U.S. Department of Energy
Hanford Site

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TECHNOLOGY EVALUATION AND TREATABILITY STUDIES ASSESSMENT FOR THE HANFORD CENTRAL PLATEAU DEEP VADOSE ZONE, DOE/RL-2017-58, REVISION 0

This letter transmits the Technology Evaluation and Treatability Studies Assessment for the Hanford Central Plateau Deep Vadose Zone, DOE/RL-2017-58, Revision 0 to the Washington State Department of Ecology and the U.S. Environmental Protection Agency.

This document identifies additional laboratory tests that have potential to assist in remediation of the deep vadose zone. The performance of these multi-year laboratory tests will be performed in accordance with the priorities identified in the Integrated Priority List.

The Review Comment Record is also provided for your information.

If you have any questions, please contact me, or your staff may contact, Mike Cline, of my staff, on (509) 376-6070.

Sincerely,

William F. Hamel, Assistant Manager
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DOE/RL-2017-58
Revision 0

TECHNOLOGY EVALUATION AND TREATABILITY STUDIES ASSESSMENT FOR THE HANFORD CENTRAL PLATEAU DEEP VADOSE ZONE

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
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Approved for Public Release;
Further Dissemination Unlimited

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Assistant Secretary for Environmental Management

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Executive Summary

Over decades of operation, the U.S. Department of Energy (DOE) and its predecessors have released nearly 2 trillion L (450 billion gal) of liquid into the vadose zone at the Hanford Site. Much of this liquid waste discharged into the vadose zone occurred in the Central Plateau, a 190 km^2 (75 mi^2) area that includes approximately 800 waste sites. Some of the inorganic and radionuclide contaminants have migrated to the deep vadose zone (DVZ) to depths where direct exposure pathways are not of concern but may need to be remediated to protect groundwater (DOE/RL-2007-56 [hereinafter called the DVZ Treatability Test Plan];[1] Dresel et al., 2011[2]). The Central Plateau DVZ begins at a depth of approximately 15 m (50 ft) below ground surface (bgs) and extends to the top of the groundwater, approximately 76 m (250 ft) bgs.

Purpose

This document provides a comprehensive evaluation of currently available DVZ technologies, building upon previous Hanford Site technology evaluation studies and workshops as well as literature searches, and recent treatability testing (conducted per the DVZ Treatability Test Plan [DOE/RL-2007-56]) to identify additional relevant technology development and demonstration activities outside of the Hanford Site. These technologies were assessed to identify data needed to support remedial technology screening and alternative evaluation, and recommends additional treatability studies for the most promising DVZ technologies. The evaluation considered the potential need for laboratory, modeling, or field studies to provide suitable information for future feasibility studies (FSs) for the 200-DV-1 Operable Unit (OU) and other source OUs in the Hanford Site Central Plateau. The 200-DV-1 OU consists of 43 waste sites in the B Complex, S Complex, and T Complex, and includes a zone of perched water below B Complex near the B-BX-BY Tank Farms. The technology evaluations performed herein do not screen out any remedial technologies for consideration in future FSs/corrective measures studies (CMSs). The fact that technologies are not recommended for treatability studies (e.g., excavation) does not imply these are considered poor remedial technologies. All

[1] DOE/RL-2007-56, 2008, *Deep Vadose Zone Treatability Test Plan for the Hanford Central Plateau*, Rev. 0, U.S. Department of Energy, Richland Operations Office, Richland, Washington. Available at: http://pdw.hanford.gov/arpir/index.cfm/viewDoc?accession=0804160110.

[2] Dresel, P.E., D.M. Wellman, K.J. Cantrell, and M.J. Truex, 2011, "Review: Technical and Policy Challenges in Deep Vadose Zone Remediation of Metals and Radionuclides," *Environ. Sci. Technol.* 45(10):4207-4216.

applicable DVZ remediation technologies will be included in the FS evaluations for DVZ waste sites.

This report also summarizes the results and conclusions of treatability testing conducted under the DVZ Treatability Test Plan, which identified treatability studies for six technologies for remediating technetium-99 and uranium in the DVZ. Results from those treatability tests were included in this technology evaluation and treatability study assessment.

Conclusions

Comprehensive evaluation of vadose zone technologies identified a list of technologies to consider when assembling remedial alternatives for the 200-DV-1 OU and other Hanford Site Central Plateau vadose zone OU FSs. A preliminary assessment of the effectiveness, implementability, and applicability of these technologies to Central Plateau DVZ treatment areas and contaminants of interest (COIs) was conducted to identify data needs to support technology screening and alternative evaluation in future FSs. This document provides recommendations for technologies where additional information on treatment effectiveness is needed to supplement existing technology information to evaluate effectiveness, implementability, and cost (EIC) in an FS.

The technology evaluation and associated treatability study recommendations are based on the current general understanding of the nature and extent, fate and transport, and risk to groundwater of the vadose zone contamination. The 200-DV-1 OU Remedial Investigation (RI)/ FS and Resource Conservation and Recovery Act Facility Investigation (RFI)/CMS will determine which waste sites and contaminants pose a risk to groundwater.

The information from the recommended treatability studies needs to be obtained so these technologies can be appropriately evaluated in the FS to expand on the limited number of viable DVZ remediation technologies. The treatability study assessment concluded the need for the following field and laboratory scale information:

- Laboratory studies to determine the effectiveness and scale-up potential for particulate-phase and liquid-phase in situ technologies are needed to support evaluation of contaminant sequestration approaches for perched water.

- Laboratory studies of the same technologies selected for the perched water, but using the geochemical conditions relevant for the water table, are needed to support evaluation of injecting a permeable reactive barrier at the water table interface with the vadose zone. This information will enable evaluation of this approach as a potential option for locations where contaminants in the vadose zone are at or near the water table.

- Limited number of in situ technologies to sequester or degrade contaminants were identified for use in the unsaturated portion of the DVZ. Three technologies have potential for applicability based on available technical information, but data are not available to determine their effectiveness for specific Hanford Site applications. Laboratory studies are needed to provide information to evaluate the effectiveness of these candidate technologies in an FS.

- To support an evaluation of surface barriers, modeling based on existing field data is needed to quantitatively relate barrier size and placement to the effective depth for mitigating DVZ contamination.

The additional laboratory and modeling treatability studies recommended in this report will likely provide enough information to perform remedial alternative evaluations in the FS. The information obtained for technology effectiveness from the treatability studies, when combined with the other available technology information, will likely be sufficient for evaluating these technologies in the FS. After completing the laboratory studies and the 200-DV-1 OU RI (and RFI), results will be evaluated to determine whether field studies are needed to provide additional information on effectiveness, implementability, or costs for evaluating these technologies in the FS.

While the need for field studies was considered for all technologies, no additional field studies are recommended at this time because either the technology:

- Is already sufficiently mature for consideration in an FS

- Has poor effectiveness or implementability

- Has limited applicability that requires identification of an appropriate waste site during the RI (and RFI) process
- Has identified data gaps that can be addressed through laboratory or modeling studies to enable their consideration in an FS

While no field studies are recommended at this time as described above, the need for field studies will be evaluated based on the results of the recommended laboratory studies and completion of the remedial investigations of the waste sites. Because only limited laboratory and modeling studies were identified, it is recommended that the 200-DV-1 OU RI/FS and RFI/CMS and these additional treatability studies be conducted concurrently. This is important because the RI/FS will help to identify the waste sites that have the potential for future groundwater contamination.

This document also summarizes the results and recommendations from the treatability studies performed under the DVZ Treatability Test Plan (DOE/RL-2007-56) and fulfills the requirement of the test plan for a final evaluation of the treatability effort. One follow-on study was identified to provide refined surface barrier information that will enable this technology to be effectively evaluated in an FS. All other technologies studied in the DVZ Treatability Test Plan have suitable information for direct consideration in an FS evaluation.

Recommendations

The following modeling and laboratory studies are recommended from this evaluation to provide enough information to perform remedial alternative evaluations in the FS:

- Initiate a modeling study based on existing field data to assess surface barrier design to correlate surface barrier size and placement to depth of barrier effectiveness.
- Initiate laboratory studies to assess effectiveness of in situ gas-phase technologies for contaminants in the unsaturated DVZ.
- Initiate laboratory studies of in situ technologies to sequester contaminants in the perched water to expand remedial alternatives beyond the current response action.
- Initiate laboratory studies of in situ technologies to sequester contaminants at the water table to enable evaluation of this approach for locations where contaminants in the vadose zone are at or near the water table.

Table ES-1 summarizes the recommended treatability studies and provides examples of waste sites in 200-DV-1 and other Hanford Site Central Plateau OUs that these technologies could be applied to if the studies show they are effective and implementable. The 200-DV-1 OU perched water and BY Cribs are likely continuing sources of technetium-99 and uranium to groundwater, but these waste sites and the other listed waste sites need to be evaluated in the RI process to assess potential impacts to groundwater.

Table ES-1. Recommended Studies and Potential Site Applications

Technology Process Option	COI to Study	Examples of Potentially Applicable 200-DV-1 Waste Sites	Examples of Other Potentially Applicable Waste Sites
Laboratory quantification of effectiveness is needed for use in combination with existing field-scale information from other sites to evaluate these technologies in a feasibility study			
Technologies for Unsaturated Zone Applications			
Gas-phase combined bioreduction and chemical sequestration	**Tc-99**	BY Cribs [a]	BC Cribs and Trenches [b]
Gas-phase bioremediation	**Nitrate**	Unknown [b]	Unknown [b]
	CN	BY Cribs [a]	Unknown [b]
	Cr(VI)	Unknown [b]	216-S-10 [b], 216-S-8 [b], 216-T-4a [b]
Gas-phase chemical sequestration	**I-129**	Unknown [b]	216-A-10 [b], 216-A-5 [b], 216-S-7 [b]
Technologies for the 200-DV-1 Perched Water and Use as a Horizontal Permeable Reactive Barrier at the Water Table			
Particulate-phase chemical sequestration	**U and Tc-99**	Perched Water [a], below Perched Water [a], and below BY Cribs [a]	216-U-1&2 [a], S-SX Tank Farm [a], C Tank Farm [a], BC Cribs and Trenches [b]
	Cr(VI)	Unknown [b]	216-S-10 [b], 216-S-8 [b], 216-T-4a [b]
	I-129	Unknown [b]	216-A-10 [b], 216-A-5 [b], 216-S-7 [b]
Particulate-phase combined chemical reduction and sequestration	**U and Tc-99**	Perched Water [a], below Perched Water [a], and below BY Cribs [a]	216-U-1&2 [a], S-SX Tank Farm [a], C Tank Farm [a], BC Cribs and Trenches [b]
Liquid-phase chemical sequestration	**U and Tc-99**	Perched Water [a], below Perched Water [a], and below BY Cribs [a]	216-U-1&2 [a], S-SX Tank Farm [a], C Tank Farm [a], BC Cribs and Trenches [b]
	Cr(VI)	Unknown [b]	216-S-10 [b], 216-S-8 [b], 216-T-4a [b]
	I-129	Unknown [b]	216-A-10 [b], 216-A-5 [b], 216-S-7 [b]
Liquid-phase combined chemical reduction and sequestration	**U and Tc-99**	Perched Water [a], below Perched Water [a], and below BY Cribs [a]	216-U-1&2 [a], S-SX Tank Farm [a], C Tank Farm [a], BC Cribs and Trenches [b]

Table ES-1. Recommended Studies and Potential Site Applications

Technology Process Option	COI to Study	Examples of Potentially Applicable 200-DV-1 Waste Sites	Examples of Other Potentially Applicable Waste Sites
Liquid-phase combined bioreduction and chemical sequestration	**U, Tc-99, nitrate**	Perched Water [a], below Perched Water [a], and below BY Cribs [a]	216-U-1&2 [a], S-SX Tank Farm [a], C Tank Farm [a], BC Cribs and Trenches [b]
	CN	BY Cribs [a]	Unknown [b]
Model/Paper Study to Support Barrier Design			
Surface barrier: relate surface barrier size to depth of barrier effectiveness	All	Unknown [b]	Unknown [b]
No field studies are recommended at this time. The need for field studies will be evaluated based on results of the above treatability studies and waste site investigations			
None identified	N/A	N/A	N/A

Note: Bolded COIs are primary known contaminant targets. Other COIs are potential co-contaminants to evaluate with primary COIs.

a. These are likely continuing sources of contaminants to groundwater.

b. The remedial investigation evaluation will determine the waste sites that impact groundwater.

COI = contaminant of interest

DVZ = deep vadose zone

N/A = not applicable

The recommended laboratory studies are anticipated to take 2 to 3 years to implement from the time of sediment sample receipt until reporting of results and should be completed to support submission of the 200-DV-1 OU FS to regulatory agencies for their review by 2023. The surface barrier modeling/paper study is anticipated to take less than a year to fully evaluate.

Technology Evaluation and Treatability Study Assessment Approach

To provide a comprehensive evaluation of available DVZ technologies, the DVZ technologies compiled from previous Hanford Site studies and workshops (which culminated in the tables presented in Appendix A of SGW-50339[3]) were used as a starting point. This list was augmented by performing a literature search to identify additional relevant technology development and demonstration activities conducted since 2011 at the Hanford Site, other DOE facilities, and other federal agencies and environmental remediation resources (e.g., U.S. Environmental Protection Agency,

[3] SGW-50339, 2011, *Remediation Technologies Screening Report for the Deep Vadose Zone, Hanford's Central Plateau*, Rev. 0, CH2M HILL Plateau Remediation Company, Richland, Washington. Available at: https://pdw.hanford.gov/arpir/index.cfm/viewDoc?accession=0064784H.

U.S. Department of Defense, Federal Remediation Technologies Roundtable's Remediation Technology Screening Matrix) and combined into a list of potentially implementable DVZ technologies.

The DVZ technologies were evaluated to provide a range of viable remediation technologies to develop remedial alternatives for FSs and to identify promising remediation technologies that require further treatability testing. The technologies were evaluated with respect to the known EIC information, similar to the technology screening performed in an FS. Evaluation of effectiveness considered the degree to which a technology reduces toxicity, mobility, or volume through treatment, minimizes residual risks and affords long-term protectiveness and permanence, minimizes short-term impacts, and how quickly it achieves protectiveness. For this evaluation, a preliminary list of COIs was generated based on higher mobility contaminants in the Central Plateau groundwater, from process knowledge of Hanford Site operations, and from available vadose zone characterization data (e.g., characterization of 200-DV-1 completed in 2018 in accordance with DOE/RL-2011-102[4]).

Four treatment areas were identified to represent various stratigraphy and deployment characteristics to assess the implementability of the remediation technologies. The four treatment areas are higher permeability zones, lower permeability zones, perched water zones, and water table interface zones. This qualitative approach assessed relative strengths and weaknesses of technologies for each COI and treatment area to determine which technologies may warrant treatability studies. Technology data needs were then identified using the information compiled in the technology EIC evaluation. Based on the identified data need, the type of treatability study required to address this need was determined based on what would be required for input to an FS. This assessment included considering the potential need for laboratory, modeling, or field studies to provide suitable information for FSs for the 200-DV-1 OU and other vadose zone OUs in the Hanford Site Central Plateau.

Closeout of Previous Treatability Test Plan Activities

The DVZ Treatability Test Plan (DOE/RL-2007-56) submitted pursuant to Milestone M-015-50, *Hanford Federal Facility Agreement and Consent Order*, provided

[4] DOE/RL-2011-102, 2016, *Remedial Investigation/Feasibility Study and RCRA Facility Investigation/Corrective Measures Study Work Plan for the 200-DV-1 Operable Unit*, Rev. 0, U.S. Department of Energy, Richland Operations Office, Richland, Washington. Available at: http://pdw.hanford.gov/arpir/index.cfm/viewDoc?accession=0075538H.

a strategy and a framework to evaluate specific vadose zone remediation technologies and included evaluation criteria for a comprehensive set of laboratory, modeling, and field tests. This document fulfills the requirement of the DVZ Treatability Test Plan to summarize the final results and recommendations of those treatability study efforts. The scope of the DVZ Treatability Test Plan focused on technetium-99 and uranium, because these contaminants are mobile in the subsurface environment compared to other DVZ contaminants and have been detected at high concentrations deep in the vadose zone, as well as in groundwater. Testing of technologies for remediation of technetium-99 and uranium also provided information relative to remediation of other contaminants in the DVZ.

The treatability studies performed under the DVZ Treatability Test Plan (DOE/RL-2007-56) were conducted to obtain technical performance data for full-scale use of a technology at the Hanford Site and provide a technical basis to evaluate the technology as part of a remedy when developing and screening remedial alternatives in FSs. The strategy focused on testing the most promising in situ treatment and surface barrier technologies as determined based on several technology evaluation efforts at the Hanford Site as a first step in considering technologies for the DVZ. The technologies selected for inclusion in the test plan and the results and conclusions of those treatability studies are summarized in Table ES-2. The results, conclusions, and recommendations of the treatability evaluations performed in the DVZ Treatability Test Plan (DOE/RL-2007-56) are provided in Table ES-2.

Table ES-2. Treatability Test Plan Results, Conclusions, and Recommendations

Treatability Study	Technology Description	Treatability Results, Conclusions, and Recommendations
Desiccation	Desiccation involves injecting dry air to evaporate soil moisture from the contaminated zone to augment the impact of a surface barrier to impede water movement and the transport of contaminants into groundwater. Desiccation has a limited impact on contaminant concentrations, so long-term effectiveness relies on limiting moisture recharge.	Desiccation is considered a viable technology for remediation of most COIs except organics in the DVZ. It is ready for FS evaluations, and no further treatability studies are recommended. Desiccation is potentially applicable for all unsaturated zone sites.
In Situ Gaseous Reduction	A reducing gas (e.g., hydrogen sulfide) is used to directly reduce some contaminants and render them less soluble while they remain reduced or can reduce sediment-associated iron, which can subsequently reduce contaminants.	In situ gaseous reduction was evaluated as an option for field testing, but was not tested in favor of testing desiccation and URGS. This decision was informed by a modeling and experimental study indicating poor longevity of the reducing conditions on which this technology relies in the vadose zone.

Table ES-2. Treatability Test Plan Results, Conclusions, and Recommendations

Treatability Study	Technology Description	Treatability Results, Conclusions, and Recommendations
Multi-Step Geochemical Manipulation	Geochemical manipulation uses amendments that cause dissolution and then precipitation of the target contaminant or combine oxidation-reduction reactions with other chemical reactions to immobilize/encapsulate the target contaminant.	The goal of this laboratory study was to select a gas-phase technology for field testing. The testing showed ammonia (NH_3) was the most promising gas-phase approach and led to the URGS studies. There is no additional continuation from this specific treatability test component.
	Uranium reactive gas sequestration (URGS): Gas phase ammonia is injected into the contaminated zone to create alkaline pore water conditions that dissolve aluminosilicates. Re-precipitation that occurs as the system buffers back toward pre-injection conditions creates uranium silicates and coats some uranium with aluminosilicates, decreasing uranium mobility.	Technology limitations were identified during baseline laboratory testing and analysis that was conducted as part of the treatability study using sediment samples obtained from the 216-U-8 field test site. These tests showed that ammonia treatment did not reduce uranium mobility as intended, and in many of the samples, resulted in increased uranium mobility. Because of these test results, field testing activities were stopped and ammonia injection was not conducted. URGS has limited applicability because (1) the treatment chemistry is sensitive to site geochemical conditions, (2) significant laboratory efforts to ensure effectiveness for a specific site are needed prior to field implementation, (3) there are implementation risks from handling and monitoring the reactive gas (ammonia), and (4) the treatment process adds nitrate to the subsurface, which may be problematic at locations where nitrate could potentially reach the groundwater at concentrations above levels of concern. There are 11 sites on the Hanford Central Plateau where a high inventory of uranium was discharged: 5 had a waste discharge with neutral to basic pH and URGS would likely not have the same type of limitations observed at the field test site; 6 sites had acidic discharge (including the 216-U-8 site) and URGS would likely have poor effectiveness. Because of the technological limitations and few applicable waste sites, it is recommended that no URGS field studies be conducted at this time.
Subsurface Grout Injection	Grout injection reduces subsurface contaminant mobility by injecting grout or a binding agent into the subsurface to physically/chemically bind or encapsulate contaminants.	Permeation grouting was found to have a limited radius of influence for the unsaturated zone; therefore, it rated poorly for implementability. It is not recommended for widespread treatment of contaminants. No additional activities are needed to support consideration of subsurface grouting in FSs.
Soil Flushing	Soil flushing operates by adding water and, if necessary, a surfactant or lixiviant to mobilize contaminants and flush them from the vadose zone and into the groundwater where they are subsequently captured by a pump and treat system.	Modeling and literature information for soil flushing showed that there are potential issues with flushing the thick Central Plateau vadose zone, primarily due to the potential for lateral spreading of the flushing solution and associated contaminants. Therefore, it rated poorly for implementability and is not recommended for most applications in the DVZ of the Hanford Central Plateau. It is ready for FS evaluations, and no further treatability studies are recommended.

Table ES-2. Treatability Test Plan Results, Conclusions, and Recommendations

Treatability Study	Technology Description	Treatability Results, Conclusions, and Recommendations
Surface Barriers	Surface barriers reduce water infiltration, which diminishes the hydraulic driving force for contaminant migration downward through the vadose zone to the groundwater.	The treatability study provided baseline information for surface barrier evaluation. However, as noted in the study, an additional modeling assessment is needed and is recommended to better define the effective depth and areal extent of the barrier in support of FS evaluations. Surface barriers are recommended for consideration in an FS as a stand-alone technology or in conjunction with desiccation to address most COIs.

