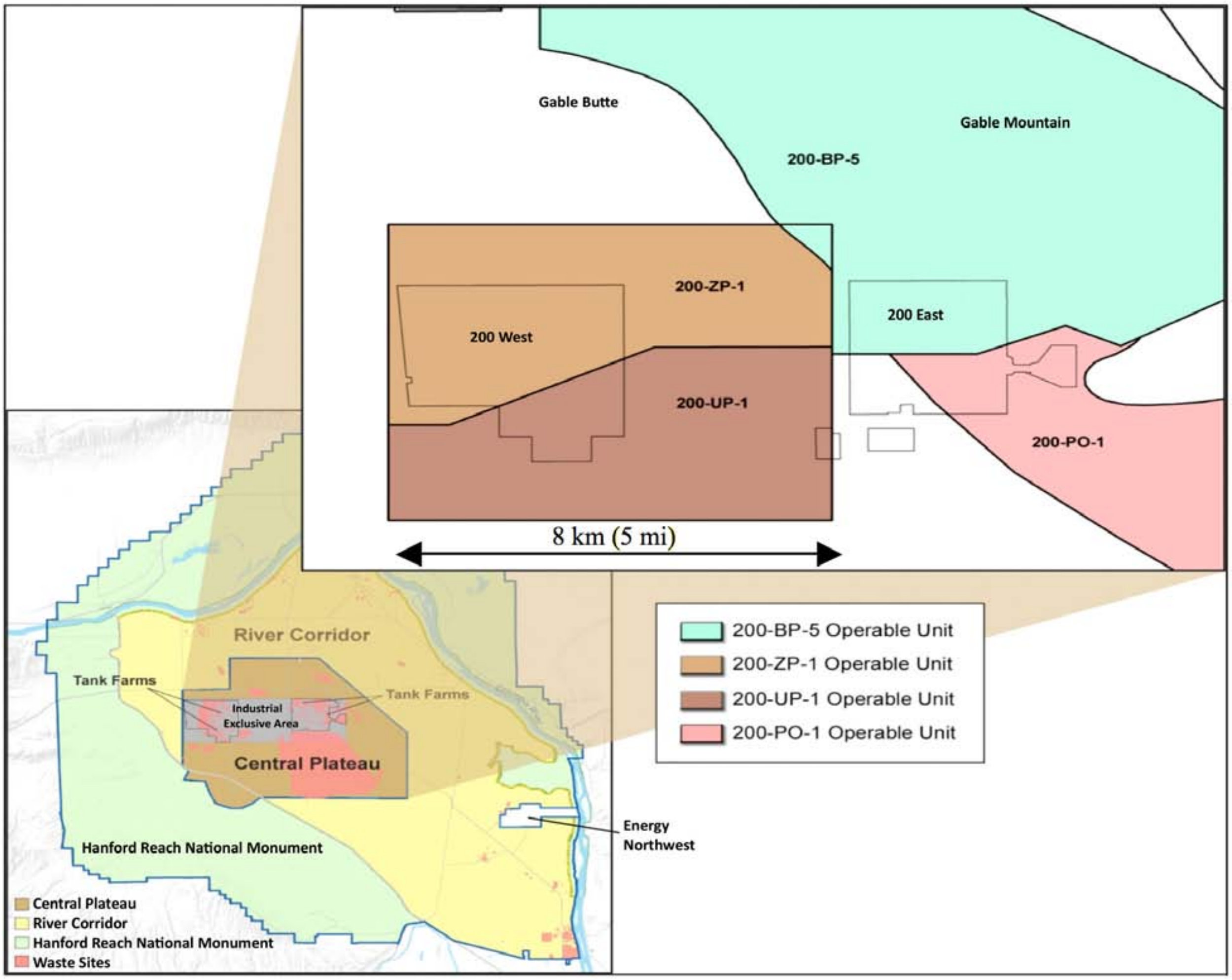

Figure A.22. Groundwater Operable Units on the Central Plateau

Currently, groundwater pump-and-treat systems operate in the two 200 West Area groundwater operable units. DOE's strategy is to enhance the effectiveness of these existing systems to improve contaminant containment and capture.

Groundwater treatment is not underway in the 200 East Area. DOE is scheduled to investigate those plumes and make remedy decisions. For both the 200-PO-1 and 200-BP-5 Operable Units, the likely response will be to monitor the existing plumes to verify that radionuclide decay takes place or attenuate contaminants to below drinking water standards. Section A.1.3.1 contains additional descriptions of these operable units.

A.1.2.4 Remediation Strategy for the Deep Vadose Zone

DVZ contamination presents unique characterization and remediation challenges. While it does not pose environmental or health risks through direct exposure or uptake, it is a source for further groundwater contamination and exposure to human or ecological receptors. Groundwater in the Hanford Site's unconfined aquifer eventually discharges to the Columbia River.

The vadose zone beneath the Central Plateau consists of 50 (165 ft) to 100 m (330 ft) of water-unsaturated, unconsolidated to semi-consolidated, stratified sediments of varied physical and geochemical character. In many places, the vadose zone is contaminated with mixtures of radionuclides, metals, and organic chemicals resulting from both international and accidental release of liquid waste into the ground. The vadose zone overlies an unconfined aquifer ranging in thickness from 10 (30 ft) to 120 m (390 ft).

The DVZ contains radionuclides, metals, and organic chemical contaminants that may impact groundwater in the future. Geochemical reactions between Hanford sediments and contaminants can retain some contaminants, such as ^{137}Cs, ^{90}Sr, and ^{60}Co, effectively immobilizing them except under conditions of extreme saline or acidic conditions existing near certain liquid release sites. However, tritium, ^{99}Tc, ^{129}I, nitrate, and carbon tetrachloride are mobile, enabling them to move deep into the vadose zone, posing a longer-term threat to groundwater. Certain radionuclides, such as uranium and transuranic elements, can also undergo chemical sorption, holding them in place (Gee et al. 2007).

The depth of Hanford Site contaminants and the heterogeneous nature of the vadose zone make it difficult to determine the distribution, extent, or behavior of contamination. A lack of understanding the key processes (e.g., biogeochemical and hydrologic) affecting contaminant migration challenges scientists' ability to predict the location and fate of subsurface contaminants. These same factors challenge the design and deployment of sustainable remedial approaches and make it difficult to validate the performance of remedial actions.

DOE has initiated a series of treatability tests to identify and evaluate potential approaches to DVZ contamination. These tests (DOE-RL 2008b) are focused on technologies for remediating deep ^{99}Tc and uranium. Initial test plans have been developed for field testing of desiccation technology to reduce the mobility of ^{99}Tc in the vadose zone located in the BC Crib Area.

On a national level, the DOE-Environmental Management Advanced Remediation Methods for Metals and Radionuclides in the Vadose Zone initiative focuses on 1) developing technologies to access and deliver remedial amendments—such as foams—to the vadose zone, 2) developing advanced geophysical methods for emplacing remedies, 3) enhancing remediation performance, and 4) deploying long-term monitoring techniques. Starting in fiscal year (FY) 2009 at the Hanford Site, this initiative targeted laboratory and intermediate-scale tests to evaluate and develop foam-based delivery of remedial amendments. Investigations through FY 2010 are focused on foam quality, pressure, mass transport, distribution, and shear thinning. Numerical models for subsurface foam transport are being adapted to incorporate water-air simulations critical to designing foam delivery for both laboratory and field-scale application, such as remediation at the BC Cribs and Trenches (Section A.1.4.4 and Appendix D).

DOE is committed to initiating other treatability tests to evaluate potential approaches to treat, recover, or stabilize DVZ contamination using new or adapted existing technologies. If viable technologies are developed locally or elsewhere, remedies could be selected, tested onsite, and implemented. If viable technologies are not available, institutional controls focused on groundwater monitoring would be emplaced to provide early warning of new contamination entering groundwater below the Central Plateau. Such detection could allow time to implement other groundwater protection strategies.

A.1.2.5 Central Plateau Completion

Cleanup of the Hanford Site's Central Plateau will take decades to complete. Afterwards, a significant amount of hazardous and radioactive material—requiring long-term monitoring—may still remain in the subsurface. An integrated monitoring scheme designed to provide an early warning of significant contaminant movement or impact to groundwater will be a necessary element in the institutional management of the vadose zone. Developing such monitoring capabilities is one of the technical needs identified in Section 4.0.

A.1.3 Previous Vadose Zone and Groundwater Remediation Activities and Results

This section contains summaries of previous groundwater and vadose zone remediation activities undertaken within the Central Plateau of the Hanford Site.

A.1.3.1 Groundwater Remediation Activities

Former and ongoing groundwater remediation activities in the Central Plateau are summarized in this section.

A.1.3.1.1 200 West Area: Carbon Tetrachloride Recovery

The largest quantity of discharged organic chemical wastes on the Hanford Site consists of carbon tetrachloride mixed with lard oil, tributyl phosphate, and dibutyl butyl phosphonate dumped in the 200 West Area near the Plutonium Finishing Plant (Gee et al. 2007). Perhaps 920,000 kg (1000 tons) of carbon tetrachloride were discharged into the ground (see Table A.3 in Section A.2.2).

Two interim remediation technologies have been applied to remove carbon tetrachloride from both the vadose zone and groundwater (DOE-RL 2006). Since 1991, about 79,500 kg (88 tons) of carbon tetrachloride was removed using a soil vapor extraction system in the vadose zone (DOE-RL 2010). In addition, a pump-and-treat system for the unconfined aquifer removed nearly 11,800 kg (13 tons) of carbon tetrachloride from groundwater since 1994. Therefore, a total of about 91,300 kg (100 tons) or about 10% of the carbon tetrachloride volume thought disposed of has been extracted from the subsurface.

Improved conceptual and numerical modeling has also been developed to complete a more thorough understanding of carbon tetrachloride gas and dense, nonaqueous phase liquid (DNAPL) dispersed underground (Oostrom et al. 2007). Simulation results suggest that vapor plumes below the waste release sites are more extensive than the DNAPL plume itself. Results also indicate that the low-permeability Cold Creek Unit retains more of the DNAPL than other geohydrologic units during contaminant infiltration and redistribution. Oostrom et al. (2007) also reported that laboratory and theoretical investigations into the kinetic behavior of all phases of the carbon tetrachloride are needed.

In their review of the Hanford Site's subsurface remediation program, the National Research Council reported that the impact of groundwater pump and treat on the deeper portion of the carbon tetrachloride plume cannot be evaluated (NRC 2009). To better support remediation planning and decision-making, additional knowledge of the subsurface, including groundwater biogeochemical and geohydrologic characterizations of the processes controlling carbon tetrachloride movement, is required.

A.1.3.1.2 200 West Area: Groundwater Remediation Near U-Plant

The following information summarizes groundwater contamination and remedial actions undertaken near U-Plant in the 200 West Area. A more thorough discussion is contained in DOE-RL (2006).

The basis for remedial action within the 200-UP-1 Groundwater Operable Unit (Figure A.22) is because multiple primary contaminants (^{99}Tc, uranium, and carbon tetrachloride) and secondary contaminants (e.g., nitrate, hexavalent chromium, trichloroethylene, tritium, and ^{129}I) are present in concentrations exceeding drinking water standards. Over the years, U-Plant discharged nearly 380 million L of steam process condensate into the subsurface.

A pilot groundwater pump-and-treat test began in 1995 and continued 2 years. Beginning in 1997, contaminated groundwater has been piped 11 km (7 mi) from extraction wells near U-Plant to the 200 East Area Effluent Treatment Facility.

Since 1995, over 869 million L (225 million gallons) of contaminated liquids were treated. A total of 216 kg (0.24 ton) of uranium, 124 g (4 ounces) of ^{99}Tc, 38 kg (77 pounds) of carbon tetrachloride, and 41,500 kg (46 tons) of nitrate have been removed (Hartman et al. 2009).

After interim remedial action objectives for ^{99}Tc and uranium were achieved, the extraction wells were turned off in 2005 to begin a 1-year rebound study.

Pump-and-treat technology was effective in reducing the concentrations of uranium and ^{99}Tc in the plume south of U-Plant to less than 10 times the maximum contaminant level.

Periodic evaluation of the extraction well rebound study showed a gradual increase of uranium concentrations though the concentration remains less than 10 times above the remedial action objective.

In the absence of source control remedies, contaminants are expected to continue migrating from the vadose zone into the groundwater. Source controls are needed to make certain that the contaminant concentration continues to decline. Carbon tetrachloride concentrations migrating into portions of 200-UP-1 Operable Unit continue to rise and now represent an increasing risk to groundwater in addition to other primary contaminants of concern.

Tests of potential uranium sequestration at the field scale using reactive gases were conducted in 2009. Ammonia, CO_2, and PO_4 worked best. Work also includes an assessment of a foam-phosphate carrier to facilitate contaminant removal. Ammonia treatment was selected for field testing to begin in FY 2011.

A.1.3.1.3 Study of 200-PO-1 Operable Unit

Information describing this operable unit study is summarized in DOE-RL (2006).

Groundwater in the 200-PO-1 Operable Unit (Figure A.22), extending from the 200 East Area to the Columbia River, is contaminated with a variety of radionclides, metals, and chemicals, including large groundwater plumes of tritium, ^{129}I, and nitrate (Figure A.23). At this time, viable technologies are not available to remediate these plumes. Groundwater monitoring is taking place. Contaminants are attenuating naturally through dispersion and radioactive decay.

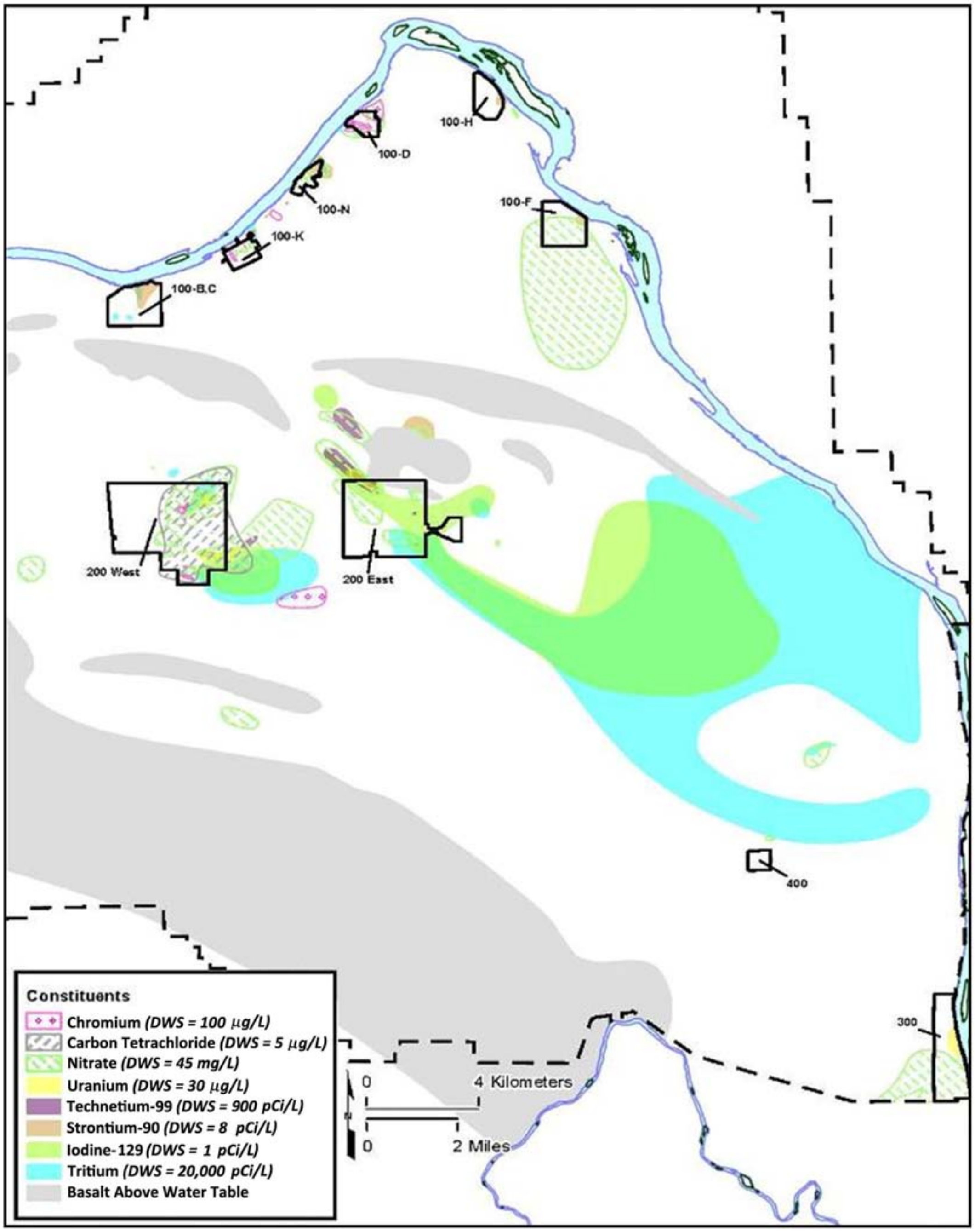

Figure A.23. Groundwater Plumes Beneath the Hanford Site. Plumes show where contamination concentrations are above drinking water guidelines. (Source: after Hartman et al. 2009)

Contaminants in this operable unit that exceed drinking water standards include arsenic, chromium, ^{129}I, manganese, ^{90}Sr, tritium, vanadium, and nitrate. Tritium and ^{129}I are the principal contaminants of concern because of their high mobility and plume size.

Review of the literature and contacts with groundwater equipment manufacturers identified no capabilities to effectively remediate groundwater contaminated with ^{129}I. Groundwater extraction and treatment with ion exchange, activated carbon, reverse osmosis, or precipitation technologies have potential for removing iodine. However, the ability to treat groundwater to the low concentrations required to reintroduce the treated effluent to the aquifer has not been demonstrated.

Monitoring data reveal that the areal extent of the three largest groundwater plumes has changed slowly over the years, although some groundwater contamination has reached the Columbia River.

While vadose zone contaminants beneath the 200 East Area and vicinity will continue to be characterized, significant uncertainty exists in the extent and mobility of contamination contained in the vadose zone.

A.1.3.1.4 Groundwater Remediation in the 200-BP-5 Operable Unit

Information describing this operable is taken mostly from DOE-RL (2006).

Groundwater in the 200-BP-5 Operable Unit (Figure A.22) is contaminated with a variety of radionuclides, metals, and chemicals. Contamination includes large tritium, ^{129}I, and nitrate plumes. Additional contaminants of concern include ^{99}Tc, ^{60}Co, cyanide, uranium, ^{137}Cs, ^{90}Sr, tritium, and $^{239/240}$Pu.

As with the 200-PO-1 Operable Unit, there are no viable technologies to remediate these plumes. Contaminants are attenuating naturally through dispersion and radioactive decay.

The 200-BP-5 Operable Unit includes several liquid waste release sites, including a reverse well, cribs, trenches, and the decommissioned Gable Mountain pond. This area also includes 40 SSTs in three tank farms (B-BX-BY), 20 of which may have leaked nearly 455,000 L (120,000 gal) or more of high-activity waste into the vadose zone. It is difficult to discern between potential tank leaks, tank farm infrastructure leaks, or other contaminant sources.

Activities to evaluate groundwater remediation started in 1995. An operable unit treatability test report summarized the performance of pilot-scale treatability tests conducted to assess the ability of a pump-and-treat system to extract and treat groundwater from the 216-B-5 reverse well and BY cribs plumes located in the northwest corner of the 200 East Area. Aquifer conditions did not allow meaningful contaminant removal to justify continued treatability operations.

Technetium-99, uranium, and nitrate contamination in groundwater have risen in the past years as water table levels drop because of decreasing local liquid recharges. Tritium and ^{129}I distributions have remained relatively unchanged. Cesium-137 and ^{90}Sr have relatively low mobility and are expected to remain in the vadose zone near their source. Plutonium-239 and ^{240}Pu have been detected in the groundwater from wells near the 216-B-5 injection well, located near B Plant, where waste was once injected directly into the aquifer.

Based on the outcome of the treatability test, interim remedial measures for treatment or recovery of contaminants of concern were considered not warranted. Because a remedy has not been determined for groundwater remediation, protectiveness is based on groundwater monitoring. Significant uncertainty exists in the extent and mobility of contamination contained in the vadose zone.

A.1.3.2 Vadose Zone Remediation Activities

Former and ongoing vadose zone remediation activities or water reduction/containment measures undertaken inside the Central Plateau are summarized in this section.

A.1.3.2.1 200 West Area: Carbon Tetrachloride Recovery

Carbon tetrachloride recovery from the vadose zone and groundwater beneath the 200 West Area since interim remedies began in 1991 and 1994, respectively, is summarized in Section A.1.3.1.1. Of the perhaps 920,000 kg (1000 tons) of carbon tetrachloride discharged into the ground (see Table A.3 in Section A.2.2), about 79,500 kg (88 tons) were removed from the vadose zone using a soil vapor extraction system as of 2009 (DOE-RL 2010).

A.1.3.2.2 Surface Water Infiltration Reduction and Containment Measures

Water infiltrating the subsurface can carry contaminants into the vadose zone, and depending upon contaminant mobility, to the groundwater aquifer. Steps have been taken to reduce onsite water discharges to the soil. These activities include the following.

Reduced Recharge from Surface Ponds: Large volumes of liquids were discharged into ponds, ditches, and hundreds of cribs and trenches. Most of these release sites were in the Central Plateau. This provided a hydraulic driving force moving contamination deeper into and faster through the vadose zone than would take place under natural conditions.

Most liquid discharges were piped to three ponds: U-Pond built in the 200 West Area (see Figure A.24), B-Pond (composed of a main pond plus three extension ponds) operated east of the 200 East Area, and Gable Mountain Pond constructed between the 200 East Area and Gable Mountain.

As the need for fuel reprocessing lessened, ponds were no longer required. This led to ending water discharges to both U-Pond and Gable Mountain Pond in 1984. Effluent releases to the B-Pond area ceased by 1997. No other waste management actions had such a dramatic impact on reducing the volume of waste discharged into the vadose zone in and around the Central Plateau than the elimination of these ponds.

Reduced Surface Infiltration Inside Tank Farms: In 1998, a project began to reduce both natural and artificial infiltration in and around tank farms. This also lowered infiltration to nearby waste sites. The project centered upon four components:

- **Design and construct surface water run-off control measures up-gradient of SST farms and waste sites.** Berms were constructed around SST farms to divert surface water away from the farms and into existing or newly constructed gutters. The effectiveness of these barriers was successfully tested during the wet winter of 2004-2005.
- **Remove from service leaking water lines adjacent to SST farms and waste sites.** All waterlines entering and exiting SST farms were tested and lines showing leaks or that were no longer needed were capped or stubbed off outside the tank farms.

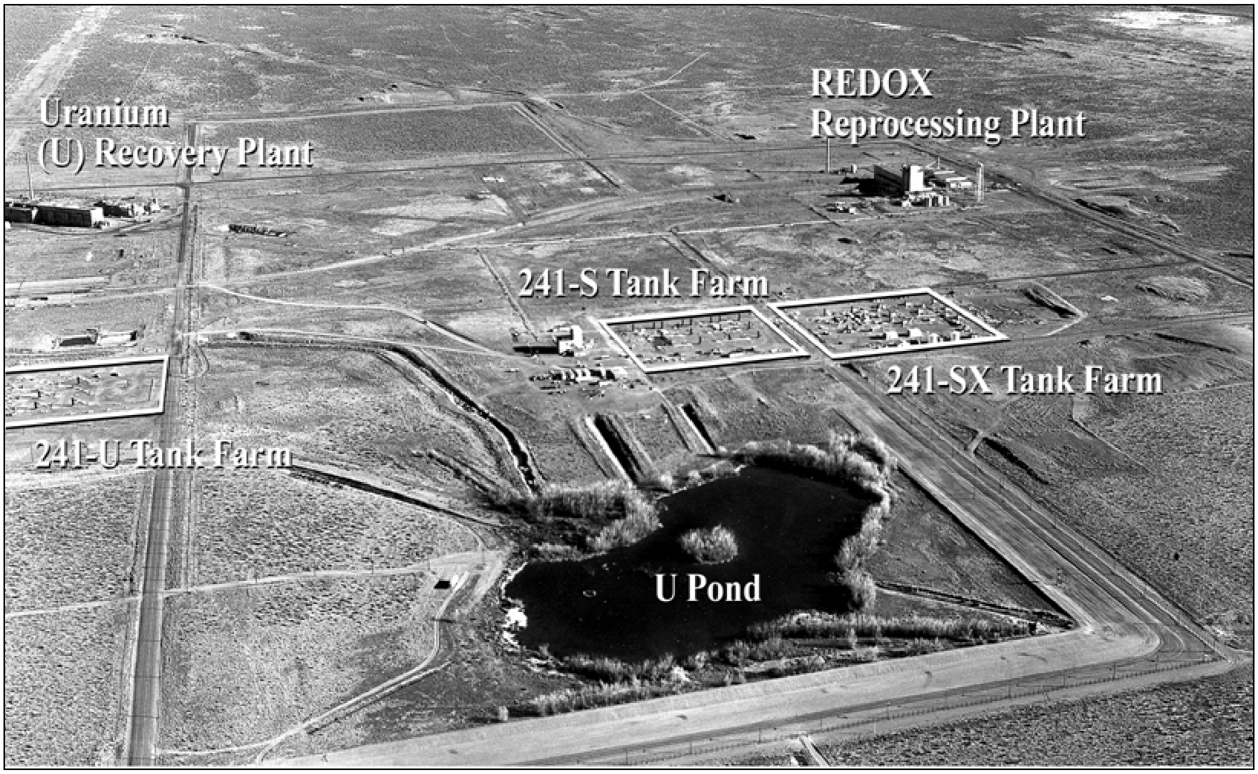

Figure A.24. Photograph of U-Pond Located in the 200 West Area. Photograph taken in 1962.

- **Replace nonoperational caps on upgrade monitoring drywells near SSTs.** Numerous boreholes are used in the tank farms to monitor the vadose zone. At one time, each borehole was capped to prevent surface water from entering. Over time, many caps were misplaced or damaged. These caps were replaced.
- **Install an interim surface barrier over SST farms to reduce infiltration until the closure barrier is installed.** In 2008, an interim surface barrier was installed atop the T-Tank Farm. This topic is addressed in Section A.1.4.3.

A.1.4 Previous Scientific Studies and Treatability Testing Results

Appendix A summarizes a representation of the many scientific, technology, and treatability-related articles and reports published in recent years.

In 2007, a special Hanford Site edition of the *Vadose Zone Journal* was issued (Gee et al. 2007). It is an excellent source to gain an overview of the wide range of DVZ challenges facing remediation of the Hanford Site and the investigations undertaken to date. Examples of topics covered include the following:

- Evaluate the use of borehole geologic data to provide a geologic framework for vadose zone flow and transport simulations (Last et al. 2007)
- Demonstrate how geophysical characterization is sometimes used to delineate contaminant plumes and assist with vadose zone characterization (Rucker and Fink 2007)

- Examine the impact that clastic dikes have on contaminant migration (Murray et al. 2007)
- Describe methods to estimate effective hydraulic properties for anisotropic unsaturated flow (Ward and Zhang 2007)
- Summarize the extensive body of work evaluating the reactive chemistry of highly radioactive tank wastes discharged to sediments beneath the Hanford Site (Zachara et al. 2007a)
- Summarize carbon tetrachloride flow and transport in the vadose zone (Oostrom et al. 2007)
- Examine the geochemical speciation of uranium (McKinley et al. 2007, Christensen et al. 2007, and Conrad et al. 2007)
- Illustrate isotope geochemistry tracking of vadose zone waste plumes (Evans et al. 2007)
- Use *in situ* treatments to immobilize wastes (Thornton et al. 2007)
- Rely on landfill barriers where waste removal is not practical (Fayer and Gee 2006).