COI = contaminant of interest
DVZ = deep vadose zone
FS = feasibility study
URGS = uranium reactive gas sequestration

Contents

1 Introduction 1-1

1.1 Purpose 1-1

1.2 Objectives 1-4

1.3 Regulatory Context 1-4

1.4 Integration of Central Plateau Operable Units and Waste Management Areas 1-6

1.4.1 Central Plateau Source Operable Units 1-7

1.4.2 Central Plateau Groundwater Operable Units 1-7

1.4.3 Tank Farm Waste Management Areas 1-9

1.5 Report Organization 1-9

2 Environmental Setting and Background 2-1

2.1 Environmental Setting 2-1

2.1.1 Physiography and Topography 2-1

2.1.2 Climate and Meteorology 2-2

2.1.3 Geologic Setting 2-2

2.1.4 Hydrogeology 2-5

2.1.5 Hydrogeologic Perching Zones 2-6

2.2 Central Plateau Deep Vadose Zone Contamination 2-6

2.2.1 Identification of Groundwater Contaminants of Interest 2-7

2.2.2 Groundwater Impacts Analysis 2-10

2.2.3 Contaminant Attenuation and Transport Characterization 2-11

2.3 Description of Treatment Areas 2-11

3 Deep Vadose Zone Technology Review 3-1

3.1 Deep Vadose Zone Treatability Test Summaries and Recommendations 3-1

3.1.1 Desiccation Field Test 3-1

3.1.2 In Situ Gaseous Reduction 3-4

3.1.3 Uranium Reactive Gas Sequestration Field Test 3-5

3.1.4 Multi-Step Geochemical Manipulation 3-8

3.1.5 Grout Injection 3-10

3.1.6 Soil Flushing 3-11

3.1.7 Surface Barriers 3-13

3.1.8 Treatability Test Plan Closeout 3-14

3.2 Summary of Previous DVZ Technology Evaluations 3-16

3.3 Additional Deep Vadose Zone Technology Identification 3-17

3.4 Summary of Remedial Technologies Applicable to the Hanford Deep Vadose Zone 3-18

4 Deep Vadose Zone Remediation Technology Evaluation 4-1

4.1 Deep Vadose Zone Technology Evaluation Criteria 4-2

4.2 Deep Vadose Zone Technology Evaluation 4-3

5 Deep Vadose Zone Treatability Study Assessment Conclusions and Recommendations 5-1

5.1 Deep Vadose Zone Treatability Study Assessment Determination 5-1

5.2 Recommendations for Additional Treatability Studies 5-12

5.2.1 Containment Technologies 5-14

5.2.2 Removal Technologies 5-14

5.2.3 Ex Situ Technologies 5-14

5.2.4 In Situ Technologies 5-14

5.3 Conclusion 5-17

6 References 6-1

Appendices

A Deep Vadose Zone Science and Technology Advances ..... A-i

B Deep Vadose Zone Technology Summary Tables ..... B-i

Figures

Figure 1-1. Hanford Site 1-2

Figure 1-2. Operable Units in the Central Plateau 1-3

Figure 1-3. Groundwater Operable Units 1-8

Figure 2-1. Generalized Geologic Structure Map of the Pasco Basin 2-1

Figure 2-2. Stratigraphic and Hydrostratigraphic Columns for the Central Plateau 2-3

Figure 2-3. Overview of Central Plateau Groundwater OUs and Contaminant Concentrations 2-8

Figure 2-4. Sitewide Groundwater Contaminant Plumes, 2016 2-9

Figure 2-5. Central Plateau Waste Sites with Contamination Known or with Potential to Impact Groundwater 2-10

Figure 2-6. Inner Area Section Locations 2-12

Figure 2-7. North-South Section View of 200 East Area 2-13

Figure 2-8. North-South Section View of 200 West Area 2-13

Figure 2-9. Southwest-Northeast Section View of 200-DV-1 OU Perched Water 2-14

Figure 2-10. Emplacing a Horizontal Permeable Reactive Barrier on Top of the Water Table 2-15

Figure 3-1. Conceptual Depiction of Desiccation and a Surface Barrier 3-2

Figure 3-2. Overview of the Processes That Occur with Injection of Ammonia Vapor into an Unsaturated Uranium-Contaminated Hanford Site Sediment 3-6

Figure 4-1. Deep Vadose Zone Technology Evaluation and Treatability Assessment Process 4-1

Tables

Table 1-1. Central Plateau Groundwater and Source OUs 1-6
Table 2-1. Summary of Deep Vadose Zone Contaminants of Interest 2-7
Table 3-1. Treatability Test Plan Conclusions and Recommendations 3-15
Table 4-1. Evaluation of Technology Effectiveness by COI 4-5
Table 4-2. Technology Implementability and Cost Evaluation 4-14
Table 4-3. Technology Effectiveness, Implementability and Cost Evaluation Summary 4-21
Table 5-1. Treatability Study Determination 5-3
Table 5-2. Technology Applicability 5-9
Table 5-3. Recommended Technologies to Consider for Feasibility Studies 5-11
Table 5-4. Recommended Studies and Potential Site Applications 5-12

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Terms

bgs	below ground surface
CCU	Cold Creek unit
CCU_c	Cold Creek unit caliche
CCU_g	Cold Creek unit gravel
CCU_z	Cold Creek unit silt
CERCLA	*Comprehensive Environmental Response, Compensation, and Liability Act of 1980*
COC	contaminant of concern
COI	contaminant of interest
DOE	U.S. Department of Energy
DVZ	deep vadose zone
Ecology	Washington State Department of Ecology
EIC	effectiveness, implementability, and cost
EPA	U.S. Environmental Protection Agency
ESTCP	Environmental Security Technology Certification Program
FS	feasibility study
Hf	Hanford formation
Hf1	Hanford formation unit 1
Hf2	Hanford formation unit 2
Hf3	Hanford formation unit 3
HMS	Hanford Meteorological Station
INGR	in situ gaseous reduction
MNA	monitored natural attenuation
NCP	National Contingency Plan
NPL	National Priorities List
OU	operable unit
P&T	pump and treat
PRB	permeable reactive barrier
RCRA	*Resource Conservation and Recovery Act of 1976*

REDOX	Reduction Oxidation (Plant)
RFI/CMS	RCRA Facility Investigation/Corrective Measures Study
RI/FS	remedial investigation/feasibility study
ROD	record of decision
Rtf	Ringold Formation member of Taylor Flat
Rwie	Ringold Formation member of Wooded Island – unit E
SST	single-shell tank
Tri-Party Agreement	*Hanford Federal Facility Agreement and Consent Order*
TSD	treatment, storage, and disposal
URGS	Uranium Reactive Gas Sequestration
WMA	waste management area
WP	work plan

1 Introduction

The U.S. Department of Energy (DOE) Hanford Site is a 1,500 km^2 (580 mi^2) federal facility located in southeastern Washington State along the Columbia River (Figure 1-1). For administrative purposes, the Hanford Site was divided into four National Priorities List (NPL) sites in 1989 (Appendix B of 40 CFR 300, "National Oil and Hazardous Substances Pollution Contingency Plan," hereinafter called the National Contingency Plan [NCP]) under the *Comprehensive Environmental Response, Compensation, and Liability Act of 1980* (CERCLA). One of the four NPL sites is the 200 Area. In anticipation of the NPL listing, DOE, the U.S. Environmental Protection Agency (EPA), and the State of Washington (through the Washington State Department of Ecology [Ecology]) entered into the *Hanford Federal Facility Agreement and Consent Order* (Tri-Party Agreement) (Ecology et al., 1989) in May 1989. This agreement established a procedural framework and schedule for developing, implementing, and monitoring CERCLA response actions at the Hanford Site. The agreement also addresses *Resource Conservation and Recovery Act of 1976* (RCRA) compliance and permitting.

The 200 Area NPL site, which is commonly referred to as the Central Plateau, encompasses approximately 190 km^2 (75 mi^2) near the center of the Hanford Site and contains multiple waste sites, contaminated facilities, and groundwater contamination plumes. The CERCLA site identification number for the 200 Area is No. WA1890090078. To facilitate cleanup, these waste sites, facilities, and groundwater plumes have been grouped by geographic areas, process types, or cleanup components into several operable units (OUs).

A majority of waste sites with deep vadose zone (DVZ) contamination in the Central Plateau are assigned to the 200-DV-1, 200-EA-1, 200-WA-1, and 200-BC-1 OUs. This document supports DOE/RL-2011-102, *Remedial Investigation/Feasibility Study and RCRA Facility Investigation/Corrective Measures Study Work Plan for the 200-DV-1 Operable Unit* (hereinafter called the 200-DV-1 remedial investigation/feasibility study [RI/FS] and RCRA Facility Investigation/Corrective Measures Study [RFI/CMS] work plan [WP]) efforts, but the information is also relevant to other OUs within the Central Plateau with DVZ contamination. Figure 1-2 shows the location of Central Plateau vadose zone source OUs. The DOE Richland Operations Office is the lead agency for remediation of the Central Plateau source OUs, including the 200-DV-1 OU. Section 5.1 and Appendix C of the Tri-Party Agreement (Ecology et al., 1989) identify the lead regulatory agency for each OU. Ecology is the lead regulatory agency for the 200-DV-1 and 200-EA-1 OUs. EPA is the lead regulatory agency for remediation of the 200-WA-1 and 200-BC-1 OUs.

1.1 Purpose

This document addresses the requirement from the 200-DV-1 RI/FS and RFI/CMS WP (DOE/RL-2011-102) to identify appropriate treatability testing in support of the upcoming feasibility study (FS), as well as providing input for future remedy selection efforts at other Central Plateau source OUs with waste sites that have DVZ contamination. It identifies additional potential DVZ treatment technologies for vadose zone contaminants on the Central Plateau that have the potential to impact groundwater and recommends additional treatability studies, where appropriate. This document summarizes and closes out the DVZ treatability studies performed under the DOE/RL-2007-56, *Deep Vadose Zone Treatability Test Plan for the Hanford Central Plateau* (hereinafter called the DVZ Treatability Test Plan).

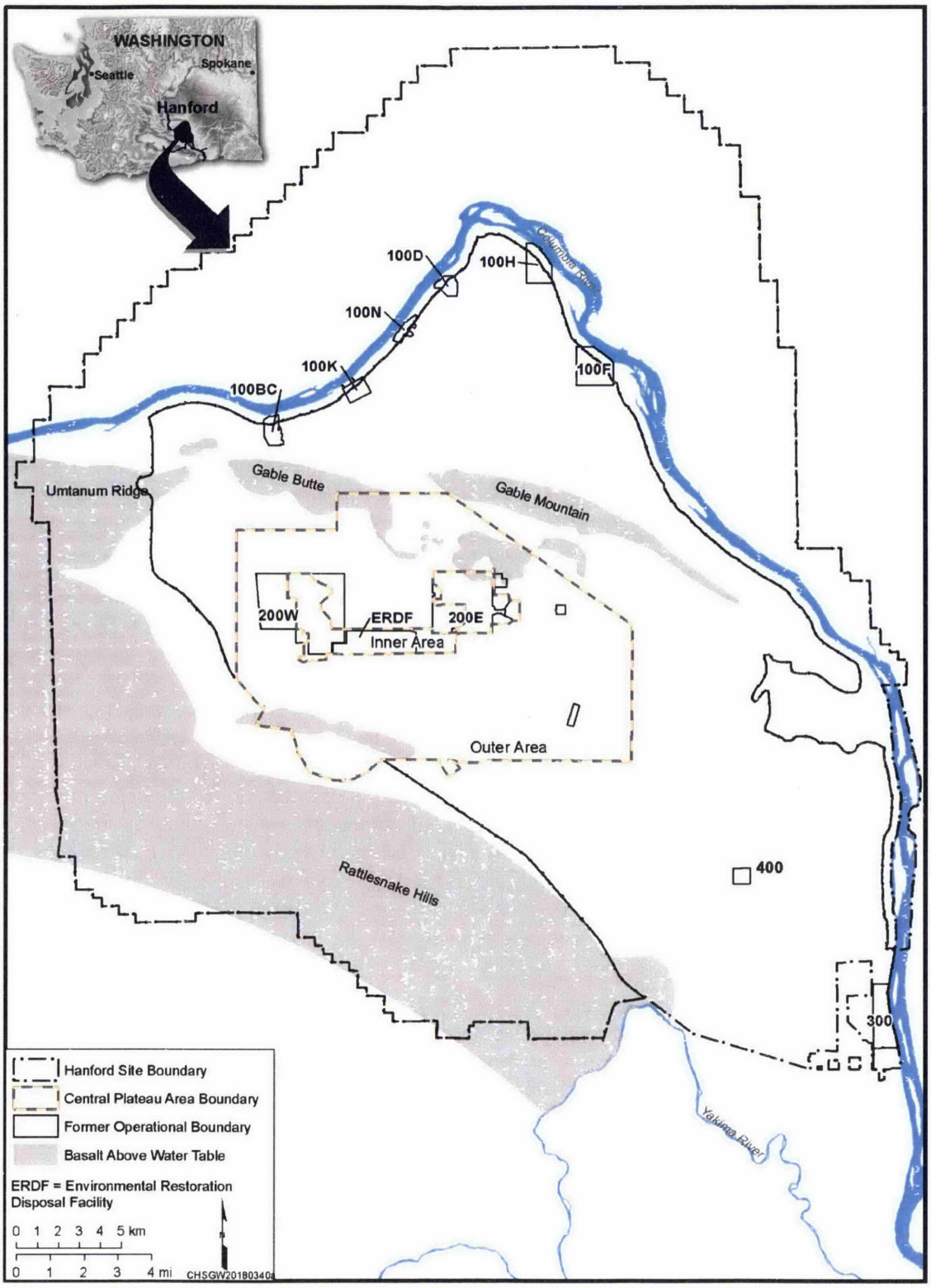


Figure 1-1. Hanford Site

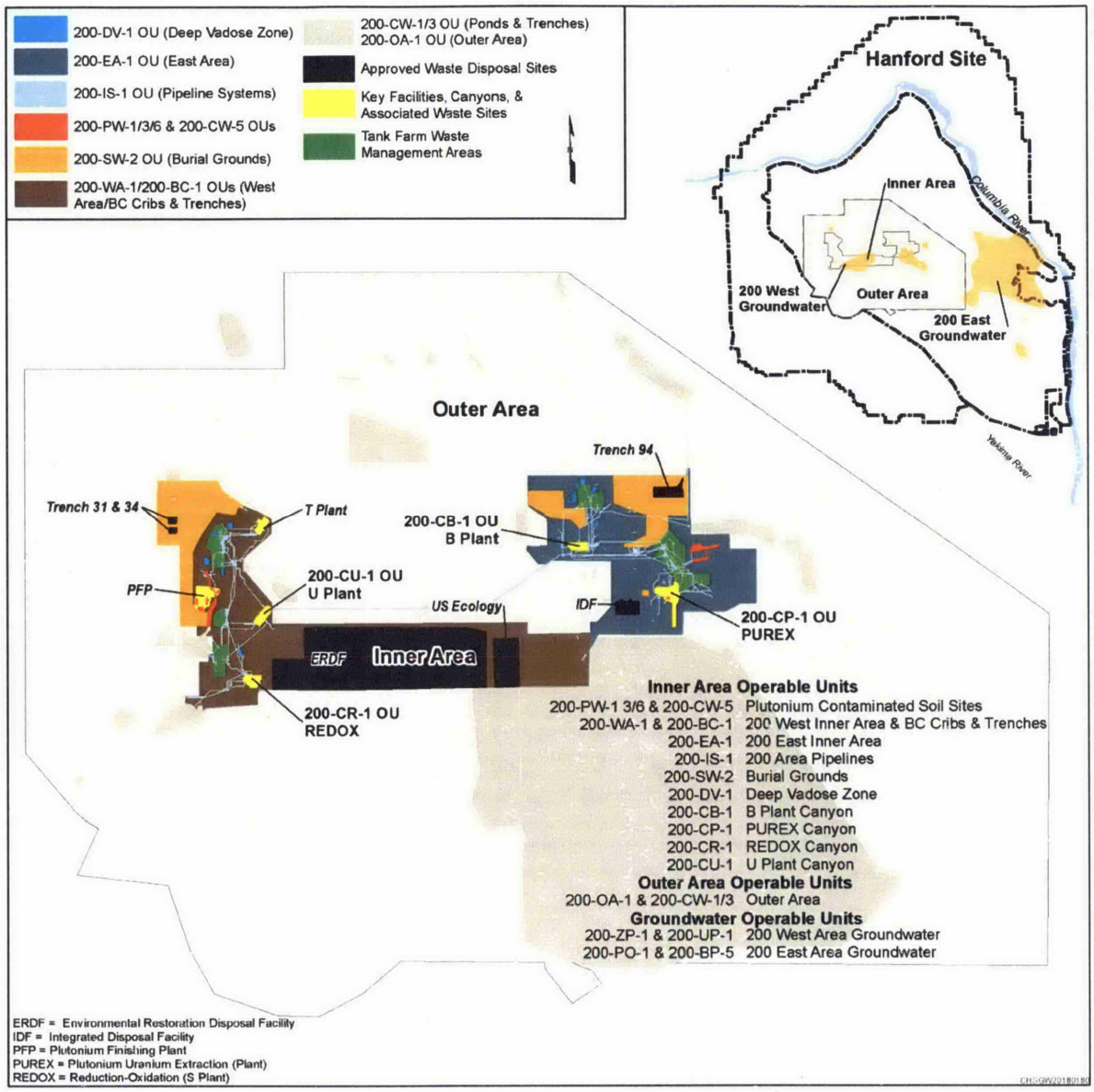


Figure 1-2. Operable Units in the Central Plateau

Technologies are evaluated with respect to the information available about their effectiveness, implementability, and cost (EIC) for the Central Plateau vadose zone contaminants and the treatment areas (stratigraphic units and the interface with the saturated zone) where these technologies can be deployed. The focus of treatability studies and technology evaluations provided in this document is limited to groundwater protection within the DVZ. As such, the evaluations do not address remediation of vadose soils to concentrations that meet cleanup levels for human health direct contact and ecological exposure scenarios within the upper 4.6 m (15 ft) of the vadose zone. For this report, the Central Plateau DVZ begins at a depth of approximately 15 m (50 ft) below ground surface (bgs) and extends to the top of the groundwater. The technology evaluations performed herein do not screen out any remedial technologies for consideration in future FS/CMSs and the fact that technologies are not recommended for

treatability studies (e.g., excavation) does not imply these are considered poor remedial technologies. All applicable DVZ remediation technologies will be included in the FS evaluations for DVZ waste sites.

1.2 Objectives

The 200-DV-1 RI/FS and RFI/CMS WP (DOE/RL-2011-102) specifies that following characterization of the waste sites, DVZ remediation technologies will be evaluated to identify potential technologies that could enhance future remediation and determine whether to conduct a treatability test to support remedy selection. The overall objective of the technology evaluations and treatability study assessment described in this report is to support the decision-making process for CERCLA Remedial Action and RCRA Corrective Action for DVZ waste sites on Hanford's Central Plateau, including those in the 200-DV-1 OU. To support this over-arching objective, this report focuses on the following elements:

- Define DVZ contamination treatment areas (categories of representative stratigraphic units and interfaces with the saturated zones described in Section 2.3) where remedial technologies may be needed for groundwater protection, including integration of the most recent characterization and attenuation/transport study results.
- Identify DVZ technology candidates for groundwater protection and describe their state of development.
- Assess DVZ technologies for application at the DVZ treatment areas and determine if sufficient information exists such that the EIC of each technology can be assessed to support future FS evaluations. Provide a list of recommended technologies to consider for FSs of DVZ contaminants in the designated treatment areas.
- Define remedial technology data gaps for DVZ treatment areas and determine whether additional treatability evaluations are needed to address those data gaps.
- Provide a final treatability test evaluation to close out the DVZ Treatability Test Plan (DOE/RL-2007-56).

1.3 Regulatory Context

This section discusses the role of treatability studies within the RCRA-CERCLA cleanup framework. This section also discusses this document's focus on pre-Record of Decision (ROD) treatability studies.

DOE's remediation activities are governed by CERCLA and the substantive requirements of RCRA and other environmental laws. It is DOE's policy to rely on the CERCLA process to meet the technical requirements of RCRA corrective action and the regulatory guidance documents cited within this document are primarily CERCLA guidance documents.

Treatability studies provide data to support technology screening and evaluation, remedy selection, and remedial design and implementation. Selection of remedial actions involves several risk management decisions. Uncertainties with respect to the performance, reliability, and cost of treatment alternatives underscore the need for well-planned, conducted, and documented treatability studies.

Treatability studies provide valuable site-specific data necessary to support Superfund/RCRA remedial/corrective actions and serve the following purposes:

- To support remedial technology screening and evaluation
- To aid in the selection of the remedy
- To aid in the design and implementation of the selected remedy

Treatability studies conducted during an RI/FS indicate whether a given technology can meet preliminary remedial goals for the site and provide important information to aid in remedy selection. Treatability studies conducted during remedial design/remedial action establish the design and operating parameters necessary to optimize technology performance and implement a sound, cost-effective remedy.

Site characterization and treatability investigations are two of the main components of the RI/FS study process. As site and technology information is collected and reviewed, additional data needs for evaluating remedial action alternatives are identified. Treatability studies may be required to fill some of these data gaps.

In the absence of data in the available technical literature, treatability studies can provide the critical performance and cost information needed to evaluate and select treatment-based alternatives. The purpose of a treatability investigation performed prior to a ROD is to provide the data needed for technology screening and evaluation and to support the detailed analysis of alternatives in the FS. This report evaluates DVZ technologies to determine the need for treatability studies prior to the ROD to provide information needed in an FS and proposed plan to evaluate and select treatment-based alternatives.

In addition to the technical and scientific value of conducting tests, EPA and Ecology have formally requested that DOE evaluate and test technologies for remediation of DVZ contamination. In Ecology and EPA, 2004, "Treatability Investigations for Technetium-99," EPA and Ecology requested that DOE "develop a strategy for improved methods to understand the nature and extent of vadose zone contamination and to develop remedial options for addressing such contamination," specifically for technetium-99. Remedial technology evaluations have largely been addressed to date through literature reviews and conducting two technical workshops employing panels of outside experts with input solicited from the regulatory agencies. Significant efforts in the laboratory and in the field addressing the behavior of technetium-99 and uranium using specific remediation techniques have been completed to satisfy the requirements of the DVZ Treatability Test Plan (DOE/RL-2007-56).

Making cleanup decisions for the DVZ is complicated by the following factors:

- The Tri-Party Agreement (Ecology et al., 1989) has administratively segregated the investigation and decision making for source OUs from the groundwater OUs that may be affected by those sources.
- DVZ contamination is distributed across many different waste site OUs and tank farm waste management areas so there is not currently a single investigation or decision process addressing this problem.
- DVZ contamination from multiple sources, OUs, and areas under different regulatory authority is often commingled in the subsurface.
- The schedule for addressing potential tank farm sources in the DVZ currently occurs many years later than other sources, which may complicate early or delay final remedy decisions for contaminated groundwater.

1.4 Integration of Central Plateau Operable Units and Waste Management Areas

This section discusses the integration of Central Plateau OUs and waste management areas (WMAs). In 2010, the Tri-Parties (DOE, EPA, and Ecology) realigned the Central Plateau source OUs into 10 groups established per Tri-Party Agreement Change Package M-15-09-02, *Federal Facility Agreement and Consent Order Change Control Form: Modify Tri-Party Agreement M-15 Series Milestones for Central Plateau Waste Sites and Groundwater*. To facilitate consistent remedial decisions across the Central Plateau Inner Area, the Tri-Parties modified the Tri-Party Agreement in 2010 to restructure the Central Plateau remediation activities. Restructuring included consolidating some of the Inner Area waste sites into geographical area-based OUs, resulting in the creation of the 200-EA-1 and 200-WA-1 OUs, and retention of the 200-BC-1 OU (Figure 1-2). An additional OU, 200-DV-1, was created to include waste sites in the Inner Area with DVZ contamination. The Tri-Parties created the 200-DV-1 OU to address the challenges of cleaning up the deeper, mobile contamination in the Central Plateau. On the Central Plateau, the DVZ is defined as the region below the practical depth of surface remedy influence (e.g., shallow excavation or barriers) and above the regional aquifer. The Tri-Parties created the 200-DV-1 OU to support investigation and remedy selection for waste sites with DVZ contamination.

Table 1-1 lists the Central Plateau groundwater and source OUs. Figure 1-2 shows the CERCLA source OUs located in the Central Plateau Inner Area.

Table 1-1. Central Plateau Groundwater and Source OUs

OU	OU Type	Description
200-UP-1	Groundwater	Groundwater contamination in the southern 200 West Area and surrounding 600 Area primarily originating from U Plant and REDOX Plant waste sites.
200-ZP-1	Groundwater	Groundwater contamination in the northern 200 West Area and surrounding 600 Area primarily originating from T Plant and Plutonium Finishing Plant waste sites.
200-BP-5	Groundwater	Groundwater contamination in the northern 200 East Area and surrounding 600 Area primarily originating from B Plant.
200-PO-1	Groundwater	Groundwater contamination in the southern 200 East Area and surrounding 600 Area primarily originating from PUREX Plant.
200-DV-1	Source	Addresses waste sites with deep vadose zone contamination posing a threat to groundwater quality and for which standard surface-based remedies cannot be used. It currently consists of waste sites in the vicinity of WMA B-BX-BY in the 200 East Area, and WMA T, WMA TX-TY, and WMA S-SX in the 200 West Area, although other waste sites may be added in the future.
200-PW-1 200-PW-3 200-PW-6 200-CW-5	Source	Waste sites in the Inner Area contaminated primarily with plutonium and/or cesium.
200-WA-1 200-BC-1	Source	Majority of the waste sites in the 200 West Inner Area and the BC Cribs and Trenches.
200-EA-1 200-IS-1	Source	Majority of the waste sites in the 200 East Inner Area and pipelines in the Inner Area.

Table 1-1. Central Plateau Groundwater and Source OUs

OU	OU Type	Description
200-SW-2	Source	Burial grounds and landfills located in the Inner Area.
200-CB-1	Source	B Plant canyon and associated waste sites.
200-CP-1	Source	PUREX Plant canyon and associated waste sites.
200-CR-1	Source	REDOX Plant canyon and associated waste sites.
200-CU-1	Source	U Plant canyon and associated waste sites.
200-OA-1 200-CW-1 200-CW-3	Source	Waste sites located in the Outer Area.

OU = operable unit
PUREX = Plutonium Uranium Extraction (Plant)
REDOX = Reduction-Oxidation (Plant)
WMA = waste management area

The 200-DV-1 OU RI/FS and RFI/CMS WP (DOE/RL-2011-102) and subsequent decision documents must be closely integrated with the overall Hanford Site closure strategy. Integration with other regulatory programs and other OUs in the Inner Area are discussed in the following subsections. Specific ongoing sampling, analysis, and remedial action activities that are critical to the Central Plateau OU decision process are also discussed.

1.4.1 Central Plateau Source Operable Units

The current OUs in the Central Plateau Inner Area contain waste sites that received liquid wastes (200-EA-1 OU; 200-WA-1 OU and 200-BC-1 OU; 200-PW-1 OU, 200-PW-3 OU, 200-PW-6 OU, and 200-CW-5 OU; and 200-DV-1 OU); waste sites that received solid wastes (200-SW-2 OU); and waste sites associated with inactive waste transfer pipelines (200-IS-1 OU). The Inner Area also contains OUs for former processing plants (canyons) and associated waste sites. The OUs are shown in Figure 1-2.

While the source OUs in the Central Plateau are in various stages of the cleanup process, RODs have been published for interim or final remedial action at the 200-PW-1, 200-PW-3, 200-PW-6, and 200-CW-5 OUs (a grouping of primarily plutonium- and cesium-contaminated waste sites) (DOE/RL-2016-01, *Hanford Fourth CERCLA Five-Year Review Report*). DOE/RL-2010-49, *Remedial Investigation/Feasibility Study Work Plan for the 200-WA-1 and 200-BC-1 Operable Unit*, was approved in January 2017. DOE/RL-2011-102 was approved in July 2016. An RFI/CMS and an RI/FS work plan for the 200-IS-1 OU are currently being prepared.

A removal action for the 200-DV-1 OU is being implemented under DOE/RL-2014-34, *Action Memorandum for 200-DV-1 Operable Unit Perched Water Pumping/Pore Water Extraction*, and DOE/RL-2014-37, *Removal Action Work Plan for 200-DV-1 Operable Unit Perched Water Pumping/Pore Water Extraction.*

1.4.2 Central Plateau Groundwater Operable Units

Four groundwater OUs underlie the 200 Areas in the Central Plateau Inner Area: 200-BP-5, 200-PO-1, 200-UP-1, and 200-ZP-1. Figure 1-3 shows the groundwater OUs at the Hanford Site.

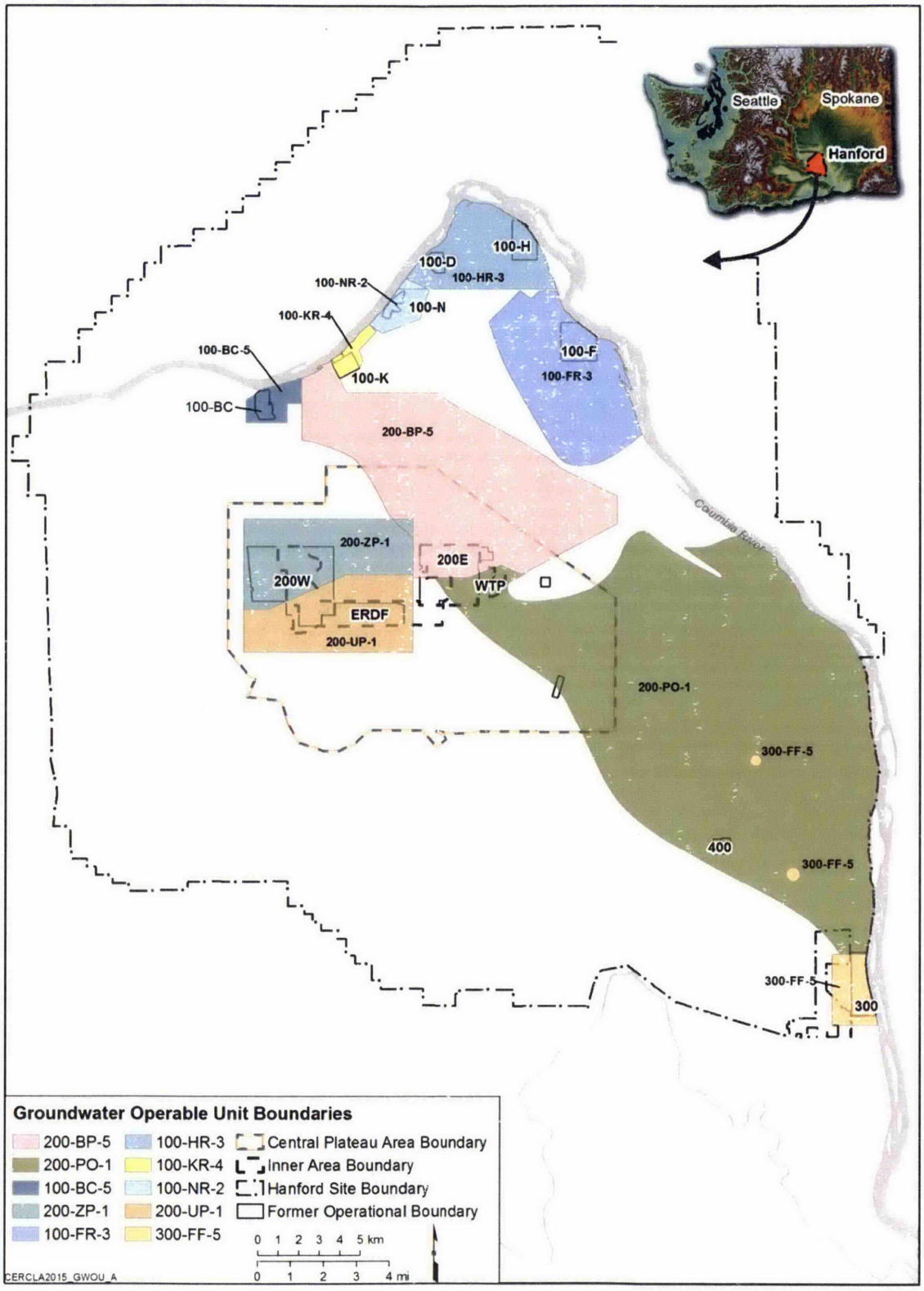


Figure 1-3. Groundwater Operable Units

Groundwater impacts resulted from discharges to waste sites and, in some cases, it is suspected that vertical transport was enhanced by poorly sealed nearby wells. Contaminants present in the four groundwater OUs originated from historical discharges to the Central Plateau waste sites.

A groundwater pump and treat (P&T) system was constructed to address contaminated groundwater present in the 200-ZP-1 and 200-UP-1 OUs. A ROD (EPA et al., 2008, *Record of Decision Hanford 200 Area 200-ZP-1 Superfund Site Benton County, Washington*) was issued in 2008, and an interim remedial action ROD (EPA et al., 2012, *Record of Decision for Interim Remedial Action Hanford 200 Area Superfund Site 200-UP-1 Operable Unit*) was issued in 2012. DOE/RL-2016-41, *Action Memorandum for 200-BP-5 Operable Unit Groundwater Extraction,* was issued in 2016 implementing a non-time critical removal action for the 200-BP-5 OU. A focused FS in support of an interim action at 200-BP-5 and 200-PO-1 is also being prepared.

Carbon tetrachloride, trichloroethene, total and hexavalent chromium (Cr(VI)), nitrate, technetium-99, iodine-129, and tritium are contaminants of concern (COCs) that were identified in the 200-ZP-1 and 200-UP-1 OUs. In addition, uranium has been identified as a COC in the 200-UP-1 OU. Uranium, technetium-99, iodine-1-29, tritium, strontium-90, cyanide, and nitrate have been identified as contaminants of interest (COIs) in the 200-BP-5 OU. Chapter 2 discusses the potential contaminant migration from Central Plateau vadose zone waste sites to the underlying groundwater.

1.4.3 Tank Farm Waste Management Areas

There currently are no RCRA treatment, storage, and disposal (TSD) units in the 200-DV-1 OU and 200-BC-1 OUs. Several RCRA TSD units are assigned to the 200-WA-1 and 200-EA-1 OUs. While most Central Plateau OU waste sites are not RCRA TSDs, these OUs do have waste sites adjacent to the single-shell tank (SST) system TSD units in the WMAs for the B-BX-BY, T-TX-TY, and S-SX Tank Farms, resulting in co-mingled DVZ contamination. Remedy selection for the Central Plateau OUs will be coordinated with the closure action for the WMAs.

The SSTs are grouped into WMAs, which will be closed following a defined closure process. Each WMA contains part of an SST RCRA TSD unit that includes tanks and ancillary equipment. Closure of the tanks and tank farms was evaluated in DOE/EIS-0391, *Final Tank Closure and Waste Management Environmental Impact Statement for the Hanford Site, Richland, Washington (TC & WM EIS),* with a ROD issued in December 2013 (78 FR 240, "Record of Decision for the Final Tank Closure and Waste Management Environmental Impact Statement for the Hanford Site, Richland, Washington [TC & WM EIS]"). The WMAs are not included in the 200-DV-1 OU.

Remedial action alternatives developed in the 200-DV-1 OU RI/FS and RFI/CMS report for waste sites adjacent to tank farm WMAs will take into consideration the proximity of the TSD units. The detailed evaluation of alternatives performed in the 200-DV-1 OU RI/FS and RFI/CMS will need to consider whether the waste site alternatives are compatible or complementary with a closure action planned for the nearby TSD units.

1.5 Report Organization

This report includes the following chapters and appendices:

- **Chapter 1, Introduction**: Describes the purpose, objectives, regulatory context, integration of Central Plateau OUs and WMAs, and organization of the evaluation report.
- **Chapter 2, Environmental Setting and Background**: Describes the environmental setting of the Central Plateau, identifies the COIs in the vadose zone and the fate and transport of these

contaminants with potential to impact groundwater, and describes the treatment areas used to evaluate the remediation technologies.

- **Chapter 3, Deep Vadose Zone Technology Review**: Summarizes the treatability studies completed to date at the Hanford Site, summarizes previous DVZ technology evaluations, identifies additional remedial technologies that may be applicable to the Hanford DVZ, and summarizes the preliminary list of DVZ remedial technologies being considered for inclusion in future DVZ FSs.
- **Chapter 4, Deep Vadose Zone Remediation Technology Evaluation**: Describes the DVZ technology evaluation and treatability assessment process and presents the results of the technology evaluation.
- **Chapter 5, Deep Vadose Zone Treatability Study Assessment Conclusions and Recommendations**: Summarizes the conclusions of the DVZ technology evaluation, provides data needs and treatability evaluation to address those data needs, and provides recommendations for additional treatability testing.
- **Chapter 6, References**: Lists the references cited in this summary report.
- **Appendix A, Deep Vadose Zone Science and Technology Advances**: Summarizes specific elements of science and technology activities relevant to the Central Plateau DVZ.
- **Appendix B, Deep Vadose Zone Technology Summary Tables**: Provides summary tables for DVZ remediation technologies and for DVZ access and delivery technologies.

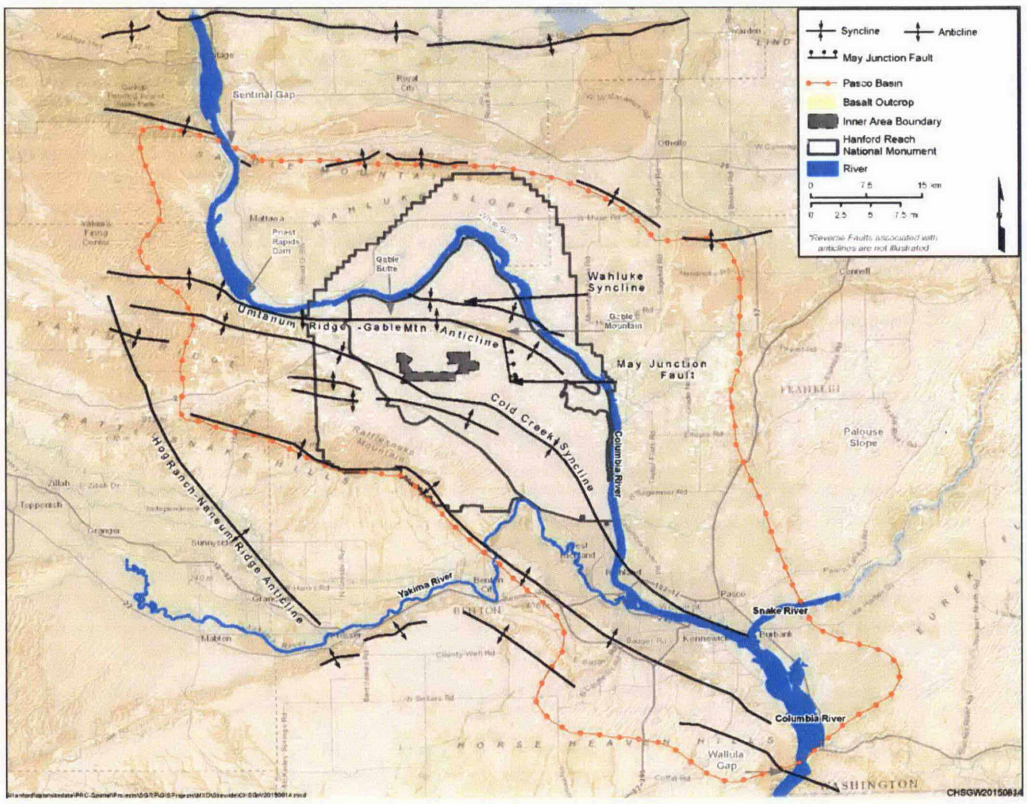
2 Environmental Setting and Background

2.1 Environmental Setting

This chapter describes the environmental setting of the Central Plateau including physiography, topography, climate, meteorology, geologic setting, and hydrogeology. The description includes characteristics of surface and subsurface features and processes that are relevant to developing a preliminary understanding of contaminant distribution for the Central Plateau Inner Area waste sites. This understanding provides the foundation for identifying the DVZ treatment areas and evaluating the remediation technologies. Although this report is being completed as part of 200-DV-1 OU RI/FS and RFI/CMS WP activities, the technology review was conducted to be relevant across all the Central Plateau OUs with DVZ waste sites (i.e., 200-WA-1 and 200-EA-1 OUs).

2.1.1 Physiography and Topography

The Hanford Site lies within the Pasco Basin (Figure 2-1). The physiographic setting of the Hanford Site is relatively low relief, resulting from river and stream sedimentation filling the synclinal valleys and basins between the anticlinal ridges. The Central Plateau Inner Area waste sites are located on the Cold Creek bar, a large compound flood bar formed during the Pleistocene Ice Age floods. The elevation (above mean sea level) of the upper surface of the bar ranges from approximately 210 m (700 ft) at B Plant to approximately 221 m (725 ft) along the eastern part of T Plant to approximately 197 m (647 ft) in the western part of U Plant and the Reduction-Oxidation (REDOX) Plant (Figure 1-2). No natural surface water drainage channels are located within these areas.



Note: This figure is modified from PNNL-6415, *Hanford Site National Environmental Policy Act (NEPA) Characterization*.

Figure 2-1. Generalized Geologic Structure Map of the Pasco Basin

2.1.2 Climate and Meteorology

The Pacific Ocean moderates the temperatures throughout the Pacific Northwest and the Cascade Mountains generate a rain shadow that limits rain and snowfall at the Hanford Site. Climatological data for the Hanford Site are compiled at the Hanford Meteorological Station (HMS), which is located on the Central Plateau.

Daily maximum temperatures at the HMS vary from an average of 2°C (35°F) in late December and early January to 36°C (96°F) in late July. Average annual precipitation at the HMS is 17 cm (6.8 in.) with most precipitation occurring in the late autumn and winter.

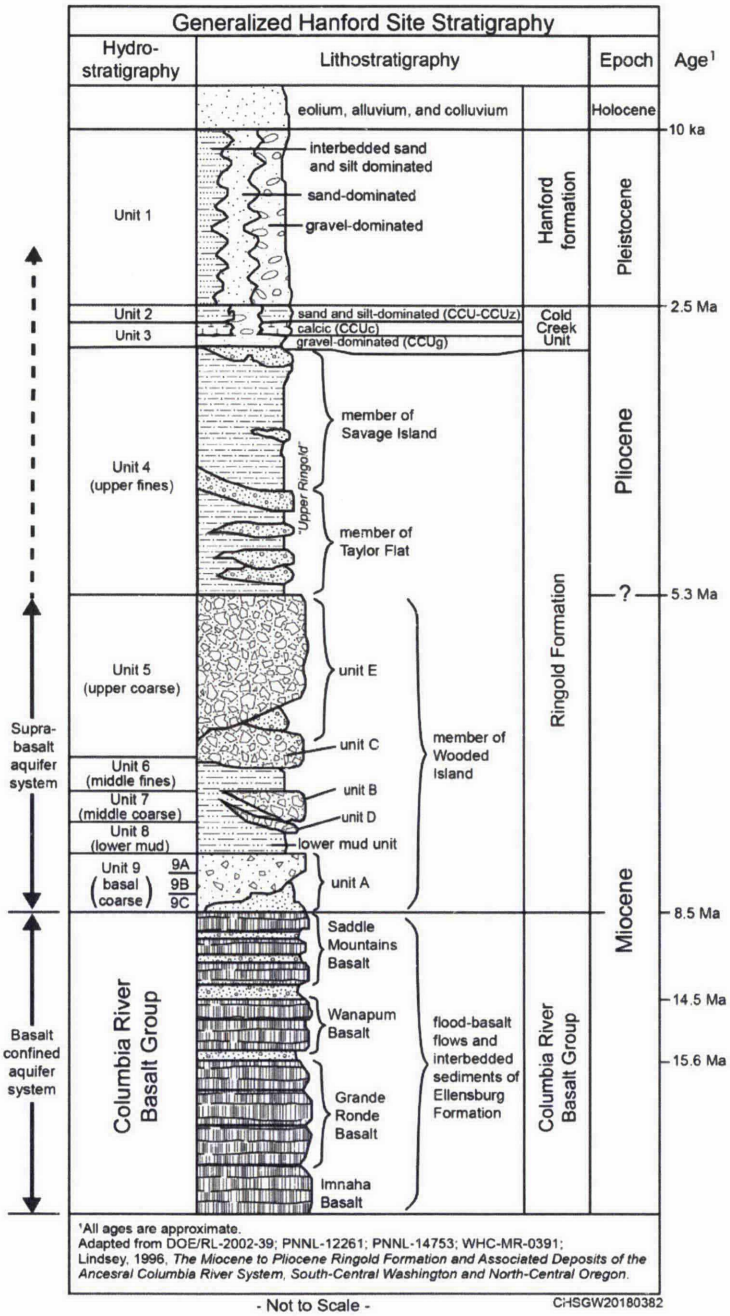
2.1.3 Geologic Setting

The geology of the Hanford Site has been extensively characterized during previous investigations. The Inner Area of the Hanford Site is located in the central portion of the Pasco Basin. Over the last 16 million years, the basin filled with igneous materials that formed bedrock (i.e., volcanic lava flows) and sedimentary materials (e.g., silt, sand, and gravel). These sedimentary deposits overlie the basalts and include unconsolidated and partly consolidated fluvial (river-derived), lacustrine (lake), and cataclysmic flood sediments of the Miocene through Holocene ages (approximately 8.5 million years to the present). Beneath the ground surface, these rocks and sediments are defined by several major geologic units of interest to the DVZ that include (from oldest to youngest) the Ringold Formation, Cold Creek unit (CCU), and Hanford formation.

Previous studies containing geologic interpretations, related maps, and cross sections pertaining to the Central Plateau include the following:

- PNNL-12261, *Revised Hydrogeology for the Suprabasalt Aquifer System, 200-East Area and Vicinity, Hanford Site, Washington*
- PNNL-13858, *Revised Hydrogeology for the Suprabasalt Aquifer System, 200-West Area and Vicinity, Hanford Site, Washington*
- DOE/RL-2002-39, *Standardized Stratigraphic Nomenclature for Post-Ringold-Formation Sediments Within the Central Pasco Basin*

Figure 2-2 presents the generalized stratigraphic and hydrostratigraphic columns for the Central Plateau.



Note: This figure has been modified from PNNL-6415, *Hanford Site Environmental Policy Act (NEPA) Characterization*.

Sources: DOE/RL-2002-39, *Standardized Stratigraphic Nomenclature for Post-Ringold-Formation Sediments Within the Central Pasco Basin*.

Lindsey, 1996, *The Miocene to Pliocene Ringold Formation and Associated Deposits of the Ancestral Columbia River System, South-central Washington and North-central Oregon*.

PNNL-12261, *Revised Hydrogeology for the Suprabasalt Aquifer System, 200-East Area and Vicinity, Hanford Site, Washington*.

PNNL-14753, *Groundwater Data Package for Hanford Assessments*.

WHC-MR-0391, *Field Trip Guide to the Hanford Site*.

Figure 2-2. Stratigraphic and Hydrostratigraphic Columns for the Central Plateau

2.1.3.1 Ringold Formation

The fluvial-lacustrine Ringold Formation, which overlies basalt over much of the Hanford Site, is present beneath the western Inner Area and limited in extent beneath the eastern Inner Area. The Ringold Formation is described as an unconsolidated to semiconsolidated sedimentary sequence deposited unconformably on the basalt and consists of clay, silt, sand, and granule- to cobble-size gravel deposited by the ancestral Columbia River (PNNL-12261; PNNL-13858). The Ringold Formation consists of four distinct hydrostratigraphic units (informally designated as units 4, 5, 8, and 9 [Figure 2-2]) that may not always be present beneath the Central Plateau. These units generally correspond to the following (from youngest to oldest) (PNNL-13858):

- Ringold Formation member of Taylor Flat (Rtf) – unit 4, which is composed of predominantly fine-grained silt and sand
- Ringold Formation member of Wooded Island – unit E (Rwie) unit 5, which is a fluvial deposit composed of silty, sandy gravel
- Ringold Formation member of Wooded Island – lower mud unit 8, which is composed predominantly of fine-grained lacustrine silt and clay
- Ringold Formation member of Wooded Island – unit A unit 9, which is a fluvial deposit composed of silty, sandy gravel

The entire Ringold Formation sequence is present beneath most of the western Inner Area (Figure 2-2). Most of the Ringold Formation is absent from the eastern Inner Area; depositional thinning or removal by paleo-erosion along the northern, uplifted basalt surface resulted in the loss of most of the formation (Figure 2-2).