As Hanford Site cleanup continues, vadose zone studies will be performed to characterize the extent of contaminant plumes, determine their rates of migration, and evaluate potential remediation solutions such as *in situ* treatment to immobilize wastes (Thornton et al. 2007) or the use of landfill covers where waste removal may be impractical and cause excessive risk to workers (Fayer and Gee 2006).

A.1.4.1 Lysimetery Studies

Water is the primary driving force for moving contaminants into and through the vadose zone; gravity drives this transport.

At the Hanford Site, three large field lysimeters have measured natural infiltration rates for over 30 years. Two sites are located in the Central Plateau, and the third is located along the southern portion of the Hanford Site (Gee et al. 2005). The quantity of water drainage and resulting infiltration into the soil is large for a desert-type climate, averaging 180 mm/yr (7 inches/yr). Annual infiltration averaging greater than 60 mm (2 inches) was measured at one lysimeter site for more than 25 years (Gee et al. 2007). Such infiltration appears typical of bare soil surfaces void of vegetation and where the natural shallow sediment layers were dug up and redeposited.

Freeman et al. (2001) identifies the laboratory and field facilities where Hanford unsaturated flow data have been collected over the years, provides an overview of the soil physic studies undertaken, and summarizes the hydraulic properties measured and the operational status of each facility.

Hanford Site soil studies have dispelled the myth that dry desert conditions prevent deep water drainage. Significant drainage can occur even when potential evaporation rates exceed precipitation. Studies show accelerated water infiltration is facilitated by gravel-covered, barren ground surfaces. Therefore, when such sediments overlie buried wastes or tank farms, water drainage can more readily transport shallow contamination downward into the DVZ.

A.1.4.2 200 East Area Surface Engineered Barrier

Surface barriers limit contaminant flux into the subsurface by reducing water infiltration. They have proven effective for shallow contamination, but their capability to reduce contaminant movement in the deeper vadose zone is unknown. The question surrounding the depth to which surface barriers are effective is one of the key capability challenges facing the Hanford Site.

In 1994, a 5-acre multi-component barrier was constructed over an existing liquid waste disposal trench (216-B-57) using mostly natural materials (Figure A.25). The 4.5-m (15 ft) thick barrier included a 1-m (3-ft) thick silt loam surface layer with 15% pea gravel to control erosion as well as a capillary break, an asphaltic concrete layer at the base, and two protective side-slope configurations. The cover was designed to meet a 0.5-mm/yr (0.02 inches/yr) drainage criterion.

A treatability test conducted from 1994 to 1998 included irrigation at a rate of 480 mm/yr (19 inches/yr), including a simulated 1000-yr storm event each March in which 68 mm (2.3 inches) of water was applied over an 8-hr period. Barrier monitoring was nearly continuous for the last 15 years and has focused on barrier stability, vegetative cover, plant and animal intrusion, and the main components of the water balance, including precipitation, runoff, storage, drainage, and deep percolation.

Water storage in the fine-soil layer shows a cyclic pattern, increasing in the winter and decreasing in the spring and summer, regardless of precipitation, in response to surface/plant evapotranspiration.

Over 15 years, only three runoff events have been observed. However, the 600-mm (23-inches) design storage capacity has never been exceeded. Total percolation ranged from near zero under the soil-covered plots to over 600 mm (23 inches) under the side slopes. An asphalt layer prevented any of this water from reaching the buried waste. The barrier has also performed as an effective infiltration barrier overlying the liquid disposal trench.

A relatively high ground cover of native plants still persists after the initial revegetation. The vegetative cover, in addition to the silt-loam-gravel admix, proved effective in minimizing erosion, but a recent removal of vegetation from the north half resulted in significant soil movement. There is evidence of insect and small mammal use, suggesting that the barrier is functioning like a recovering ecosystem.

Barrier performance data have proven useful in developing more rigorous methods for evaluating long-term performance and quantifying associated risk and uncertainty. For example, Ward et al. (2004) conducted a modeling study for the 216-B-26 trench, located in the BC crib and trench area, comparing the potential benefits gained by installing a surface barrier to the increased time required for ^{99}Tc contamination at MCL concentrations to migrate through the vadose zone and into the underlying groundwater.

Those researchers reported that under natural surface infiltration rates, ^{99}Tc travel time across nearly 75 m (250 ft) of vadose zone sediment to the local groundwater took nearly 1500 years. This time increased to over 7500 years with installation of a surface barrier that lowered infiltration rates to 0.5 mm/year (0.02 inches/yr). Nonetheless, as noted in the abovementioned text, field confirmation coupled with predictive modeling of the deep isolation potential afforded by surface barriers is needed.

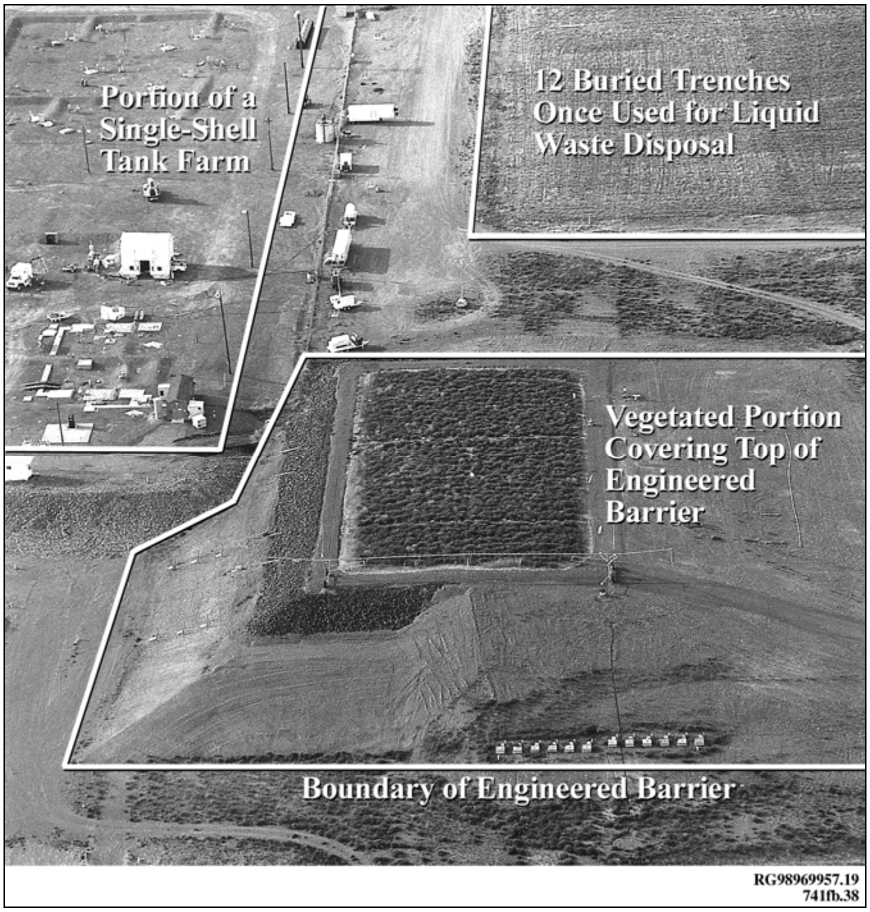

Figure A.25. Aerial Photograph of Surface Engineered Barrier Built in the 200 East Area. (Source: Gephart 2003)

A.1.4.3 Interim Surface Barrier Demonstration

Interim surface barriers were evaluated in 1992 for potential use at the Hanford Site as part of an effort to identify and evaluate alternatives to cover all 149 SST farms (WHC 1999). The four concepts developed and evaluated included:

- Fine-textured top soil to absorb and retain precipitation for subsequent evaporation
- Above-grade roofed structures
- Low permeability surface materials
- Low-permeability membrane liner below-grade materials to cause lateral water migration.

A polymer-modified asphalt was identified as the preferred alternative because of its low permeability and cost considerations.

The U.S. Department of Energy's Office of River Protection constructed a temporary barrier over a portion of the T-Tank Farm as part of the T Farm Interim Surface Demonstration Project. The following description of this interim barrier is mostly summarized from Myers (2005), DOE/ORP (2008), and Zhang et al. (2010).

The T-Tank Farm was built in the 200 West Area from 1943 to 1944 and started receiving T-Plant reprocessing waste in 1945. It contains 12 SSTs, each with a capacity of 2,006,000 L (530,000 gal). The tank farm also contains four smaller SSTs, each with a capacity of 208,000 L (55,000 gal).

Seven of the 12 largest SSTs have leaked waste into the subsurface. The largest leak took place in 1973 when Tank T-106 released approximately 435,000 L (115,000 gal) of fluid. This waste contained 40,000 curies of cesium-137, 14,000 curies of strontium-90, 4 curies of plutonium, and various other fission products, including technetium-99 (Atomic Energy Commission 1973). Tank T-106 was the largest tank leak ever reported for the U.S. nuclear weapons complex. The plume, now residing in the underlying shallow vadose zone to the DVZ, is estimated to be about 70 m (225 ft) in diameter and has migrated 27 m (90 ft) below the bottom of Tank T-106.

Construction of an interim barrier of a sprayed-on and sloped polyurea liner (similar to the material used to line pickup truck beds) covering nearly 6000 m^2 (64,000 ft^2 or about 1.5 acres) of the T-Farm surface, including all or part of 9 of the largest tanks (including T-106) began in 2007 and was competed in 2008 (Figure A.26).

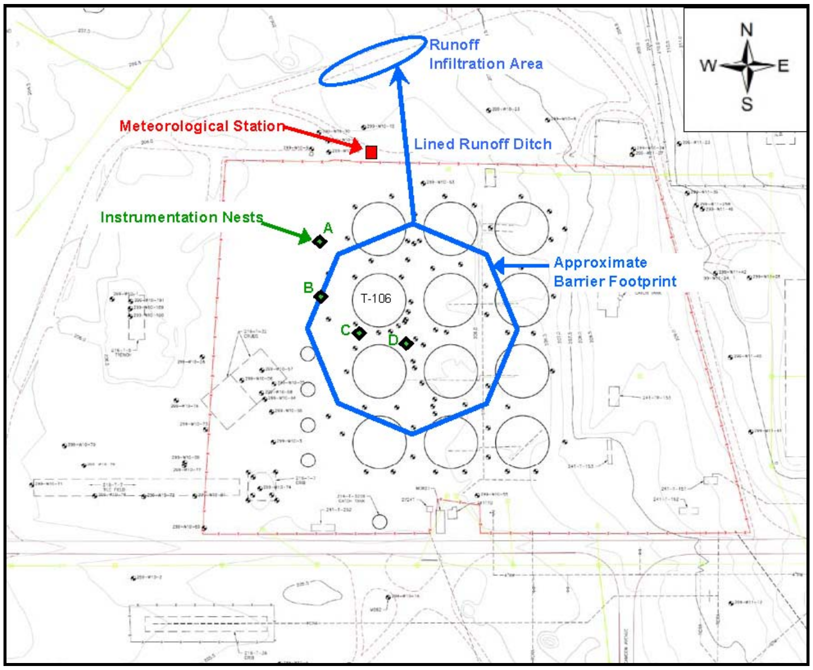

Figure A.26. Illustration Showing T-Tank Farm Interim Surface Barrier (marked by octagon). (Zhang et al. 2010)

As part of the demonstration effort, instrument nests were installed to monitor subsurface moisture behavior to assess the effectiveness of the barrier both directly beneath the barrier and outside its footprint.

During fiscal year 2009, instruments located outside of the barrier (Nest A) showed large variations in soil moisture conditions above approximately 2 m (6 ft) in depth during seasonal wetting-drying cycles—infiltrating during winter and drying during summer. Below this depth, the soil water change was relatively small. In the soil beneath the barrier (instrument Nests C and D), the water content between

0.6 (2 ft) and 2.3 m (8 ft) depths was stable while soil water drainage was taking place between 3.4 m (11 ft) and 9.1 m (30 ft). Barrier performance results to date indicate it prevents meteoric water from infiltrating into the soil.

The interim surface barrier is expected to minimize precipitation from entering the soil and consequently reduce the rate of downward water movement and contaminant transport in the vadose zone (McMahon 2007). In deeper sediment below 10 m (30 ft), the subsurface is expected to continue receiving drainage from the overlying soil column for some time before slowing down. It may take years for drainage rates deep in the sediment profile to significantly reduce.

In 2010, a modified, 4-in.-thick, low-permeability asphalt barrier was also installed atop a 7200 m^2 (78,000 ft^2 or 1.8 acres) portion of the TY Tank Farm where five of the tank farm's six SSTs built in 1951 are suspected to have leaked radioactive waste into the ground. A polymer was mixed into the asphalt to produce a waterproof mixture that will not crack and compacts better than asphalt alone.

A.1.4.4 Treatability Study at the BC Cribs and Trenches

Descriptions of treatability studies at the BC crib and trench site located just south of the 200 East Area are primarily summarized from Pierce et al. (2009).

The 26 BC cribs and trenches cover 35 acres and have received nearly 190 million L (50 million gal) of scavenged tank waste from the bismuth phosphate spent fuel reprocessing that occurred inside T and B Plants. These wastes had cascaded between tanks between 1956 and 1965. Based on inventory estimates, these waste release sites contain the largest inventory of ^{99}Tc disposed of in Hanford Site soil—about 410 curies.

Initial characterization indicates that the ^{99}Tc inventory is located mostly between 30 and 45 m (100 and 150 ft) below ground level and is spread across an area of nearly 0.14 km^2 (35 acres) in that portion of the vadose zone composed of Hanford formation sediments. Transport model predictions suggest that this contamination will migrate the additional 70 m (230 ft) to groundwater unless remedial actions are successful (Ward et al. 2004).

Remediation is not feasible using existing technologies. Therefore, a DVZ treatability test replying upon soil desiccation with nitrogen gas injection is underway to examine the effectiveness and implementability of this technology (DOE-RL 2008b). As of mid-2010, 25 monitoring boreholes were installed and over 700 instruments emplaced for upcoming tests. This 6-month test targets the desiccation of about 300 m^3 (10,000 ft^3) of sediment within an interval 9 to 15 m (30 to50 ft) below ground level (Triplett et al. 2010). The goal is to evaluate vadose zone remediation technologies, including laboratory, modeling, and field tests.

DOE and the remediation contractor have performed geochemical and hydrodynamic characterization of the field site. Characterization included installing boreholes through several trenches, sediment sampling, and analysis. The analysis results showed there was ^{99}Tc at depth in the vadose zone, although the areal extent remained unknown (Serne and Mann 2004). Subsequent modeling by Ward et al. (2004) predicted lateral spread, which was investigated by high-resolution electrical resistivity geophysical surveys (Rucker and Benecke 2006).

A related investigation includes laboratory modeling to evaluate the effect that high vacuum and high air velocity applications might have on contaminant removal. This approach is expected to strip the pore water and associated ^{99}Tc from the targeted subsurface zone.

The DOE Office of Science (SC), through the Scientific Focus Area (SFA), is also investigating the redox chemistry of ^{99}Tc in Hanford Site sediments and evaluating the biogeochemistry of microbial isolates toward ^{99}Tc (and uranium) in different Hanford Site sediments. These investigations target improved predictions of transport behavior for both metals.

A.1.4.5 Laboratory Testing of Ammonia Gas Injection to Sequester Uranium

Some reactive gases induce geochemical changes in sediments that render contaminants less mobile. Szescody et al. (2010) evaluated a range of potential gas-amendments in the laboratory.

Based upon these tests, pH manipulation with ammonia gas proved effective in reducing uranium mobility and appears amenable to application in the vadose zone beneath the Hanford Site. When ammonia gas at a concentration of 5% flows into the vadose zone, it partitions into the pore water between sediment grains. A portion of the ammonia then dissociates, increasing pore water pH from about 7 to near pH 12. Under such conditions, desorption of ions and dissolution of alumino-silicates occurs. Following cessation of gas injection, buffering and the loss of ammonia occur as pH declines, and precipitation of ions in solution occurs. These precipitates coat and bind uranium contamination. Laboratory experiments reported by Szescody et al. (2010) demonstrate this process to be robust in many Hanford Site sediment types. Field testing is planned.

A.1.4.6 Grouting Technologies

Grout injection involves placing a slurry mixture into the subsurface that when cured or reacted, stabilizes or isolates the contaminant in a matrix-like solid (DOE-RL 2008b).

Currently, laboratory modeling and bench-scale testing are underway to evaluate the potential of grouting technologies for DVZ application. Studies are evaluating the injection properties of candidate materials with different viscosity, density, and composition. Tests and modeling will also evaluate the distribution, location, and stratigraphic factors that control grouting distribution once emplaced underground so the technology can be scaled to field test demonstrations.

A.1.4.7 Soil Flushing

Soil flushing targets contamination in the vadose zone with a leaching solution (DOE-RL 2008b). This solution mobilizes contaminants with the intent of later recovering contaminants deeper in the groundwater using, for example, pump-and-treat technologies. The subsurface application and distribution of the leaching solution poses a significant challenge. Currently, laboratory modeling and bench-scale testing are underway to evaluate the potential for DVZ application to assess the distribution, location, and stratigraphic factors controlling injected fluid movement and the resulting distribution of contaminants present after flushing. Laboratory work will also evaluate the impact of vadose zone sediment properties on the performance of leaching solutions.

A.1.4.8 Examples of Geochemical Research on Contaminant Reactivity in the Vadose Zone Sediments

As summarized in Cantrell et al (2007), geochemical studies are used to understand the migration potential of contaminants found in the subsurface and to identify potential risks posed by mobile contaminants reaching the aquifer that underlies the DVZ. This information is used to develop descriptive (conceptual) models of the subsurface environment. When that understanding is incomplete, research is conducted to fill critical knowledge gaps about the properties, mechanisms, and processess controlling contaminant fate and transport. As the conceptual model is being refined, numerical and risk assessment models are relied upon to perform analyses to develop defensible remedial strategies. Examples of geochemical research carried out at Hanford are summerized in the following paragraphs.

Concerns exist over the subsurface migration of radionuclides released from SSTs, some placed into service as early as 1945. Sixty-seven of the 149 SSTs on the Hanford Site are suspected to have leaked 3.8 million L (1 million gal) or more of high sodium and nitrite brine solutions into the subsurface. One radionuclide of particular interest is ^{137}Cs. As noted in Table A.2, this leaked tank waste contains perhaps 150,000 curies of ^{137}Cs (decayed as of 2005).

Zachara et al. (2002) reported on the sorption of ^{137}Cs onto sediments collected from the Hanford formation underlying the S-SX Tank Farms located in the 200 West Area. These samples were extracted from a well drilled between Tanks SX-108 and SX-109. These tanks were declared or confirmed as leakers between 1962 and 1965 (Hanlon 1998).

Studies reveal that the coarser grained fraction of sediments contain micaceous minerals (e.g., biotite and muscovite) exhibiting a strong sorption for ^{137}Cs along their edges (Figure A.27). This is due to the removal of cations during past weathering of these minerals. Finer sediment fractions containing clay minerals, such as smectite, could also sorb cesium if not for tank waste solutions that had high sodium concentrations that suppressed cesium absorption in smectite.

McKinley et al. (2001) reported that approximately 70 to 80% of the sorbed ^{137}Cs was bound by the weathered edges of mica flakes—mostly biotite.

Evidence reported in Zachara et al. (2002) suggests that these vadose zone sediments limit the vertical migration of cesium to depths of approximately 7 to 32 m (20 to 100 ft). At the same time in select locations where hot tank waste solutions once crossed, core samples reveal cesium experiencing little retardation, therefore reaching greater depths. Experimental and modeling results concluded that tank waste sodium is an effective competitor for high-affinity absorption sites located in sediment minerals along the leading edge of the original waste plume.

Tank waste also contains high concentrations of hydroxides [OH^-] and aluminates [$Al(OH)_4^-$] that can also influence the extent of cesium migration through dissolution and precipitation reactions. Potassium found naturally in the sediments may also expedite deeper migration of cesium.

Nonetheless, research into the partitioning of ^{137}Cs by micas and clays in the subsurface and the potential effects that high concentrations of competing cations may have on contaminant movement must be completed before definitive conclusions can be drawn regarding any re-mobility of once sorbed cesium. However, uncontaminated micas found down-gradient from the original point of cesium desorption would strongly retard future ^{137}Cs migration (McKinley et al. 2001).

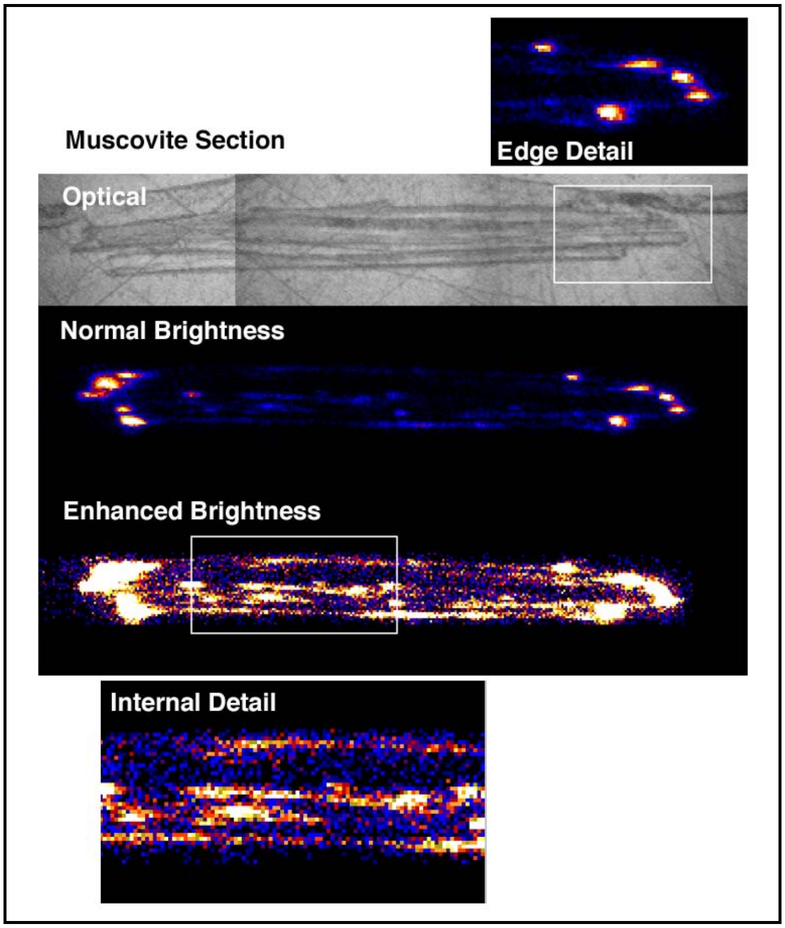

Figure A.27. Cesium Distribution Shown in Cross Section of Mica Grain. The mica was removed from sediment sampled beneath Tank SX-108. The muscovite grain is about 1 mm in length. The white color shows the highest cesium concentration, and blue is lowest concentration. Cesium is observed on the edge sites and in intra-grain cleavage planes.

Zachara et al. (2007a) summarized the state-of-knowledge of geochemical processes controlling the migration of Hanford Site tank waste that once leaked into the vadose zone. In summary, laboratory research using sediments collected from contaminant plumes from beneath tanks demonstrate that ion exchange, precipitation and dissolution, and surface complexation reactions have taken place between these wastes and sediments, moderating contaminant chemical character and movement. The geochemical and biogeochemical processes controlling contaminant behavior can be simulated using reaction-based transport models. These models simulate the chemical, and sometimes biogeochemical, driven reaction network (e.g., between sediment minerals, water chemistry, waste chemistry, and geohydrologic features) controlling contaminant mobility and plume evolution.

Research into the geochemical behavior of uranium in vadose zone sediments beneath the 200 Area (BX Tank Farm) and 300 Area (former waste disposal ponds) was reported by McKinley et al. (2007). Laboratory testing of field-collected sediment revealed that at both sites, uranium resided as secondary minerals dictated by the chemical nature of the original released waste. For example, in the 200 Area, large volumes of high-alkaline tank waste reacted with Hanford formation sediments to form solid uranyl silicate phases. Figure A.28 shows scanning electron microscope images of two mineral types (mica on left and quartz on right) found to contain a form of U^{+6} sampled 41 m (136 ft) beneath Tank BX-108 in the 200 East Area. The uranium exists as precipitates in mineral cavities and fractures.

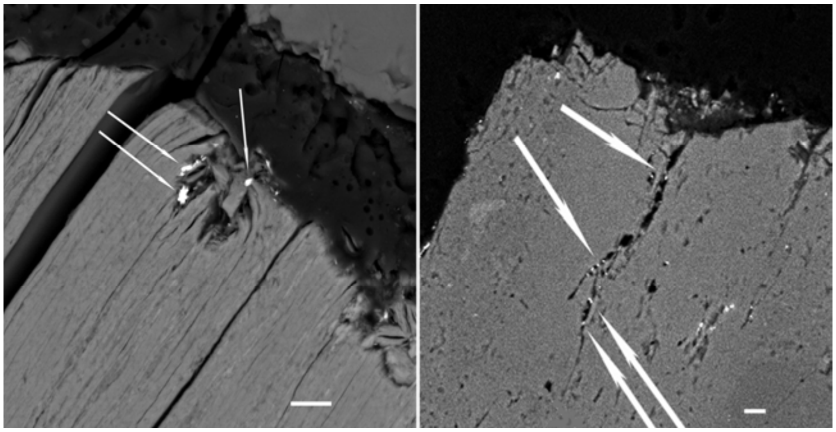

Figure A.28. Scanning Electron Microscope Images of Uranium Precipitates. Sediment samples were removed from beneath a Hanford Site tank. White bars on lower right of each image represent a length of 10 microns (one-tenth width of human hair).

In the 300 Area, the alternating disposal of both alkaline and acidic liquids, laden with copper, uranium, and aluminate, into ponds created aluminosilicates and several uranyl-bearing solid phases (e.g., hydroxides, carbonates, and phosphates). This suggests that uranium mobility depended upon the composition of the original waste, which in turn determined the chemical form of secondary minerals created. Thus, the widely varying chemistry of liquid discharges across the Hanford Site can result in vastly different chemical reactions—and ultimately uranium mobility. Therefore, a predictive model populated with data from one waste release site may not adequately describe the most likely series of reactions occurring at another site of dissimilar disposal history.

A.1.4.9 Example of Isotopic Studies to Assess Contaminant History

Isotopic studies of natural or anthropogenic radionuclides analyzed from water sampled from the subsurface can provide insights into contaminant sources and behavior as well as the processes that affect contaminant transport and mobility.

For example, natural strontium isotopic composition ($^{87}Sr/^{86}Sr$) is sensitive to water/rock interactions and can reveal areas of enhanced recharge through elevated $^{87}Sr/^{86}Sr$ ratios in groundwater (Christensen et al. 2007). The nitrogen and oxygen isotopic compositions of nitrate (NO_3) can show contrasts between subsurface fluids contaminated by single-shell tank waste and lower activity sources such as liquids once disposed of in cribs or trenches. Uranium isotopic measurements are also useful in understanding water/rock interactions. In addition, because uranium isotopic ratios of some contamination sources changed over time as a result of using uranium fuel with varying amounts of ^{235}U enrichment in Hanford reactor operations, uranium isotopic comparisons can identify the source and timing of contamination releases. Combining multiple isotopic measurement techniques with conventional chemical data can enhance our understanding of contaminant sources and transport paths/rates in the underlying vadose zone.

One study by Christensen et al. (2007) implicated tank-sourced waste, possibly associated with the T-106 tank leak of 1973, in the ^{99}Tc and nitrate groundwater contamination found near the northeast corner of Waste Management Area (WMA) T (Figure A.1). The uranium and strontium isotopic data collected from nearby borehole cores as well as chemical data from previous studies revealed varying amounts of interaction between the infiltrating waste fluids and vadose zone sediments. The caustic, high–ionic-strength tank fluids enhanced their chemical reaction with the underlying sediments over that of just natural, infiltrating water recharge. Even the relatively low levels of uranium contamination seen in the WMA T and WMA TX-TY vadose zone cores were sufficient to provide considerable insights into the sources and timing of contamination releases.

A.2 Scope of Deep Vadose Zone Remediation Challenge

> "…the biggest challenges [DOE] EM faces are those that have few precedents and fewer off-the-shelf technologies and processes to address them." (DOE 2009)

Although significant advances have taken place in past years in the development of technologies and approaches to characterize and remediate subsurface systems, most efforts focused on groundwater systems—not the unsaturated vadose zone, let alone the DVZ as beneath the Central Plateau of the Hanford Site.

Traditional cleanup remedies are expected to have limited effectiveness for solving DVZ problems because of contaminant depth, distribution, and presence in a complex geologic, geochemical, and microbial environment. Such knowledge and capability shortfalls, particularly related to DOE problems, have been reported for years. Example publications include NRC (1997, 2000a, 2000b, 2001, 2009); Mann et al. (2007), Dresel et al. (2008); Looney and Falta (2000); DOE (2001), DOE-RL 2008b); and Zachara et al. (2008).

Many of the key knowledge and technology needs identified in the above publications and during meetings with Hanford Site contractor personnel are summarized in Appendix C. In addition, Section 4.0 and Appendix B identifies challenges facing the characterization, modeling, access, monitoring, and remediation of the DVZ that was identified by participants attending a Deep Vadose Zone Technical Forum held in July 2010. A fuller description of that meeting is introduced in Appendix B.

In 2001, the National Research Council published its review of science and technology needs for subsurface cleanup and decision-making beneath the Hanford Site. A study was requested by DOE's Assistance Secretary for Environmental Management. The following quote summarizes its perspective about vadoze zone cleanup:

> "The vadose zone is arguably the most important region of the Hanford Site from both a scientific and an environmental restoration perspective: it contains most of the chemical and radionuclide contaminants that have been discharged or leaked into the environment and is host to the site's waste storage and disposal facilities, including the high-level waste tanks, buried pits and trenches, disposal ponds and cribs, and injection (or "reverse") wells. The present-day distributions and chemical forms of contaminants in the vadose zone are poorly known, as are the fate and transport processes that will

> govern the future migration of these contaminants to the groundwater and the Columbia River." (NRC 2001)

Nearly a decade later, in its review of DOE's cleanup technology roadmap (NRC 2009), the National Research Council continued echoing similar concerns:

> "Currently, available technologies, including EM's baseline technologies, are insufficient to remediate many of DOE's groundwater and vadose zone contaminants….technologies and approaches to characterizing, conceptually understanding, and modeling subsurface properties and processes are both inefficient and insufficient, and can lead to unreliable predictions of subsurface contaminant behavior." (NRC 2009)

DOE recognizes that there are no immediate solutions to many Hanford DVZ contamination problems. Nonetheless, this does not detract from the importance of marshaling existing knowledge and capabilities to address DVZ issues to the best of our ability. Section 6.0 addresses how new capability investments are being targeted to yield usable results in both the near and long-term to achieve regulatory compliance, cleanup, and waste site closure. This balances a bias-for-action remediation strategy with problem-focused scientific investments to verify that the right knowledge and capabilities are available when required.

For example, as noted in Section 4.1 and Appendix B of this Program Plan, early model conceptualizations of the subsurface, often based on coarse theoretical understandings and sparse site-specific data, guide subsequent data acquisition and experimentation. The insights gained enable researchers to target subsequent laboratory and field investigations to refine the conceptual model(s) and reduce uncertainty about the controlling parameters/processes needed to understand overall system behavior and likely responses to remediation treatments applied.

Therefore, a sustained, long-term, and focused effort is needed to create, test, and implement transformational capabilities that can carry out remediation more efficiently and cost effectively. Transformational technologies are not merely better than current technologies but are significantly better.

Investments into short- to long-term basic research through novel technology development are essential to vadose zone characterization, innovative modeling, remediation, and monitoring. Upon development, capability advances will be inserted into the Hanford Site cleanup baseline (see Section 6.0).

One exceptional example of research impacting vadose zone decision making stems from laboratory studies of contaminated sediments collected beneath tanks that once leaked high-alkali, radioactive waste (Section A.1.4.8). Research demonstrated that ion exchange, precipitation and dissolution, plus surface complexation reactions can significantly retard the migration of select radionuclides, such as ^{137}Cs, making them unavailable for further migration (Zachara et al. 2007a).

The reprocessing of irradiated uranium metal at the Hanford Site resulted in the release of nearly 205,000 kg (225 tons) of uranium to the ground in a variety of aqueous solutions. Any of these solutions affects uranium behavior in the subsurface. Zachara et al. (2007b) documents a side-wide perspective on uranium geochemistry beneath the Hanford Site.

Such information, coupled with more traditional geohydrologic studies, is irreplaceable in supporting regulatory decisions affecting restoration and management of subsurface contaminants. Without new problem-targeted knowledge, it will difficult to perform reliable performance assessments supporting decision making or executing remedial actions where projected outcomes match field results.

A.2.1 Challenges Facing Deep Vadose Zone Characterization, Testing, Remediating, and Monitoring

Broadly, key knowledge and technology gaps identified in the publications noted above that pertain to Hanford fall into the following categories:

- **Characterization and Monitoring:** Locating and characterizing the concentrations, speciations, release rates, and movement of contaminants distributed within a heterogeneous sedimentary environment crosscut by discontinuities. Advancing subsurface monitoring technologies, including novel sensors, detectors, and data transmission techniques tracking the long-term performance of the natural and engineered systems.
- **Subsurface Processes and Predictive Modeling:** Characterizing the coupled physical, geochemical, and microbiological properties/processes functioning within the subsurface that control contaminant transport over multiple time and spatial scales. Creating validated conceptual and predictive models to depict subsurface dynamics and contaminant behavior spanning the molecular-to field-scale. Account for uncertainty in the parameterization of vadose zone properties, as well as the non-linearity of transport properties in modeling. Quality modeling also requires preserving and enabling access to laboratory through field-generated data sets supporting modeling, performance assessments, and decision making.
- **Subsurface Access and Remediation:** Developing improved subsurface access capabilities plus less costly and more effective contaminant treatment, recovery, containment, and stabilization techniques through coupled laboratory- and intermediate-scale testing before field tests and deployment programs.

Knowledge and capability challenges are discussed further in Section 4.0 and Appendices B and C.

Little is known about how DVZ characteristics and processes interact over the spatial (molecular to field) and time (present to thousands of years) scales critical to DOE decision-making nor how subsurface processes interplay to dominate contaminant movement and recovery (Figure A.29). Though captured under the abovementioned “Characterization” bullet, understanding how geologic discontinuities impact contaminant movement and remediation effectiveness cannot be overstated. Identifying, investigating, and modeling these features will be challenging.

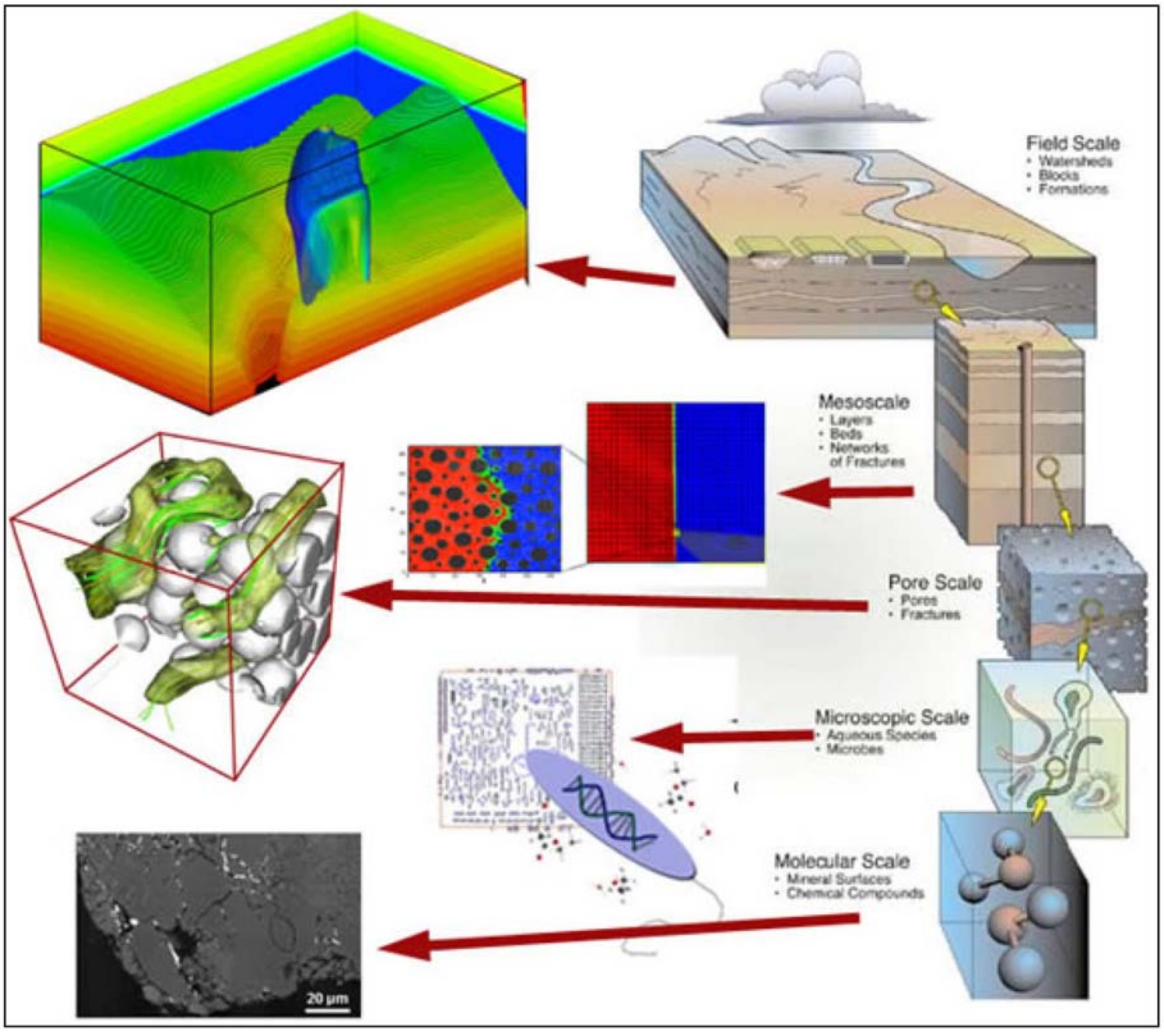

Figure A.29. Model Simulations of the Molecular to Field-Scale Subsurface Environment

Dresel et al. (2008) summarized the major variables controlling contaminant transport and fate in the DVZ. These hydrogeologic, biogeochemical, and site-specific factors, along with their significance and potential impacts, are listed in Table A.1.

In past subsurface performance assessments, hydrogeologic layers beneath the Hanford Site were generally assumed to have homogeneous properties. In reality, and as noted in Section A.1, these units display complex, overlapping and crosscutting sedimentary structures controlling liquid movement and contaminant transport over both short and long distances. Such structures can enhance lateral waste spreading and redirect and/or impede contaminant movement.

A critical challenge faced centers upon answering "what is characteristic" of a given waste site or across the Central Plateau. The parameterization of subsurface properties and processes remains the subject of considerable debate and uncertainty.

For example, no field data exist on large-scale dispersivities for the vadose zone beneath the Hanford Site. What values are available versus what values adequately depict the subsurface? Ward et al.[1] obtained dispersivity estimates from small-scale field measurements in the shallow Hanford formation. Analysis provided dispersivities from 1.3 to 7.8 cm (0.5 to 3 in.) for travel distances ranging from 25 to 125 cm (0.8 to 4 ft). Dispersivity increased with depth to about 0.75 m (2.5 ft). Using modeling, Khaleel (1999) estimated a longitudinal macro-dispersivity of about 1 m (3 ft) or the sand-dominated facies of the Hanford formation beneath the 200 East Area. However, the hydraulic properties of sedimentary layers, such as dispersivity, compromising the vadose zone can span orders of magnitude, depending upon the volume of sediment investigated. As noted, little is known of these values in the DVZ.

Geochemical processes, starting at the molecular scale and extending to the field-scale, are also not well quantified. Field studies are in progress on select contaminated sites to improve current knowledge of contaminant transport processes, and directed laboratory research is underway to address contaminant/rock matrix geochemical and biochemical interactions. The goal of these studies is to evaluate those processes driving the absorption and movement of contaminants. Process examples studied include adsorption, mineral precipitation and dissolution, bio-mineralization, matrix diffusion, pore plugging, and colloid formation and transport.

A.2.1.1 How Much Information is Enough?

The above question centers on whether learning more (and therefore reducing uncertainty) will lessen the chance of making an incorrect decision. Knowledge should be adequate to assess a range of defensible interpretations of existing information.

Hanford Site officials are seeking to develop an understanding of the subsurface to make well-informed remediation decisions. This is a central theme in the defense-in-depth approach discussed in Section A.3. Complete characterization is not feasible unless the system studied is homogenous and isotropic; the vadose zone is not.

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[1] AL Ward, RE Clayton, and JS Ritter. 1998. “Hanford Low-Activity Tank Waste Performance Assessment Activity: Determination of In Situ Hydraulic Parameters of the Upper Hanford Formation.” In: Letter to Dr. Fredrick M Mann (CH2M HILL Hanford, Inc., Richland, Washington) from AL Ward (Pacific Northwest National Laboratory, Richland, Washington).

Table A.1. Major Factors Controlling Long-Term Contaminant Transport and Fate in the DVZ (based upon Dresel et al. 2008)

Hydrogeologic Variables	Variable(s)	Significance	Impact
Hydrostratigraphy	Horizontally and vertically oriented fine-textured strata	Local mitigation of vertical or lateral flow in adjacent fine-textured strata	Neglecting small-scale textural changes could lead to an underestimation of lateral or vertical spreading, and erroneous predictions of penetration depth and rate of transport.
Hydraulic properties	• Water content-capillary pressure relationship • Unsaturated hydraulic conductivity versus capillary pressure relationships	• Difference between air and water pressure; function of saturation affects preferential transport pathways in heterogeneous sediments. • Moisture content, hydraulic conductivity, and capillary pressure relationship shows hysteresis during wetting/drying.	• Central role in predicting water flow in unsaturated soils • Typically assume steady state for DVZ
Transport properties	Dispersivity	Function of sediment texture and scale-dependent	Dispersivity increases as the proportion of fine-textured sediment increases.
Site Event	Feature(s)	Significance	Impact
Contaminant release	Release quantity and duration	Conceptual and numerical models source terms	Affects the initial and boundary conditions.
Recharge event	Annual precipitation, topography, climate, soil type, and vegetation	Subsurface contaminant behavior is dependent upon both short- and long-term recharge rates.	Subsurface contaminant distribution depends on the extent of recharge (i.e., diffuse or focused).
Evapotranspiration	Water loss to atmosphere from ground surface or vegetation	Water loss from shallow vadose zone depends on soil texture and vegetation type/rooting depth.	Reduces recharge and water available for contaminant transport to groundwater.
Biogeochemical Property	Process(es)	Significance	Impact
Precipitation/dissolution	Chemical composition of infiltrating water	Chemical disequilibrium between infiltrating water and mineral or contaminant species lead to precipitation/dissolution reactions as water migrates through the vadose zone.	Affects plume distribution and the rate of contaminant migration.
Sorption/desorption	Ion exchange and surface complexation	Can potentially have a large affect on attenuation of contaminants.	Affects distribution and rate of contaminant migration.
Degradation /transformation	Chemical (abiotic) and microbiological (biotic) reactions	May result in compounds that are less toxic, more or less strongly sorbed, or compounds that are less soluble.	Controls the quantity, concentration, or activity of a contaminant reaching the groundwater.

Because of the depth and complexity of the subsurface environment beneath the Central Plateau, our knowledge of the vadose zone and how it will respond to remediation will always remain less than perfect, less than “complete.” Perfect knowledge or understanding will not exist. Unknowns will always remain because the scale of interest for making predictions is far longer and far greater than the scales over which information is collected.

Over the short-term (<5 years), subsurface investigations will be used to explore the subsurface and recalibrate and validate conceptual and numerical models. Long-term (decades long) subsurface monitoring will provide the information backbone to more convincingly approximate the behavior and performance of the DVZ and to reduce, or at least bound, the uncertainties faced.

It’s important to recognize that while some contaminants could exist for hundreds to millions of years, predicting such long-term subsurface behavior and remediation performance with a high-degree of certainty is beyond what science and engineering can offer. Estimating long-term fate and performance is full of uncertainties, assumptions, and approximations. Nonetheless, remedial actions must be undertaken and cleanup decisions faced. This underscores the need for high-quality models, knowledge, scientific understanding, and engineering tailored to the issues faced.

The number and complexity of the issues faced is why DOE formed the Advanced Simulation Capability for Environmental Management (ASCEM) project in 2009—to use transformational, high-performance computer modeling capabilities to predict contaminant fate and transport in both natural and engineered systems while integrating between multi-scale data sets.

A.2.2 Vadose Zone Contaminants Released into Sediments Underlying the Central Plateau

As noted in Section 1.0 and reported in Gephart (2003), large volumes of uncontaminted to contaminated liquids were discharged into 30 ponds, unlined ditches, and hundreds of other waste release sites during Hanford’s plutionum production era. Most of this took place in or near the Central Plateau. Some 800 waste sites now exist within the center of the Hanford Site. The primary sources of these contaminants are the reprocessing plants and the Plutonium Finishing Plant, plus their associated liquid release sites (Corbin et al. 2005). Discharged liquids provided a hydraulic driving force moving contamination deeper into the vadose zone and underlying aquifer than otherwise possible.

In addition, 3.8 million L (1 million gal) or more of high-alkali, ^{137}Cs -laced tank waste once leaked into the ground from SST farms on the Hanford Site.

In 2009, groundwater plumes covering 170 km^2 (65 mi^2) or nearly 10% of the Hanford Site contained contaminants such as metals (e.g., chromium), chemicals (e.g., nitrates, trichloroethene, and carbon tetrachloride), and radionuclides (e.g., tritium, ^{129}I, and ^{99}Tc) at concentrations above safe drinking-water standards or other guidelines (DOE-RL 2010). Smaller pockets of ^{60}Co, ^{137}Cs, uranium, and plutonium were also found. Except where one reverse well discharged waste directly into the groundwater, most contaminants now in the groundwater once passed through the DVZ. Both mobile contamination and more sediment-retained metals, radionuclides, and hazardous chemicals remain in the vadose zone, serving as potential future groundwater contaminant sources.

The Hanford Site is reported to contain as much as 28,300 m^3 (1 million ft^3) of contaminated soil released near reprocessing plants (Gee et al. 2007).

Kincaid et al. (2006) and Corbin et al. (2005) provided an inventory of potential radioactive contaminants released to the ground as a function of time and the location of waste releases. These now form overlapping contaminant plumes, some confined to the vadose zone and others stretching into the groundwater aquifer. Results from this soil inventory model form a basis for identifying the key radionuclides listed in Table A.2.

As of 2009, nearly 550,000 curies of radioactivity exist in Hanford Site soil and groundwater. These range from mobile and short-lived tritium to effectively immobilized ^{137}Cs, ^{241}Am, and plutonium. A significant fraction of these radionuclides likely remains in the vadose zone.

Table A.2. General Inventory Estimates for Select Radionuclides Released into the Central Plateau Subsurface. Numbers are approximated and rounded from Corbin et al. (2005), Kincaid et al. (2006), and best estimate inventory values. Inventories are in curies except for right column.

Radionuclides	Discharges to Soil	Tank Leaks to Soil*	Total (Curies)	Total (Kg)
Tritium	180,000	-	180,000	0.02
^{137}Cs	75,000	150,000	225,000	2.5
^{90}Sr	38,000	14,000	52,000	0.4
^{99}Tc	600	100	700	40
^{129}I	4.6	0.1	4.7	25
^{241}Am	28,700	-	28,700	8.4
U (total)	270	15	285	205,000
^{237}Np	55	-	55	80
$^{-239}$Pu, $^{-240}$Pu, $^{-241}$Pu	52,000	-	52,000	205

* Column includes waste leaks from tanks, overflow events, underground pipes, and other support infrastructure.

Table A.3 summarizes the general inventory of nonradioactive metals and chemicals released into the subsurface from waste sites and tank leaks in the Central Plateau. The total amount is approximately 150 million kg (150,000 metric tons), mostly from waste discharged into liquid waste sites such as cribs and trenches.

The primary contaminants of concern at the Hanford Site driving long-term risk are ^{99}Tc and uranium (DOE-RL 2008b). Reasons include their potential biological risk, high inventory in the vadose zone, mobility, difficulty in predicting subsurface behavior, and long-half life. The Hanford Site Inventory Model indicates that 700 curies of ^{99}Tc and over 200,000 kg (225 tons) of uranium were released into the subsurface (see Table A.2). Other potential contaminants of interest include chromium, ^{90}Sr, plutonium, ^{137}Cs, ^{129}I, carbon tetrachloride, and tritium.

In the Central Plateau, there are several locations where leaked tank waste has mixed with contaminants released from cribs, trenches, etc. This is particularly evident near the B-BX-BY, T, and S-SX tank farms (Triplett et al. 2010). Other vadose zone challenges include remediation of laterally extensive plumes of mobile contaminants such as technetium in the BC cribs area plus deep contaminant plumes underlying large-volume disposal sites that have already contaminated the underlying groundwater.

Table A.3. General Inventory Estimates for Select Metals and Hazardous Chemicals Released into the Central Plateau Subsurface. Numbers approximated and rounded from best estimate inventory values developed by Intera using the Site Inventory Model (SIM) data for 2005.

Chemical or Metal Released into Subsurface	Liquid Waste Release Sites (Kg)	Tank Leaks* (Kg)
Nitrate + Nitrite	9.8E+07	2.5E+05
Sodium	4.1E+07	2.0E+05
Chloride	4.0E+06	5.1E+03
Phosphate	3.6E+06	7.8E+03
Carbon tetrachloride	9.2E+05	0
Tributyl Phosphate	7.4E+05	0
Chromium	3.1E+05	2.0E+03
Lead	8.1E+04	1.0E+02
Iron	3.8E+05	4.6E+02
Bismuth	5.3 E+04	5.0E+01

* Column includes waste leaks from tanks, overflow events, underground pipes, and other support infrastructure.

Co-contaminants, such as organic chemicals and non-radioactive metals, are considered in evaluating remediation technologies because they may impact remediation effectiveness and human/environmental health.

A.2.3 Vadose Zone Waste Site Groupings

DOE and its regulatory agencies, the Washington State Department of Ecology and the U.S. Environmental Protection Agency (the Tri-Party Agencies), have created a single *Comprehensive Environmental Response, Compensation, and Liability Act* (CERCLA) operable unit, entitled 200-DV-1, encompassing the previous 50 DVZ sites originally organized around process-based operable units. One operable unit creates a single focused project to support more integrated, consistent, and streamlined investigations, remedial selections, and remediation actions.

The current structure of 23 operable units in the Central Plateau was designed for the purpose of completing the initial characterization phase and is based on grouping waste sites similar in nature and waste management history. Some are geographically far apart. Such multiple, independent remediation decision units can create redundancy in decision making, causing the same issues to be revisited by multiple decision-makers. This could contribute to treatability testing, remedy selection, and remediation delays plus inconsistencies in risk assessments. To address this problem, the Tri-Party Agencies have realigned operable units within the Inner Area of the Central Plateau (see Section A.1.2.2.1) to support a geographic focus.

Within Operable Unit 200-DV-1, waste sites contributing to DVZ contamination will be prioritized for remedial investigations, feasibility studies, and eventually cleanup.

One of the primary resources used in the past to evaluate the potential contaminant threat to groundwater from pollutants released in the vadose zone of the Central Plateau is written by Eslinger et al. (2006). Researchers used contaminant inventory records, contaminant releases into and out of the vadose zone, and future projected concentrations in groundwater to rank the potential threat posed to the aquifer by both individual waste sites and groups of waste sites.

Based in large part on the analysis by Eslinger et al. (2006) supplemented by site inventories and other information from Corbin et al. (2005) and Kincaid et al. (2006), targeted waste problem sites for the two contaminants of greatest long-term threat at Hanford, technetium-99 and uranium, were identified by DOE-RL (2008b) for the following waste sites:

Technetium-99

- BC cribs and trenches
- BY cribs and vicinity
- T Tank Farm and vicinity
- S/SX Tank Farms and vicinity

Uranium

- B/BX/BY Tank Farms (e.g., BX-102 Tank)
- U Cribs (e.g., 216-U-8 Crib)
- U Tank Farm
- B Plant Cribs (e.g., 216-B-12)
- PUREX Plant cribs and trenches (e.g., 216-A-4 Crib)

The remediation of Hanford’s DVZ will focus upon identifying waste sites of highest priority. The above two lists are examples from past work. Future remedial investigation and feasibility study efforts (see Sections 5.0 and 6.0) covering these and/or other sites will include 1) collecting characterization data, 2) developing conceptual models describing the natural processes controlling contaminant fate and transport, 3) delineating the nature and extent of subsurface contamination, 4) performing predictive modeling of contaminant behavior, and 5) assessing the potential impact of applied remedies. Knowledge and capability gaps will be identified and addressed.

A.2.4 CERCLA RI/FS Process

CERCLA, commonly known as Superfund, is the primary federal law designed to identify and clean up abandoned hazardous waste sites. On the other hand, the Resource Conservation and Recovery Act (RCRA) is the principal law regulating ongoing operations involving the generation, transport, treatment, storage, and disposal of hazardous waste. Amendments to RCRA enable the U.S. Environmental Protection Agency to address environmental problems that could result from underground tanks storing hazardous substances. RCRA’s corrective action provisions are designed to investigate and guide the cleanup of contaminated air, groundwater, surface water, or soil from hazardous waste releases as a result of past and present activities at RCRA-regulated facilities.

As noted in Section A.2.3, DOE’s intent is to work with the regulators to implement a streamlined approach to integrate RCRA and CERCLA authorities covering the Central Plateau to not only address

CERCLA sites but also RCRA past-practice sites and tank farm corrective actions. A consolidated decision structure, combining the existing 23 process-based CERCLA Operable Unit groupings into fewer and more geographically focused decision groupings is envisioned to encompass the entire Central Plateau subsurface.

The *Hanford Federal Facility Agreement and Consent Order* (Tri-Party Agreement) identifies a subset of waste sites in the Central Plateau as “RCRA past-practice” sites. The Tri-Party Agreement establishes the expectation that either a RCRA corrective action or a CERCLA cleanup will lead to an equivalent remedy. Though RCRA authority does not extend to radionuclides, Hanford Site radionuclide cleanup in RCRA waste sites will be protective and consistent with CERCLA practices.

For CERCLA-designated waste sites, a remedial investigation (RI) and feasibility study (FS) process will be conducted for those sites posing unacceptable present or future risks.

The primary purpose of RIs is twofold: site characterization and treatability studies. The following actions are conducted under site characterization:

- Conduct field studies
- Define the nature and extent of contamination
- Identify initial cleanup goals
- Develop baseline risk assessments
- Refine remedial action objectives.