2.1.3.2 Cold Creek Unit

The CCU includes several post-Ringold Formation and pre-Hanford formation units deposited beneath portions of the Inner Area (DOE/RL-2002-39, *Standardized Stratigraphic Nomenclature for Post-Ringold-Formation Sediments Within the Central Pasco Basin*). Three different facies deposits generally comprise the CCU beneath the Inner Area (from youngest to oldest):

- Fine-grained (silt-dominated) deposit (CCU_z)
- Variably cemented calcium carbonate fine- to coarse-grained deposit (caliche) (CCU_c)
- Coarse-grained (gravel) deposit (CCU_g)

The CCU_z is a fine-grained silt to sand facies that overlies the CCU_c in the western Inner Area and the CCU_g in the northwest part of the eastern Inner Area. This unit grades laterally from fluvial to eolian deposits ranging from a sandy silt to a silt; where silt content dominates, perched water horizons have been found (e.g., in the B-Complex area [Section 2.1.5]). Calcium carbonate in this sequence varies from a few percent to absent. Where higher calcium carbonate content is found, consolidated clumps of silt and sand are generally reported. In recent vadose zone modeling, the uppermost Cold Creek unit has been defined as simply the CCU to differentiate the different lithofacies found within it (such as silt-dominated CCUz or the sand-dominated CCU facies in parts of 200 West).

The CCU_c (caliche) is a secondary deposit (mineral coating or cement) that accumulated on and within older sediment. It is composed of calcium carbonate that precipitated in available pore spaces between sediment grains (sand, silt, or gravel). The caliche binds the sediment grains together, forming one or more hardpan layers that vary from soil-like to rock-like. This facies is not present in the eastern Inner Area.

The CCU_g is predominantly sandy gravel with occasional cobble-size clasts and minor silty sand and extends from the Gable Butte/Gable Mountain Gap southeastward, traversing the eastern Inner Area from northwest to southeast. The CCU_g is best distinguished from the underlying Ringold Formation sediments by its higher hydraulic conductivity and faster drilling rate. The CCU_g is very permeable and extends throughout most of the saturated zone (i.e., beneath the water table) and the lower vadose zone underlying the B-Complex area. In areas where the CCU_z is absent, it can be difficult to distinguish the CCU_g from the overlying gravel-dominated Hanford formation unit 3. The hydraulic conductivities of the two units are similar, but CCU_g is characterized by a greater percentage of well-rounded felsic gravels than the Hanford formation. The CCU_g influences aquifer boundaries and groundwater contaminant flow throughout the eastern portion of the Central Plateau.

The CCU_z and the underlying CCU_c units are present in the vadose zone throughout the western Inner Area. Within the western Inner Area, the relatively thin CCU sequence (CCU_z plus CCU_c) forms a significant liquid flow baffle within the DVZ because of relatively low hydraulic properties.

The CCU_z and the underlying CCU_g units are the predominant CCU facies underlying the eastern Inner Area, where they are typically encountered in the DVZ and saturated zone.

The CCU_z (silt-dominated unit) generally exhibits much lower hydraulic conductivity than the overlying Hanford formation and therefore, exhibits much higher retention capacity (PNNL-19277, *Conceptual Models for Migration of Key Groundwater Contaminants Through the Vadose Zone and Into the Unconfined Aquifer Below the B-Complex*). The hydraulic properties of the CCU_z have historically resulted in accumulation and subsequent lateral spread of perched water within the vadose zone atop this unit and beneath high-volume discharge facilities (e.g., ditches, ponds, trenches, and cribs).

2.1.3.3 Hanford formation

The Hanford formation overlies the Ringold Formation, the CCU, and/or basalt within the Inner Area. The cataclysmic floodwaters eroded or reworked much of the pre-existing Ringold Formation and CCU sediment across the Gable Gap area and unconformably deposited thick, unconsolidated, basalt-rich sediments known as the Hanford formation. The floodwaters deposited a thick sand and gravel bar (Cold Creek bar) that constitutes the Central Plateau.

The Hanford formation is the primary vadose zone geologic formation (comprising about one-half of the vadose zone thickness in 200 West and nearly all the vadose zone thickness in 200 East); contaminants released at the surface must pass through the Hanford formation to reach groundwater. The Hanford formation consists predominantly of unconsolidated mafic sediments that range from boulder-size gravel to sand, silty sand, and silt. There are three broadly correlatable units of the Hanford formation (Hf) identified in the Central Plateau: the gravel-dominated Hanford formation unit 1 (Hf1), the sand-dominated Hanford formation unit 2 (Hf2), and the gravel-dominated Hanford formation unit 3 (Hf3) (CP-60925, *Model Package Report: Central Plateau Vadose Zone Geoframework*). The Hf1 is the uppermost Hanford unit and grades from a gravelly sand to a gravel facies. The Hf2 is sand-dominated with thin non-continuous silt or gravel stringers throughout. The Hf3 is a gravel-dominated unit at the base of the Hanford formation.

2.1.4 Hydrogeology

This section describes the hydrogeology of the Inner Area.

2.1.4.1 Vadose Zone

The thickness and stratigraphy of the vadose zone varies across the Inner Area. The vadose zone thickness ranges from approximately 71 to 78 m (234 to 255 ft) in the North 200 West area and

from approximately 67 to 73 m (221 to 238 ft) in the South 200 West area. In these areas, the vadose zone is composed of the Hf, the CCU_z (silt) and CCU_c (caliche) units, the Rtf, and part of Rwie. The vadose zone in the North 200 East area ranges from 70 to 82 m (230 to 270 ft) thick and is composed of the Hf, the CCU_z unit, and the CCU_g (gravel) unit. Beneath the South 200 East waste sites, the vadose zone ranges from 85 to 104 m (280 to 340 ft) thick and is composed of Hf, the CCUg in places, the Rtf locally in the vicinity of the BC-cribs, and the Rwie. The water table lies within the Rwie in the 200 West area and within the Hanford formation and CCU_g unit in the North 200 East area and in the CCUg, Rtf, and Rwie in the South 200 East area (Figure 2-2).

2.1.4.2 Uppermost Aquifer

The uppermost aquifer is important to the assessment of the DVZ because it is the first groundwater to be potentially affected by contaminants originating from the DVZ waste sites. The uppermost aquifer is unconfined in all locations underlying the DVZ waste sites. In the 200 West area, the uppermost aquifer is contained within the Rwie. In the North 200 East area, the uppermost aquifer occurs in the CCU_g (gravel) unit and Hanford formation. In the South 200 East area, the uppermost aquifer occurs in the CCU_g, Rtf and Rwie.

The water table elevation (and subsequently the groundwater gradient, flow direction, and flow velocity within the uppermost aquifer underlying the Central Plateau wastes sites) has been historically altered by discharges of large quantities of wastewater to the vadose zone within the Inner Area and more recently by operation of the 200 West P&T system. Currently, the water table across eastern Inner Area is essentially flat. The water table across the Inner Area shows a generally west to east groundwater flow direction from the western Inner Area to the eastern Inner Area.

2.1.5 Hydrogeologic Perching Zones

The CCU silt and caliche unit (CCU_z and underlying CCU_c) and the Ringold Formation member of Wooded Island – lower mud unit within the vadose zone beneath the Inner Area have relatively low permeability, which can result in perched water above or within these intervals under high liquid recharge conditions. The liquid waste discharged to the ground above these two perching intervals created localized perched water zones. The perched water most likely included mixed effluent from various disposal sources. During operations, these perched conditions persisted, but most perched water eventually drained to the unconfined aquifer following cessation of waste disposal operations.

Cold Creek Unit—Where present above the water table, the CCU_z and underlying CCU_c consist of fine sandy silt to silt and/or caliche-rich intervals. These intervals exhibit very low hydraulic conductivity that can result in impeded downward liquid migration, depending on infiltration rate. Within the North 200 East area, liquid wastes from past-practice disposal to the 200-DV-1 OU waste sites and unintentional tank releases have been accumulating on and within the CCU. Recent perched zone drainage is known to have occurred from these liquid waste accumulations within the CCU and to have impacted the underlying unconfined aquifer. Perched water is being extracted to reduce additional migration of contaminants to the unconfined aquifer.

2.2 Central Plateau Deep Vadose Zone Contamination

Identification of COIs for DVZ waste sites is based on process knowledge of Hanford Site operations, documented contaminant waste inventories and discharge volumes for DVZ waste sites, groundwater plumes identified for the four Central Plateau groundwater OUs, and vadose zone characterization and groundwater monitoring data that suggest emerging contaminants that may impact groundwater in the future.

2.2.1 Identification of Groundwater Contaminants of Interest

The field investigation and laboratory analysis of field samples for the 200-DV-1 OU in support of the RI/FS was completed in 2018 (DOE/RL-2011-102). Results of the 200-DV-1 field samples can be found in SGW-60265, *200-DV-1 Operable Unit BY Cribs Field Summary Report*; SGW-61384, *200-DV-1 Operable Unit B-Complex Field Summary Report*; SGW-61595, *200-DV-1 Unit T-Complex Field Summary Report*; SGW-61596, *200-DV-1 Operable Unit S-Complex Field Summary Report*; and SGW-62096, *200-DV-1 Operable Unit Shallow Soil Risk Sampling Field Summary Report*. During the RI/FS and RFI/CMS processes, the list of COIs will be refined into a final list of COCs through the nature and extent of contamination analysis, fate and transport modeling, and baseline risk assessment.

Characterization for other Central Plateau OUs that have DVZ waste sites (e.g., 200-WA-1 and 200-EA-1) have been scoped under their respective RI/FS WPs, but characterization has not yet been completed. Because characterization has not been completed for all DVZ waste sites and OUs, the final COC list for DVZ waste sites cannot be determined.

While a definitive list of DVZ COCs has not yet been determined, this report defined a list of COIs for the technology evaluation that are the moderate to high-mobility contaminants. Higher mobility contaminants have a higher likelihood of migrating through the vadose zone to reach groundwater at concentrations above cleanup levels and therefore may require remediation in the vadose zone. Selected COIs for this report are listed in Table 2-1. Cr(VI) was selected for assessment of remediation technologies because it is the mobile form of chromium that may need to be remediated in the vadose zone to protect groundwater. This list of COIs is consistent with the 200-DV-1 OU list of mobile contaminants identified for characterization of contaminant attenuation and transport processes (DOE/RL-2011-104-ADD1, *Characterization Sampling and Analysis Plan for the 200-DV-1 Operable Unit Addendum 1: Attenuation Process Characterization*).

Table 2-1. Summary of Deep Vadose Zone Contaminants of Interest

Radionuclides	
Iodine-129	Strontium-90
Technetium-99	Carbon-14
Nonradioactive Metals	
Cr(VI)	Uranium
Inorganics	
Cyanide	Nitrate
Organics	
Trichloroethylene	Methyl isobutyl ketone (MIBK)

Due to the length of time since discharges to DVZ waste sites and the large volumes of liquid disposed to many of the DVZ waste sites, many of the selected COIs have already been identified as discrete or co-mingled groundwater contaminant plumes. Figure 2-3 provides an overview of groundwater contaminant concentrations observed at the four Central Plateau groundwater OUs. Figure 2-4 depicts groundwater plumes identified for the Hanford Site. All the contaminants, except carbon tetrachloride and tritium, shown in Figure 2-3 were included in the technology evaluations for this report. Carbon tetrachloride was not included as a COI because vadose zone contamination from the primary source area has already been addressed (DOE/RL-2014-48, *Response Action Report for the 200-PW-1 Operable Unit Soil Vapor Extraction Remediation*). There are no remediation technologies applicable to tritium, and natural attenuation is currently considered as the approach for tritium, given its short half-life.

In addition to the 10 COIs observed in groundwater (Figures 2-3 and 2-4), 2 additional COIs are considered for the DVZ treatability evaluation provided in this report. Carbon-14 was detected in 200-DV-1 OU perched water at a concentration 1,840 pCi/L (DOE/RL-2016-69, *Calendar Year 2016 Annual Summary Report for the 200-ZP1- and 200-UP-1 Operable Unit Pump-and-Treat Operations*) compared to the maximum contaminant level of 2,000 pCi/L. While this concentration is below the maximum contaminant level, the carbon-14 concentration in perched water is close enough to warrant further consideration.

Methyl isobutyl ketone (also known as hexone) is an organic chemical that was used to separate plutonium and uranium from the dissolved fuel rod solutions (DOE/RL-98-28, *200 Areas Remedial Investigation/Feasibility Study Implementation Plan – Environmental Restoration Program*) at the REDOX Plant (S Plant). The REDOX low-level waste (Tank D-1 cell drainage and Tank D-2 redistilled process condensate) was discharged to the 216-S-1 Crib (with overflow to the 216-S-2 Crib) beginning in January 1952. Liquid waste from the 203-S Decontaminated Metal Storage Facility, the 204-S Uranyl Nitrate Hexahydrate Lag Storage Facility, and the 276-S Hexone Storage Facility was discharged to the 216-S-13 Crib beginning in January 1952. The 216-S-14 and 216-U-15 Trenches also received hexone related waste (DOE/RL-2010-49). Hexone was also detected in DVZ characterization samples collected for the 216-S-13 Crib (SGW-61596).

Central Plateau Overview

Ground-water Operable Unit	Primary Operations	Status of Ground-water ROD	Groundwater Remedial Action	Groundwater Contamination: Maximum Concentration and Plume Area									
				Carbon Tetrachloride (µg/L)	Hexavalent Chromium (µg/L)	Cyanide (µg/L)	Iodine-129 (pCi/L)	Nitrate (mg/L)	Strontium-90 (pCi/L)	Trichloroethene (µg/L)	Technetium-99 (pCi/L)	Tritium (pCi/L)	Uranium (µg/L)
200-BP	B Plant Pu separation: 1945-1952; B Plant Sr and Cs recovery: 1967-1985	FS Drafted in 2015 (with 200-PO-1)	B Complex groundwater extraction treatability test 2015; Perched water P&T 2011-2015	N	160	1,350	5.27	1,510	4,470	5.07[a]	32,700	61,400	3,790
200-PO	PUREX Plant Pu separation: 1956-1972 and 1983-1989	FS Drafted in 2015 (with 200-BP-5)	Vadose zone desiccation test: 2011	0.17	350	7	8.91	146	13.7	1.3	1,950	418,000	23.9
200-UP	REDOX Plant (Pu separation) 1952-1967; U Plant (U recovery) 1952-1957	Signed 2012 (interim action)	Uranium plume P&T began 2015; I-129 containment began 2015; S-SX P&T 2012-present; U Plant P&T 1994-2011	See 200-ZP	460	4.7	20.2	531	15.3	See 200-ZP	39,000	250,000	2,400
200-ZP	T Plant (Pu separation) 1944-1956; Pu Finishing Plant: 1949-1989	Signed 2008 (final action)	Groundwater P&T and MNA: 1995-present. Soil vapor extraction 1991-2013	2,320	420	N	1.2	708	N	14	10,700	58,800	6.5
Standards[b]				5	48	200	1	45	8	5	900	20,000	30
Half-life (years)				N/A	N/A	N/A	1.60E+07	N/A	28.8	N/A	212,000	12	>159,000
Mobility in subsurface				Multi-phase	High to Moderate	Moderate	High	High	Slight	Moderate	High	High	Moderate

Legend

Colors and listed values indicate maximum concentration in groundwater in 2016

- ≥100 x standard and <1000 x standard
- ≥10 x standard and <100 x standard
- ≥Standard and <10 x standard
- N Not detected or not analyzed

Height of bar indicates plume area above standard (km^2)

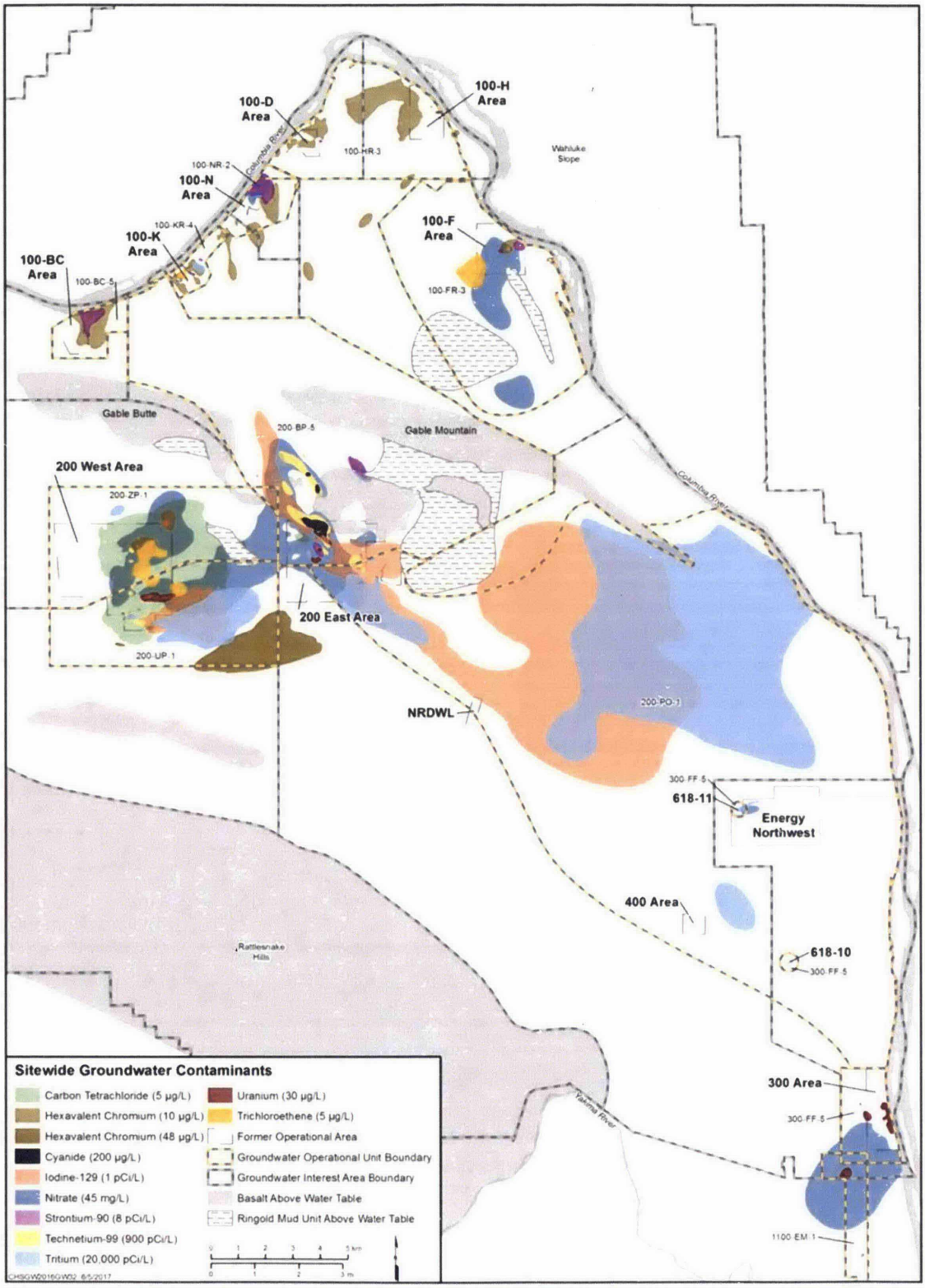
- >10
- >1 and ≤10
- >0.1 and ≤ 1
- >0, ≤0.1

a. TCE in a 100-K well within footprint of 200-BP.
b. Drinking water standards for all but (MTCA standard for hexavalent chromium)

ABBREVIATIONS
N/A = Not applicable P&T = pump and treat ROD = record of decision MTCA = Model Toxics Control Act

Source: Modified from DOE/RL-2016-67, *Hanford Site Groundwater Monitoring Report for 2016*.

Figure 2-3. Overview of Central Plateau Groundwater OUs and Contaminant Concentrations

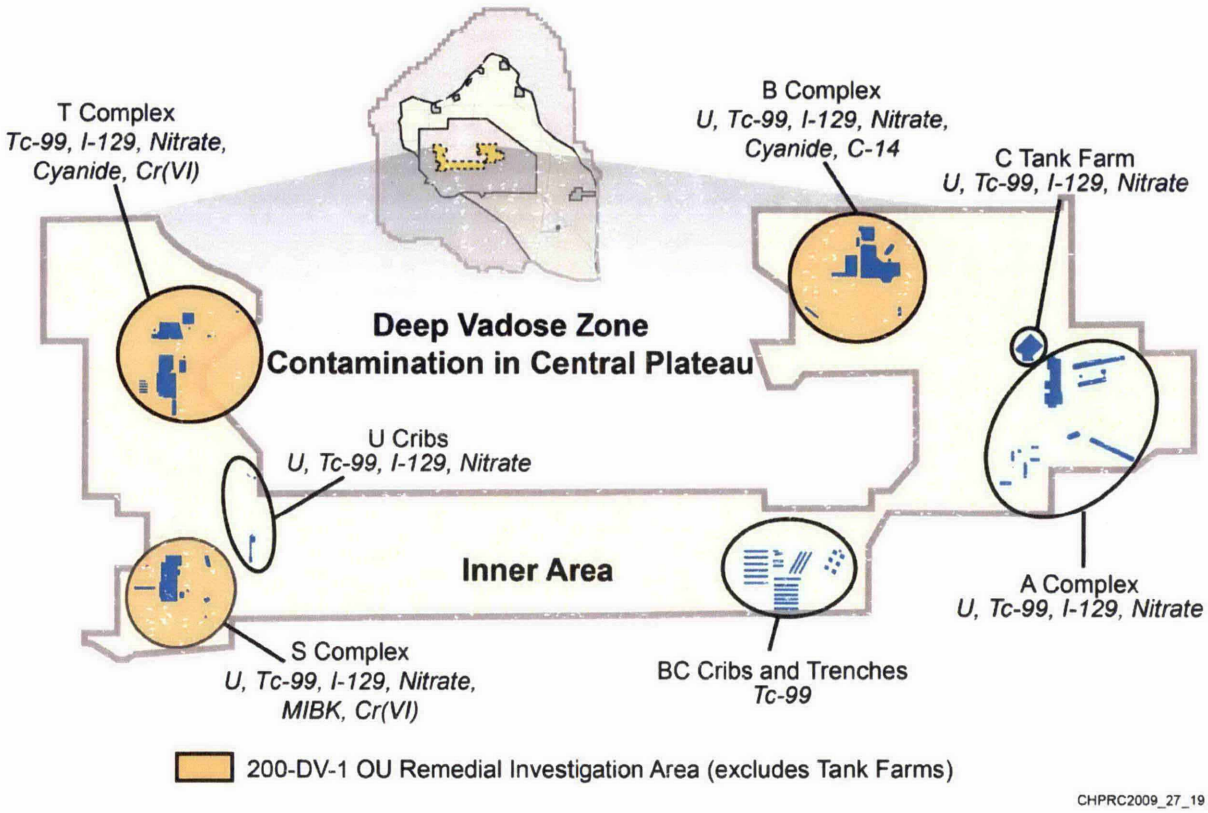


Source: DOE/RL-2016-67, *Hanford Site Groundwater Monitoring Report for 2016*.