Treatability studies, as detailed in the DVZ test plan for the Hanford Site Central Plateau (DOE-RL 2008), provide invaluable site-specific data required to support remedial actions. These studies provide:

- Aid in remedy *selection*, and
- Aid in selected remedy *implementation*.

Treatability studies conducted during an RI/FS study indicate whether a given technology can meet cleanup goals and provide critical information to aid in remedy selection. Treatability studies conducted during later remedial design/remedial action establish the design and operating basis to optimize technology performance and implement a sound, cost-effective remedy.

Treatability comparisons involve literature surveys, research, and bench-scale, pilot-scale, and/or field-scale tests. In the absence of data from available literature, treatability studies can provide critical performance and cost information needed to evaluate and select treatment alternatives. The purpose of a treatability investigation performed before a record of decision is to provide the data needed for analyzing remedial alternatives during the feasibility study. Nine evaluation criteria are normally considered in the assessment of remedial alternatives:

- Overall protection of human health and environment
- Compliance with Applicable or Relevant and Appropriate Requirements (ARARs)
- Long-term effectiveness and permanence
- Reduction of toxicity, mobility, or volume through treatment

- Short-term effectiveness
- Implementability
- Cost
- Regulatory acceptance
- Community acceptance.

Treatability studies provide data to address the first seven of these nine criteria.

The purpose of an FS is to identify remedial alternatives best tailored to site characteristics and contamination problems. This is accomplished by identifying potential treatment technologies, screening/comparing technologies, assembling the best technologies into remedial alternatives, and identifying action-specific ARARs. Criteria for remedial alternative comparisons include the following:

- Effectiveness
  - Protect human health and environment
  - Attain applicable ARARs
  - Reduce toxicity, mobility, or volume of contaminant.
- Implementability
  - Technically feasible
  - Reliable
  - Able to monitor, maintain, and replace technologies over time.
- Construction, operation, and maintenance costs.

New, innovative capabilities are required if they are potentially more effective, demonstrate fewer adverse impacts, are less expensive to conduct, and/or can expedite remediation. Of course, new capabilities are essential if existing capabilities are inadequate to achieve cleanup goals.

One of the primary questions facing Hanford and other DOE complex-wide sites undergoing remediation is how well suited our remediation policies and regulatory systems are when they must deal with emerging and novel technologies when performance outcomes and environmental consequences are not well identified nor agreed upon by key decision-making partners. For example, regulations exist to guide assessing remedial treatments and enhanced monitoring approaches when cleanup capabilities are limited. However, regulations are unclear as to the assessment process needed to secure such alternative decisions.

A.3 Defense-in-Depth Approach for Remediation of the Central Plateau

> “It is time to create a ‘learning culture’…to constantly evolve new, applicable, and efficient management policies and technologies that lead to even more environmentally sound cleanup…We must do well all that we know how to do, and we must persist in seeking answers for the questions

> that remain… that which is unknown must be acknowledged so that our research and development energies might be clearly focused and wisely applied.” (Hanford Future Site Uses Working Group 1992)

This section addresses DOE’s defense-in-depth approach to make sure that remediation is protective of the underlying groundwater aquifer and ultimately the Columbia River. A cornerstone principle of this strategy is applying existing knowledge and technology where it works and creating new knowledge/capabilities where opportunities exist to more effectively clean up contaminants, reduce costs, accelerate schedules, and/or minimize risks.

As summarized in Triplett et al. (2010), the objectives of DOE’s strategy to solve the DVZ problems faced include:

- Develop a sufficient and workable understanding of DVZ properties and processes affecting contaminant fate and transport.
- Improve predictive capabilities of contaminant fate and transport under both natural and remediation conditions.
- Develop, test, and deploy effective alternative remediation techniques.
- Develop and deploy effective monitoring methods for assessing remediation performance, long-term contamination behavior, and potential threat to groundwater. After all, long-term monitoring provides the information backbone to convincingly demonstrate system performance

This defense-in-depth approach will implement multiple strategies to understand, predict, control, and monitor contaminant flux both within the DVZ and its potential movement to the underlying groundwater. Why are multiple approaches needed? It is unlikely that any single remediation technology will solve Hanford’s deep vadose contamination problems. A collection of innovative approaches, tailored to site and contaminant conditions, is needed. These approaches require targeted investments in innovative science and technology solutions.

As noted in Pierce et al. (2009), the most effective research program supporting site remediation is one that “successfully links basic science knowledge to real-world schedules and challenges.”

Close collaboration is required between the applied engineering, technology development, and science programs to translate scientific and advanced treatability findings into improved models of migration and swiftly use new capabilities to meet the DVZ remediation program goals. This program will maintain an active interface with other programs supporting the Hanford Site cleanup baseline.

As previously depicted in Figure A.29, this defense-in-depth approach will include studies across the spatial and time scales required to investigate and represent processes relevant to DVZ applications. This includes molecular scale functions taking place at solid/liquid interfaces through small-and large-field scale investigations covering cubic meters to cubic kilometers investigated by borehole tests, waste site remediation, and watershed size modeling.

A.3.1 Defense-In-Depth Concept

Groundwater treatment, relying upon years of water pumping, can eventually remove non-absorbed contaminants from a permeable aquifer. However, if mobile contaminants remain in the overlying vadose zone, recontamination can occur.

Groundwater pumping and treating is a long-term commitment to hydraulically control the spread of contamination plumes and recover some contamination as more effective treatment options are developed and deployed. Section A.1.3 summarizes examples of interim groundwater pump-and-treat activities undertaken at the Hanford Site.

As documented for Superfund cleanup sites across the nation, the commonly used capability of groundwater pump-and-treat rarely provides a solution to groundwater cleanup (GAO 2000). A DOE Inspector General's audit of Hanford Site cleanup efforts stated that the pump-and-treat systems installed for groundwater cleanup were "largely ineffective" (DOE 2004).

This is why the Hanford Site's subsurface cleanup program is linking basic and applied science to create innovative remediation schemes that not only address groundwater contamination, but also the more challenging task of DVZ cleanup.

One onsite example of this linkage was the replacement of groundwater pump-and-treat activities with the use of a permeable apatite sequestration barrier below the water table for underground sorption of ^{90}Sr in the 100-N Area.

Another example, now in the laboratory test phase, involves injecting polyphosphate underground to stabilize a soluble uranium plume at the Integrated Field Research Challenge located within the 300 Area. This work links science through bench-and field-scale tests with coupled hydrologic, geochemical, and microbiological characterization/modeling to address such challenges as quantifying the rates of U(IV) immobilization via the formation of uranium-polyphosphate phases, establishing the identify of uranium-phosphate phases formed (and therefore the long-term stability of uranium), and evaluating the optimum infiltrate rate for polyphosphate stabilization.

Such science-field scale collaborations are essential to remediation success. For example, before the Integrated Field Research Challenge noted above was initiated in the 300 Area, uranium-contaminated sediment was removed from near the surface with the expectation that the underlying groundwater plume would meet water quality standards within 10 years (NRC 2009). That did not happen because of incomplete site characterization of the uranium source zone, lack of understanding the controlling subsurface geochemical interactions taking place, and the absence of a suitable source cleanup remedy.

New technologies and innovative ideas must be tested and the most promising methods applied. However, no single technology is expected to solve all contamination problems in the DVZ. Effective long-term remediation and protection will rely upon coupled chemical, physical, and biological approaches tailored to the contaminant problems and geohydrologic settings faced. This overcomes the shortcomings in individual methodologies. For example, potential promising hybrid approaches may include the following (Dresel et al. In press):

- Chemical reduction of contaminants followed by geochemical manipulation to sequester the reduced species as precipitated mineral coatings such as carbonate minerals or iron oxides. This would inhibit contaminant reoxidation.
- Gaseous reduction to fix contaminants in place followed by liquid treatment for permanent sequestration. This reduces contaminant mobilization at the liquid front.
- Stimulate aerobic biological activity to develop biomass, and then induce anaerobic conditions for bioreduction of contaminants.
- Coupled abiotic and/or biotic processes such as bioremediation of co-contaminants (e.g., nitrate) for enhanced reduction of metals and radionuclides.
- Apply advanced geophysical techniques to monitor remedy emplacement and performance in conjunction with microbial community profiles to monitor the long-term remediation performance and contaminant plume behavior.

A.3.2 Components of Defense-in-Depth Approach

Implementing a defense-in-depth approach to remediation requires a sufficient technical basis to understand and reasonably predict contaminant movement, quantify the impact of remedial actions, develop workable monitoring strategies, and demonstrate that a given remediation strategy, or linked set of actions, best protects the subsurface. A closely coordinated, collaborative, and engaged science through applied engineering expertise from the DOE Office of Environmental Management, DOE SC, Hanford Site contractors, national laboratories, and others are required to verify that the right knowledge and capabilities are available when needed.

DOE’s defense-in-depth approach to remediation of the DVZ will be framed around the following components:

- Start by using **best available knowledge and capabilities** gained from the Hanford Site and other cleanup site experiences.
- Invest in problems targeted **treatability tests** to evaluate approaches to remediate DVZ contamination.
- Sustain investments in **advanced scientific knowledge and technology solutions** to address DVZ challenges hindering characterization, predictive modeling, remediation, and monitoring.
- Focus the nation’s **science infrastructure** (instruments, laboratories, staff, and resources) on critical cleanup problems.
- Assess the key **geochemical and biogeochemical processes** controlling key contaminants (e.g., technetium and uranium) behavior.
- Sustain integrated **laboratory and intermediate-scale testing** to advance the most promising remediation approaches to field-scale evaluation by **bridging-the-gap** between fundamental research and needs-driven technology development.
- Implement **surface remedies**, coupled as needed with subsurface remedial actions, to mitigate the impacts of DVZ contamination.

- **Combine treatment approaches** to overcome limitations of individual techniques.
- Integrate **groundwater and vadose zone monitoring** to provide an early warning of any significant contaminant movement or impact to groundwater.
- Deploy **groundwater treatment systems** that can expand or be redesigned to address emerging plumes if necessary.
- Revisit **effectiveness of remedies** and possible changes in environmental conditions resulting from natural or anthropomorphic induced changes.

Broadly, this defense-in-depth concept for the DVZ is illustrated in Figure A.30.

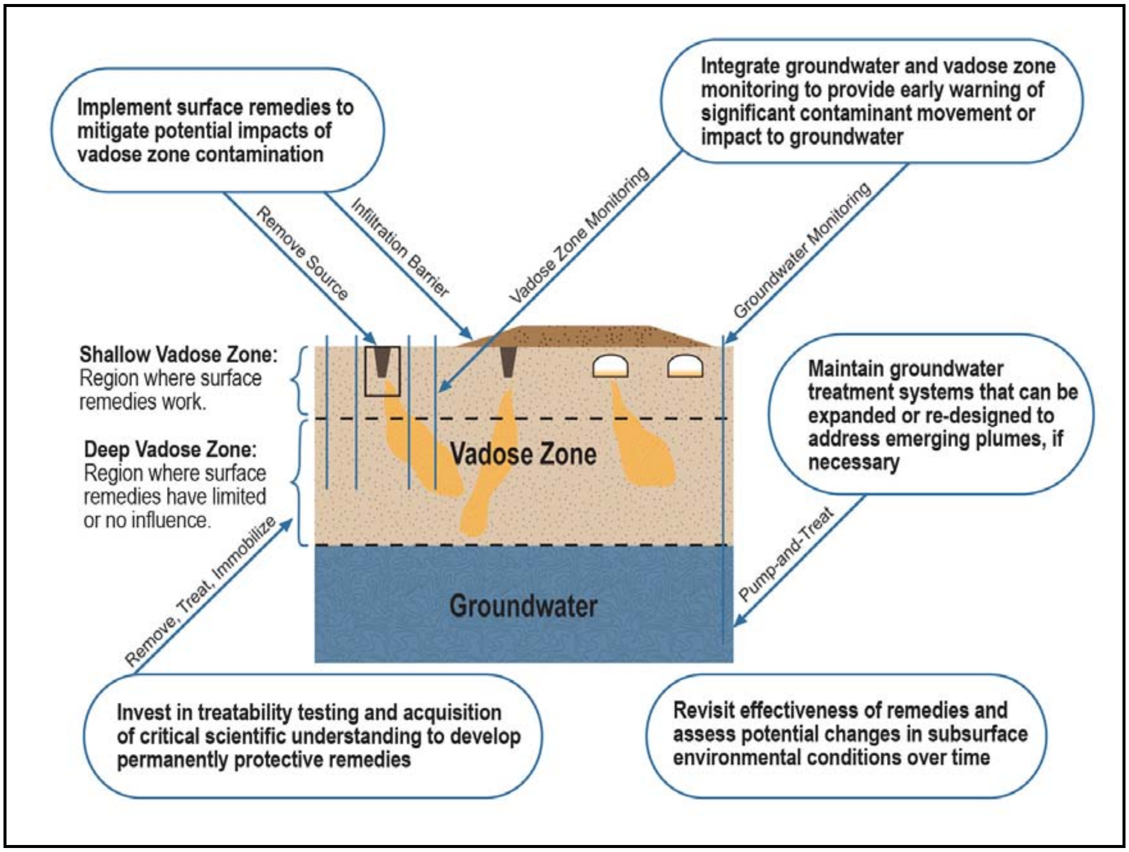


Figure A.30. Defense-in-Depth Strategy for the DVZ

The Central Plateau remediation schedule is dependent upon many future events, including targeted cleanup levels, resources available, effectiveness of existing and new remediation technologies, outcomes of treatability studies, contaminant inventories faced, vadose zone complexities encountered, closure of critical knowledge/capability gaps, and tank closure schedules.

At the completion of Central Plateau remediation activities, some DVZ contamination will remain. There is a regulatory basis for leaving contamination in the vadose zone, provided its downward flux is limited and will not cause groundwater concentrations to exceed drinking water standards or other concentration guidelines.

Inclusion of an integrated monitoring approach within DOE's defense-in-depth strategy is designed to provide early warning of any significant or unexpected contaminant movement impacting groundwater quality. This is a necessary element of long-term institutional controls and confirming model predictions and remediation effectiveness.

Nonetheless, achieving just this monitoring goal will be challenging because monitoring strategies must move from adapting standard down-gradient detection well networks, which have limited applicability in DVZ environments, to new approaches tailored at deciphering contaminant behavior within a partially saturated environment before pollutants reach the water table in unacceptable quantities. It is relatively straightforward to demonstrate a decline in vadose zone mass flux through a decline in existing groundwater contaminant levels. However, it is difficult to monitor the vadose zone itself and demonstrate that groundwater will remain uncontaminated over the long term.

A.3.3 Outcomes Needed to Support Defense-in-Depth Approach

As summarized in Sections 1.0 and 2.0, most of the Hanford Site's remaining subsurface contaminants reside in the vadose zone beneath the Central Plateau. Though years have passed since the Hanford Site ceased disposing large volumes of liquids and spent fuel reprocessing wastes in and around the 200 Area, contaminants now in the vadose zone will continue acting as waste sources for centuries to come.

Cleanup, or at least mitigating future contaminant entry into the underlying aquifer, will be a challenging task because significant gaps exist in the knowledge and capabilities required to understand, predict, control, and monitor this contamination (see Section 4.0). The National Research Council underscored this challenge when they wrote:

> "DOE, its regulators, and the public face some hard truths about Hanford Site cleanup; the knowledge and technology to address the most difficult problems at the site do not yet exist. Consequently, much of the waste and contamination that is now in the subsurface, especially in the 200 Area, will very likely remain there for the foreseeable future. In addition, completion of Hanford cleanup could add substantially to this contamination, for example, during retrieval of tank waste. Currently, the range of available end-state, cleanup, containment, and monitoring options is greatly limited because of these knowledge and technology gaps." (NRC 2001)

The primary outcome of the defense-in-depth approach is to make sure that the scientific knowledge and technical capabilities exist to address DVZ problems. Actions supporting DOE's defense-in-depth cleanup strategy include the following:

- Cross-match program goals with existing knowledge and capabilities to identify gaps
- Provide a new technical and scientific basis to address DVZ contamination where existing capabilities and knowledge fall short
- Integrate basic research with applied science through field-scale engineering activities to test and mature remediation approaches
- Focus research upon the most intractable cleanup problems and those providing the greatest benefit

- Use a portfolio of restoration approaches tailored to provide the most effective and efficient cleanup strategies
- Link research and innovative treatability activities to the Hanford Site's subsurface remediation program baseline
- Leverage knowledge, capabilities, and funding sources across multiple subsurface cleanup programs.

A.3.4 Science and Technology Insertion into Program Baseline

As noted in Dresel et al. (2010, In press), "transformation of basic science principles into viable remedial strategies and transfer of remediation technologies from groundwater, shallow vadose zone, or waste treatment applications to the DVZ generally will require significant adaptation and demonstration."

DOE's defense-in-depth approach emphasized in Section A.1.3 is designed to provide an integrated approach to bring new understanding and technologies to Hanford Site subsurface remediation activities. This will be accomplished by integrating the DVZ project into the site's subsurface program baseline and solving targeted problems hindering remediation progress. The roles and responsibilities of discovery research through applied technology deployment are summarized in Figure A.31 and discussed in detail in Section 5.0 of this program plan. The proposed insertion points for science and technology into the program baseline are covered in Section 6.0.

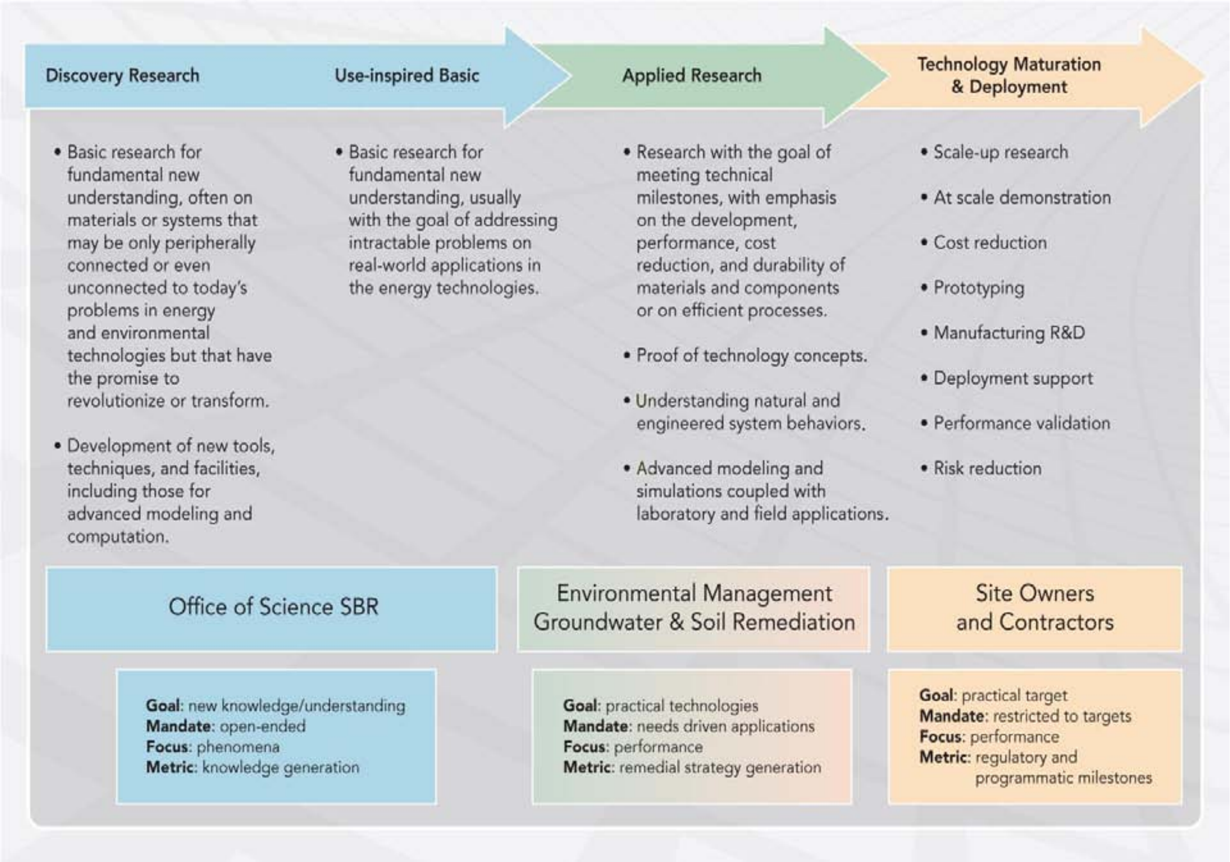
One of the most important and visible metrics of how well integration and new technology development are progressing centers upon the number, complexity, and variety of intermediate field-scale demonstrations that are in progress. Deploying new capabilities requires field-scale testing prior to deployment. However, historically the testing of promising new capabilities is commonly neglected, therefore weakening the ability to create new solutions that may out perform existing baseline approaches.

Pierce et al. (2009) identified five crosscutting themes central for integrated strategic planning. Those themes are as follows:

- **Understand and overcome heterogeneity:** Develop the research tools, discovery techniques, and basic scientific understanding for improving existing approaches and capabilities used to decipher subsurface properties controlling contaminant fate and transport with sufficient spatial coverage and resolution to constrain models predictions.
- **Identify, understand, and evaluate the key biogeochemical and hydrodynamic controls on contaminant behavior under varying conditions:** Integrate and translate biogeochemical and hydrodynamic research findings into usable forms to advance the technical foundation supporting remediation decisions and actions.
- **Apply predictive models to understand contaminant behavior and support effective and sustainable remediation approaches:** Develop robust computational models and refined hydrodynamic and biogeochemical input to verify the credibility of contaminant fate and transport predictions across spatial and time scales of importance to decision making.

- **Develop new approaches for sustainable remediation:** Scale potential remedial approaches from the laboratory to the field and develop new remediation approaches to remove, stabilize, and/or immobilize contaminants.

- **Monitor remediation performance over stewardship time frames:** Develop novel, more efficient multiscale approaches to monitor subsurface processes, test output of predictive models, and verify long-term performance of remediation actions/systems.



- Basic research for fundamental new understanding, often on materials or systems that may be only peripherally connected or even unconnected to today's problems in energy and environmental technologies but that have the promise to revolutionize or transform.
- Development of new tools, techniques, and facilities, including those for advanced modeling and computation.

- Basic research for fundamental new understanding, usually with the goal of addressing intractable problems on real-world applications in the energy technologies.

- Research with the goal of meeting technical milestones, with emphasis on the development, performance, cost reduction, and durability of materials and components or on efficient processes.
- Proof of technology concepts.
- Understanding natural and engineered system behaviors.
- Advanced modeling and simulations coupled with laboratory and field applications.

- Scale-up research
- At scale demonstration
- Cost reduction
- Prototyping
- Manufacturing R&D
- Deployment support
- Performance validation
- Risk reduction

Office of Science SBR

Goal: new knowledge/understanding
Mandate: open-ended
Focus: phenomena
Metric: knowledge generation

Environmental Management Groundwater & Soil Remediation

Goal: practical technologies
Mandate: needs driven applications
Focus: performance
Metric: remedial strategy generation

Site Owners and Contractors

Goal: practical target
Mandate: restricted to targets
Focus: performance
Metric: regulatory and programmatic milestones

Figure A.31. Linkage of Use-Inspired Basic Research and Applied Science to Support Technology Deployment.

These findings cover several of the same knowledge and capability gaps identied in previous years by the National Research Council and others as summarized in Section A.2.1.

In a report describing the status of remedation capabilities for metals and radionuclides found within the DVZ, Dresel et al. (2008) provided suggested priorities for research and development investments plus considerations for technology selection and implementation. Example suggestions included:

- Use a balanced investment portfolio when developing remediation capabilities at different stages of maturity. For example, near-term payoffs are possible with modifying existing technologies whereas novel methods contain greater risk but may overcome, with time, hurdles hindering existing methods.

- Target scale limitations when comparing technologies.

- Consider remediating a mixture of dispersed and concentrated contamination problems.
- Consider hybrid remediation combinations to overcome shortcomings of individual techniques. For example, reduction of uranium or technetium followed by geochemical manipulation to sequester contaminant species as a precipitated mineral coating, or perhaps gaseous reduction to fix contaminants in place followed by liquid treatment for permanent sequestration while avoiding contaminant remobilization.
- Create stable sequestered contaminants. Transformation kinetics must be slow enough to provide longevity to control contaminant flux from the treated subsurface zone.
- Compare rates of different remedial reactions to make sure of their practical use.
- Evaluate the potential for remobilization of contaminants left in place after active remediation completed. For example, uranium and technetium are subject to reoxidation while hexavalent chromium tends to remain reduced.
- Research effective protection depth of surface barriers to understand how their use might be combined with *in situ* remediation technologies.
- Appraise use of novel gas phase or foam-based subsurface delivery of reactants, nutrients, or nanoparticles to contaminated area of interest.

DOE Office of Science—Scientific Focus Area

The DOE SC, through their SFA research, supports DOE’s cleanup mission and long-term stewardship responsibilities by providing new insights into the behavior of contaminants. Insights derived from micro-scale studies or laboratory tests ultimately require validation in natural materials and at the field scale. This is critical to assessing the accuracy of conceptual and computational models of subsurface contaminant transport

Presently, DOE SC funds the Pacific Northwest National Laboratory (PNNL) SFA to resolve critical onsite basic subsurface science issues through an integrated, multi-disciplinary research focused on the role of microenvironments and transition zones in the reactive transport of technetium, uranium, and plutonium (PNNL 2010). It has been documented onsite that microenvironments and the transition zone can dominate subsurface reaction activity, often disproportionate to their mass, by coupling chemical reaction, physical transport (advection and diffusion), and microbiologic processes.

Microenvironments are small subsurface domains (submicron to multi-meter scale size) that significantly influence the water chemistry of larger scale vadose or aquifer zones because of microbial, geochemical, and/or hydro-physical processes occurring at dissimilar or accelerated rates compared to the surrounding sediment matrix. Examples include internal fractures or microbiologic niches within porous media, grain coatings, bio-films, or micro-colonies on larger mineral particles. Even compact silt/clay stringers sandwiched within more gravel-dominated subsurface sediments can create highly reactive microenvironments (Triplett et al. 2010).

Transition zones are field-scale features where chemical, physical, or microbiologic properties change dramatically over short distances such as less than 1 m (3 ft). For example, silt-textured stringers containing micas with high-cation exchange capacity and water retention properties are common features of Hanford Site subsurface sediments.

Microenvironments and transition zones frequently dominate subsurface contaminant reactivity. DOE-sponsored research under the Environmental Management Sciences Program (EMSP) and the Natural and Accelerated Bioremediation Research (NABIR) Program documented the importance of these zones beneath the Hanford Site. Example publications include Zachara et al. (2007a) and McKinley et al. (2007).

DOE SC also funds field research at three field sites across the nuclear weapons complex, including at the Hanford Site 300 Area. These studies are part of DOE's Integrated Field-Scale Subsurface Research Challenge. The IFRC in the 300 Area is a new program that commits multi-investigator teams to perform large, benchmark-type experiments on formidable field-scale science issues (PNNL 2010a). The field site provides capabilities to collect and ship environmental samples of different types to other program investigators and provides site access to researchers interested in testing specific concepts or capabilities relevant to the study of subsurface contaminant fate and transport. A similar concept to this has been proposed by DOE EM-32 (Groundwater and Soil Remediation) for the DVZ in Hanford's Central Plateau. The subject of research into the mobility of uranium and technetium underlying the 300 Area is summarized in Section A.1.4.8.

DOE Office of Environmental Management—Groundwater and Soil Remediation

DOE's Office of Groundwater and Soil Remediation (EM-32) has initiated efforts to develop advanced remedial methods for metals and radionuclides in the vadose zone at DOE sites. EM-32 is seeking to create transformational technologies (i.e., capabilities significantly better than available baseline technologies) and innovative strategies to meet DOE's commitments, remedial action objectives, and long-term stewardship goals. These efforts target advancing our understanding of fundamental controlling processes, described through SC research, to provide remediation solutions that complement the Hanford Site DVZ science and technology development activities (Triplett et al.2010).

One such advanced strategy is to transform foam technology into a viable method for potentially delivering remedial amendments to targeted DVZ environments. In contrast to saturated flow found in a groundwater aquifer, foam flow under vadose zone conditions is not dominated by gravity and therefore can be directed by pressure gradients in the sediments. The use of foam may also reduce the volume of fluid (typically < 20% vol.) required for remedial delivery, thereby reducing the potential for unintended contaminant mobilization.

Nonetheless, the inability to characterize the controlling contaminant migration properties and induced remediation processes at a high enough spatial resolution and across large enough spatial scales using conventional monitoring technologies prohibits a reasonable assessment of the effectiveness for foam-based delivery. Therefore, DOE is advancing the application of radar and complex resistivity methods to address this challenge.

Radar methods are expected to provide information about the dielectric constant, which is sensitive to soil moisture and may also respond to the subsurface placement of reactive foam. Advances in using electrical conductivity are expected to prove useful for monitoring the change in saturation and total dissolved solids associated with a reactive foam.

In addition, EM-32 is funding the development of microbial community profiles as a long-term monitoring technique to assess the effectiveness of remedial treatment and reaction of community dynamics. This profiling can be performed rapidly both at the point source and at downstream gradients where microbial community changes may occur in advance of measurable geochemical metrics. Such microbial profiles might provide an "early warning" of possible changes in contaminant plume behavior or remediation effectiveness.

EM-32 also prepared integrated research remediation strategies for addressing key problems within the DOE complex (Pierce et al.2009). These approaches provide examples of how to more effectively link basic and applied research activities with DOE site field remediation projects. A specific example was prepared for the BC cribs and trenches at the Hanford Site. DOE's current DVZ planning effort will build upon this model.

In a review of DOE's cleanup technology roadmap, the National Academy of Sciences predicted that as DOE addresses more difficult remediation challenges, they will need increased scientific investments into better understanding the release, fate, and transport of subsurface contaminants (NRC 2009). Hanford's vadose zone is one of these problems.

In response to the Academies recommendations, DOE formed the ASCEM project in 2009. ASCEM is overseen by DOE's Office of Groundwater and Soil Remediation (EM-32). ASCEM's mission is to develop transformational, high-performance computer modeling capabilities to improve scientists' ability to predict the fate and movements of underground contaminants and the degradation of engineered materials that contribute to contaminant release.

ASCEM's advances will include the creation of next-generation performance assessment capabilities, vastly improving upon today's predictive capabilities. This will enable more realistic modeling of key processes controlling contaminant behavior and account for the underlying uncertainty in modeling predictions.

Benefiting from this advanced capability places a significant burden upon making certain that waste sites and the processes controlling contaminant movement are adequately characterized. As stressed by the U.S. General Accounting Office (GAO 1998) in its assessment of decision-making supporting subsurface remediation, "reliable computer models of groundwater contamination cannot be developed without reliable data on the transport of contaminants within the vadose zone."

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Appendix B

Knowledge and Capability Needs Identified During the Deep Vadose Zone Technical Forum Held July 20-21, 2010

Contributions from

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Susan Hubbard	Lawrence Berkeley National Laboratory
Mark Rockhold	Pacific Northwest National Laboratory
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Appendix B

Knowledge and Capability Needs Identified During the Deep Vadose Zone Technical Forum Held July 20-21, 2010

Contents of Appendix B

Approximately 80 participants attended the Deep Vadose Zone (DVZ) Forum held in Richland, Washington, on July 20-21, 2010. Attendees included, but was not limited to, the public, interest groups, the Hanford Advisory Board, state agencies, DOE, representatives from Tribal Nations, Hanford contractors, national laboratories, universities, and the regulatory community. The purpose for organizing the Forum was to accomplish the following objectives:

- Introduce U.S. Department of Energy's (DOE's) increased emphasis upon remediation of the DVZ beneath the Hanford Site's Central Plateau.
- Discuss vadose zone concepts to a broad range of participants attending the Technical Forum.
- Have Technical Forum participants identify the challenges they believe will be faced to characterize, monitor, model, access, and remediate the DVZ and then capture those needs in the new DVZ Program Plan.
- Emphasize the importance of new science and technology investments, including laboratory through field-scale testing, to resolve critical remediation challenges.

This appendix contains the knowledge and capability needs identified by participants. These needs were captured by the Chairs and Co-chairs of three breakout sessions around which the Technical Forum was organized. These sessions, followed by brief explanations, were entitled as follows:

- **Characterization and Monitoring (Section B.1)**: Characterize the physical, chemical, and biologic properties controlling contaminant fate and transport. Monitor subsurface behavior, contaminant movement, and remediation performance.
- **Subsurface Processes and Predictive Modeling (Section B.2)**: Simulate controlling subsurface processes plus model moisture flux, contaminant movement, and remediation performance.
- **Subsurface Access and Remediation (Section B.3)**: Access the subsurface to characterize, perform cleanup, monitor, etc. Carry out surface and subsurface actions to remediate DVZ contamination.

The major sections of this appendix follow these three topics. The writing style for each section and how ideas were captured are slightly different, reflecting the topics covered, the nature of participant discussions, and the writing style of each Chair/Co-Chair team. Some topics, such as subsurface characterization and information management, were addressed in more than one breakout session.

A summary of this appendix is captured in Section 4.0 of this DVZ Program Plan.

The organizers of the Technical Forum appreciate the expertise and dedication of the following individuals who served as the Chairs and Co-Chairs for the breakout sessions:

- **Characterization and Monitoring Breakout Session**: **Susan Hubbard** (Chair), Lawrence Berkeley National Laboratory; and **Carol Eddy-Dilek** (Co-Chair), Savannah River National Laboratory
- **Subsurface Processes and Predictive Modeling Breakout Session**: **Carl Steefel** (Chair), Lawrence Berkeley National Laboratory; and **Mark Rockhold** (Co-Chair), Pacific Northwest National Laboratory
- **Subsurface Access and Remediation Breakout Session**: **Joe Rossabi** (Chair), Redox-Tech; and **Dawn Wellman** (Co-Chair), Pacific Northwest National Laboratory.

After participants identified DVZ challenges and the chairs of each break session summarized the feedback of their groups before all participants, an anonymous and informal “resource” allocation exercise was conducted to gain audience views about potential investments targeting the highest priority DVZ needs. That exercise and its results are captured in Appendix E.

B.1 Vadose Zone Characterization and Monitoring

Foreword

Characterizing subsurface properties and monitoring processes that govern contaminant plume distribution, attenuation capacity, and remediation efficacy in the DVZ are challenging tasks. The challenge arises because of multiple factors, including the large spatial variability of contaminant controlling hydrological-geochemical-microbiological processes, the coupled nature of many of those processes, and the difficulty and cost of accessing the DVZ. Beneath the Hanford Site’s Central Plateau, the vadose zone extends about 50 to 100 m (150 to 330 ft) below ground level.

Although significant advances have been realized in the last decade in developing technologies and approaches to characterize subsurface systems, the majority of this effort has focused on characterizing individual hydrological, geochemical, and microbiological components in fully saturated (aquifer) systems.

Characterization strategies need to be developed that aim at quantifying not only key vadose zone properties, but also their interactions and control on contaminant mobility and remediation efficacy in the vadose zone—over field-relevant scales in a tractable and cost-effective manner.

The Characterization and Monitoring Breakout Group identified the following three topics as high priority needs that could be addressed through the development of a DVZ applied field research site:

1. Living Conceptual Models of a DVZ System
2. Improved Tools and Approaches Applicable to the DVZ
3. Protocols for Best DVZ Characterization Practices

These three topics are related to each other because the conceptual model guides and relies upon the development of new tools and approaches; plus, evaluating these methods at DVZ sites will lead to best characterization practices. The topics are also closely linked with needs identified in the other two breakout groups. Relevant to the “Subsurface Processes and Predictive Modeling” breakout topic, characterization and monitoring are needed to parameterize and validate numerical models and to assist in developing process models. Relevant to the “Subsurface Access and Remediation” breakout session, access is needed to deploy characterization and monitoring tools. Characterization is required to optimize treatment design, and monitoring is essential to assess treatment success. These three high priority needs are described below.

Priority # 1: Living Conceptual Models of a DVZ System

A site conceptual model includes assessing the nature and extent of contamination and identifying the key physical, chemical, and biological parameters/processes that govern contaminant fate and migration in the subsurface. Ideally, site conceptual models are "living" in that they are developed and improved in an iterative manner.

Early conceptualizations, which are often based on a coarse, theoretical understanding and sparse site-specific data, are used to guide subsequent data acquisition and experimentation. Insights from these investigations are used to iteratively refine the conceptual model(s). Breakout session participants ranked this as a key priority to emphasize that there is no single sensor or measurement that will allow us to develop an understanding of the behavior of complex subsurface systems with the confidence needed to parameterize reactive transport models or successfully guide a comprehensive remediation treatment design. Instead, a sustained and iterative approach focused on identifying and reducing the uncertainty of the controlling parameters/processes is needed to understand the behavior of the overall system and responses to remediation treatments.

Three aspects were identified as being critical to establishing and evolving a site conceptual model.

Developing an initial site conceptual model is a first step in this process, and the approach used will be dictated by the amount and type of available information. Historical contaminant release information (verbal and written) as well as current records and data should be analyzed to develop an understanding of plume history and current distribution. Existing well logs and other site-specific information should be evaluated to identify significant geologic and stratigraphic features and to place the system in the context of a larger depositional framework. Theoretical understanding of vadose zone processes and information from analogue sites are expected to be useful in the early interpretation of (typically sparse) field data in terms of controlling properties and features.

The initial conceptual model can be used to identify gaps in data and process understanding. Guided by prioritization of the gaps, the **second step** is maturing the site's conceptual model(s) by undertaking new problem-solving characterization and experimentation performed in an iterative manner to probe and refine this model, with a key goal of identifying the hydrogeological, geochemical, and microbiological components of the vadose zone system and their associated couplings that most influence contaminant behavior.

Many different hydrogeological, geochemical, and microbiological parameters were identified as potentially critical for developing a site conceptual model. For example, efforts in Hanford's Central Plateau suggest that characterizing the three-dimensional architecture of the vadose zone is critical for understanding contaminant distribution: thin, fine-grained layers appear to contribute to substantial horizontal spreading of contaminants, and geological discontinuities (such as breaks in caliche, clastic dikes) may influence lateral and/or vertical transport under certain loading conditions. Moisture and matric potential are recognized as critical controls on contaminant infiltration in an arid environment, as are permeability and its associated anisotropy and spatial correlation.

Subsurface geochemical properties play a significant role on plume mobilization and susceptibility to natural attenuation or remedial treatments. Geochemical characterization objectives might include the following:

- Identification of contaminant speciation and phase
- Distribution and abundance of reactive minerals (including hydrous ferric oxide, clay minerals, and carbonate minerals)

- Identification of type and form of sorption reactions.

Subsurface microorganisms often possess the metabolic capability to degrade or transform contaminants of concern. Through their direct or indirect interactions with each other and the geochemical environment, microorganisms can modify the geochemistry of the contaminated subsurface, rendering the contaminant less mobile or less toxic. As such, critical microbiological characterization objectives for vadose zone investigations might include assessing the following:

- Dynamic makeup, structure, and function of the *in situ* microbial community and its relationship to soil texture and moisture
- Potential for microbial reactivation (with moisture and nutrients)
- Role that vadose zone microbial communities play in contaminant migration and remediation.

Recognizing that contaminant behavior in the vadose zone is governed by a variety of coupled hydrogeological, geochemical, and microbiological properties, which are typically characterized individually and at different scales using different types of measurement approaches, the **third key step** of the site conceptual model priority is to develop strategies that can honor these disparate and key datasets. This might involve developing constructs that enable us to exploit linkages between natural geological depositional units and associated hydrological and geochemical properties during a characterization effort or to exploit the presence of pH or redox gradients in the design of remediation strategies. It also might entail developing approaches that permit the integration of more spatially extensive (yet indirect) geophysical methods with direct (but sparse) borehole measurements to improve vadose zone characterization and modeling. Such integration could take the form of a joint inversion or coupled modeling strategy and rely on petrophysical or pedotransfer functions to relate different types of measurements.

Priority #2: Improved Tools and Approaches Applicable to the DVZ

This priority focuses on the need to develop new tools and approaches to characterize specific vadose zone properties.

This priority builds upon the challenges also identified by the “Subsurface Access and Remediation” breakout session, particularly the challenge of sampling reliably and cost effectively in the DVZ. Participants identified examples that included the need for screening tools to identify gross contaminant distribution, ideally quickly, and over field-relevant scales. Developing approaches for documenting source migration pathways in the vadose zone was identified as a priority, and the use of isotopic ratios and laser approaches for soil gas isotopic analysis were discussed as potentially useful approaches.

Improved pore fluid characterization approaches are needed to provide information about speciation and form of complexes in low moisture environments. Sensors or novel approaches are needed to characterize hydrologic properties in the vadose zone and in 3D, including flux (of moisture, specific contaminants and gas), moisture, permeability, and porosity. Tools such as nuclear magnetic resonance (NMR) and pneumatic cross-hole may partially address these needs. Subsurface tools are needed to quickly and less expensively identify species of particular radioactive contaminants (such as ^{99}Tc and ^{129}I).

Novel approaches or sensors are also needed to enable *in situ* quantification of mineralogy and mechanisms, perhaps using approaches such as Fourier Transform Infrared Spectroscopy (FTIR) and vadose zone reactive gas tracers.

In addition to characterization needs, advanced sensing methodologies are needed to quantify the distribution of injected remediation treatment and induced transformations *in situ* and over field-relevant scales.

FLUTe[1] technologies (flexible borehole liners) were suggested as potentially appropriate for sampling by moisture wicking (or other), sensor emplacement (by forcing direct contact with sediments, direct sensing (e.g., pH reactive strips), or simply maintaining borehole shape and integrity without hard well casing (for logging tools). As a site conceptual model is developed and site-specific controls on contaminant behavior are identified, additional approaches will likely be needed to characterize and monitor those controls over field scales.

Priority #3: Protocols for Best DVZ Characterization Practices

Several practices were identified that would facilitate current as well as future vadose zone investigations. Although many of these concepts are not new, several participants felt that the development of a DVZ-applied research program offered a perfect opportunity to develop and document protocols and standards, and that such an effort would be generally helpful for the DOE complex. Four key aspects of this priority were identified.

The **first aspect** focused on modifying Hanford Site sampling, drilling, and completion standard practices to permit improved characterization of vadose zone properties and processes. Recommendations identified included enabling routine implementation of downhole log suites (including neutron, density) and evaluating alternatives to standard Hanford Site well practices (that use non-stainless-steel casings, which prohibit the use of electrical sensors). With the probability that DVZ monitoring will entail downhole and cross-hole geophysical instrumentation, the concept of using dedicated geophysical holes to permit improved contact of sensors and the geologic formation and reduction of noise was emphasized as important.

A **second aspect** focused on developing standard sampling and implementation protocols for vadose zone characterization approaches and documentation of these approaches. This might include developing a portion of an Applied Field Study site (e.g., in a non-contaminated zone) dedicated to testing and comparing different types of sensors under controlled conditions and documenting best practices associated with the use of methods such as soil gas indicators or geophysical approaches for vadose zone characterization.

A **third aspect** focused on the need to coordinate, leverage, and transfer knowledge, capabilities, and lessons learned from this new DVZ program to other Hanford Site contaminated vadose zone sites, as well as with other key DOE investments at instrumented test sites. Two existing government examples are the Vadose Zone Research Park at the Idaho National Engineering and Environmental Laboratory, and the Integrated Field Research Challenge (IFRC) and Subsurface Scientific Focus Area (SFA) research underway at the 300 Area of the Hanford Site. It was recognized that by doing so, we have an

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[1] Flexible Liner Underground Technologies, LLC.

opportunity to improve our understanding of contaminant mobility and remediation efficacy in a variety of vadose zone environments that could also benefit the DOE complex.

Finally, participants in the breakout session identified a need to develop a centralized, web-accessible data management system that uses a community-accepted protocol for archiving and documenting hydrological, biological, geochemical, geophysical, and other subsurface data relevant to contaminant fate and transport. This issue was also captured in the Subsurface Access and Remediation breakout session.

Building such a data management system would facilitate investigations at a site and comparison between sites as well as linkages between datasets, visualization, and modeling. The system could build on ongoing DOE efforts (e.g., the Advanced Simulation Capability for Environmental Management [ASCEM] and the Hanford Environmental Information System [HEIS]), as well as approaches in development by other communities (e.g., CUAHSI Hydrologic Information System) and could be developed to house both vadose zone and saturated system datasets relevant to the DOE remediation and stewardship missions.

The comings and goings of Hanford Site contractors and personnel over the years presents significant challenges to preserve Site memory and enable access to and continued use of critical subsurface knowledge gained at considerable expense. Nearly half of today's Hanford Site workforce is not expected to work onsite 10 years from now. Unless preserved, their knowledge leaves with these workers. Today's knowledge is tomorrow's historical record to defend remediation decisions. A more integrated and enduring approach is required for onsite information management to deliver the right data and information in a usable form and at an acceptable cost to people who need it, where they need it, and when they need it. This necessitates investments in data preservation and in computational tools permitting data and record management.

B.2 Subsurface Processes and Predictive Modeling

Foreword

The breakout session on Subsurface Processes and Predictive Modeling was tasked with developing a description of the applied research needs on these subjects for the Deep Vadose Zone Technical Forum. Deliberations took place over 2 days: the first day was a meandering tour through some of the most important and stubborn research questions related to the DVZ, and the second day focused on developing a specific set of recommendations for an applied research program.

The first day—although largely unfocused—turned out to be key in developing a comprehensive set of suggestions for research on subsurface processes and predictive modeling. The understanding of the participants was that this was not to be "business as usual" for DOE Environmental Management and that the objective was to go beyond relatively simple (and fast) "cook and look" field tests of technologies. In other words, the objective of this new DVZ Program Plan was to tackle the tough research questions that need to be answered to develop and apply successful cleanup strategies. In this respect, the breakout session participants may have had a slightly different perspective from some in the other sessions where rapid fire field testing of technologies was again the primary interest.

A number of research challenges were discussed in the preliminary session:

- What is the role of preferential transport in the vadose zone, including narrow “finger flow” and horizontal spreading? What conceptual and numerical methods are needed to capture these effects and what is the required grid resolution to do so?
- How do we make use of the historical leaks in the Hanford Site DVZ given that leak rates and compositions are typically poorly known? It was generally agreed that there is a wealth of historical data for the Hanford Site that could be used to better support a subsurface processes and predictive modeling task. Improved correlation between field data and modeling would build confidence in model simulations. Participants noted that there have been efforts in the past to do this, but only a few sites have been identified for which sufficient contaminant disposal and leak history data exist to have confidence in the source terms.
- What is the horizontal extent and depth scale that would be needed to study flow and transport processes of interest? One vadose zone field experimental site, the so-called Sisson and Lu site in the 200 East Area, has well coverage that enables monitoring of plumes measuring about 20 m (65 ft) in diameter and 18 m (60 ft) in vertical extent. However, experiments performed at that site have indicated that introduced plumes moved beyond the monitored domain (laterally) within a relatively short period of time (weeks). The IFRC site in the 300 Area of the Hanford Site consists of a triangular domain about 60 m (200 ft) on a side and 15 m (50 ft) deep that monitors both the vadose zone and shallow unconfined aquifer near the Columbia River. No controlled vadose zone experiments have been performed at the 300 Area IFRC site yet, but aquifer injection experiments indicate that introduced plumes persist for a period of 2 to 5 weeks. In general, plumes generally become deeper and broader as they invade the DVZ, which can be greater than 100 m (330 ft) deep in portions of the 200 Area. Hence, it can be very challenging to map the full extent of plumes in the unsaturated zone, particularly owing to sparse well coverage. The difficulty of this challenge is compounded by the fact that we need characterization and modeling of the smaller-scale structures to evaluate the effect of small-scale heterogeneity on larger scale plume migration.
- The suggestion was made to develop a multi-scale research approach because uniformly high resolution characterization and modeling is generally not feasible given the depth of the contamination. The multi-scale approach, which should be conducted *in situ*, is necessary for the purposes of up-scaling smaller scale processes.
- In terms of broader research questions and challenges, it became apparent that we actually do not know much about the pore water and solid phase chemistry in the DVZ. Are the reactive phases there the same as those in the shallow vadose zone? What are CO_2 and O_2 gas concentrations at depth? Do the Plio-Pleistocene-age silts and caliche of the Cold Creek Unit, which act as a low-permeability flux-limiting layer to the underlying aquifer, also reduce the gas-phase diffusive flux of O_2 and CO_2 from the atmosphere? These questions have relevance to the effectiveness of potential remediation strategies and whether conditions that influence this effectiveness are different in the deep and shallow vadose zones.

These above challenges led to a series of broad recommendations:

- To develop a shallow site, similar to the Sisson and Lu site but with larger spatial extent, for very high resolution studies of vadose zone flow and transport. A geo-statistical description will be one of the outcomes and will be evaluated and assessed by the capability of high resolution models to capture the system behavior (moisture distribution, tracer distribution, etc). Reactive geochemistry can also be investigated.
- Develop models of mixing in addition to spreading and descent, particularly for the purposes of understanding reactive chemistry.
- Test a multi-scale research approach at shallow depths and apply it in the DVZ.

These broad suggestions formed much of the basis for the detailed research plan that was developed the second day and presented to all Technical Forum participants. This included five key research needs:

1. Develop models for coupled reactive flow and transport processes.
2. Assess data assimilation and conceptual model analysis of historical plumes.
3. Analyze long-term system-scale response to water flow through the DVZ.
4. Resolve technical issues associated with reactive gas and foam delivery.

A fifth research need was presented as a crosscutting one that applied to all of the preceding, but which is mentioned explicitly because of the need for a discrete research element related to this topic:

5. Uncertainty quantification.

These key research needs were then outlined in greater detail.

Develop models for coupled reactive flow and transport processes. It quickly became apparent from participant discussions that relatively little is known about coupled processes in the DVZ and how these might differ from the shallow vadose zone. Are the pore water and gas compositions different in the DVZ from the shallow vadose zone, and if so, how? Most importantly, how may these differences affect applied remediation technologies? For example, lower O_2 gas concentrations could negatively impact any redox sensitive techniques, especially those involving ammonia, which is being tested as a means for immobilizing uranium. High CO_2 concentrations would be likely to affect uranium transport behavior through its effect on uranium complexation.

Are the microbiological communities different in the DVZ, and will this affect contaminant behavior and remediation efficacy? What is the geochemical reactivity of solid phases in the DVZ, including their close to equilibrium behavior? What are the inter-grain (fluid-gas-solid) geometries and dynamical behaviors in the DVZ, especially with regard to surface areas and inter-phase mass transfer of reactive components? What are the spatial auto- and cross-correlation structures in the DVZ? What is the correlation between hydrologic (e.g., permeability) and geochemical (e.g., reactive surface area) parameters?

Another issue participants identified centered upon co-contamination. This is, how does the presence of multiple contaminants mixed in the DVZ influence contaminant behavior, “native” subsurface conditions, and remedial processes?

Data assimilation and conceptual model analysis of historical plumes. The extensive historical record of leaks and plumes at the Hanford Site is an unmatched resource for understanding contaminant behavior in the DVZ. But the challenges are daunting as well. Most importantly, there is a lack of data on the original leak volumes, rates, and compositions in most cases, making it difficult to reconstruct the plume behavior uniquely. Nonetheless, the potential for improved understanding is significant, so it was felt that every effort should be made to take advantage of the historical records. The objective is to analyze historical data for consistency in terms of plume behavior, with adequate accounting for anomalies that may be apparent with the large data set. Of particular interest are the effects of recharge, lateral spreading, fast vertical flow paths, and perched water.

Participants believed it was important to use risk and cost/benefit analysis to determine the need for additional data and to determine the level of uncertainty that is acceptable. The overall approach would be to use history matching for the purposes of model testing and confidence building. Anomalies in or between observed and simulated results could be used to posit and test specific hypotheses related to DVZ transport and mass-transfer processes and to focus further data collection efforts.

Analyze long-term system-scale response to water flow. Another important research question appertained to the long-term, system-scale response to water addition and flow in the DVZ. This question was considered distinct to some extent from the research question(s) focusing on remediation technologies, which typically address a smaller spatial scale and shorter time frame. The long-term effectiveness of the DVZ remediation, however, is clearly linked to the system-scale response over larger spatial scales. A number of research challenges were identified, including the following:

- Flow and transport under very dry conditions and/or in gravel is poorly understood, but may be important. Under these conditions, film flow may be significant. Modifications to the standard equations representing constitutive relations between relative permeability, saturation, and capillary pressure may be needed, and/or changes to the governing flow equations may be required to account for such processes.
- The impacts of widely differing ionic strength on unsaturated flow (e.g., osmotically driven water vapor flow and subsequent condensation leading to enhanced aqueous flow) are poorly known.
- The long-term three-dimensional response to water addition into the DVZ is poorly known, so experimentation and characterization at relevant scales is necessary.
- The influence of antecedent moisture conditions on preferential flow and related geochemical effects may be important. For example, flow paths that are established during a leak event may persist over long periods of time as zones of slightly elevated antecedent moisture conditions. These zones may then serve as preferential flow paths in future leak events and/or during long-term migration of contaminants through the DVZ.
- The behavior of the transition between unsaturated and saturated zones over time, related in part to a large-scale, post-operational period decline of the water table in the 200 Areas, needs to be better understood.

Resolve technical issues associated with reactive gas and foam delivery. A whole series of technical questions exist that are related to the use of various remediation technologies in the DVZ. These questions are overlain by uncertainties about the longe term, large-scale system response to water addition and flow. Some of these have to do with how these short-term perturbations will be affected by coupling with longer-lived processes in the DVZ, but there are also issues specific to the remediation technology itself.

For example, foam was suggested as a means of maximizing the delivery of reactive agents to the DVZ without adding large quantities of water that might serve to mobilize contaminants. However, foam behaves as a non-Newtonian fluid, the flow of which is poorly understood and generally not represented in current flow and reactive transport simulators.

Similarly, the delivery of reactive gases represents a highly transient invasion of the ambient DVZ that would likely impact the inter-grain and inter-fluid geometries, and thus ultimately the transfer rate of reactive constituents and their spatial extent. For example, a worst-case scenario in terms of remediation is probably a single “bubble” with a narrowly delineated interface or reaction front—reactive constituent transfer would be at a minimum in this case and the effectiveness of remediation would likely be limited. Presumably, better results would be obtained if the reactive gases move through as large a region of the contaminant plume as possible without unduly disturbing the local regime.

Other questions arose that had to do with the long-term behavior of the remediation strategies. Is ammonia gas likely to be oxidized on time scales that are shorter than the time scales for sequestration of the contaminants? Is re-oxidation of immobilized (normally redox-sensitive) contaminants likely to take place over time? To address these questions, participants felt that a program involving combined characterization, monitoring, and modeling across multiple spatial and time scales is needed.

Uncertainty quantification. The last topic might be argued to properly belong to all of the foregoing research challenges and efforts, but it was felt that since uncertainty quantification would likely involve a discrete set of activities, approaches, and challenges, it was best to highlight it as a separate component. Nonetheless, it was clear to those involved that uncertainty quantification was crosscutting to all of the above research elements.