Figure 2-4. Sitewide Groundwater Contaminant Plumes, 2016

2.2.2 Groundwater Impacts Analysis

Estimates of the contaminants in the Central Plateau vadose zone with the potential to impact groundwater are shown in Figure 2-5. This general depiction of groundwater impact is currently being updated for 200-DV-1 OU sites as part of the RI process. The update will consider new characterization data and refined predictive modeling. Updates for other vadose zone OUs will be conducted as their RIs are conducted. Current vadose zone and groundwater characterization data contaminants were used to generate the COI listed in Table 2-1 (Section 2.2.1) for use as targets for remediation technologies in this treatability test evaluation report. Target COIs were grouped into primary COIs (uranium, technetium-99, iodine-129, and nitrate), secondary COIs (Cr(VI), strontium-90, cyanide, and carbon-14), and tertiary COIs (trichloroethene and methyl isobutyl ketone) based on potential groundwater impact for the Central Plateau (Figure 2-5). Primary COIs are associated with large groundwater plumes and significant vadose zone inventory, and they are mobile in the vadose zone. Secondary COIs have smaller groundwater plumes and/or lower vadose zone inventories and for strontium-90 and carbon-14 are less mobile (for the Central Plateau). Tertiary COIs are found only in a few instances, have low inventories, and small or no groundwater plumes.



Source: Modified from CHPRC-01056-VA, *Hanford Site – Deep Vadose Zone Cleanup Challenge.*

Figure 2-5. Central Plateau Waste Sites with Contamination Known or with Potential to Impact Groundwater

2.2.3 Contaminant Attenuation and Transport Characterization

Contaminants disposed of near the ground surface must migrate through the vadose zone before entering groundwater. Processes that occur in the vadose zone can attenuate contaminant concentrations during transport through the vadose zone. Thus, quantifying contaminant attenuation and contaminant transport processes in the vadose zone, in support of the conceptual site model and fate and transport assessments, is important for assessing the need for, and type of, remediation in the vadose zone and groundwater. The framework to characterize attenuation and transport provided in EPA guidance documents was applied to recent vadose zone characterization activities at the 200-DV-1 OU. The specific elements of characterization for contaminant attenuation and transport address the following three objectives:

- Define the contaminant distribution and the hydrologic and biogeochemical setting
- Identify attenuation processes and describe the associated attenuation mechanisms
- Quantify attenuation and transport parameters for use in evaluating remedies

These objectives are elements of the framework identified in EPA guidance for evaluating monitored natural attenuation of inorganic contaminants, and they directly support updating the conceptual site model for the 200-DV-1 OU and generally for the Hanford Central Plateau. Importantly, the information supports defining suitable contaminant transport parameters that are needed to evaluate transport of contaminants through the vadose zone and to the groundwater. This type of transport assessment supports a coupled analysis of groundwater and vadose zone contamination. The characterization information and associated transport analyses are complementary to the technology information and evaluation reported herein.

Results of attenuation and transport characterization for the 200-DV-1 OU are reported in four documents:

- PNNL-26208, *Contaminant Attenuation and Transport Characterization of 200-DV-1 Operable Unit Sediment Samples*
- PNNL-26266, *Geochemical, Microbial, and Physical Characterization of 200-DV-1 Operable Unit B-Complex Cores from Boreholes C9552, C9487, and C9488 on the Hanford Site Central Plateau*
- PNNL-27524, *Contaminant Attenuation and Transport Characterization of 200-DV-1 Operable Unit Sediment Samples from Boreholes C9497, C9498, C9603, C9488, and C9513*
- PNNL-27846, *Physical and Hydraulic Properties of Sediments from the 200-DV-1 Operable Unit*

These results are being integrated with the 200-DV-1 OU characterization in the RI report.

2.3 Description of Treatment Areas

Due to the large number of sites on the Central Plateau that have DVZ contamination, and the varying states of characterization of those sites, it is not feasible to evaluate remedial technologies on a site-by-site basis in this document prior to evaluation during the FSs for vadose zone OUs. This limitation requires that a representative description of treatment areas be used to evaluate remedial technologies that are applicable to the DVZ contamination on the Hanford Central Plateau.

The evaluation of DVZ remediation technologies is based on representative treatment areas for the DVZ. Figures 2-6 to 2-10 show section views of the Inner Area that illustrate site conditions that can be categorized into the treatment areas.

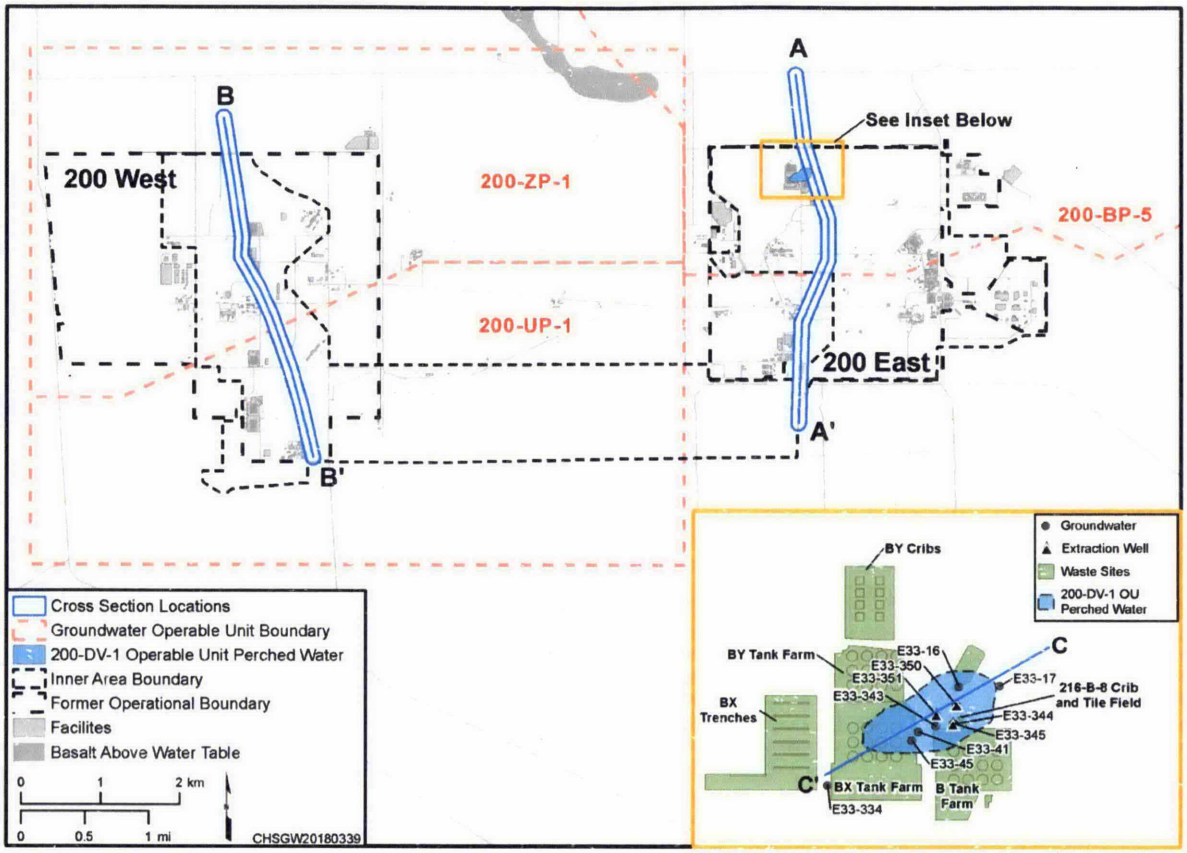


Figure 2-6. Inner Area Section Locations

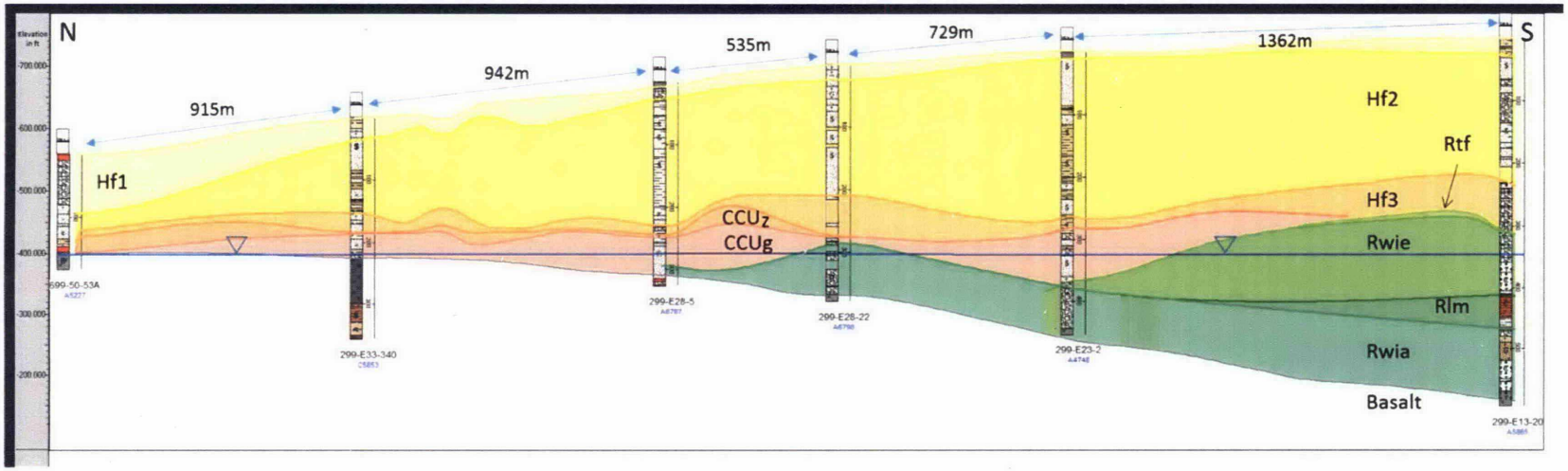


Figure 2-7. North-South Section View of 200 East Area

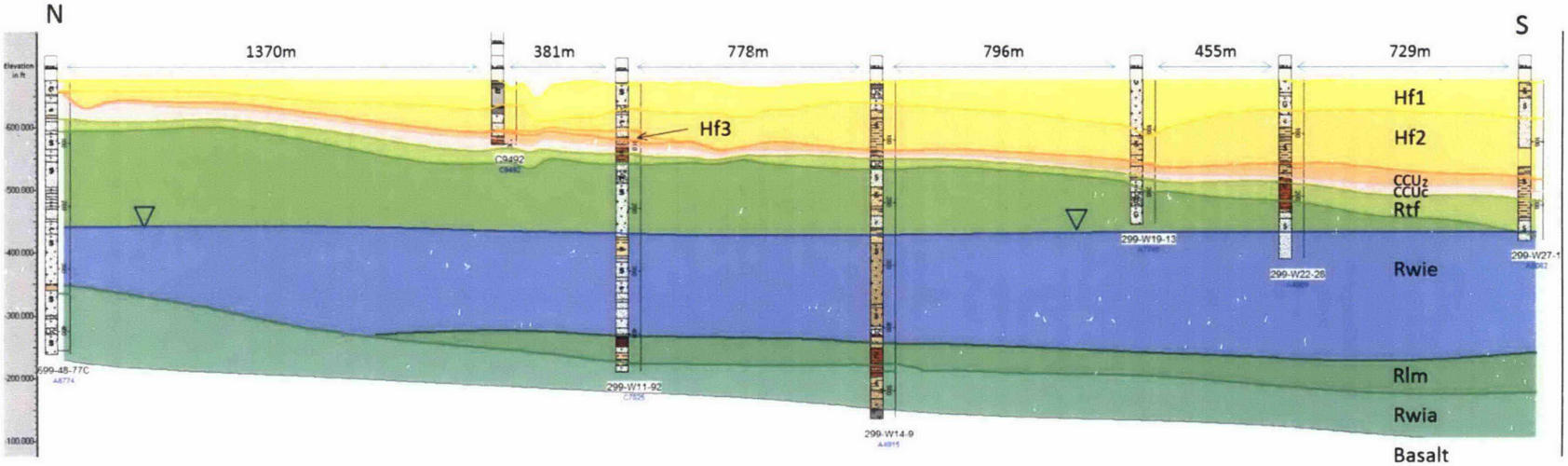
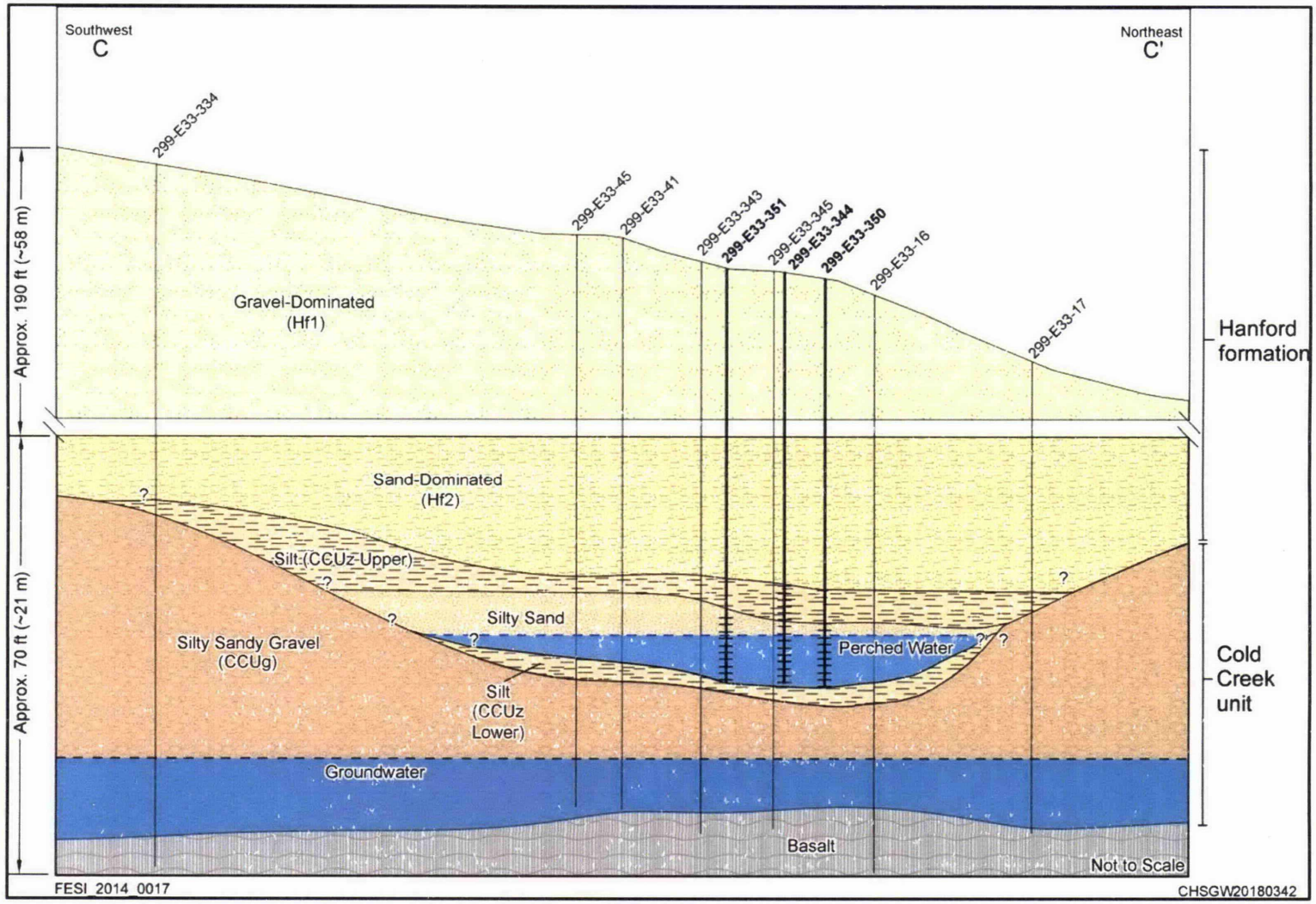


Figure 2-8. North-South Section View of 200 West Area



Source: Modified from DOE/RL-2014-34, *Action Memorandum for 200-DV-1 Operable Unit Perched Water Pumping/Pore Water Extraction*.

Figure 2-9. Southwest-Northeast Section View of 200-DV-1 OU Perched Water

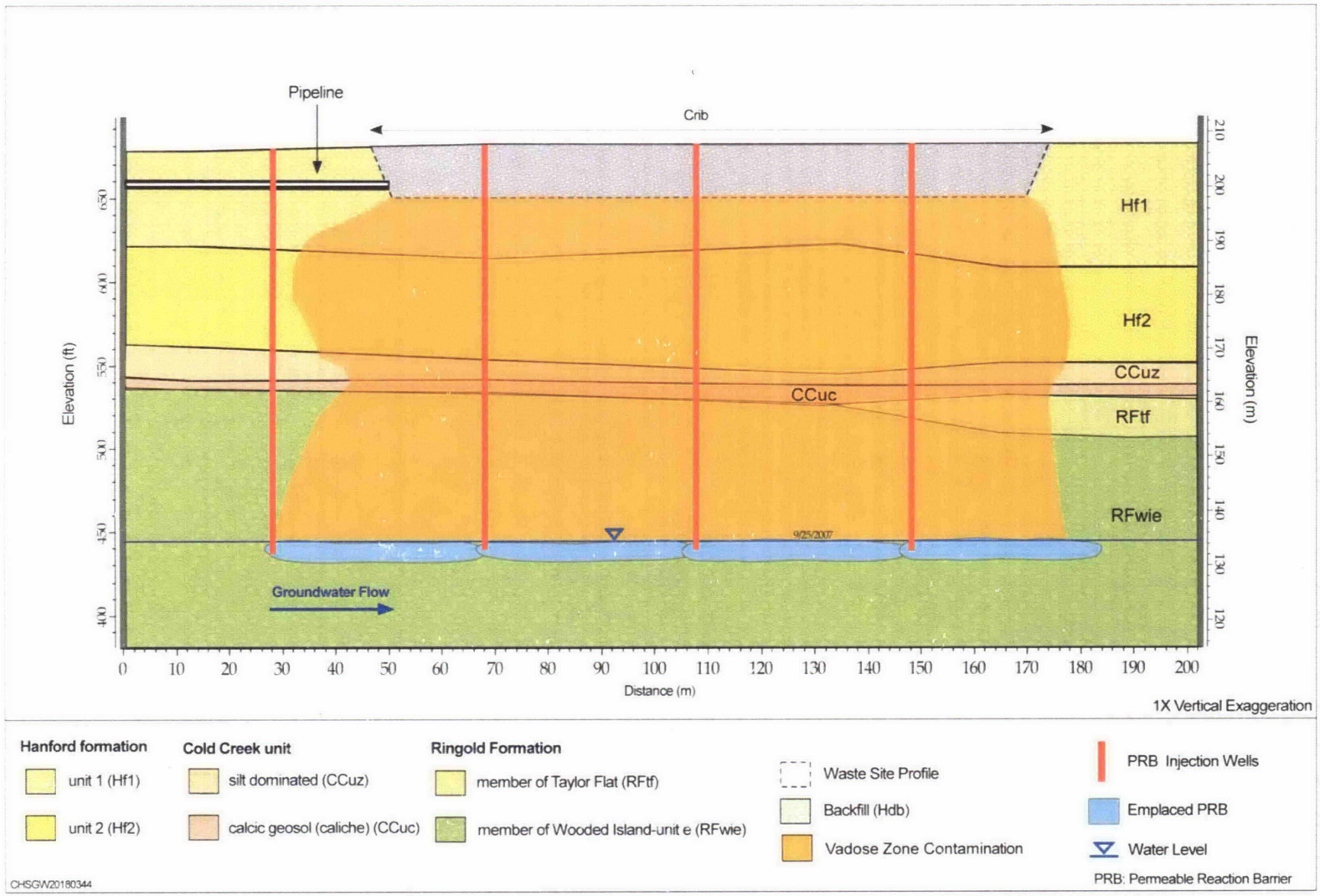


Figure 2-10. Emplacing a Horizontal Permeable Reactive Barrier on Top of the Water Table

The section views in Figures 2-6 to 2-10 show the four categories of treatment areas for vadose zone remediation technology implementation:

- Higher Permeability Zones – where remediation would be implemented to address contaminants currently located in higher permeability zones such as the Hf and Ringold Formation shown on Figures 2-7 and 2-8.
- Lower Permeability Zones – where remediation would be implemented to address contaminants currently located in lower permeability zones such as the CCU_z shown on Figures 2-7 and 2-8.
- Perched Water Zones – where remediation would be implemented to address the unique contaminant situation of the B-Complex perched water as depicted in Figure 2-9.
- Water Table Interface Zones – where remediation would be implemented to address contaminants that are deep in the vadose zone near the water table such that deploying a remedy at the water table interface would be a potentially effective means to reduce the contaminant flux into a groundwater plume. For example, a horizontal permeable reactive barrier (PRB) could be emplaced at the water table interface to address the portion of contaminants near the water table as shown in Figure 2-10.

The first two treatment areas are defined based on the permeability of the unsaturated soil. The permeability of the soil strata can have a significant impact on how remedial technologies are deployed, and how effectively in situ treatment reagents are delivered. In general, higher permeability soil strata are more amenable to delivery of in situ treatment reagents, whereas lower permeability soil strata present a greater challenge. Heterogeneous formations further complicate uniform delivery of in situ treatment reagents. Higher permeability zones include the Hanford formation (Hf1, Hf2, and Hf3), Ringold Formation (Rtf), and CCU_g. The lower permeability zones include the CCU_z/CCU and CCU_c.

The final two treatment areas are defined by the saturation of the soil and their relation to the groundwater table, which affect how DVZ technologies are deployed. The perched water zone presents unique challenges for deployment and effectiveness of technologies because it is a thin saturated zone within a relatively low permeability matrix and has high contaminant concentrations. The water table interface treatment area may be suitable for use of technologies similar to those used for groundwater treatment but focused on addressing the flux from the vadose zone into the groundwater.

3 Deep Vadose Zone Technology Review

This chapter summarizes treatability testing completed to date at the Hanford Site, summarizes previous DVZ technology evaluations, identifies additional remedial technologies that may be applicable to the Hanford Site DVZ, and summarizes the preliminary list of DVZ remedial technologies being considered for inclusion in future Central Plateau source OU FSs with DVZ waste sites.

3.1 Deep Vadose Zone Treatability Test Summaries and Recommendations

The Tri-Parties established Milestone M-015-50, which directed DOE to submit a treatability test plan for remediation of technetium-99 and uranium in the DVZ. These contaminants are mobile in the subsurface environment and have been detected at high concentrations deep in the vadose zone and have reached groundwater at some locations. Testing of technologies for remediating technetium-99 and uranium also provide information relevant to remediation of other contaminants in the vadose zone. The milestone was addressed by submitting the DVZ Treatability Test Plan (DOE/RL-2007-56). This section summarizes the six treatability studies performed under that test plan, including conclusions and recommendations of the studies, fulfilling the requirement of the test plan for a final evaluation of the treatability effort.