The principle objective here would be to develop and apply a coherent methodology for uncertainty quantification within the DVZ. Why? Because only an extremely small sediment volume of the DVZ environment beneath the Central Plateau will ever be sampled or tested. Therefore, accounting for uncertainty is all the more important because of the scarcity of existing or future data. The components of the uncertainty quantification include the following:

- Uncertainty due to data scarcity/measurement and interpretation errors
- Parameter estimation error
- Conceptual model (assumptions and subjective decisions) uncertainty
- Scenario uncertainty (e.g., disposal history, remediation alternatives, and future conditions)
- Error propagation through models.

It was felt that each of these types of uncertainties needed to be treated separately and quantified so that conclusions about contaminant behavior in the DVZ and remediation effectiveness could be defended. Ultimately, uncertainty quantification needs to be built into any successful remediation program and performance estimation used to support decision making.

B.3 Subsurface Access and Remediation

Foreword

This session began with approximately 40 participants attending. There was overall agreement on many of the points made during discussion, and perspectives from all were civilly regarded and politely responded to or augmented.

The initial topic focused on subsurface access methods. We were focused by one of the participants who reminded us that the ultimate goal is remediation of the vadose zone, which was assumed to mean the limitation or prevention of contaminants from migrating into the Columbia River. There was much discussion on the philosophies and general principles of access and remediation methods, along with characterization needs/techniques and conceptual model development sprinkled throughout the two breakout sessions. Many participants shared anecdotes and experiences about the Hanford Site and other sites to illustrate their points.

Although the discussion formally began with access methods, there was not a rigid structure or pathway through which remediation and access topics were covered. Indeed, we often revisited points and topics as the discussion ensued. At the end of the first day, the Chairs tried to organize the heterogeneous list of discussion topics under broad categories to help participants focus, review, and limit redundancy. The broad categories noted below were condensed into four categories to facilitate the “vadose zone bucks” prioritization exercise carried out during the Technical Forum’s final afternoon.

- measures of success
- long-term effectiveness
- pilot-scale testing
- improved access methods
- improved delivery methods
- knowledge management.

Measures of Success

Some of the most important challenges confronting an action that must be protective of human health and the environment for thousands of years are ways to measure the success of the remediation strategy. In this section, we tried to collect and capture the important points made by participants related to the effectiveness of remediation strategies. The bulleted points below explore fundamental questions with respect to the definition of success, as well as methods for clearly determining success.

- What is a measure of remediation success? While groundwater protection is often quoted, evidence supporting that measure may remain unknown for decades, centuries, or longer. Measures of success need to be agreed upon as a decision basis or as part of a line of evidence for remedy performance. Researchers may need new techniques to determine and establish remedy performance and confirmatory monitoring of that performance.
- Risk of contaminant source (e.g., concentration) to environment versus cost. A cost and benefit analysis of each technology should be performed as part of the overall evaluation of that technology.

This analysis should be performed for all potentially viable ground level (surface), as well as *in situ* technologies, including excavation. The scenarios for the Hanford Site may be unusual or unique, so the technology evaluation and review process should not be cut short based upon technology down-selection from other sites.

- Stakeholders need to understand what they are buying (e.g., revised Toxicity Characteristic Leaching Procedure [TCLP], which is testing for waste-form performance). Even though a method for evaluating a technology's performance may be a standard method or practice (e.g., American Society for Testing and Materials [ASTM]), it may not be appropriate to evaluate the long-term performance required for the Hanford Site.
- We need to use strategies with multiple technologies or suites of technologies (realize that they change in time and space). It may be beneficial and appropriate to immediately use a technology with an effective life of less than 100 years for high risk contamination, realizing that other solutions must be employed later. Stakeholders must be involved early—they are willing to participate in making cost-effective choices when the process is clear, and they are included.
- Examples of tangible items to invest in include the following: 1) document(s) that provides baseline evaluation of cost and expected effectiveness of proposed technologies and 2) technologies and methods for determining endpoints and risk-appropriate decisions for DVZ treatment to support the Remedial Investigation/Feasibility Study (RI/FS) process.

The purpose of DVZ remediation is to protect the underlying aquifer by reducing contaminant flux. This is accomplished by undertaking remediation actions and monitoring the reduction of contaminant concentrations at strategic locations in the vadose zone and/or aquifer using standardized, agreed-upon protocols, well completions, and subsurface stratigraphic monitoring.

However, how and when do we confirm that contamination from the DVZ exceeds drinking water standards or other guidelines—especially when contamination confirmation may required years of monitoring? Are we attempting to measure the first release into the aquifer of pore water from the DVZ holding higher than acceptable concentrations of contaminants? Are we monitoring contaminant concentrations in the aquifer at some select stratigraphic locations and at a given distance from a waste site, an operable unit, or on the edge of the Inner Area of the Central Plateau? The stratigraphic intervals covered and the length of borehole completions can significantly impact the contaminant concentrations monitored. Discussions are needed upon standard modeling, monitoring, and decision tools to provide a consistent approach to understand the benefits provided by remedial actions that can be confirmed. The foundation of such these discussions likely involves three-dimensional plume assessments consensually established, understood, modeled, and monitored.

Long-term Effectiveness

Initial remediation strategies and solutions are being developed based on our understanding and emulation of the basic physical, chemical, and microbial processes affecting subsurface processes and contaminants of concern existing within the DVZ. Topics raised by participants about the long-term effectiveness of remedies include the following:

- We currently do not have a long-term perspective on the behavior of radioactive and some nonradioactive contaminants.

- Because these are very complicated problems, we need to have linked remedial strategies. Do not expect a single remedy to solve the Hanford Site's remediation problems for technetium, uranium, or other contaminants of concern.
- How do we understand the long-term fate of these contaminants when their lifetime is of the same order as geologic and evolutionary processes? How do we monitor them when changes are slower than our current ability to measure? What is short-term versus long-term?
- From the Native American or First Nations perspective, long-term solutions may imply in perpetuity. Generations to come may not remember names, but they will remember actions and consequences of those actions.
- Ideally, stakeholders want "permanent" solutions (implying removal of contaminants); leaving in place is a second choice. Clear communication between all parties is vital. Hanford Site officials need to be careful not to promise things that cannot be delivered. If contaminants are removed, where are they stored—and for how long? Is this storage more environmentally sound than leaving contaminants in the subsurface and monitoring their behavior?
- Who signs up to the responsibility of long-term monitoring for 10,000 years? If conventional or currently available technologies are used and costs are extrapolated, the price becomes unreasonable. How do we reduce these costs so that a long-term strategy can be realistically implemented? This is an example of why a better scientific understanding is needed—for defensible underpinning of remediation decision-making supporting the DVZ.
- It may be possible to borrow some strategies from Monitored Natural Attenuation (MNA) practices, such as sentry wells and transect wells that provide indicators in a slowly changing system. Borrowing from MNA practices may work, but remember there are differences between MNA in groundwater and the vadose zone; in addition, most MNA solutions are designed for time frames that may be 1 to several orders of magnitude shorter than what is needed for some Hanford Site DVZ issues.
- Examples of tangible items identified to invest in included the following: 1) new practical monitoring methods for the vadose zone, 2) new site and scenario-specific leach tests, and 3) methodologies that use multiple lines of evidence.

Pilot-Scale Testing

There was essentially unanimous agreement that pilot scale or small field tests should be rapidly implemented and facilitated to test technologies and to probe information gaps needed to develop effective remediation strategies. The value of getting out to the field was expressed by many participants. Most participants also made it clear that the technology applied need not be perfect or totally understood before field testing, although careful attention should be paid to reduce any impact of unintended negative consequences of an action. In addition, field tests do not have to meet 100% of their objectives to be successful. In addition to tests on targeted contaminated sites, valuable information can be obtained in field tests on clean sites or analog sites/contaminant scenarios and then transferred to contaminated sites of interest.

There was also discussion supporting the development of dedicated, well-characterized demonstration sites to test remediation, characterization, monitoring, and access technologies. The following ideas were shared by participants:

- Need intermediate test beds in non-radiation areas to test technologies and work out deployment issues and logistics without first trying to work in radiation areas that require significant additional complexity, costs, and potential risks. Use site or scenario analogs—e.g., chromium immobilization technologies may provide analogous information for uranium immobilization. Potentially use clean or near-clean sites to test access technologies.
- How do we better design demonstration test plots to reuse the wells, monitoring networks, and other infrastructure that already exist, are being installed, or are planned for installation for scheduled pilot scale tests (i.e., desiccation or reactive gas injection) to maximize resources and minimize costs? Need better technical and management coordination of technology and resource use across site activities, contractors, and funding sources (e.g., DOE Environmental Management and Office of Science).
- Examine the merits of innovative test sites for studying the DVZ such as constructing a subsurface DVZ facility (e.g., the Deep Underground Science and Engineering Laboratory at Homestake, South Dakota). This kind of facility may attract industry, universities, and other laboratories. It might also inspire different types of experiments (not necessarily just environmental remediation), providing a magnet for resolving DVZ fundamental science and engineering questions pertinent across the DOE complex as well as private sites.
- Examples of tangible items to invest in include the following: 1) test sites in different locations/strata, 2) test sites in clean areas for equipment and strategy testing before testing in contaminated areas or the Central Plateau, and 3) multiuse sites: single test site for multiple technologies.

Improved Access Methods

Access was the first topic discussed during the breakout session because of the historically high cost for drilling at the Hanford Site compared to commercial and other government sites. Although still expensive, participants clarified that direct penetration (e.g., hydraulic hammer) and novel applications of conventional technologies (e.g., cable tool for shallow drilling, combinations of methods) were being used to reduce the cost and improve access. Nearly all of the access and drilling technologies that have been tried at the Hanford Site have an appropriate niche. Some examples are listed below.

- Direct push technology can work well until the Cold Creek Unit is encountered. In some areas where this unit is absent, the direct push technology has exceeded 60 m (200 ft) penetration. It would be useful to develop new tools for this low-cost platform. For the same cost, several holes (lateral coverage) are often better than a few deep ones.
- Cable tool drilling can be cost effective when used in shallow areas. This approach has been cost effective when used to grab contaminated samples up to 20 m (70 ft) below the ground surface.
- Combine access techniques when appropriate. Use cable tool drilling or direct push technology for shallow sampling followed by other methods (e.g., rotary, sonic, etc.)
- All new excavations should be publicized for better coordination and collection of data on geochemistry, hydrology, geology, microbiology, etc. Data and information should be more

effectively preserved and shared among groups onsite and across the DOE complex using readily accessible and easy to use electronic databases/catalogues.

- Optimize the value of sediment sampling. It is expensive to obtain subsurface samples, so Hanford Site contractors need to maximize collection opportunities and availability of samples for long-term research and technology development uses. This is part of the data sharing described in the previous bullet.
- Need new techniques to characterize spatial and temporal changes beyond drilling wells and taking samples for physical and chemical analysis. This includes geophysical measurements and the installation of sensors.
- Coordinate “dirt—dig and haul” with the “groundwater” people/contractors. Actions in the vadose zone will affect groundwater.
- In addition to vertical samples from conventional drilling methods, consider slant or horizontal boreholes near critical sources, locations, etc. Slant drilling sometimes provides a better perspective on contaminant distribution. This can also be used to install sensor lines to monitor flux and migration within the DVZ. Direct penetration slant access can be 60 degrees from horizontal.
- New monitoring techniques are needed in the near-term to reduce “subsurface swiss-cheese” (i.e., many boreholes). Novel long-term techniques are also needed.
- Examples of tangible items to invest in include the following:
    - practical new tools and strategies for subsurface access, characterization, and monitoring (e.g., transfer tools developed for cone penetrometer or conventional drilling).
    - remediation-focused characterization techniques.

Improved Delivery Methods

This session included discussions on remediation techniques and strategies as well as thoughts on improved delivery of amendments. Several participants made the point that a variety of technologies and strategies should be considered because it is unlikely that a single technology will satisfy all objectives (no “silver bullet” exists). Some participants voiced their concern about remediation methods that may have adverse impacts or unintended consequences on the non-targeted species. An example is the lixiviant effect that high pH may have on the currently bound shallow contaminants (e.g., Cs and Sr). This point was explored and partially resolved with the understanding that successful remediation methods may incur some adverse impacts and that the benefits of the technology or strategy must be weighed against any drawbacks—as routinely done in the medial profession and health industry.

- Controlled soil flushing is one technology that will be evaluated. There is a variety of fluids that can be used for flushing. Both chemical properties (e.g., extraction, bonding) as well as physical properties (e.g., viscosity) can be varied in the fluids tested.
- Use foam to push contaminants to the surface, laterally, or otherwise control movement. Potentially the foam can carry other remedial solutions, e.g., coatings, or other property-affecting amendments.
- Consider *in situ* grouting to immobilize target contaminants in a matrix recalcitrant to erosion or other change.

- Consider *in situ* soil blending or mixing as a method for distributing amendments.
- Consider electro-kinetic migration to move contaminants through the vadose zone to locations more convenient for treatment or removal.
- Consider grout injection to prevent water from infiltrating, contacting, and leaching contaminants.
- Consider making small but standard changes to practice incremental remediation. For example, if an amendment with phosphate is known to help immobilize contaminants, perhaps inject a phosphate solution or use phosphate in grout whenever abandoning wells.
- *In situ* remediation may not be the only remediation method but rather be part of an overall strategy, along with *ex situ* methods or dig and haul. Select and combine technologies to fit the site and specific challenges faced. In the commercial world, if a site has more uncertainty, we often use bigger hammers for remediation (less precise but able to accommodate uncertainties in characterization).
- It is important that we all understand that although we strive to do no harm in a remediation, we actually will likely do some harm analogous to medical practice when dealing with diseases or injury. We need to weigh short-term harm to long-term benefits (e.g., a person undergoing cancer treatment using an aggressive treatment strategy). We must understand the nature and extent of potential harm and impact and have the necessary scientific understanding and justification for comparing this potential harm with long-term benefits. For example, strontium-apatite sequestration is now an acceptable remediation approach in the 100-N Area. This was not the case nearly 20 years ago when only groundwater pump-and-treat was considered acceptable to the public and regulators at that site.
- For baseline technologies (e.g., excavation, pump-and-treat), evaluate where and when these methods are applicable. There are some currently unresolved (but potentially solvable) issues for contaminants at the Hanford Site such as if we were to excavate the ^{99}Tc contaminated geologic media. However, there is currently no waste disposition path (cannot be dumped into the Environmental Restoration Disposal Facility located near the 200 East Area).
- Examples of tangible items to invest in include the following:
    - Improved or new technologies (e.g., gas, foam, shear-thinning fluids, combinations of technologies).
    - Practical methods to sequester ^{99}Tc and uranium independent of redox manipulation.
    - Determination of the depth effectiveness of surface and near-surface barriers (e.g., engineered covers, injection grouting).
    - Identification and development of remediation scenarios to provide a platform for evaluation remediation, characterization, and monitoring technologies.
    - Document technology challenges, misunderstandings, limitations, and failures as well as positive outcomes (lessons learned).

Knowledge Management

This topic was also captured and discussed in the Characterization and Monitoring breakout session.

Knowledge management was universally posited as an important asset for the Hanford Site. The breakout session participants agreed that there is a tremendous amount of data, information, and knowledge at the Hanford Site, but this information may be in forms that are not readily accessible and will "come and go" as staff and contractors change. For example, historical processes, practices, and disposal knowledge may currently only exist in the minds and memory of Site personnel (some retired). Other information exists as unpublished reports or laboratory notes. As noted earlier, about half of the Site's present staff are not expected to work at the Site in about 10 years. Knowledge preservation, electronic access, etc. for researchers through stakeholders is a critical activity that must receive elevated DOE attention.

- It would be very useful to digitize existing and new Hanford Site information so it is more user friendly and accessible, and minimize knowledge loss during contractor transitions and changeovers that increasingly dominate the Site management landscape.
- There should be more use of existing information and data as well as a cross-fertilization of ideas throughout industry and across the Hanford Site to create lists of technologies. Lists should include pros, cons, Site experiences, and outcomes. Lists should be a current snapshot with periodic updates maintained.
- Need to include information from vendors (industry), Department of Defense, etc. with new technologies that are not "stove-piped" within the DOE complex and could significantly advance current DOE practices (e.g., mining, excavation). Remember that if vendor technologies are used, the vendor must have some freedom to practice according to its methods. Institute contractor incentives to use new and better technologies—*both* technology developers and prime contractor should be considered for incentives.
- There are some locations for Hanford Site documents (e.g., Environmental Dashboard Application database [http://environet.hanford.gov/eda/]), but a comprehensive repository is needed for access to documents related to the Hanford Site remediation and activities similar to other public-accessible databases.
- Examples of tangible items to invest in include the following:
  - Online, near real-time information repository (e.g., website) accessible to many that contains field data, results, Hanford Site activity summaries, activity plans and goals, and geographic maps showing activity distributed across the Site. The repository should have features that enable users to click on projects for access to specific activity details, etc. Most importantly, this knowledge repository must be kept updated with concise, factual, and timely information.
  - Digitizing existing and new information from within and outside the Hanford Site so it is more user-friendly and accessible. Verify that knowledge is preserved during contractor transitions and change-overs. Information should include technology challenges and limitations.
  - Technology Readiness Assessment and Tracking (e.g., CLU-IN for vadose zone).
  - Reinstitute the Technology Coordination Group.
  - Archiving sediment samples collected during well drilling within a "Core Lab". This is particularly critical for preserving samples contaminated with radionuclides. These are expensive to collect and safely handle. Long-term preservation is needed for non-radioactive, radioactive, and biological samples for future analytical tests. Must have contractor take responsibility for maintaining the library to go from now through remediation and into monitoring—likely lasting at least three generations.

Appendix C

Knowledge and Capabilities Challenges Covering the Deep Vadose Zone Underlying the Hanford Site

Appendix C

Knowledge and Capabilities Challenges Covering the Deep Vadose Zone Underlying the Hanford Site

Contents of Appendix C

This list of knowledge and capability needs is extracted from the references given at the end of this appendix and captured during meetings held in the spring of 2010 with onsite contractor personnel. Many of those staff also attended the Deep Vadose Zone (DVZ) Technical Forum held in July 2010 in Richland, Washington (see Section 4.0). These needs are divided into the following three categories:

- Characterization and Monitoring
- Subsurface Processes and Predictive Modeling
- Subsurface Access and Remediation.

These categories match the topics discussed in three breakout sessions around which the Deep Vadose Zone Technical Forum was organized. The chairs and co-chairs of those breakout sessions (see Appendix B) used this list to familiarize themselves with DVZ needs reported in the literature. In addition, an abbreviated list of these knowledge and capability gaps was given to all Forum participants to provide examples of the level of detail being captured during the meeting.

The sentences introducing each category identify some of the key questions that underpin the needs that are listed as bulleted items. Information in this appendix is neither exhaustive nor prioritized.

C.1 Characterization and Monitoring

What enhanced characterization techniques are needed to adequately describe the vadose zone and identify where contaminant plumes are located?

How can the types of contaminants contained in DVZ plumes be identified less expensively and more efficiently?

What characterization and performance data should be collected to understand the potential of surface barriers to contain contamination?

What advanced, less-invasive geophysical methods could be developed to image and characterize the subsurface vadose zone and contaminant plumes?

What are the dominant contaminant pathways into and through the DVZ?

How do geologic discontinuities impact contaminant flow paths?

What research facilities that span the laboratory scale to the field scale are needed to test advanced characterization, remediation, and monitoring techniques?

What techniques exist to cost effectively monitor moisture/gas flux and contaminant behavior in the DVZ?

Can the short- to long-term performance of *in situ* cleanup techniques and containment systems such as barriers be verified through monitoring?

What is the importance of episodic mositure flow in the DVZ to contaminant movement and remedial performace?

- **Contaminated Sediment Sampling Using Direct Push Method**. Develop shielded sediment sample holders that will enable the push method to be used to collect more highly contaminated sediment samples from the subsurface.
- **Field Subsurface Contaminant Measurements**. Develop new *in situ* and less expensive contaminant measurement capabilities for both short-term sampling and long-term monitoring.
- **Contaminant Identification**. Create high-resolution, field-deployable isotopic methods to identify the location and distribution of radioactive contaminants.
- **Down-Hole Neutron Activation Detection**. Improve the sensitivity of the neutron-capture technique for detecting down-hole gamma ray emissions. The detection system should be sensitive to identifying sodium nitrate and leaked tank waste that contains cesium.
- **Down-Hole Beta Radiation Detection**. Metal-encased boreholes and probe holes prevent detection of beta radiation emitted by Tc^{99} and I^{129}. A more sensitive beta detector that enables measurement of key contaminant concentrations with depth needs to be developed. The system should be able to discern beta emissions from natural occurring ^{40}K, ^{99}Tc, or ^{129}I.
- **Higher Resolution Laboratory Analyses**. Improve resolution and reduce cost of detecting contaminants (e.g., ^{129}I) and the measurement of selected subsurface properties (e.g., hydraulic properties at very low moisture content).
- **Geophysical Three-Dimensional Stratigraphic Imaging**. Develop less invasive natural isotope and subsurface geohydrologic property characterization tools (e.g., through spectral gamma logging and electrical resistivity) to characterize subsurface properties such as particle size and geologic layering.
- **Geophysical Approaches to Three-Dimensional Contaminant Plume Imaging**. Couple new, low-invasive geophysical tools, such as high-resolution resistivity techniques, with controlled laboratory/field test bed experiments to identify the fundamental relationships between geophysical responses of differing contaminant plume distributions and moisture contents.
- **Deep Electrical Resistivity Electrode Application**. Develop methods for using deeply buried electrodes to enhance the vertical resolution of resistivity-detected anomalies and provide resolution beneath shallow infrastructure features such as buried pipelines and tanks.
- **Surface Remote Sensing**. Improve surface-remote sensing and noninvasive techniques to provide subsurface characterization and performance data.
- **Subsurface Remote Sensing**. Develop techniques to remotely and noninvasively provide information about subsurface characteristics (e.g., hydrology, chemistry, and structural characteristics).
- ***In Situ* Measurements of Migration Velocities and Moisture Flux**. Develop methods for directly measuring contaminant migration rates and moisture fluxes, likely using high-density geophysical data sets, directed at key mobile contaminants.
- **Pipe Line Leakage**. Develop advanced geophysical capabilities, such as electricity resistivity, to detect past tank pipeline leaks where the soil is no longer moist.

- **Discontinuity Impacts on Lateral Flow**. Develop field-testing and modeling approaches to quantify the impact that subsurface heterogeneities and anisotropic conditions have on moisture flow and contaminant transport.
- **Identify Dominant Contaminant Transport Pathways**. Identify key geologic and stratigraphic pathways that link waste sites, contaminant plumes, and Central Plateau scales required to characterize dominant DVZ contaminant migration paths.
- **Field Research and Test Facilities**. Establish field test facilities at uncontaminated locations that are analogous to contaminated DOE sites for investigators to test advanced characterization approaches and remedial technologies.
- **Field Tests at Former Contaminant Release Sites**. Characterize and install instrumentation at selected past contaminant or tracer release sites to monitor moisture and contaminant behavior.
- **Systems-Level Simulation Framework**. Develop an integrated systems-level (micro- to field- scale) conceptual simulation framework that integrates best available information describing vadose zone characteristics, contaminants, and reactive transport processes.
- **Conceptual Models**. Establish integrated, scaled-up, models that can simulate waste sites at the Central Plateau scale. These models must be capable of integrating key knowledge from field and experimental data with methods that represent system behavior and established bounds of parameter accuracy.
- **Natural Microbial Profiling**. Characterize and monitor changes in microbial community composition as an indicator of chemical flux that can be integrated with measurements of subsurface system performance and potential contaminant impacts on the environment.
- **Transitional Monitoring Techniques**. Develop, demonstrate, and validate monitoring techniques that transition from point measurements to integrated waste-site and landscape-scale measures.
- **Source and Plume Monitorin**g. Develop improved approaches and durable sensors for characterizing field-scale contaminant sources and plumes.
- **Subsurface Monitoring Technology.** Evaluate minimally invasive geophysical approaches to delineating subsurface plumes and monitoring their migration.
- **Monitor *In Situ* Moisture Infiltration Rates Inside Tank Farms**. Expand moisture infiltration instrumentation now installed in a limited number of tank farms.
- **Monitor Fluid and Gaseous Flux**. Develop novel methods for monitoring fluid and gaseous fluxes through vadose zones in response to diurnal and seasonal changes that can be extrapolated to the longer term (e.g., decades).
- **Real-Time Monitoring**. Develop real-time monitoring instruments for field use and remote/automated data collection covering a range of chemical/radiological species relevant to DOE. Includes advanced, long-term, reliable geophysical sensors, detectors, and data-transmission (e.g., wireless) technology for subsurface monitoring.
- **Recharge and Moisture Flow**. Improve and validate long-term moisture flux estimates beneath specific disturbed sites (e.g., tank farms or cribs) and undisturbed, lower moisture, ground locations.

- **Monitoring Performance of Containment Systems**. Validate characteristics and processes needed to model the performance of remediation systems under current and potential future conditions. Includes identifying spatial and temporal resolutions at which measurements are made.
- **Monitoring Performance of Remedial Actions**. Demonstrate the ability to refine subsurface DVZ performance through monitoring and evaluating both predictive tools and remedial action impacts on subsurface systems.
- **Deep Vadose Zone Monitoring for Surface Barrier Applications**. Develop monitoring techniques capable of resolving deep yet subtle and transient changes in moisture flow and contaminant movement in the DVZ beneath surface barriers.
- **Tracers and Surrogates**. Develop and apply tracers, markers, or contaminant/stress-indicator surrogates to provide direct and early warnings of remedial action failures or unexpected contaminant behaviors.
- **Identify Early-Warning Thresholds of Unexpected Performance**. Test and establish bases for early-warning monitoring "thresholds" of unexpected or unacceptable DVZ behaviors such as changes in moisture flow and contaminant movement. Possibilities include buried sensors, surface surveillance, bio-markers, and performance-modeling indicators.

C.2 Subsurface Processes and Predictive Modeling

How well do existing physical (conceptual) models depict liquid flux and contaminant movement in the DVZ?

How well do existing simulation models depict fluid flux and contaminant movement in the DVZ under natural and remediation conditions? Are advanced computing capabilities needed?

How do the geochemical and biogeochemical processes active in the DVZ affect contaminant movement? How well do we understand these processes, and can we reasonably simulate them?

How do simulation models account for uncertainty, especially across time and spatial scales?

How do we create an integrated approach to data management, use, and information preservation in support of model development/use and remediation design?

- **Geochemical and Biogeochemical Processes**. Study contaminated sediments from the vadose zone using representative sampling beneath waste sites to improve conceptual models of geochemical and biogeochemical processes and unique species that control contaminant behavior.
- **Microbiologic Transformations and Reactions**. Identify prominent organism types, evaluate microbiologic subsurface activities, and assess the potential of biologic-induced transformation and reactions to influence, enhance, or sequester contaminants.
- **Coupled Ion Exchange and Precipitation/Dissolution Reactions**. Quantify predictions of ion exchange and precipitation fronts required to describe geochemical reactions between contaminants and in-earth materials to perform reactive transport analyses.

- **Mass Transfer and Slow Reactions**. Study the roles of mass transfer and slow reactions and develop mass transfer models to address contaminant movement resulting from slow sediment-waste geochemical reactions in inaccessible sediment micropores and microfractures that took place in the past.
- **Contaminant Sequestration and Release**. Study microscopic and spectroscopic analytical techniques to identify host mineral phases that control contaminant release and their short- to long-term behavior.
- **Kinetic Database**. Develop an experimental, scientifically defensible kinetics database that can be used to determine first-order reactions controlling source-term contaminant behavior.
- **Recharge and Moisture Flow**. Improve and validate long-term moisture flux estimates beneath specific waste sites (e.g., tank farms or cribs) as well as undisturbed lower moisture locations. Account for seasonal and decades-long variations.
- **Heterogeneity Incorporation into Predictive Models.** Create new approaches for incorporating subsurface heterogeneities into conceptual models at scales at which contaminant flow and transport behavior are impacted.
- **Advanced Computing Capabilities.** Develop an advanced coupled process computing capability to simultaneously support modeling DVZ-site geohydrological, geochemical, and biogeochemical interactions and performance. Link the new models with models that simulate remediation treatment processes, process design/redesign, and contaminant movement.
- **Contaminant Mobility and Transport Modeling.** Develop calibrated and validated numerical models to predict solid-liquid mobility of risk-driving contaminants, including anionic chemicals, and their reactive transport for the range of waste, geochemical, and hydrological conditions prominent in the DVZ.
- **Model Remediation Technology Performance at Waste Site Scales.** Develop modeling approaches to support the design and evaluation of *in situ* and surface barrier technologies at waste site scales.
- **Evaluate Methods for Application of Surface Barriers.** Develop a methodology for predicting the effect of surface barriers on shielding deep contamination from moisture flux.
- **Integrated Databases and Preserved Information Archives**. Maintain data and synthesize into integrated, accessible, and searchable databases of existing and to-be generated knowledge pertinent to scientific, engineering, and regulatory decision-making.
- **Integrated Data Engine**. Develop a distributed data search engine with comprehensive coverage of environmental information resources within and outside the DOE complex.
- **Advanced Computing Capabilities Supporting Characterization**. Apply advanced computing capabilities to enable faster processing of large characterization data sets, such as data sets acquired through geophysics.

C.3 Subsurface Access and Remediation

What are the remediation goals for the DVZ? Are those goals reasonable, attainable, and verifiable?

Can the subsurface only be accessed by drilling boreholes?

What *in situ* techniques could prove useful for remediating contaminants in a heterogeneous system such as the DVZ?

How do we extrapolate small-scale treatability tests to full-scale remedial actions used for entire waste sites?

How do we confirm the long-term effectiveness of remediation actions through monitoring?

How do we detect the early warnings of remediation failure?

- **Subsurface Access**. Develop and test new, improved, more cost-effective methods to access the subsurface for sediment/contaminant sampling and characterization.
- **Desiccation Barrier**. Scale up current treatability field tests underway in the BC Crib/Trench area to larger waste site scales. Model and field test the extent that desiccation of pore water reduces contaminant flux.
- **Application of Remediation Technologies at Multiple Sites**. Test the effectiveness of remediation technologies at multiple sites, at multiple scales, and across time scales having varying subsurface properties (e.g., contaminant concentrations, geochemistry, pore-water chemistry, microbial interactions).
- **Gas Phase Remediation**. Examine sequestration effects from geochemical manipulation using reactive gas injection (e.g., ammonia) on various soil types, contaminants such as ^{99}Tc and ^{129}I, and leaked tank waste.
- **Remediation Amendment Delivery**. Research advanced capabilities, such as foams, to more effectively deliver chemical, physical, or biological amendments into the deep subsurface.
- **^{99}Tc and Uranium Remediation**. Evaluate technologies for high-priority remediation contaminants at the Hanford Site, such as ^{99}Tc and uranium.
- **Soil Flushing**. Examine factors that affect whether mobile contaminants can be effectively flushed through a 100-m (330-ft) thick vadose zone and captured before or soon after entering the underlying groundwater.
- **Phosphate Stabilization**. Research emplacement and delivery of phosphates to the subsurface. Phosphates may provide significant hydraulic control.
- **Carbonate and Silicate Phase Emplacement**. Research the emplacement of carbonate and silicate phases for chemical and physical sequestration. The technetium-carbonated geochemical relationship is not as well developed as for uranium.
- **Reductants**. Increase the number and variety of reductants used for *in situ* vadose zone remediation. The goal is to provide preferential reaction with target constituents or to produce reduced phases with greater stability.
- **Alter Subsurface Permeability**. Research chemical, electrochemical, or biochemical manipulations that alter subsurface permeability to allow greater targeted sequestration. This method likely will perform better than grouts or polymer methods.

- **Chemical and Biological Kinetics**. Research the mechanisms and kinetics of chemically and biologically controlled reactions that can be innovatively applied to new remediation capabilities.
- **Advanced Subsurface Remediation Technologies.** Identify, develop, and deploy new remediation technologies to recover, isolate, or contain contaminants. The new technologies should significantly improve the cost, efficiency, effectiveness, and risk of implementation compared to existing technologies.
- **Bioremediation**. Study the viability of bioremediation and gene expression monitoring to examine the *in situ* physiological basis for bioremediation technology where other remediation options are not feasible.
- **Evaluate Potential Remedies for the Hanford Vadose Zone**. Expedite treatability testing opportunities for candidate technologies that support future feasibility studies.
- **Long-Term Effectiveness of Potential Remedies**. Develop technically defensible data and methodologies to evaluate how potential technologies will perform over long time periods, in particular for technologies that leave contaminants in place.
- **Technology Implementation at Very-Large Scales**. Design remedies at very-large scales. Components should include subsurface access and methods to physically deliver amendments or otherwise implement remedies at scales of tens to hundreds of meters laterally and tens of meters vertically.
- **Depth Protection**. Conduct studies to determine the depth at which surface barriers of different designs eliminate or reduce moisture flux. Begin studies using interim barriers covering selected tank farms, and then proceed to more extensive surface barriers such as the Hanford Prototype Barrier in the 200 East Area.
- **Surface Barrier Components.** Study the mechanisms and kinetics of chemically and biologically mediated reactions occurring between contaminants, sediment, and surface barrier components to increase longer term, barrier-induced, contaminant containment and stabilization.
- **Improved Surface Engineered Barriers**. Field test and model new surface barrier designs and materials for improved isolation and long-term (50 to 100+ year) durability in reducing moisture flux and contaminant movement.

C.4 Further Reading

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Appendix D

Example of Investment Leveraging Taking Place at the BC Cribs and Trenches Site Located on the Central Plateau

Appendix D

Example of Investment Leveraging Taking Place at the BC Cribs and Trenches Site Located on the Central Plateau

Contents of Appendix D

Figures

This appendix summarizes how integrated investments in basic (Department of Energy's [DOE's] Office of Science [SC]) and applied research (DOE's Office of Environmental Management [EM]) programs being applied at the BC Cribs and Trenches site located south of the 200 East Area in the Central Plateau has benefited the study and development of remediation approaches for that site. The distinct roles for DOE's basic science, applied research, and end users are discussed in this example. Such integration would be captured in the implementation plans developed to cover each of the principal deep vadose zone sites at the Hanford Site.

Bridging the gap between basic science and "needs-driven" research is a universal challenge for all areas of technology development. This is particularly challenging when confronting intractable problems, such as the environmental cleanup of the DOE complex, for which well-established economic incentives for translating basic scientific advances into commercial products and services do not exist. Therefore, it is incumbent upon DOE to facilitate this transition of scientific results into applied solutions.

The motivation and goals for DOE's basic science and applied research programs in subsurface science are previously summarized in Figure 3.1. The motivation of much discovery research is to develop a deeper understating of fundamental processes, such as those controlling contaminant fate and transport, and to continually advance the state of the science commonly without specific time constraints. Complementary to these efforts, applied research advances uses of existing scientific principles and discoveries obtained through basic science to solve site-specific problems and to guide remediation and management strategies across a range of contaminated sites. The motivation for "needs-driven" applied research is to address site-specific challenges that prevent successful, cost effective, and timely implementation of sustainable remediation strategies.

The suite of deep vadose zone problem areas that should be summarized in implementation plans includes:

- BC Cribs and Trenches
- B Complex—including BX-102 uranium, BY Cribs (^{99}Tc), B-BX-BY Tank Farms (sites of lesser importance in this region include BX Trenches, 216-B-8, 216-B-11, 216-B-7A&B)
- T Complex—including T Cribs and Trenches, T, TX, and TY Tank Farms
- U Cribs—including 216-U-8 and 216-U-12
- WMA C
- WMA S-SX
- S/REDOX Cribs
- PUREX Cribs and Trenches (uranium liquid discharge sites)
- WMA A-AX (lower priority)
- WMA U (lower priority).

The specific or general locations (e.g., WMA C covers C tank farm) for these sites are identified in Figure 6.1.

As noted, an example of how investments in basic and applied research programs are coordinated with end-user site activities to solve challenging environmental problems is being carried out at the BC Cribs and Trenches Site at Hanford.

D.1 BC Cribs and Trenches Research Integration Example

The following text is modified from Pierce et al. (2009). Characteristics and preparation for treatability testing conducted at the BC Cribs and Trenches site also is summarized in Section A.1.4.4 of Appendix A.

During the 1950s, wastes stored in tanks at Hanford were reprocessed to recover uranium. Wastes from these reprocessing activities were disposed of directly into the soil or were returned to a tank or a series of tanks where the solids, containing most of the actinides plus strontium, were allowed to settle. The remaining supernatant, which was highly concentrated radioactive and hazardous waste, was then discharged to the soil. The BC Cribs and Trenches received more than 190-million L (50-million gal) of this so-called scavenged tank waste. Based on inventory estimates, this group of sites contains the largest inventory of ^{99}Tc disposed of to the soil at Hanford. Groundwater monitoring data for the BC Cribs and Trenches are limited, but little of the inventory from disposal of wastes at these sites appears to have reached the water table. The release of ^{99}Tc from these waste sites is projected to lead to future groundwater contamination above drinking water standards.

Technetium-99 associated with the BC Cribs and Trenches resides deep within the vadose zone of the Central Plateau, and remediation of this contamination is not feasible with existing technologies. Therefore, the Hanford remediation contractor, currently CH2M HILL Central Plateau Contractor (CHPRC), is conducting a deep vadose zone treatability test (DOE-RL 2008). The goal of the field test is to evaluate vadose zone remediation technologies, including a comprehensive set of laboratory, modeling, and field tests. While the field test is being conducted at the BC Cribs and Trenches, characterizing and remediating the site are not goals of the testing program. The field test will result in technical performance data for soil desiccation and other technologies, thereby providing the technical basis for comparing and evaluating potentially usable technologies as part of subsequent remedial alternative assessments conducted at multiple sites.

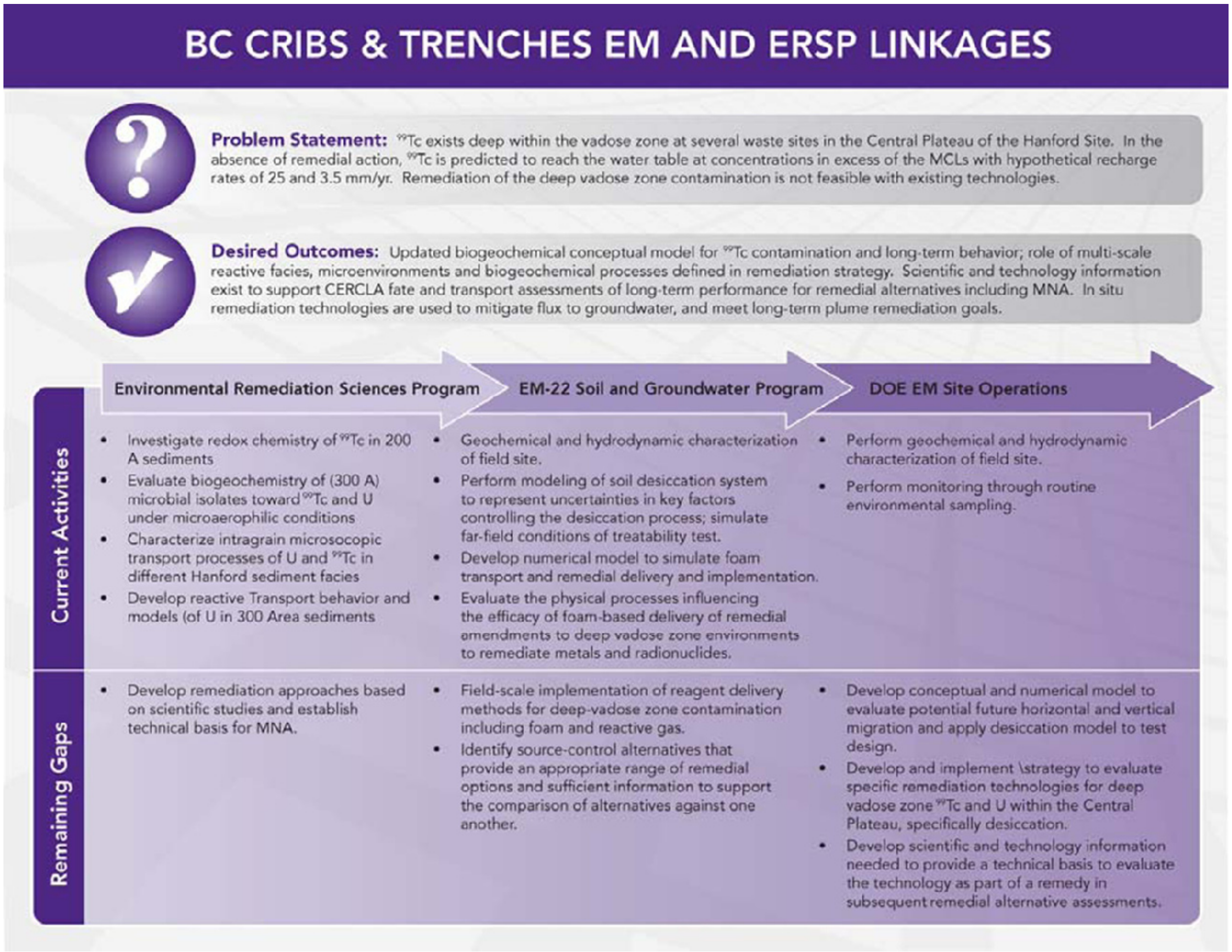
DOE Richland Operations Office (DOE-RL) and the remediation contractor have performed geochemical and hydrodynamic characterization of the field site. Characterization included installing boreholes through several trenches, sediment sampling, and analysis. The analytical results (Serne and Mann 2004) showed that there was ^{99}Tc at depth in the vadose zone beneath the trench, although the areal extent of the contamination was unknown. Subsequent modeling by Ward et al. (2004) predicted that the contamination had spread laterally, which was investigated by high-resolution electrical resistivity geophysical surveys (Rucker and Benecke 2006). Work was then carried out to ground truth the resistivity survey by installing boreholes and sampling and analyzing sediments. DOE-RL and the remediation contractor will be responsible for implementing the final remedy for remediating ^{99}Tc and uranium in the deep vadose zone.

The DOE Office of Technology Innovation and Development (EM-30) is supporting the BC Cribs and Trenches remediation work through activities funded by the Enhanced Remediation of Metals and Radionuclides Initiative. The initiative is investigating methods to control, reduce, and/or remove metals and radionuclides (e.g., Cr, Pu, Sr, Tc, and U) from the vadose zone. This collaborative effort includes teams from Pacific Northwest National Laboratory (PNNL), Idaho National Laboratory, MSE Technology Applications, Inc., and private industry collectively working together.

One of the first undertakings of the initiative was to conduct a literature review documenting the state of knowledge for ^{99}Tc, its behavior in the environment, and possible remediation approaches. The feasibility of foam-based delivery of amendments is now being evaluated by the project, along with support from DOE's Advanced Fate and Transport Models Initiative, which is developing simulation capabilities to support foam delivery of reagents. The modeling initiative also is extending the model of the BC Cribs and Trenches to evaluate uncertainties associated with soil desiccation, including the effects of heterogeneities.

DOE's Office of Science, through the PNNL Subsurface Science Focus Area, is investigating the redox chemistry of ^{99}Tc in Hanford sediments and evaluating the biogeochemistry of microbial isolates toward ^{99}Tc and uranium in different Hanford sedimentary facies. These investigations will result in improved predictions of transport behavior for both ^{99}Tc and uranium that can be used to remediate the deep vadose zone contamination through *in situ*, enhanced attenuation or monitored natural attenuation methods.

The technical gaps for BC Cribs and Trenches remediation include field-scale approaches based on scientific studies. A strategy is needed to evaluate specific remediation technologies for deep vadose zone ^{99}Tc and uranium. Scientific and technical information is required to provide a supportable basis for decisions regarding deep vadose zone remediation across the Central Plateau. Figure D.1 describes the integration and collaboration between EM and Environmental Restoration Science Program (ERSP) activities conducted at the BC Cribs and Trenches.



BC CRIBS & TRENCHES EM AND ERSP LINKAGES

Problem Statement: ^{99}Tc exists deep within the vadose zone at several waste sites in the Central Plateau of the Hanford Site. In the absence of remedial action, ^{99}Tc is predicted to reach the water table at concentrations in excess of the MCLs with hypothetical recharge rates of 25 and 3.5 mm/yr. Remediation of the deep vadose zone contamination is not feasible with existing technologies.

Desired Outcomes: Updated biogeochemical conceptual model for ^{99}Tc contamination and long-term behavior; role of multi-scale reactive facies, microenvironments and biogeochemical processes defined in remediation strategy. Scientific and technology information exist to support CERCLA fate and transport assessments of long-term performance for remedial alternatives including MNA. In situ remediation technologies are used to mitigate flux to groundwater, and meet long-term plume remediation goals.

	Environmental Remediation Sciences Program	EM-22 Soil and Groundwater Program	DOE EM Site Operations
Current Activities	• Investigate redox chemistry of ^{99}Tc in 200 A sediments • Evaluate biogeochemistry of (300 A) microbial isolates toward ^{99}Tc and U under microaerophilic conditions • Characterize intragrain microsocopic transport processes of U and ^{99}Tc in different Hanford sediment facies • Develop reactive Transport behavior and models (of U in 300 Area sediments	• Geochemical and hydrodynamic characterization of field site. • Perform modeling of soil desiccation system to represent uncertainties in key factors controlling the desiccation process; simulate far-field conditions of treatability test. • Develop numerical model to simulate foam transport and remedial delivery and implementation. • Evaluate the physical processes influencing the efficacy of foam-based delivery of remedial amendments to deep vadose zone environments to remediate metals and radionuclides.	• Perform geochemical and hydrodynamic characterization of field site. • Perform monitoring through routine environmental sampling.
Remaining Gaps	• Develop remediation approaches based on scientific studies and establish technical basis for MNA.	• Field-scale implementation of reagent delivery methods for deep-vadose zone contamination including foam and reactive gas. • Identify source-control alternatives that provide an appropriate range of remedial options and sufficient information to support the comparison of alternatives against one another.	• Develop conceptual and numerical model to evaluate potential future horizontal and vertical migration and apply desiccation model to test design. • Develop and implement \strategy to evaluate specific remediation technologies for deep vadose zone ^{99}Tc and U within the Central Plateau, specifically desiccation. • Develop scientific and technology information needed to provide a technical basis to evaluate the technology as part of a remedy in subsequent remedial alternative assessments.

Figure D.1. Integration and Collaboration between the EM and ERSP Activities at the Hanford Site BC Cribs and Trenches

D.2 Further Reading

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Appendix E

Summary of Results from the Resource Allocation Exercise Conducted During the Deep Vadose Zone Technical Forum, July 20-21, 2010

This resource allocation exercise was designed and facilitated by **Brian B. Looney** of the Savannah River National Laboratory.

Appendix E

Summary of Results from the Resource Allocation Exercise Conducted During the Deep Vadose Zone Technical Forum, July 20-21, 2010

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Figures

After participants attending the July 2010 Deep Vadose Zone (DVZ) Technical Forum identified knowledge and capability challenges (see Section 4.0), an anonymous and informal “resource” allocation exercise was conducted to gain audience views regarding potential investments targeting the highest priority DVZ needs. That exercise and a summary of its results are captured in Appendix E.

E.1 Overview of the Resource Allocation Exercise

At the end of the Deep Vadose Zone Technical Forum held July 20-21, 2010 (see Appendix B), Forum participants were given the opportunity to invest surrogate money, or “Vadose Bucks,” in nine investment categories that were derived from the breakout group discussions. The specific objectives of the resource allocation exercise were to 1) elicit information from the participants using a simulated portfolio investment exercise, 2) provide insight into the participants’ values and preferences, and 3) generate information to assist DOE and Hanford as they plan future DVZ applied research activities.

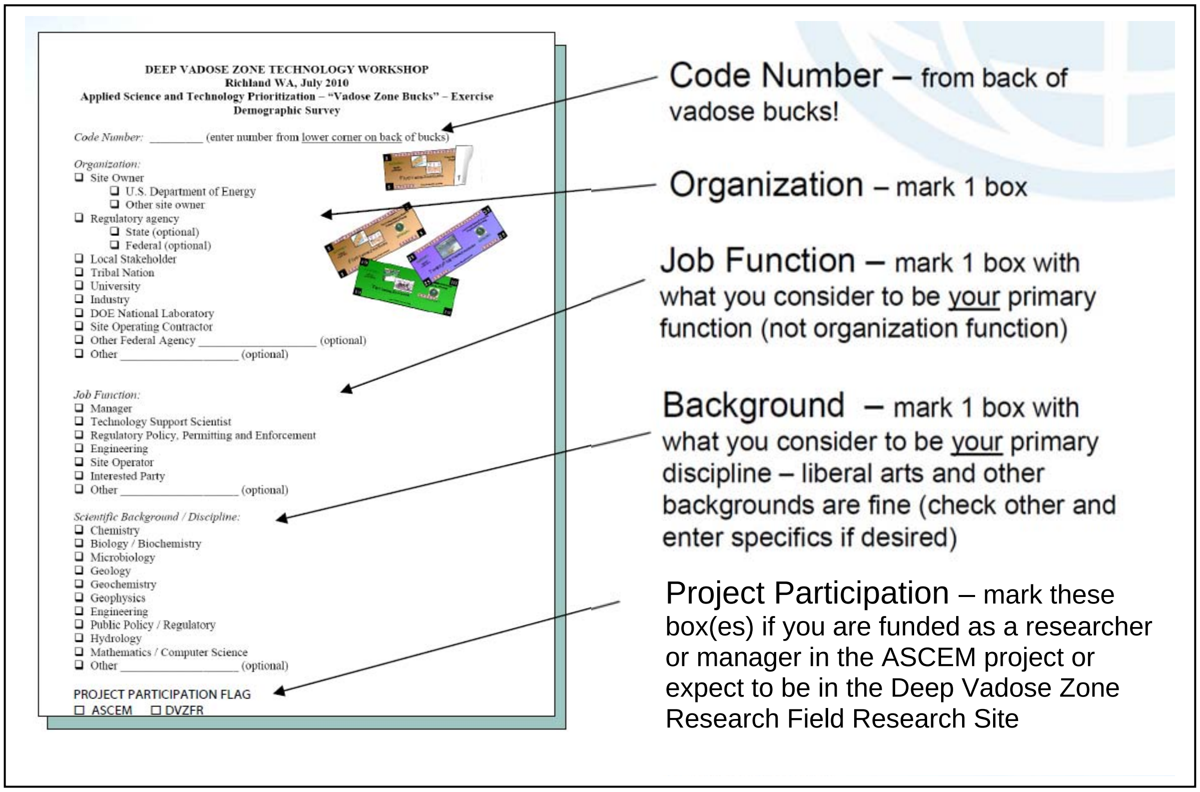
A simple process was developed for the elicitation. This process was based on an investment portfolio problem in which limited resources, in this case, vadose bucks, were issued to each participant who could then allocate his/her “money” among the available investment categories. The resulting allocations reflected the background, knowledge, and perspectives of each participant. The participants were encouraged to develop their investments using their own criteria/considerations and were provided the following examples to assist them in getting started:

- Scientific merit and assessment/belief about the probability of success
- Relative value, or importance of the idea, versus other investments
- Expected cost of the types of activities in the investment category
- Alignment of the investment with what you think are the most important or critical needs
- Alignment of the idea with creative and innovative solutions that target vadose-specific opportunities or needs
- Alignment of the idea with your values and desires for environmental protection and restoration.

Note that the vadose bucks provided to each person included some large bills (two $25), medium bills (three $10) and small bills (four $5) to encourage the development of a diverse portfolio. Participants were allowed to split the bills in half, if desired. The investment options/approaches from the breakout sessions were composited into nine final topics (described in more detail Section E.2), and boxes were set up to receive vadose bucks for each topic. The participants placed their vadose bucks in the boxes, and the total investment in each category was tabulated to provide a sense of the overall perspective of the total Forum participants. Using surrogate “money” for the structured exercise was intended to encourage critical thinking and to engage the everyday prioritization and balancing skills that have been culturally developed in all of the participants.

We also collected supplementary demographic information from each participant to support a more robust interpretation of the results. Specifically, this “anonymous” survey provided information about demographic factors that might influence values and investment decisions. The demographic survey form (Figure E.1) gathered data on each participant’s organization, job function, background, and potential for participation in DVZ-related projects. The demographic information and vadose bucks were linked by a code number to facilitate later data analysis.

Finally, in preparation for the exercise, the participants were encouraged to write their thoughts and notes on the invested vadose bucks or on their demographic survey to provide additional insights into the rationale for their investments.



DEEP VADOSE ZONE TECHNOLOGY WORKSHOP
Richland WA, July 2010
Applied Science and Technology Prioritization – "Vadose Zone Bucks" – Exercise
Demographic Survey

Code Number: _________ (enter number from lower corner on back of bucks)

Organization:
- ☐ Site Owner
  - ☐ U.S. Department of Energy
  - ☐ Other site owner
- ☐ Regulatory agency
  - ☐ State (optional)
  - ☐ Federal (optional)
- ☐ Local Stakeholder
- ☐ Tribal Nation
- ☐ University
- ☐ Industry
- ☐ DOE National Laboratory
- ☐ Site Operating Contractor
- ☐ Other Federal Agency ____________________ (optional)
- ☐ Other ____________________ (optional)

Job Function:
- ☐ Manager
- ☐ Technology Support Scientist
- ☐ Regulatory Policy, Permitting and Enforcement
- ☐ Engineering
- ☐ Site Operator
- ☐ Interested Party
- ☐ Other ____________________ (optional)

Scientific Background / Discipline:
- ☐ Chemistry
- ☐ Biology / Biochemistry
- ☐ Microbiology
- ☐ Geology
- ☐ Geochemistry
- ☐ Geophysics
- ☐ Engineering
- ☐ Public Policy / Regulatory
- ☐ Hydrology
- ☐ Mathematics / Computer Science
- ☐ Other ____________________ (optional)

PROJECT PARTICIPATION FLAG
☐ ASCEM ☐ DVZFR

Code Number – from back of vadose bucks!

Organization – mark 1 box

Job Function – mark 1 box with what you consider to be your primary function (not organization function)

Background – mark 1 box with what you consider to be your primary discipline – liberal arts and other backgrounds are fine (check other and enter specifics if desired)

Project Participation – mark these box(es) if you are funded as a researcher or manager in the ASCEM project or expect to be in the Deep Vadose Zone Research Field Research Site

Figure E.1. Demographic Survey Used for the Resource Allocation Exercise

Before the exercise, the participants were provided the following important disclaimers:

- This is not real money! It is not good at the local store so you are encouraged to spend it during the Forum.
- This is not a carefully controlled scientific study! It is not designed to provide definitive and statistically based information.
- The results do not directly determine funding! The objective is to help DOE in their planning and allocation efforts.
- The results will be only as good as your efforts in participating!