3.1.1 Desiccation Field Test

Desiccation was tested as a potential vadose zone remediation technology to control subsurface moisture and decrease contaminant mobility in the vadose zone, thereby protecting groundwater (PNNL-26902, *Deep Vadose Zone Treatability Test of Soil Desiccation for the Hanford Central Plateau: Final Report*). Full-scale application of the desiccation technology would be used in conjunction with a surface infiltration barrier. The test involved the following:

- Demonstrated desiccation of a targeted zone in the subsurface
- Showed that the process and rate of rewetting is predictable
- Evaluated equipment and monitoring approaches for implementation
- Provided design information that can be used in a future FS

A synopsis of the testing, results, and recommendations is provided below.

3.1.1.1 Desiccation Test Summary

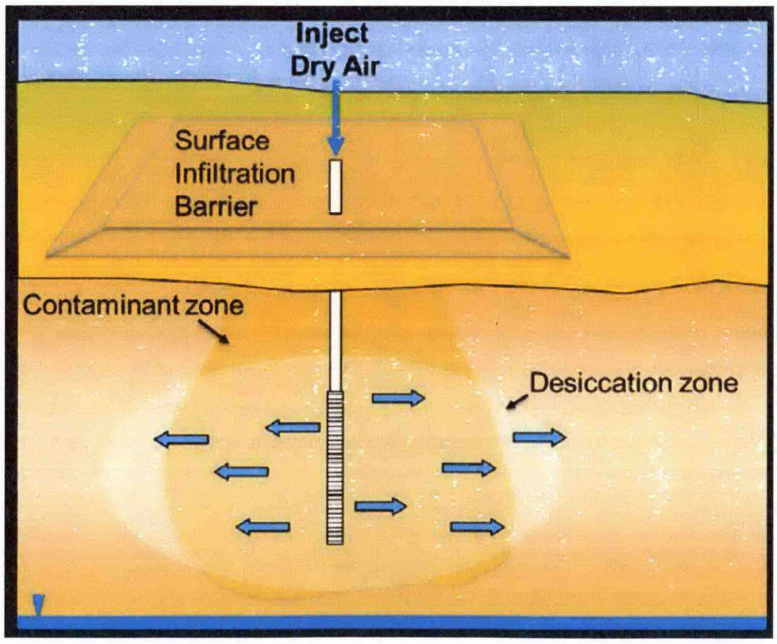
The desiccation field test was conducted at the Hanford Site 200-BC-1 OU. This OU contains 26 cribs and trenches that received about 110 million L (29 million gal) of liquid waste primarily in the mid-1950s. The waste contained about 410 curies of technetium-99 (RPP-26744, *Hanford Soil Inventory Model, Rev. 1*). There is no evidence that the contamination has reached groundwater, which is present at a depth of about 100 m (330 ft) bgs. Initial characterization efforts indicated that most of the technetium-99 inventory is present at vadose zone depths between about 30 and 70 m (98 and 230 ft) bgs. However, transport model predictions (PNNL-14907, *Vadose Zone Contaminant Fate-and-Transport Analysis for the 216-B-26 Trench*) have indicated the potential for this contamination to adversely impact groundwater in the future.

The test was conducted to provide desiccation technology information for use in subsequent FSs for waste sites with inorganic and radionuclide contaminants in the DVZ. Field-scale test site characterization was conducted to support this treatability test, as described in DOE/RL-2008-67, *Sampling and Analysis Plan for Characterization of the Soil Desiccation Pilot Test Site*. Results of the characterization effort were reported in DOE/RL-2009-119, *Characterization of the Soil Desiccation Pilot Test Site,* and PNNL-18800, *Characterization of Sediments from the Soil Desiccation Pilot Test (SDTP) Site in the BC Cribs and Trenches Area*. DOE/RL-2010-04, *Field Test Plan for the Soil Desiccation Pilot Test*, was

prepared and used to guide the desiccation field testing effort. Laboratory and numerical modeling efforts (PNNL-20146, *Laboratory and Modeling Evaluations in Support of Field Testing for Desiccation at the Hanford Site*; PNNL-17274, *Experimental and Numerical Investigations of Soil Desiccation for Vadose Zone Remediation: Report for Fiscal Year 2007*; Oostrom et al., 2009, "Desiccation of Unsaturated Porous Media: Intermediate-Scale Experiments and Numerical Simulation"; Oostrom et al., 2011, "Determination of Water Saturation in Relatively Dry and Desiccated Porous Media Using Gas-Phase Partitioning Tracer Tests;" Oostrom et al., 2012a, "Sensor and Numerical Simulator Evaluation for Porous Medium Desiccation and Rewetting at the Intermediate Laboratory Scale"; Oostrom et al., 2012b, "Effects of Porous Medium Heterogeneity on Vadose Zone Desiccation: Intermediate-Scale Laboratory Experiments and Simulations") preceded and accompanied the field test.

The desiccation technology (Figure 3-1) relies on removal of water from a portion of the subsurface such that the resultant low moisture conditions inhibit downward movement of water and dissolved contaminants. Implementation requires establishing sufficiently dry conditions within the targeted zone to inhibit downward water transport effectively. Nominally, the targeted desiccation zone would need to extend laterally across the portion of the vadose zone where contaminants have the potential to move downward at a flux that would result in groundwater contaminant concentrations above remediation goals. Overall objectives for the field test were to provide technical data as a design basis for desiccation, demonstrate desiccation at the field scale, and provide scale-up information for use in subsequent feasibility tests. Key performance factors identified for the field test included providing field-scale information to evaluate the following:

- Location and extent of the desiccated zone within the subsurface
- Desiccation rate
- Achievable end-state moisture conditions within the desiccated zone
- Rate and extent of moisture content increase after desiccation was completed



Source: PNNL-26902, *Deep Vadose Zone Treatability Test of Soil Desiccation for the Hanford Central Plateau: Final Report.*

Figure 3-1. Conceptual Depiction of Desiccation and a Surface Barrier

3.1.1.2 Desiccation Test Results

The objectives outlined in the desiccation field test plan (DOE/RL-2010-04) were successfully addressed through the field testing and associated laboratory and modeling efforts. A design basis to apply desiccation for vadose zone remediation was developed and is available for use in future feasibility and remedial design efforts. Analysis of the data and use of numerical simulations indicates that full-scale designs can be made more cost effective than the design of the field test (which was designed to collect specific data, not as a full-scale remediation) through use of ambient air as the injected dry gas and use of an injection-only design (i.e., no extraction well). Using desiccation performance calculations developed from the treatability test information, a nominal Hanford Site design with a 10-year air injection period and an injection rate of 47 L/s (100 cfm) per meter of well screen leads to an injection well radius of influence on the order of 25+ m (80+ ft) or two to three wells per acre.

The field test successfully provided information regarding key performance factors for desiccation. During the 6-month air injection field test, a zone of the subsurface about 3 m (10 ft) thick out to a radius of about 3 m (10 ft) was desiccated, creating conditions that reduced the rate of moisture and contaminant movement toward the groundwater. A larger portion of the test area had a lesser extent of moisture content reduction. The distribution of moisture reduction was controlled by sediment permeability contrasts that affect the injected subsurface gas flow patterns, with drying occurring more rapidly in higher permeability zones. During active desiccation, over 18,000 kg (40,000 lb) of water was removed from the test zone within the 164-day desiccation operational period and volumetric moisture content was reduced by up to 0.1 m^3/m^3 in over 1,300 m^3 (46,000 ft^3) of soil, with 225 m^3 (7,940 ft^3) of the test site reaching values lower than 0.04 m^3/m^3 and 68 m^3 (2,400 ft^3) of the test site reaching a moisture content less than 0.01 m^3/m^3.

The rate and extent of desiccation observed in the field test was consistent with laboratory data and associated modeling calculations. These laboratory and modeling efforts demonstrated that the desiccation rate is related to the water-holding capacity of the injected gas, which is a function of temperature and is influenced by evaporative cooling processes during desiccation. Thus, the overall desiccation rate and extent are controlled by the water-holding capacity of the injected gas, the temperature, and the number of pore volumes of dry gas that contact the targeted treatment zone. With sufficient time, the moisture content can be reduced to near zero through evaporative processes during desiccation, as shown in both laboratory tests and the field test. In the field test, a range of desiccation responses were induced over the finite duration of the test, as observed by the range in moisture content values at the end of active desiccation operations. The level of moisture reduction achieved through the desiccated zone depended on the radial distance from the injection well and the pattern of injected gas flow. While a full-scale remediation system using desiccation would be designed and operated long enough to achieve a more uniform low moisture content throughout the targeted treatment zone, the field test was conducted to provide a range of desiccation intensities so that post-desiccation rewetting could be evaluated for different desiccation conditions.

Over time, the rate of moisture rewetting of the desiccated zones is a function of the hydraulic gradient, water relative permeability, and porous media unsaturated flow properties. Rewetting data over a period of 6 years after the end of active desiccation in the field test are consistent with expectations based on related laboratory data and numerical simulation analyses. Because the rewetting process is predictable, future FS efforts can use the information herein and site-specific analyses to determine appropriate configurations for applying a desiccation zone in conjunction with a surface barrier.

3.1.1.3 Desiccation Treatability Recommendations

Desiccation has been fully tested to meet treatability test requirements and is ready for consideration in a future FS as a technology to use in combination with a surface infiltration barrier.

3.1.2 In Situ Gaseous Reduction

In situ gaseous reduction (ISGR) with diluted hydrogen sulfide (H_2S) was evaluated as a potentially effective method for immobilizing selected toxic metals (e.g., Cr(VI)) and radionuclides (e.g., uranium, technetium-99) in the vadose zone because of the lower solubility of the reduced contaminant or the formation of insoluble sulfide compounds. A laboratory column study and theoretical modeling analysis of this technology were performed as part of DOE/RL-2007-56. This study is documented in Thornton et. al., 2007, "Experimental and Theoretical Assessment of the Lifetime of a Gaseous-Reduced Vadose Zone Permeable Reactive Barrier." A summary of the testing setup, test results, and treatability recommendations of the ISGR study are summarized below.

3.1.2.1 In Situ Gaseous Reduction Study

A series of column tests was performed in which a Hanford formation sediment was treated with diluted H_2S gas mixture to reduce sediment iron oxide to ferrous sulfide. Water containing dissolved oxygen was then pumped through the columns at different flow rates to simulate variations in pore water velocity, to determine the reoxidation rate and the reductive capacity of the treated sediment. A theoretical model was used to simulate both diffusional and advectional fluxes of oxygen gas diffusing downward through the treatment zone and oxygenated water infiltrating through it. The oxygen flux estimate and the measured reductive capacity of the treated sediment was used to predict the lifetime of the barrier based on the time required to reoxidize the treated zone.

3.1.2.2 In Situ Gaseous Reduction Test Results

The results indicated that the treated sediment has a significant reductive capacity consistent with the basic reaction stoichiometry associated with the treatment and reoxidation processes. The observed reductive capacity was found to be dependent on the flow rate of water during the reoxidation phase of the tests, with the reductive capacity approaching the maximum value predicted as the flow rate was decreased. The laboratory treatment tests were found to provide a reasonable means for predicting the reductive capacity of the treatment zone under field conditions.

The theoretical modeling assessment identified that oxygen diffusion was the dominant mechanism controlling reoxidation of the treatment zone. The results of this evaluation suggest that barrier reoxidation is primarily related to diffusion of oxygen through the gas-filled portion of the sediment pore space, in which case the treatment zone lifetime could be very short (several years) in places where the sediment is course-grained and unsaturated. The analyses predicted an increase in the treatment zone lifetime to greater than 100 years where finer-grained strata with higher moisture content results in a potential decrease in the effective oxygen diffusion coefficient (Thornton et. al., 2007). However, both of these estimated lifetimes are short compared to the half-life of uranium or technetium-99 and the duration that would be required for remedy effectiveness.

3.1.2.3 In Situ Gaseous Reduction Treatability Recommendations

ISGR was evaluated as an option for the two field tests included as part of the DVZ Treatability Test Plan (DOE/RL-2007-56). It was not recommended for field testing in favor of testing desiccation (technetium-99 contamination) and Uranium Reactive Gas Sequestration (URGS) (uranium contamination). This decision was informed by the modeling and laboratory study that indicated poor longevity of the reducing conditions on which this technology relies in the vadose zone.

3.1.3 Uranium Reactive Gas Sequestration Field Test

Delivery of aqueous-phase amendments to the vadose zone for remediation can be problematic, whereas gas-phase amendment delivery may be advantageous, and therefore, has been a focus of remediation technology development efforts. The Deep Vadose Zone Treatability Test Program developed geochemical manipulation to address uranium contamination using gas-phase delivery of amendments, in particular, the use of ammonia vapor as the remediation amendment. The URGS field test described herein and in detail in PNNL-27773, *Deep Vadose Zone Treatability Test of Uranium Reactive Gas Sequestration for the Hanford Central Plateau: Final Report*, was conducted as an element of the DVZ Treatability Test Plan (DOE/RL-2007-56).

The URGS treatability study was initiated as described in the associated test plan (DOE/RL-2007-56). However, technology limitations were identified during baseline laboratory testing and analysis that was conducted as part of the treatability study using sediment samples obtained from the 216-U-8 field test site. These tests showed that ammonia treatment did not reduce uranium mobility as intended, and in many of the samples, resulted in increased uranium mobility. Because of these tests results, field testing activities were stopped and ammonia injection was not conducted.

A primary conclusion of the treatability study is that URGS has limited applicability because of the following:

- The treatment chemistry is sensitive to site geochemical conditions (with particular concerns at sites where waste discharge was acidic).
- Significant laboratory efforts to ensure effectiveness for a specific site are needed prior to field implementation.
- There are implementation risks from handling and monitoring the reactive gas (ammonia).
- The treatment process adds nitrate to the subsurface, which may be problematic at locations where nitrate could potentially reach the groundwater at concentrations above levels of concern (e.g., where treatment is near the groundwater and/or a large mass of ammonia needs to be injected).

Thus, URGS is not broadly applicable in the Hanford Central Plateau vadose zone.

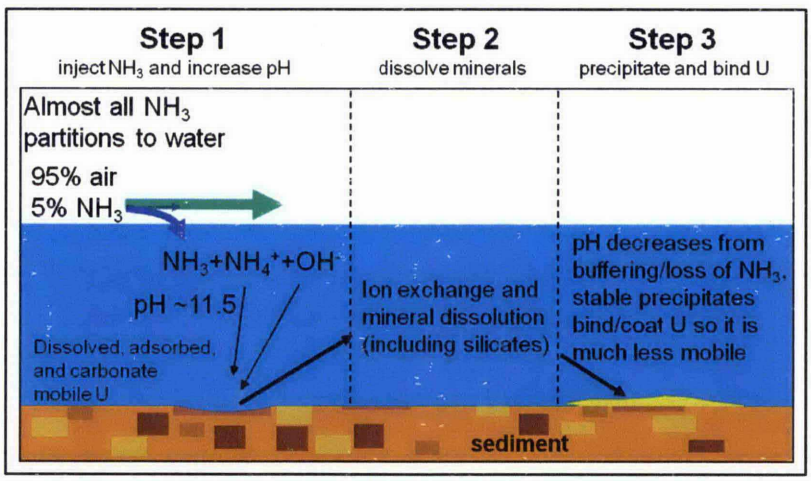
There are 11 sites on the Hanford Central Plateau where a high inventory of uranium was discharged. Of these sites, five had a waste discharge with neutral to basic pH, and URGS would likely not have the same type of limitations related to site geochemical conditions that were observed at the field test site used for the treatability study. There are six sites (including the 216-U-8 site) where acidic discharge would likely cause URGS to have the same poor effectiveness as observed at the field test site, if URGS were applied in the subsurface where the discharge changed the sediment geochemical conditions. However, given the observed sensitivity of the URGS treatment chemistry to site geochemical conditions, the effectiveness of URGS may be limited by factors other than acidic discharge. Thus, treatability study conclusions include cautions related to URGS applicability.

Conclusions from the treatability study provide criteria for assessing the applicability of URGS at candidate Hanford Central Plateau sites based on geochemical conditions, risks from handling ammonia at the surface, and the addition of nitrate to the subsurface. If this assessment for a specific site indicates a potential for successful application, the treatability study conclusions further recommend that a site-specific evaluation of ammonia treatment effectiveness be conducted in the laboratory using sediments from the zone targeted for treatment. Laboratory tests would include sequential extraction and soil column leaching tests for untreated and ammonia-treated sediments to quantify the change in

uranium mobility. This testing requires about 1 year from the sediment sample receipt until reporting of laboratory results. For sites with positive laboratory results, where the decrease in uranium mobility will meet groundwater protection needs, an evaluation will be conducted to determine whether a field study of the URGS ammonia treatment technology is warranted. A more detailed synopsis of the testing, results, and recommendations is provided below.

3.1.3.1 Uranium Reactive Gas Sequestration Test Summary

Figure 3-2 depicts the three primary elements of uranium treatment by ammonia vapor. When a gas containing ammonia is injected into an unsaturated porous medium, a large percentage of the ammonia partitions into the pore water (Step 1). For example, a 5 vol% ammonia vapor produces an equilibrium pore water concentration of about 3 M ammonia. Self-dissociation of ammonia at this concentration results in an increase in the pore water pH from initially around pH 8 to about pH 11.5. Ion exchange and mineral dissolution (including aluminosilicate dissolution) occurs due to the caustic pH (Step 2). With high total dissolved solids, precipitates start to form, especially as the pH is buffered toward neutral. The precipitates may incorporate uranium (e.g., sodium boltwoodite) or may be compounds such as quartz, chrysotile, calcite, diaspore, and hematite that could coat uranium already precipitated or adsorbed on the sediment surface (Step 3). The goal of the dissolution and re-precipitation process is to create uranium precipitates or coatings that render uranium less mobile than before treatment.



Source: PNNL-27773, *Deep Vadose Zone Treatability Test of Uranium Reactive Gas Sequestration for the Hanford Central Plateau: Final Report*

Figure 3-2. Overview of the Processes That Occur with Injection of Ammonia Vapor into an Unsaturated Uranium-Contaminated Hanford Site Sediment

Understanding the robustness of gas-phase treatment approaches and scale-up to the field is an important part of the technology development process. As part of development efforts for the ammonia technology, scale-up issues were identified and have been addressed through a series of laboratory and modeling efforts. Key scale-up elements include scoping calculations to support treatment design, ammonia transport information, field application monitoring approaches, and information about processes affecting the fate of ammonia in the subsurface.

DOE/RL-2010-87, *Field Test Plan for the Uranium Sequestration Pilot Test*, and associated DOE/RL-2010-88, *Sampling and Analysis Plan for the Uranium Sequestration Pilot Test*, were published for the URGS field test, with minor modifications documented in Tri-Party Agreement Change Notices

(TPA-CN-0764 and TPA-CN-0766). These plans guided design of field equipment, field site preparation, and laboratory testing of field test site sediments.

3.1.3.2 Uranium Reactive Gas Sequestration Technology Development Results

Laboratory testing of the ammonia treatment was conducted for a range of sediments and associated uranium precipitate phases and sediment samples that were available from the Hanford Site at the time of technology development efforts. Sediments were primarily from beneath tank farms and from other sites that received neutral to basic liquid waste (PNNL-27773). Testing evaluated the range of implementation parameters needed to achieve effective treatment of uranium by ammonia. Ammonia treatments on 18 different sediments showed good effectiveness based on sequential extraction results for over 80% of the sediments where good treatment (e.g., with an appropriate ammonia mass delivered) was expected. These tests showed consistently good reduction of mobile uranium and increases in the presence of immobile uranium after treatment. Ammonia treatments reduced the uranium present in aqueous and adsorbed states by an average of 68% and increased the acid-extractable uranium (immobile) an average of 71%. These results showed that good effectiveness could be obtained for a wide range of uranium concentrations, sample depth, moisture content, and type of uranium precipitate present (e.g., silicate or carbonate) (PNNL-20004, *Remediation of Uranium in the Hanford Vadose Zone Using Ammonia Gas: FY 2010 Laboratory-Scale Experiments*; Szecsody et al., 2012, "Geochemical and Geophysical Changes During NH_3 Gas Treatment of Vadose Zone Sediments for Uranium Remediation"; Zhong et al., 2015, "Ammonia Gas Transport and Reactions in Unsaturated Sediments: Implications for Use as an Amendment to Immobilize Inorganic Contaminants"; PNNL-23699, *Scale-Up Information for Gas-Phase Ammonia Treatment of Uranium in the Vadose Zone at the Hanford Site Central Plateau*).

Soil column uranium leachability tests were conducted on three sediments for a selected set of conditions to augment data for the uranium mobility reductions observed in sequential extraction results and to assess how the rate of uranium mobility was impacted by treatment. In the soil column tests, uranium mobility (the amount and rate of uranium that was removed from the soil by passing groundwater through the sample) was significantly reduced by ammonia treatment and was consistent with the sequential extraction results (Szecsody et al., 2012; Zhong et al., 2015).

3.1.3.3 Uranium Reactive Gas Sequestration Treatability Test Results

The field test system was designed and assembled at the selected 216-U-8 Crib field test site. The test site consisted of an ammonia injection well and five monitoring boreholes. The injection well was screened at a depth of 13.4 to 16.5 m bgs (44 to 54 ft bgs). The monitoring boreholes included downhole electrical resistivity tomography electrodes, thermistors, a distributed temperature system (fiber optic), and gas-sampling ports. A surface array of electrical resistivity tomography electrodes was installed to work in conjunction with the downhole electrodes in tracking ammonia injection. Injection equipment included liquid nitrogen tanks to supply nitrogen gas and liquid ammonia tanks to supply ammonia gas. The gases were designed to be mixed in a temperature-controlled trailer using mass-flow controllers to reach an injection concentration of 5% by volume ammonia. Ammonia sensors were deployed for safety and to measure injection gas ammonia concentration.

The field test plan was to inject about 3,000 kg (6,600 lb) of ammonia to treat a subsurface target zone about 12 m (39 ft) diameter by about 4 m (13 ft) height. Injection of this amount of gas at 100 standard cubic feet per minute would require about 25 days of continuous injection operations. Field test equipment was functionally tested and ready for injection in the field test but not operated for ammonia-gas injection.

Prior to field testing, laboratory tests were conducted with field site sediments to evaluate the effectiveness of the ammonia treatment under the site-specific conditions. The URGS field site (216-U-8 Crib) received

acidic liquid waste, in contrast to the higher pH liquid waste discharged at the sites previously used in laboratory tests. Results showed that ammonia treatment in the laboratory did not decrease uranium mobility. The acidic discharge had impacted the geochemistry of the sediments in the subsurface location targeted for the field test. The evaluation of these sediments to determine the cause of poor treatment effectiveness pointed to the low sediment carbonate concentrations and form of uranium precipitates in this impacted zone as key problems leading to poor effectiveness. This result is contrary to the uranium mobility decreases observed in previous laboratory studies with sediments from other locations at the Hanford Site where basic to neutral waste chemistry did not impact the sediment geochemistry in the same way.