E.2 Deep Vadose Zone Investment Categories

Based on the content of the detailed discussions, the chair/co-chair of each Forum breakout session (identified in front of Appendix B) generated three to five key options/approaches as initial candidate investment categories. The chairs/co-chairs then met and discussed the categories. Closely related or overlapping categories were merged to simplify the eventual investment process. The resulting nine final investment categories (and supporting descriptions and/or examples) were provided to the Forum attendees for their consideration before the investment exercise. These categories are listed below.

Assigned to "Characterization and Monitoring":

1. Improved conceptual models for vadose systems and vadose contaminant behavior and better use of available data

This investment category combined three recommended topics (one from each breakout session). Specifically, the breakout sessions recommended development of a "Living Conceptual Model," "Improved Knowledge Management," and "Data Assimilation & Conceptual Model Analysis of Historical Plumes in the Deep Vadose Zone." Examples of the types of activities to be considered in this applied research category were:

- Improved methods for integrating disparate data/information
- Iterative conceptual models that focus on key boundary conditions and future conditions (e.g., How will future moisture regimes evolve and be different than moisture regimes during site operations?)
- Development of, and better use of, historical site data (e.g., reinstate the site technology coordination group), digitize site resources, develop a "core lab" to allow efficient characterization of core materials so that data are not lost
- Additional analysis of historical datasets to refine conceptual models (consistencies in vadose zone behaviors/responses, observed differences in vadose behaviors/responses)

2. New characterization tools and techniques

This investment category combined two recommended topics (from the "Characterization and Monitoring" and the "Access and Remediation" breakout sessions). Specifically, the breakout sessions recommended development of "Improved Vadose Zone Tools and Approaches," and "Measures of Success & Long-Term Effectiveness." These were tool- and strategy-based recommendations, and examples of the types of activities to be considered in this applied research category were:

- Develop and deploy new/emerging tools to meet objectives
- Perform more pore fluid sampling
- Develop downhole tools/sensors to provide more vertical information
- Implement new methods for determining the flux of water or contaminants
- Optimize the blend of technologies to maximize information and minimize costs
- Develop new methods for demonstrating and documenting desired endpoints
- Develop site-specific leach tests
- Encourage multiple lines of evidence approaches.

3. Invest in systemic changes to implement best practices for monitoring

This investment category was recommended by the “Characterization and Monitoring” breakout session. Examples of the types of activities to be considered in this applied research category were:

- Implement state-of-the-practice and state-of-the-art geophysical tools (near-term)
- Implement technologies to sample additional phases (such as soil gas or moisture collected with high vacuum wells)
- Install dedicated electrode holes for geophysics
- Use nonconductive well materials
- Install a set of well characterized boreholes for technology verification and to allow tests of comparability.

Assigned to “Processes and Predictive Modeling”

4. Develop models for coupled reactive flow and transport in the vadose zone. This investment category was recommended by the “Processes and Predictive Modeling” breakout session. Examples of the types of activities to be considered in this applied research category were:

- Develop models that account for the unique characteristics of DVZ (e.g., versus shallow vadose systems or saturated systems)
- Incorporate additional processes to account for the reactivity of “phases” in the deep vadose zone
- Develop better DVZ spatial understanding, including the cross correlation of parameters

5. Analyze long-term system scale response to changes in water input to vadose zone

This investment category was recommended by the “Processes and Predictive Modeling” breakout session. Examples of the types of activities to be considered in this applied research category were:

- Improve characterization and processes and predictive modeling of flow and transport in “very dry” conditions and in gravel
- Improve characterization and processes and predictive modeling of ionic strength effects
- Describe the response of the DVZ to water addition (or reduced water inputs) and the influence of antecedent conditions
- Improve the understanding of the transition between the DVZ and the saturated zone.

6. Uncertainty quantification for vadose zone models

This investment category was recommended by the “Processes and Predictive Modeling” breakout session. Examples of the types of activities to be considered in this applied research category were:

- Improve the understanding of crosscutting and cumulative uncertainties in DVZ models
- Specifically examine uncertainties related to
  - data scarcity

  - parameter error
  - scenario selection
  - contaminant concentration prediction.

Assigned to “Access and Remediation”

7. Pilot scale testing of potential vadose zone treatment methods

This investment category was recommended by the “Access and Remediation” breakout session. Examples of the types of activities to be considered in this applied research category were:

- Develop intermediate-scale test beds
- Perform work at clean sites
- Develop a test site (instrumented, etc.) that would allow testing of multiple technologies

8. Develop improved access and delivery methods

This investment category was recommended by the “Access and Remediation” breakout session. Examples of the types of activities to be considered in this applied research category were:

- Gas and foam and other vadose delivery methods
- Practical subsurface access
- Data repository that allows “real-time” access and interpretation capabilities
- Technologies that target ^{99}Tc and uranium (independent of redox conditions)
- Understanding the depth of effectiveness of surface barriers

9. Resolve technical and processes and predictive modeling issues associated with reactive gas and foam delivery in the VZ

This investment category was recommended by the “Processes and Predictive Modeling” breakout session. Note that this topic (of specific delivery methods such as foam or gas) was moved to access and remediation at the suggestion of several participants “because it is an integral part of the remediation development process.” Examples of the types of activities to be considered in this applied research category were:

- Simulate delivery (e.g., foam is a non-Newtonian fluid)
- Need laboratory, shallow, and DVZ testing to parameterize and calibrate conceptual understanding and numerical models
- Increase capture of pore scale processes in conceptual and numerical models.

E.3 Summary of Results

A summary of the principal results is provided below.

Information on the Participants

Sixty-eight individuals participated in the resource allocation exercise. The breakdowns of the various demographic categories are shown in Figures E.2–E.4. There was significant diversity in the participants, including many organizations, job functions, and backgrounds. The relative representation of the various groups is considered in interpreting the investment results in the sections below.

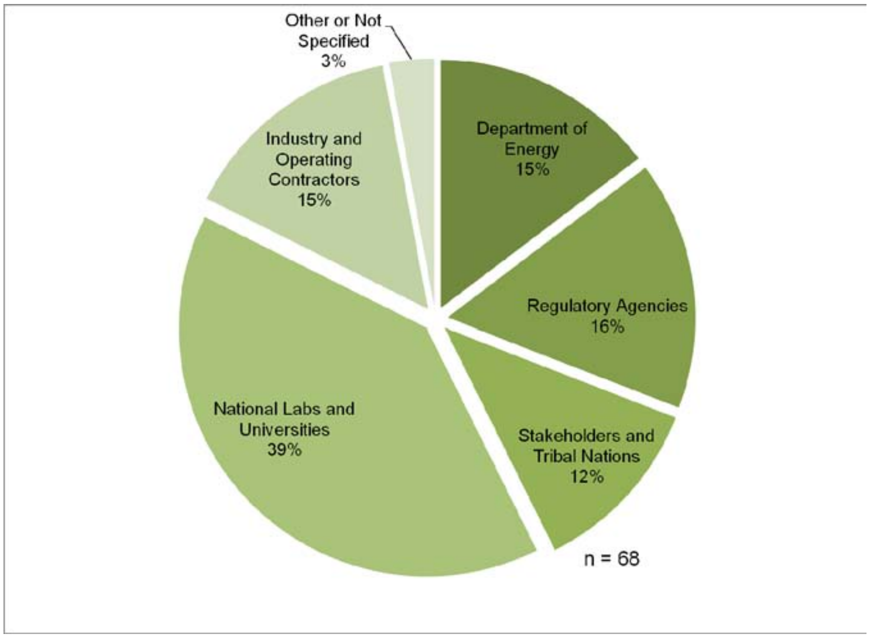


Figure E.2. Distribution of Organizations Represented

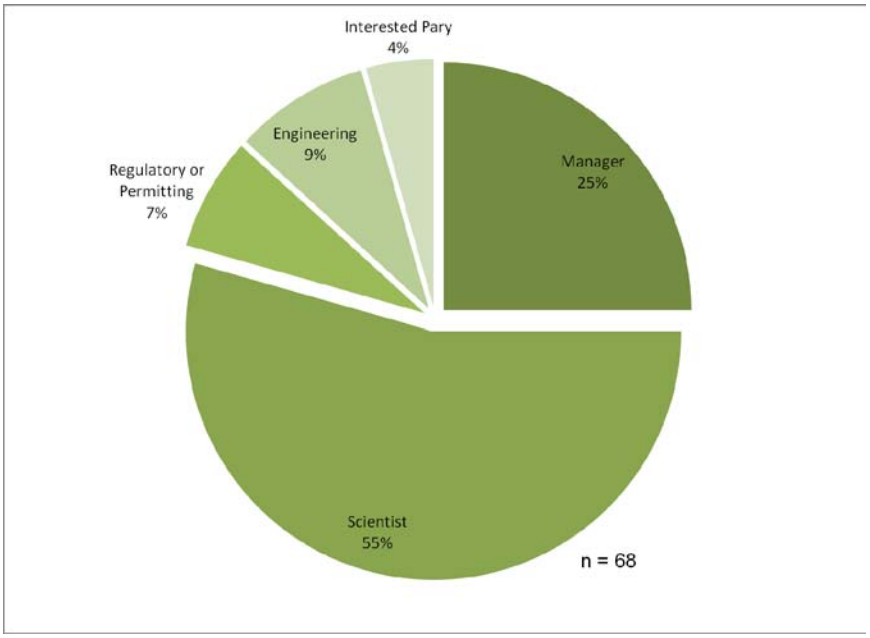


Figure E.3. Distribution of Job Functions of Participants

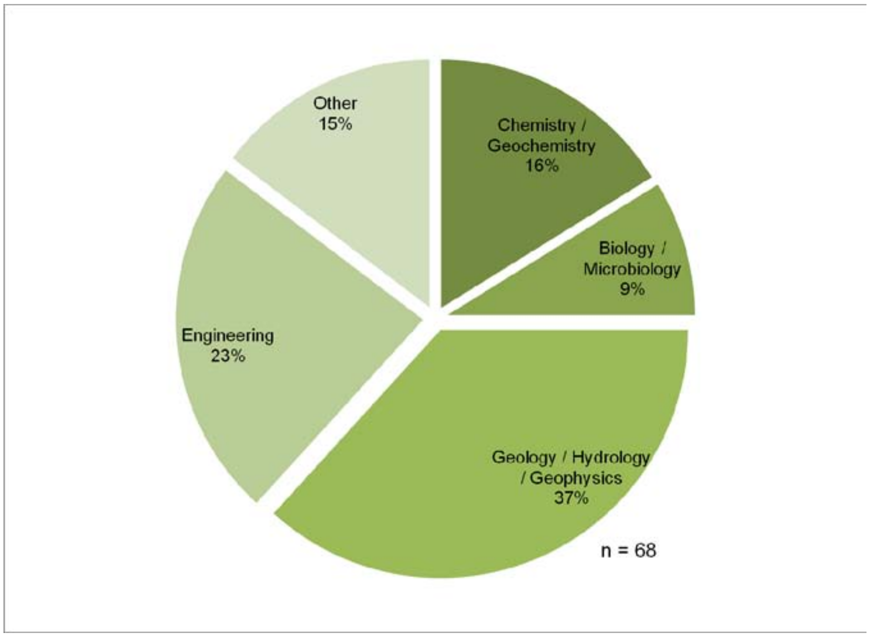


Figure E.4. Distribution of Backgrounds and/or Academic Disciplines of Participants

Total Vadose Bucks Invested at the Forum

The aggregate investments by all participants are depicted graphically in Figure E.5. The total invested amount was $6,800, or $100 per participant. One way to compare the relative investments is by reference to the investment level that would result from equal investment in all of the categories (individual investment of approximately $11 vadose bucks, and a cumulative total investment of approximately $756 vadose bucks as shown on Figure E.5). Aggregate investment levels higher than this amount suggest that, overall, the participants placed more value on a category than average, while lower investment levels suggest the participants placed less value on the category than average.

The total investments ranged from $405 to $1202.50 vadose bucks for the nine categories. While this variation indicates some overall variation in preferences across these categories, the results in Figure E.5 depict general support for investment in all nine categories and support for the three consolidated categories: characterization and monitoring, processes and predictive modeling, and access and remediation. There was a noticeable pattern in the overall investments in which the characterization, monitoring, access, and remediation categories received slightly higher investments than the processes and predictive modeling topics.

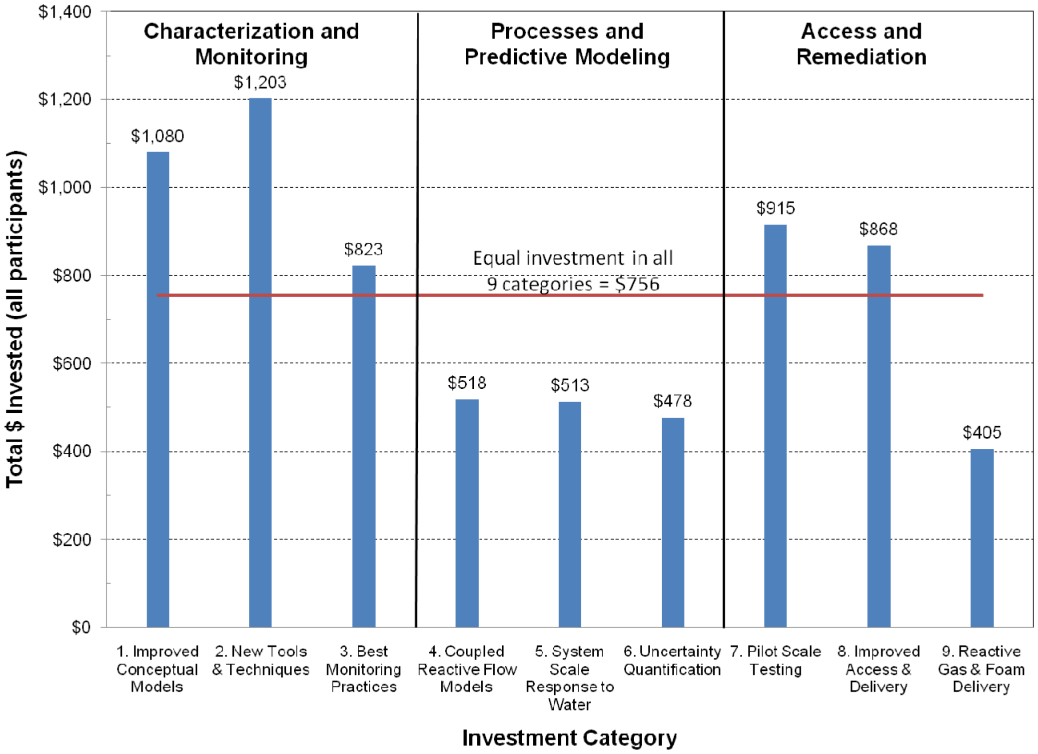


Figure E.5. Total Invested in Each Category by all Forum Participants

Observed Diversity in Investment Patterns

The pattern of individual investments by the entire population is depicted in Figure E.6. For each of the nine investment categories, this box-and-whiskers plot shows the minimum and maximum investments, the median investment, and the 1st quartile (25th percentile) and 3rd quartile (75th percentile).

The most striking feature of this graph is the significant diversity in the investments by the participants. The minimum individual investment in all categories was $0. The maximum investment in the categories ranged from $25 to $100. The substantial diversity observed in the participant population is an important result of the resource allocation exercise. This diversity was also observed in the variation in investments with organizational subgroups. Thus, the generalized conclusions based on total or median investment levels do not represent the substantial variation in preferences among Forum participants and among participants within a particular demographic. For example, if a particular demographic group tends to favor investment in access and remediation, it is likely that some fraction of the cohort favored processes and predictive modeling or characterization and monitoring. The generalized conclusions should be interpreted as broad trends rather than representations of the specific opinions of all of the individuals in the identified groups.

The pattern of investment versus non-investment (Figure E.7) provides an additional snapshot of the overall participant preferences. All but 1 of the 68 participants invested their vadose bucks in more than one category. For the remaining 67 participants, there was a pattern in their choices to either invest or skip each category. A majority of participants invested in all three characterization and monitoring categories and also invested in two of the access and remediation categories. The three processes and predictive modeling categories showed about the same number of investors (i.e., investment > $0) as non-investors (i.e., investment = $0).

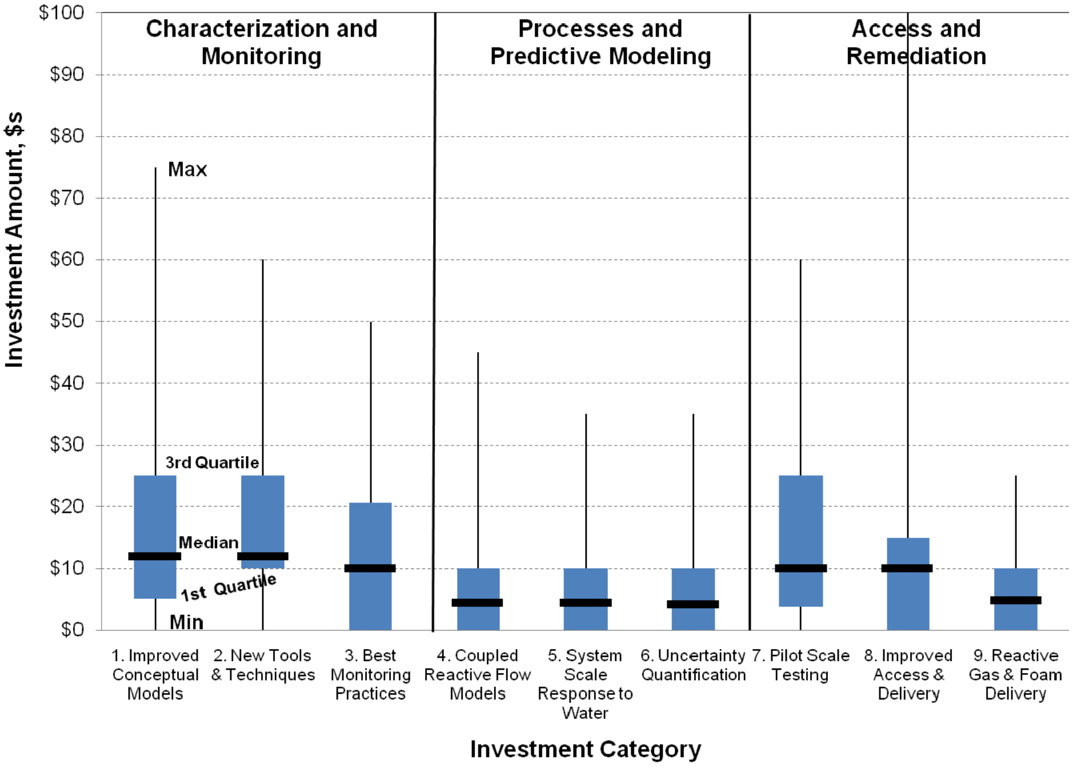


Figure E.6. Range of Individual Investment Amounts

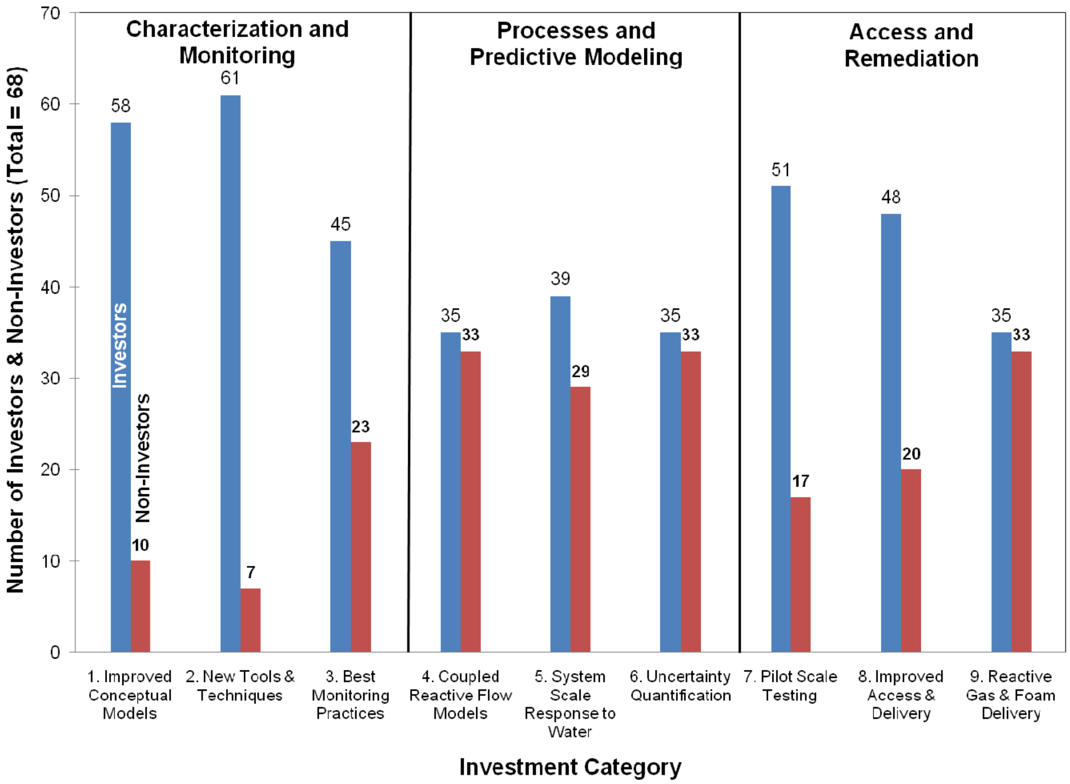
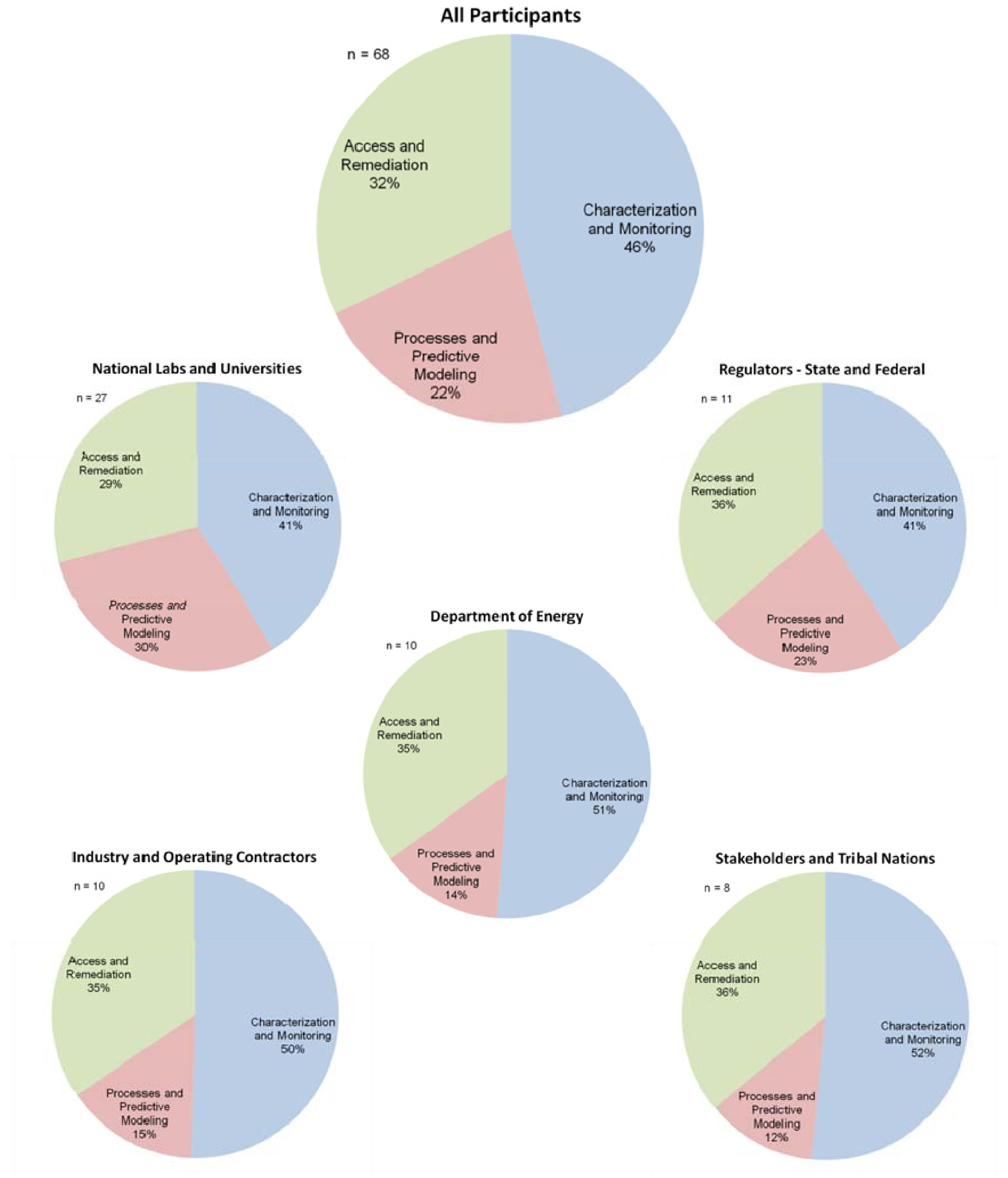


Figure E.7. Number of Investors vs. Non-Investors in each Category

Demographic Results

The data resulting from the demographic survey information offer possible insight into the relative preferences of subgroups of participants. While the aggregate results represent a “blunt instrument” to provide insight for DOE in their decision making, variations in investment behavior across organizational subgroups can provide insight into how organizations might view DVZ priorities. In addition, analysis of the results by subgroup can also remove the influence of group size in the aggregate results. For example, if 40% of the participants are from national laboratories and universities, then their aggregate investments might overwhelm those of a smaller group (e.g., regulators with 16% or stakeholders and tribal nations with 13%).

Figure E.8 shows the investment profiles for the participants when grouped by organization. The chart for “All Participants” is provided for perspective. The charts for the individual groups were derived based on the number of participants who self identified into the group, and the relative number of individuals in each organizational group is provided on each figure. The most significant pattern that emerges based on the median investments of the various organizations was related to the relative investment in processes and predictive modeling versus the other two overarching categories. In this case, the national laboratory/university participants and the regulatory agency participants invested relatively more in this category than did the other three organizational subgroups. One additional observation from Figure E.8 is that DOE, industry and operating contractors, and stakeholders and tribal nations subgroups had nearly identical distributions of vadose bucks across the three investment categories.



Subgroup charts do not include two individuals categorized as “other” or not specified in the Demographic Survey (Figure E.1).

Figure E.8. Distribution of Investments in Three Categories by Participant Organization

Based on participant comments, one possible explanation of this variation in relative investment for processes and predictive modeling may be associated with the following generalized statements: 1) an "uncertainty minimization" bias and desire to be cautious and avoid risks for the national laboratory and university participants as well as for the regulatory participants and 2) a bias for action to move things forward for stakeholders, industry, and the DOE representatives who were present at the Forum. DOE participants, industry/operating contactors, and stakeholders and tribal nations also exhibited relatively higher priority for characterization/monitoring with slightly more than 50% of their vadose bucks allocated to the three investment categories in this topic area.

E.4 Conclusions

The ideas and themes developed during the three breakout sessions at the Deep Vadose Zone Forum were evaluated by a structured process that encouraged all of the participants to provide their feedback through the investment of vadose bucks in a research portfolio of their own choosing. There was a general consensus that investment in all of the overarching topics—characterization and monitoring, processes and predictive modeling, and access and remediation—are important, but there was significant variation in investments among the Forum participants and even within identified demographic subgroups. The investment allocations and free-form comments provide insights that enhance the value of the Deep Vadose Zone Technical Forum for the U.S. Department of Energy.