Because of the poor ammonia treatment results in the laboratory tests, the field injection of ammonia was not conducted. The treatability test report (PNNL-27773) compiles the technology information gained from the laboratory testing during technology development, the field site laboratory tests, and a laboratory study assessing geochemical interferences that affect ammonia treatment performance. In addition, the treatability test report describes the field injection and monitoring equipment design and associated design calculations. Conclusions from the treatability study provide criteria for assessing the applicability of URGS at candidate Hanford Central Plateau sites. However, based on the information collected in the treatability study, URGS is not broadly applicable in the Hanford Central Plateau vadose zone. Of the 11 sites on the Hanford Central Plateau where a high inventory of uranium was discharged, there are 6 (including the 216-U-8 site) where acidic discharge would likely cause URGS to have the same poor effectiveness as observed at the field test site (if URGS were applied in the subsurface where the discharge changed the sediment geochemical conditions). However, given the observed sensitivity of the URGS treatment chemistry to site geochemical conditions, the effectiveness of URGS may be limited by factors other than acidic discharge. Thus, treatability study conclusions include cautions related to URGS applicability.

3.1.3.4 Uranium Reactive Gas Sequestration Treatability Recommendations

The URGS test demonstrated that the interaction of the ammonia treatment chemistry with the site geochemistry can limit the applicability of the technology. The URGS Treatability Test Report (PNNL-27773) documents closeout of the URGS treatability test as part of the DVZ Treatability Test Plan (DOE/RL-2007-56) effort.

As discussed above, during additional site characterization for sites where URGS is a potential treatment technology, a laboratory investigation of URGS effectiveness will be performed using sediments from the zone targeted for treatment. An evaluation will be conducted to determine whether a field study of the URGS ammonia treatment technology is warranted where the site-specific laboratory testing shows positive results with a decrease in uranium mobility that will meet groundwater protection needs.

3.1.4 Multi-Step Geochemical Manipulation

Multi-step geochemical manipulation was identified in the DVZ Treatability Test Plan as a category of treatment where the subsurface geochemistry is manipulated to sequester contaminants. For instance, the technology could include manipulating subsurface conditions to cause dissolution and then precipitating the target contaminant or combining oxidation-reduction reactions with other chemical reactions to immobilize/encapsulate the target contaminant. A series of investigations was conducted in the laboratory to assess potentially viable approaches. One of these approaches led to the URGS field test described in Section 3.1.3. A range of other techniques were tested in the laboratory as described below and in associated publications. These studies focused on gas-transported amendments.

3.1.4.1 Multi-Step Geochemical Manipulation Test Summary

A laboratory study comparing the effectiveness of different geochemical approaches was conducted and used to select the most promising candidate for field testing for uranium-contaminated sites as described in PNNL-18879, *Remediation of Uranium in the Hanford Vadose Zone Gas-Transported Reactants:*

Laboratory-Scale Experiments. In these tests, gas-delivered reactants were dosed into small soil columns that were sealed to allow reactions to occur. Reactants were advected into the soil columns as a gas for carbon dioxide, ammonia, hydrogen sulfide, and sulfur dioxide, as a mist with 0.1% water content for sodium hydroxide, ferric iron, hydrochloric acid, and phosphate, or as a 1% water content foam for phosphate. Uranium-contaminated sediment from the Hanford Central Plateau was used in these tests. Performance of the technologies was evaluated with respect to reducing uranium mobility by comparing the relative amount of mobile and immobile uranium fractions in untreated and treated sediment. Uranium mobility was measured using a sequential extraction technique. In this technique, the sediments are contacted first with groundwater, and then the groundwater is separated from the sediment and analyzed for uranium concentration. The sediments are then extracted with sequentially harsher solutions as follows: an ion exchange solution, a weak acetic acid solution, a strong acetic acid solution, oxalic acid, and then 8M nitric acid. Favorable treatment was assigned to those treatments that had lower uranium concentrations in the groundwater, ion exchange, and weak acetic acid solutions and higher uranium concentrations in the stronger acid solutions, as compared to the concentrations in untreated sediments. These changes correspond to a reduction in uranium mobility.

After the comparison testing described in PNNL-18879, and selection of ammonia as the amendment for use in the URGS field test (Section 3.1.3), an additional laboratory test was conducted to examine the use of a gas-phase combined chemical reduction and chemical sequestration approach for technetium-99 (PNNL-23665, *Gas-Phase Treatment of Technetium in the Vadose Zone at the Hanford Site Central Plateau*; Szecsody et al., 2015, "Remediation of Technetium in Vadose Zone Sediments Using Ammonia and Hydrogen Sulfide Gases"). This test used sediment contaminated with technetium-99 from the Hanford Central Plateau. The sediments were dosed with a combination of hydrogen sulfide gas (to chemically reduce technetium-99 to an insoluble form) and ammonia (to cause dissolution and precipitation of aluminosilicates as a low-solubility barrier to technetium-99 mobility). Performance was analyzed using sequential extractions as described above for PNNL-18879 and using soil column tests to quantify leaching of technetium-99 from treated and untreated sediments.

3.1.4.2 Multi-Step Geochemical Manipulation Test Results

The results of the comparative testing (PNNL-18879) showed that uranium mobility was decreased by ammonia, phosphate, sodium hydroxide mist, hydrochloric acid mist, carbon dioxide, and ferric iron mist. The best performance was attributed to ammonia, phosphate, and sodium hydroxide mist, due to the formation of low-solubility precipitates. Of these, gaseous ammonia is easiest to distribute in the vadose zone and was selected for further testing (Section 3.1.2).

For the technetium-99 tests, individual chemical reduction or ammonia-gas treatment was not effective at reducing technetium-99 mobility. However, combined gas-phase chemical reduction and gas-phase chemical sequestration for technetium-99 treatment was shown to be effective for a variety of operational and site conditions, including the following:

- Sequential and parallel addition of hydrogen sulfide and ammonia gases over a range of treatment gas concentrations
- Technetium-99 concentrations ranging from 34 to 3,800 pCi/g
- Soil moisture contents of 1, 4, and 8 wt%
- Gas delivery times into the sample ranging from minutes to hours

A large fraction of technetium-99 in treated sediments was shown be resistant to leaching in saturated soil column tests.

3.1.4.3 Multi-Step Geochemical Manipulation Test Recommendations

The multi-step geochemical manipulation evaluation resulted in selection of the uranium reactive gas sequestration activity and related laboratory testing.

3.1.5 Grout Injection

The DVZ Treatability Test Plan (DOE/RL-2007-56) identifies in situ grouting as a potential remediation technology for the DVZ and includes a planned effort to evaluate in situ grouting to provide information for future FSs. PNNL-20051, *Evaluation of In Situ Grouting as a Potential Remediation Method for the Hanford Central Plateau Deep Vadose Zone,* provided information to evaluate the effectiveness, implementability, and relative cost for in situ grouting. A synopsis of the study is provided below.

3.1.5.1 Grout Injection Evaluation Summary

Multiple types of grout/binding materials and emplacement techniques have been developed and demonstrated. Jet grouting and permeation grouting are the two general categories that are potentially applicable for subsurface contaminant applications at the Hanford Site. Jet grouting uses high energy emplacement of cement or chemical grout materials whereby the contaminated sediment is fluidized and mixed with the grouting material. Jet grouting is a well-established technology for shallow (<15 m [<50 ft]) applications and its application in the DVZ can be extrapolated from shallow zone applications. Because jet grouting information is readily available for use in FSs, the PNNL-20051 evaluation focused on permeation grouting for application in the DVZ. Permeation grouting is the injection of a liquid grout that fills the natural porosity and then gels to form a solid void-filling material. While permeation grouting is a relatively mature technology for many applications, there are uncertainties with the use of grout for in situ contaminant stabilization.

Two general types of permeation grouting approaches may be applicable to address DVZ contamination in the Hanford Central Plateau. Grout could be injected to form a low permeability layer above, and potentially surrounding the contamination to deflect infiltrating moisture and thereby slowing downward contaminant migration. The grouted layers would have grout filling the pore space between sediment grains, but voids may be present because of incomplete filling during injection, and where grout injections have not coalesced to form a contiguous barrier. For some grouts, shrinkage over time may also cause some void formation. While grout would not be an impermeable barrier, slowing the contaminant flux may be sufficient to meet remediation goals, similar to how other in situ remedies, such as desiccation or reactive gases, act to limit contaminant flux. In some cases, grout could be injected directly into the contaminated sediment zones to encapsulate contaminants and limit contact with infiltrating water (e.g., volumetric encapsulation). In the vadose zone, grout applied to encapsulate contaminants directly is not expected to create a monolith like a grouted waste form that is prepared above ground. The grout will fill the pore space between the particle grains, although some void space in the grouted region may occur. Thus, volumetric encapsulation does not create an impermeable monolith but would be expected to reduce the flux of water through the contaminated zone.

3.1.5.2 Grout Injection Study Conclusions

PNNL-20051 recommended two chemical grouts for consideration in the Hanford Site DVZ: acrylamide and silicate grouts. Both materials can be formulated for low viscosities and controlled gelling times. The two chemical grout candidates both have potential limitations because of voids from nonuniform injection. Void formation over time due to shrinkage may also occur under some conditions.
The dominant contaminant release mechanism is expected to be from contaminants that remain associated with the pore water/sediment surfaces and are transported with water infiltration through voids in the grout or where grout injections have not coalesced to form a contiguous barrier.

Grout penetration distance is a primary cost factor and potential physical limitation for permeation grout application in the Hanford Central Plateau DVZ. PNNL-20051 describes an analytical approach to estimate grout penetration and grout gelling time. In most cases, the grout penetration distance will be small relative to the lateral size of the target treatment zone for Hanford Site applications. Additionally, grout penetration is a strong function of the subsurface properties. General limits for use of permeation grouts are provided in the technical literature and are based on sediment permeability and particle size. The groutability of subsurface sediment becomes difficult at permeabilities less than approximately 1×10^{-12} m^2 (a hydraulic conductivity of about 1×10^{-3} cm/s). Groutability is also restricted when sediment particles with a diameter <0.075 mm (0.003 in.) are present. Subsurface sediment having greater than approximately 20% fine sand is generally not groutable, and difficulty in grouting starts when fine sand is present at between 5% and 10%. Verification of injected grout placement and the success in covering the desired target zone through use of multiple coalescing injections would likely be needed. These limitations and issues may restrict the viability of grouting for many Hanford Central Plateau DVZ applications. The most appropriate target for permeation grouting would be higher permeability zones where the largest grout penetration distances could be achieved.

3.1.5.3 Grout Injection Study Treatability Recommendations

Application of in situ grouting for the Hanford Central Plateau DVZ is limited by several factors and would be best applied to small target zones and high-permeability layers to limit flux of water through contaminated zones. However, like many in situ technologies, in situ grouting may be viable in some situations if applied to targets that are suitable to its use as part of an overall solution. Thus, future FSs would benefit by identifying specific targets for application of grouting in conjunction with other techniques, rather than consider grouting as a stand-alone solution. The need for potential additional treatability testing for grouting was considered as part of the treatability assessment in this document.

3.1.6 Soil Flushing

Soil flushing operates through the addition of water, and if necessary, an appropriate mobilizing agent, to mobilize contaminants and flush them from the vadose zone and into the groundwater where they are subsequently captured by a P&T system. As described in the DVZ Treatability Test Plan (DOE/RL-2007-56), investigation of vadose zone transport processes through modeling and laboratory evaluation is needed to provide information for considering soil flushing in subsequent FSs for the Hanford Site DVZ.

In PNNL-19938, *Evaluation of Soil Flushing for Application to the Deep Vadose Zone in the Hanford Central Plateau,* numerical modeling and laboratory flow-cell experiments were conducted to investigate the characteristics of water flow and solute transport through the vadose zone as a function of the imposed infiltration condition, subsurface properties, and properties of the leaching solution. Information on previous uranium leaching studies, infiltration studies at the Hanford Site, and relevant uranium mining operations were compiled and evaluated with respect to how these approaches potentially apply to soil flushing in the Hanford Central Plateau.

There are uncertainties associated with applying soil flushing technology to contaminants in the DVZ at the Hanford Central Plateau. Modeling and laboratory efforts were intended to provide a quantitative assessment of factors that impact water infiltration and contaminant flushing through the vadose zone and into the underlying groundwater. Once in the groundwater, capture of the contaminants would be necessary, but this aspect of implementing soil flushing was not evaluated in this effort. Soil flushing was evaluated primarily with respect to applications for technetium and uranium contaminants in the DVZ of the Hanford Central Plateau. A synopsis of the study is provided below.

3.1.6.1 Soil Flushing Study Summary

Contaminants such as technetium-99 do not interact significantly with the subsurface sediments and move with the infiltrating water. As such, soil flushing for technetium does not have limitations related to the chemistry of the flushing solution. Conversely, uranium interacts strongly with the subsurface sediments and both sorption and solubility-related processes can significantly slow its movement relative to the infiltrating water. Leaching solutions have been used for uranium extraction but have limited applicability for sites with uranium contamination in the vadose zone at the Hanford Site. Many leaching solutions are designed for extracting chemically reduced uranium, which is not prevalent at the Hanford Site. Mild extraction solutions would only address a portion of the uranium in the Site vadose zone. The highest strength solution, acid dissolution, is not appropriate for field application due to the acid neutralization capacity of the subsurface sediment and potential for co-contaminant releases.

As mentioned above, the potential feasibility of soil flushing applications for environmental remediation in the DVZ has limitations. However, based on the review of prior investigations, carbonate and citric acid flushing solutions may be suitable for mobilizing adsorbed and dissolved uranium in the pore water. Removal of the mobile uranium fraction may be sufficient to meet remediation goals. The most mobile fraction poses the highest risk to groundwater, and there is a possibility that the rate of release for the more refractory phases may be slow enough to be protective of the groundwater.

In addition to the characteristics of the solution used for soil flushing, the process of water infiltration and associated contaminant flushing needs to be considered. Numerical modeling and laboratory flow-cell experiments investigated the characteristics of water flow and solute transport through the vadose zone as a function of the imposed infiltration condition, subsurface properties, and the physical properties of the leaching solution. Infiltrated water moves vertically in the vadose zone until a layer with contrasting hydraulic properties is encountered. At these contacts, infiltrated water can be diverted laterally to an extent that depends on the hydraulic properties. Low permeability silt zones are of most significance for inducing lateral water flow in the Hanford Site vadose zone when they are surrounded by higher conductivity material.

Numerical simulations were conducted to quantify the amount of lateral water movement as a function of the thickness and permeability of subsurface silt layers. As expected, lateral flow increased with decreased hydraulic conductivity and increased thickness of a silt layer. Thus, where other areas with zones are present, significant lateral water movement would be expected. While lateral water movement in the numerical simulations was most significant at silt layers, some lateral water movement occurred at most contacts between layers of lower permeability and higher permeability.

The impact of lateral water movement could be beneficial in terms of increasing the size of the treatment area. However, lateral flow could also increase the size of the groundwater capture zone needed and may cause water to be diverted toward areas with preferential downward flow potentially bypassing treatment zones. Lateral water flow could also increase the time and total water volume needed for soil flushing at a specific site. The impact of lateral water movement on soil flushing effectiveness depends on the location of the contaminants relative to the infiltration area and subsurface layering.

There are some uncertainties related to soil flushing that were not evaluated as part of this study. The impact of lateral heterogeneity, such as the presence of discontinuous silt lenses, was not quantified. Preferential pathways for water movement either caused by discontinuities in subsurface properties or features such as clastic dikes were not evaluated but should be considered for a specific site. The presence of preferential pathways will limit the effectiveness of soil flushing if contaminated zones are bypassed. The numerical model also did not evaluate any slope to layers or inherent layer anisotropy that could impose lateral flow. These types of uncertainties may need to be considered in the design of a soil

flushing system for a specific site, including design of a groundwater capture system in terms of the necessary capture zone. Limitations to infiltration at the surface may be another uncertainty to consider that was not included in the simulations. Presence of features that cause ponding of water rather than infiltration may limit soil flushing effectiveness, and surface infiltration rates for a specific site may need to be quantified as part of evaluating the applicability of soil flushing.

3.1.6.2 Soil Flushing Treatability Recommendations

Soil flushing is included in this document for consideration of potential additional treatability testing. Thus, determination of the need for additional testing is described in later sections of this document. In addition, planned field testing of infiltration approaches in the 300-FF-5 and 100-KR-4 OUs at the Hanford Site will provide additional information relevant to soil flushing.

3.1.7 Surface Barriers

Surface barriers have long been used to isolate contaminants from the accessible environment. In the typical configuration, the contaminants are located relatively close to the surface, generally within 15 m (49 ft), and thus they are close to the base of the surface barrier. The proximity of the surface barrier under these conditions yielded few concerns about the effectiveness of the barrier at depth, particularly for cases in which the contaminants were in a lined facility. At the Hanford Site, however, some waste sites have contaminants located well below depths of 15 m (49 ft), which means that the contaminants are increasingly distant from the surface barrier meant to isolate them from the accessible environment. The issue raised about these waste sites is the degree of effectiveness of a surface barrier in isolating contaminants from infiltrating water in the DVZ. Previous studies at the Hanford Site and by Pacific Northwest National Laboratory (PNNL) researchers suggest that surface barriers have the potential to provide a significant degree of isolation of DVZ contaminants. The studies show that the actual degree of isolation is site-specific and depends on many factors, including recharge rates, barrier size, depth of contaminants, sediment physical properties, and the geochemical interactions between contaminants and sediment.

3.1.7.1 Surface Barrier Study Summary

In PNNL-18661, *Technical Basis for Evaluating Surface Barriers to Protect Groundwater from Deep Vadose Zone Contamination*, PNNL reviewed available information to support surface barrier evaluation for the DVZ, identified gaps in the information and the outcomes necessary to fill those data gaps, and outlined tasks to achieve those outcomes. A strategy was presented for evaluating the effectiveness of surface barriers for site-specific DVZ applications. The strategy provides a technically defensible approach to determine the depth to which a surface barrier can effectively isolate contaminants at a specific site as a function of subsurface properties, contaminant distribution, barrier design, and infiltration control performance. The strategy also provides an assessment of additional data and information needs with respect to surface barrier performance for DVZ applications. The strategy addresses the linkage between surface barriers and DVZ in situ remediation activities, monitoring issues, and emerging science, technology, and regulatory objectives.

Full understanding of contaminant behavior in the DVZ is constrained by four key data gaps: limited access, limited data, limited time, and the lack of an accepted predictive capability for determining whether surface barriers can effectively isolate DVZ contaminants. Activities designed to fill these data gaps include the following:

- *Common evaluation methodology* that provides a clear, consistent, and defensible basis for evaluating groundwater impacts caused by placement of a surface barrier above DVZ contamination

- *DVZ data* that characterize the lithology, the spatial distribution of moisture and contaminants, the physical, chemical, and biological process that affect the mobility of each contaminant, and the impacts to the contaminants following placement of a surface barrier
- *Subsurface monitoring* to provide subsurface characterization of initial conditions and changes that occur during and following remediation activities
- *Field observations* that span years to decades to validate the evaluation methodology

3.1.7.2 Surface Barrier Study Recommendations

In PNNL-18661, a set of six proposed tasks was identified to provide information needed to assess the adequacy of surface barriers. These tasks include the following:

1. **Evaluation Methodology**. Develop common evaluation methodology that will provide a clear, consistent, and defensible basis for evaluating groundwater impacts caused by placement of a surface barrier above DVZ contamination.
2. **Case Studies**. Conduct case studies to demonstrate the applicability of the common evaluation methodology and provide templates for subsequent use elsewhere. Three sites expected to have conditions that would yield valuable information and experience pertinent to DVZ contamination were chosen to cover a range of conditions. The sites are BC Cribs and Trenches, U Plant Cribs, and the T Farm Interim Cover.
3. **Subsurface Monitoring Technologies**. Evaluate minimally invasive geophysical approaches for delineating subsurface plumes and monitoring their migration in the DVZ.
4. **Controlled Field Test at an Existing Field Site**. Evaluate the ability of modeling to predict long-term liquid, vapor, and chemical transport processes at a well-characterized site containing a plume of subsurface water and tracer remaining from injections in the early 1980s and 2000s.
5. **Deep Vadose Zone Monitoring at T Farm**. Demonstrate the ability of the geophysical sensors and the model to detect and predict long-term migration of liquid and vapor between the vadose zone beneath the infiltration area and the vadose zone protected by the interim cover.
6. **Deep Vadose Zone Monitoring at the Prototype Hanford Barrier**. Demonstrate the ability of geophysical sensors and the model to detect and predict the hydrologic conditions in the vadose zone beneath the Prototype Hanford Barrier 15 years after construction.

These six proposed tasks expand and elaborate on the actions proposed in the DVZ Treatability Test Plan (DOE/RL-2007-56) and are being considered as additional treatability test actions; thus, determination of the need for additional testing is described in later sections of this document.

3.1.8 Treatability Test Plan Closeout

The DVZ Treatability Test Plan (DOE/RL-2007-56) outlined an array of technologies for treatability testing. The test plan activities were to culminate in a treatability test performance evaluation described in this section. All the identified individual technology treatability activities have been completed. These activities are described in Section 3.1 and included test activities for in situ gas-phase technologies (desiccation, in situ gaseous reduction, and uranium reactive gas sequestration), grouting technologies, soil flushing, and surface barriers. In addition to technology-specific activities, ongoing reviews of uranium and technetium-99 studies were performed that meet the DVZ Treatability Test Plan (DOE/RL-2007-56) expectation, including technology review and workshop activities described in

the 200-DV-1 OU RI/FS and RFI/CMS WP (DOE/RL-2011-102) and, most recently, the technology review as part of this document.

In terms of decisions identified in the DVZ Treatability Test Plan (Figure 4-1), Phase 1 laboratory/modeling assessments and Phase 2 contaminated site field tests were selected and conducted as required for both in situ gas-phase technology tests. It was determined that field tests of in situ gaseous reduction, grouting technologies, and DVZ soil flushing were not needed and that Phase 1 assessment activities were sufficient to meet test plan objectives. Initial assessments and technology reviews associated with surface barriers and other potential technology sources were completed. The decisions and activities associated with additional surface barrier monitoring and modeling evaluation and the need to conduct a field test for a technology identified in reviews or for a complex site are addressed in this report.

Conclusions from the treatability test plan studies and recommendations for use of these technologies in an FS per the evaluations performed in this document are summarized in Table 3-1.

Table 3-1. Treatability Test Plan Conclusions and Recommendations

Treatability Study	Conclusions and Recommendations from the Treatability Test Plan Studies
Desiccation	Desiccation is considered a viable technology for remediation of most COIs except organics in the DVZ. It is ready for FS evaluations, and no further treatability studies are recommended. Desiccation is potentially applicable for all unsaturated zone sites.
In Situ Gaseous Reduction	In situ gaseous reduction was evaluated as an option for field testing, but was not tested in favor of testing desiccation and URGS. This decision was informed by a modeling and experimental study indicating poor longevity of the reducing conditions on which this technology relies in the vadose zone.
Multi-Step Geochemical Manipulation	The goal of this laboratory study was to select a gas-phase technology for field testing. The testing showed ammonia (NH_3) was the most promising gas-phase approach and led to the URGS studies. There is no additional continuation from this specific treatability test component.
Uranium Reactive Gas Sequestration	Technology limitations were identified during baseline laboratory testing and analysis that was conducted as part of the treatability study using sediment samples obtained from the 216-U-8 field test site. These tests showed that ammonia treatment did not reduce uranium mobility as intended, and in many of the samples, resulted in increased uranium mobility. Because of these tests results, field testing activities were stopped and ammonia injection was not conducted. URGS has limited applicability because (1) the treatment chemistry is sensitive to site geochemical conditions, (2) significant laboratory efforts to ensure effectiveness for a specific site are needed prior to field implementation, (3) there are implementation risks from handling and monitoring the reactive gas (ammonia), and (4) the treatment process adds nitrate to the subsurface, which may be problematic at locations where nitrate could potentially reach the groundwater at concentrations above levels of concern. There are 11 sites on the Hanford Central Plateau where a high inventory of uranium was discharged: 5 had a waste discharge with neutral to basic pH and URGS would likely not have the same type of limitations observed at the field test site; 6 sites had acidic discharge (including the 216-U-8 site) and URGS would likely have poor effectiveness. Because of the technological limitations and few applicable waste sites, it is recommended that no URGS field studies be conducted at this time.
Subsurface Grout Injection	Permeation grouting was found to have a limited radius of influence for the unsaturated zone, therefore, it rated poorly for implementability. It is not recommended for widespread treatment of contaminants. No additional activities are needed to support consideration of subsurface grouting in FSs.

Table 3-1. Treatability Test Plan Conclusions and Recommendations

Treatability Study	Conclusions and Recommendations from the Treatability Test Plan Studies
Soil Flushing	Results showed that there are potential issues with flushing the thick Central Plateau vadose zone, primarily due to the potential for lateral spreading of the flushing solution and associated contaminants. Therefore, it rated poorly for implementability and is not recommended for most applications in the deep vadose zone of the Hanford Central Plateau. It is ready for FS evaluations and no further treatability studies are recommended.
Surface Barriers	The treatability study provided baseline information for surface barrier evaluation. However, as noted in the PNNL-18661 study, an additional modeling assessment is needed to better define the effective depth and areal extent of the barrier in support of FS evaluations. Surface barriers are recommended for consideration in an FS as a stand-alone technology or in conjunction with desiccation to address most COIs except organics.

Reference: PNNL-18661, *Technical Basis for Evaluating Surface Barriers to Protect Groundwater from Deep Vadose Zone Contamination*

COI = contaminants of interest

DVZ = deep vadose zone

FS = feasibility study

URGS = Uranium Reactive Gas Sequestration

The combination of the individual reports published for technology activities (Section 3.1) and recommendations in this document collectively address all elements of the DVZ Treatability Test Plan (DOE/RL-2007-56); thus, it is considered to be successfully completed.

3.2 Summary of Previous DVZ Technology Evaluations

Appendix D of DOE/RL-98-28 provided an initial screening level effort to identify potentially viable remedial alternatives. It noted potential technologies and process options for each general response action and screened the technologies to select a representative process option for each technology type based on EIC. Then assembled viable technologies into alternatives representing a range of removal, treatment, and containment options.

In 2005, the DOE Richland Operations Office and Fluor Hanford convened an independent technical panel to review alternative remediation technologies at a 3-day workshop in Richland, Washington. WMP-27397, *Evaluation of Vadose Zone Treatment Technologies to Immobilize Technetium-99*, documents the panel's evaluation of various treatment alternatives having the potential to minimize technetium-99 migration in the DVZ at the Hanford Site. Although the panel focused on technetium-99 contamination below the BC Cribs and Trenches, the evaluation was conducted to be usable for other contaminants and DVZ waste sites.

RPP-ENV-34028, *Central Plateau Vadose Zone Remediation Technology Screening Evaluation*, identified vadose zone soil remediation technologies potentially applicable on the Central Plateau of the Hanford Site. The report included a preliminary screening evaluation of these technologies based on EIC. These evaluations and testing recommendations were used in developing the DVZ Treatability Test Plan.

Several subsequent documents continued to evaluate DVZ technologies to include the following:

- PNNL-18114, *Remediation of Deep Vadose Zone Radionuclide and Metal Contamination: Status and Issues*
- DOE/RL-2010-89, *Long-Range Deep Vadose Zone Program Plan*
- PNNL-20209, *Implementation Plan for the Deep Vadose – Applied Field Research Center*

Building on the above documents, a 1-day information exchange was held on June 21, 2011, and documented in SGW-50339, *Remediation Technologies Screening Report for the Deep Vadose Zone, Hanford's Central Plateau.* Potentially applicable remedial technologies for the Hanford Site DVZ were identified and screened to develop a list of promising technologies for further evaluation during future RI/FS activities. This initial screening identified promising remediation technologies requiring further treatability testing to support site-specific evaluations during future FSs for the Hanford Site DVZ.

SGW-50339 listed 59 potentially applicable technologies for remediating contamination in the DVZ from a variety of sources, including the following:

- Remediation approaches from similar sites across the country
- Research and development activities performed within the DOE and U.S. Department of Defense
- Past technology research and development occurring at the Hanford Site
- Solicited input from the DOE, EPA, Ecology, and stakeholders

Information was then collected on each of the technologies that included the general description, state of development, contaminant applicability, maturity level, and limitations/development needs for full-scale deployment.

The potential remediation technologies for DVZ contamination identified in SGW-50339 were evaluated as part of the DVZ Treatability Test Plan (DOE/RL-2007-56), as described in Section 3.1. These technologies and the technologies in the reports listed below were used as the starting point for applicable technologies for this report. Additional information about Hanford Site-relevant vadose zone science and technology is provided in Appendix A.

- DOE/RL-2015-69, *UP-1 Evaluation Plan for Iodine*
- PNNL-26934, *Identification of Promising Remediation Technologies for Iodine in the UP-1 Operable Unit*

3.3 Additional Deep Vadose Zone Technology Identification

This section outlines the process used in this report to identify remediation technologies, in addition to those identified previously, that are potentially applicable to DVZ remediation on the Central Plateau. A literature search was used to compile candidate technologies, building from the literature search and workshop activities conducted in 2011 as part of the 200-DV-1 OU RI/FS WP activities described in SGW-50339. The current literature search considered relevant technology development and demonstration activities conducted at the Hanford Site since 2011. Technology information sources associated with commercial technologies or from other sites in the DOE Complex were also evaluated. These technology information sources included the following references and programs:

- EPA's CLU-IN website
- Federal Remediation Technology Roundtable Remediation Technology Screening Matrix
- Interstate Technology & Regulatory Council Publications
- U.S. Department of Defense Strategic Environmental Research & Development Program and Environmental Security Technology Certification Program
- DOE EM-50 Technology Development Program

- DOE Small Business Innovative Research Program
- A web search of scientific literature using keywords of vadose zone, remediation, and contaminant names

Identified technologies were categorized using the following hierarchy:

- General Response Action (i.e., based on CERCLA designations)
- Technology Type (i.e., divided into general types of technologies such as surface barrier, physical treatment, chemical treatment, etc.)
- Technology Process Options (i.e., a grouping of technologies with similar functionality)
- Technology Variant (i.e., variations of technology with specific modes of application)

The above categorization enabled appropriate grouping of technologies for use in the treatability test evaluation yet retained a reasonable degree of specific information about the technology variants. In most cases, individual technologies (e.g., specific bioremediation amendments or vendor-specific technologies) are not identified because the technology variant level provides enough information to evaluate treatability test needs. Additional details for individual technologies or amendments for testing would be included in subsequent treatability test plans.

In compiling technology information, applicability was considered with respect to general vadose zone, perched water, and water table interface implementation and for the identified COIs. For instance, technologies only applicable to light or dense non-aqueous-phase liquids were not compiled. A broad range of technologies were compiled using this approach. More specific assessments of applicability to Hanford Site DVZ treatment areas were then conducted as part of the process described in this report.

Representative references describing technology categories or, in some cases variants, were compiled. The references are not intended to be exhaustive, but to provide a suitable source describing the technology. The references were selected with a preference for Hanford Site-specific reports or journal publications and then based on more general references describing the technology. For some technologies that are relatively mature or for which general information is most appropriate, references such as the EPA's CLU-IN website were deemed sufficient.

3.4 Summary of Remedial Technologies Applicable to the Hanford Deep Vadose Zone

Table B-1 in Appendix B provides a broad list of DVZ remedial technologies. These technologies will be carried through the DVZ treatability test assessment described in Chapter 4 and will be considered for inclusion in future DVZ FSs.

The remedial technologies are grouped into four general response action categories: containment, removal, ex situ treatment, and in situ treatment. The remedial technology types are general categories of technologies, such as surface barrier or chemical treatment. The remedial technology types are broken down into specific process options, as described in EPA/540/R-92/071a, *Guide for Conducting Treatability Studies under CERCLA: Final*. The process options are differentiated into technology process variants to show the variations of technologies with specific modes of applications to a subset of COIs or treatment areas. Table B-1 describes each process option, applicable COIs, state of development, maturity of the process options, and reference documents.

Access and delivery or enabling technologies are presented in the Table B-2 in Appendix B. These technologies are not stand-alone technologies but must be coupled with the remediation technologies identified in Table B-1. Therefore, they are not evaluated individually in Chapter 4 but in conjunction with the remediation technologies that require them. Similarly, any treatability recommendations for the enabling technologies will be coupled with an appropriate remediation technology.

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4 Deep Vadose Zone Remediation Technology Evaluation

This chapter presents an evaluation of the DVZ technologies identified in Chapter 3. Figure 4-1 summarizes the process used to assess each DVZ technology, identify technology gaps, determine treatability study needs, and support the conclusions and recommendations for additional treatability studies presented in Chapter 5.

Step 1: Identify contaminants of interest and treatment areas (Chapter 2)
- Identifies contaminants of interest (COIs) in the deep vadose zone (DVZ) of Hanford Central Plateau
- Identifies representative treatment areas where remediation would be implemented based on stratigraphy or interfaces with the saturated zone

Step 2: Develop list of applicable DVZ technologies (Chapter 3)
- Considers previous Hanford technology evaluations and treatability work completed
- Considers new technologies for applicability in the DVZ
- Considers technology maturity/readiness

Step 3: Evaluate effectiveness, implementability, and cost (EIC) of DVZ technologies as they apply to each treatment area and COI (Chapter 4)
- Determines which DVZ technologies are applicable for each treatment area and COI based on relative effectiveness, implementability, and cost
- Prioritizes technologies that are worth investing in

Step 4: Evaluate maturity and state of development of technologies as they apply to the Hanford deep vadose zone (Chapter 5)
- Confirms which technologies are feasibility study (FS) ready
- Determines data gaps for each non-FS ready technology
- Lists specific treatability work needed to fill the data gaps

Step 5: Identify and prioritize technologies that are the best investment to get FS ready (Chapter 5)
- Identifies technologies that require paper studies, modeling, laboratory, or field studies, as appropriate, to get them FS ready
- Prioritizes technologies that rank higher in terms of EIC evaluation

Step 6: Make recommendations for additional treatability work (Chapter 5)
- Recommends additional treatability study efforts
- Lists recommended technologies to consider for feasibility studies of DVZ waste sites with designated COIs and treatment areas
- Provides path forward for additional treatability studies and 200-DV-1 remedial investigation (RI)/FS

Figure 4-1. Deep Vadose Zone Technology Evaluation and Treatability Assessment Process

4.1 Deep Vadose Zone Technology Evaluation Criteria

Early evaluation of technologies for the DVZ provides an opportunity to identify promising remediation technologies that require further treatability testing. This effort supports determining potential feasibility of technologies and identifies the technologies that are mature enough to be carried forward and evaluated during the FS/CMS. The use of technologies for which treatability testing is required—often called innovative technologies—is supported by the EPA. The "National Oil and Hazardous Substances Pollution Contingency Plan" (NCP) (40 CFR 300.430(a)(1)(iii)(E)) states:

> EPA expects to consider using innovative technology when such technology offers a potential for comparable or superior treatment performance and implementability, fewer or lesser adverse impacts than other available approaches, or lower costs for similar levels of performance than demonstrated technologies.

The goal and objectives for the DVZ technology evaluation presented in this report differ from the goals and objectives used for the screening of technologies and selection of remedial alternatives conducted during an FS/CMS. In accordance with EPA/540/G-89/004, *Guidance for Conducting Remedial Investigations and Feasibility Studies Under CERCLA*, the FS identifies the universe of potentially applicable technology types and process options and then eliminates technologies from further consideration based on technical implementability. The remaining technically implementable technologies are further evaluated and screened based on the EIC, and where possible one representative process option is selected to represent the technology type to simplify subsequent development and evaluation of alternatives. The retained technology types and process options are then assembled into remedial alternatives. These remedial alternatives are then screened based on EIC to eliminate those that do not meet threshold criteria. The remaining remedial alternatives are then carried forward through detailed and comparative analysis using the CERCLA nine criteria to support remedy selection.

In contrast, the technology evaluation conducted herein focuses on identifying a range of viable remedial technologies that are applicable to DVZ remediation to provide FS/CMS authors a tool box of available technology types and process options, to choose from to assemble a suitable range of remedial alternatives. The objective of the evaluation herein is to identify the technologies that are FS/CMS ready, and those that require further evaluation through treatability studies.

The list of technologies presented in Table B-1 represent technologies that have been determined to be potentially implementable for the DVZ. Technologies that have been demonstrated or proved viable in remediating DVZ contamination and do not require pre-FS/CMS treatability testing may be directly carried forward to the FS/CMS. These more mature technologies provide a basis of comparison for new and promising technologies to be evaluated against.

Monitored natural attenuation (MNA) is not considered an active remediation technology that would require a treatability test; therefore, it is not included in the DVZ technology evaluation and treatability study assessment. However, it is included in Table B-1 because it is typically a component of FS remedial alternatives. MNA relies on natural processes such as radioactive decay, volatilization, and biodegradation to achieve remediation objectives within a designated time frame and uses monitoring to track progress and ensure that contamination does not spread or increase. No treatability studies are needed to provide information for MNA in future FS evaluations.

As a first step in assessing technology treatability test needs, the technologies in Table B-1 of Appendix B were evaluated with respect to the known EIC information. These criteria are consistent with EPA's guidance for conducting treatability studies under CERCLA (EPA/540/R-92/071a). While this step is analogous to the technology screening performed in an FS/CMS, this evaluation does not screen out

technologies. Instead, this evaluation assesses the relative strengths and weaknesses of technologies to determine which remedial technologies might warrant treatability testing.

EPA/540/G-89/004 states that process options are "evaluated using the same criteria – effectiveness, implementability, and cost – that are used to screen alternatives prior to the detailed analysis." The NCP (40 CFR 300.430(e)(7)) defines the EIC criteria as follows:

> (i) Effectiveness. This criterion focuses on the degree to which an alternative reduces toxicity, mobility, or volume through treatment, minimizes residual risks and affords long-term protection, complies with ARARs, minimizes short-term impacts, and how quickly it achieves protection. Alternatives providing significantly less effectiveness than other, more promising alternatives may be eliminated. Alternatives that do not provide adequate protection of human health and the environment shall be eliminated from further consideration.
>
> (ii) Implementability. This criterion focuses on the technical feasibility and availability of the technologies each alternative would employ and the administrative feasibility of implementing the alternative. Alternatives that are technically or administratively infeasible or that would require equipment, specialists, or facilities that are not available within a reasonable period of time may be eliminated from further consideration.
>
> (iii) Cost. The costs of construction and any long-term costs to operate and maintain the alternatives shall be considered. Costs that are grossly excessive compared to the overall effectiveness of alternatives may be considered as one of several factors used to eliminate alternatives. Alternatives providing effectiveness and implementability similar to that of another alternative by employing a similar method of treatment or engineering control, but at greater cost, may be eliminated.

The relative cost criterion is an estimate of the overall cost of a process, including capital and operation and maintenance costs. As noted in EPA/540/G-89/004, cost "plays a limited role in the screening of process options. Relative capital and O&M costs are used rather than detailed estimates. At this stage in the process, the cost analysis is made on the basis of engineering judgment, and each process is evaluated as to whether costs are high, low, or medium relative to other process options in the same technology type." Due to the specific nature and depth of DVZ contamination, technology-specific cost estimates are not readily available for most technologies. Therefore, relative costs are based on similarity to other technologies and professional judgment. The intended use of these cost rankings is to provide a rough order of magnitude basis for comparing the relative costs of the different technologies and should not be used for planning.

This EIC evaluation does not screen out any specific remedial technologies for consideration in future DVZ FS/CMSs; however, it does provide information about technologies that rate poorly and are not likely to be developed into viable remedial alternatives. A technology that scores poorly in the EIC evaluation, particularly for effectiveness or implementability, would not be recommended for treatability testing.

4.2 Deep Vadose Zone Technology Evaluation

This section provides details of the DVZ technology evaluation and a summary table of the EIC evaluation. The technologies presented in Table B-1 were grouped into four general response action categories to aid in the assessment containment, removal, ex situ treatment and disposal, and in situ treatment. These technologies are further broken down by technology type, process option, and technology variant. Table 4-1 provides a summary of the detailed evaluation of the effectiveness of the DVZ technologies. Evaluation of effectiveness considered the degree to which a technology reduces toxicity, mobility, or volume through treatment, minimizes residual risks and affords long-term protection, minimizes short-term impacts, and how quickly it achieves protection. Table 4-2 provides a detailed evaluation of the implementability and cost for each DVZ technology. Table 4-3 summarizes the

evaluation for each DVZ remediation technology. This evaluation uses the qualitative EIC assessment (summarized in Table 4-3) for each technology, COI, and treatment area and ranks effectiveness, implementability, and relative cost as high (H), medium (M), and low (L). Collectively, Tables 4-1, 4-2, and 4-3 show the EIC evaluation with respect to the specific Central Plateau DVZ treatment areas and COIs identified in Chapter 2.

Table 4-1. Evaluation of Technology Effectiveness by COI

Technology Category	COI								
	Uranium	Technetium-99	Iodine-129	Cr(VI)	Nitrate	Strontium-90	Cyanide	Carbon-14	Organics (MIBK, TCE)
Containment									
Surface barrier	**Medium** Reduces surface water infiltration and associated contaminant migration through the vadose zone, reducing contaminant mobility and limiting potential contaminant flux to groundwater. Highly effective for shallow vadose zone contamination, but effectiveness decreases with depth as a function of lateral coverage (areal footprint). Can potentially be implemented in conjunction with other containment technologies (e.g., desiccation) to increase effectiveness of containment deep in the vadose zone.								**Low** • Effectiveness decreases with depth • Less effective for containment of volatile organics
Subsurface jet injection grouting	**Medium** Reduces water infiltration and associated contaminant migration through the vadose zone, reducing contaminant mobility and limiting potential contaminant flux to groundwater. Requires a high number of boreholes for injection points to achieve effectiveness. Effective application depends on subsurface properties. Emplacement integrity and monitoring for verification of integrity are difficult in the vadose zone, where methods used in the saturated zone are not applicable. Long-term effectiveness and permanence is difficult to predict. Cementitious grouts are prone to cracking. Effective emplacement of the barrier over a large lateral areal extent would be difficult because of potential variability for the multiple injections required.								
Subsurface permeation grouting	**Medium** Reduces water infiltration and associated contaminant migration through the vadose zone, reducing contaminant mobility and limiting potential contaminant flux to groundwater. Requires a high number of boreholes for injection points (and heating elements for molten wax permeation grouting) to achieve effectiveness. Effective application depends on subsurface properties. Emplacement integrity and monitoring for verification of integrity are difficult in the vadose zone, where methods used in the saturated zone are not applicable. Long-term effectiveness and permanence is difficult to predict. Effective emplacement of the barrier over a large lateral areal extent would be difficult because of potential variability for the multiple injections required.								
Subsurface soil freezing	**Low** Reduces water infiltration and associated contaminant migration through the vadose zone, reducing contaminant mobility and limiting potential contaminant flux to groundwater. Would require ongoing maintenance for the duration of use, and thus would not offer passive permanence. Requires relatively high moisture content or saturated conditions. Effectiveness and integrity of barrier (with respect to containing contamination) is hard to verify.								
Desiccation [a]	**High** Removes water from the vadose zone, which reduces the rate of water migration and associated contaminant migration through the vadose zone, reducing contaminant mobility and limiting potential contaminant flux to groundwater. Effectiveness in high permeability vadose zone has been demonstrated. Desiccation is not applied directly to a low permeability zone but can achieve effective desiccation of such materials by diffusion of moisture from low to high permeability zones. May need several cycles of air injection to achieve and maintain desired moisture reduction. Must be implemented in conjunction with a surface barrier.								**Not Applicable**
Removal									
Excavation with retaining walls	**High** Removal of contaminated soils effectively achieves long-term protectiveness by reducing or eliminating contaminant volume. Implementation timeframe and timeframe to achieve protectiveness are short. Reduction in mobility is achieved through removal and containment in an engineered facility (ERDF). Deep excavations can act as temporary sources of high infiltration due to disturbed soil, reduced vadose zone thickness, and collection of surface water (run-off from precipitation and/or dust suppression activities). Contaminant volume may increase if blending of high concentration radiologically contaminated soils with clean soil is used to manage implementation risk to workers. Less effective for sites where horizontal extent of contamination is not well defined because positioning of retaining walls is difficult.								**Medium** Excavation of volatile organics is problematic due to contaminant volatilization during excavation.

Table 4-1. Evaluation of Technology Effectiveness by COI

Technology Category	COI								
	Uranium	Technetium-99	Iodine-129	Cr(VI)	Nitrate	Strontium-90	Cyanide	Carbon-14	Organics (MIBK, TCE)
Excavation without retaining walls	**High** Removal of contaminated soils effectively achieves long-term protectiveness by reducing or eliminating contaminant volume. Implementation timeframe and timeframe to achieve protectiveness are short. Reduction in mobility is achieved through removal and containment in an engineered facility (ERDF). Deep excavations can act as temporary sources of high infiltration due to disturbed soil, reduced vadose zone thickness, and collection of surface water (run-off from precipitation and/or dust suppression activities). Contaminant volume may increase if blending of high concentration radiologically contaminated soils with clean soil is used to manage implementation risk to workers. More effective than use of vertical retaining walls for sites where horizontal extent of contamination is not well defined.								**Medium** Excavation of volatile organics is problematic due to contaminant volatilization during excavation.
Soil flushing/soil washing	**Medium** Effectiveness of soil flushing is dependent upon ability to mobilize contaminants from the soil matrix and is variable for each COI. Effectiveness can be increased through use of chemical additives. Effectiveness also depends upon ability to recapture flushed contaminants through groundwater extraction wells to reduce contaminant volume.								
Perched water removal	**Medium** Removal of perched water decreases contaminant mobility and reduces contaminant mass. Cannot remove all moisture; some water will remain after pumping becomes infeasible. Cannot remove all contaminant mass because of sorption or precipitation binding contaminants to soil. Long-term effectiveness and permanence depend upon ability to limit future rewetting or saturation of pore spaces. Must be coupled with a surface barrier.								
Pore water extraction	Reduces moisture content and concurrently removes some contaminant mass, thus may decrease water and contaminant flux to groundwater. Removal of contaminant mass is permanent, but pore water extraction can only remove a small percentage of the water and associated contaminants. Long-term effectiveness and permanence of flux reduction depends upon limiting future recharge.								
	Low Sorption and presence of precipitated forms will hinder removal rate.	**Medium** High mobility is conducive to removal along with the pore water.	**Low** Sorption and presence of precipitated forms will hinder removal rate.	**Medium** High mobility is conducive to removal along with the pore water.	**Medium** High mobility is conducive to removal along with the pore water.	**Low** Sorption will hinder removal rate.	**Medium** High mobility is conducive to removal along with the pore water.	**Low** Sorption and presence of precipitated forms will hinder removal rate.	**Low** Difficult to extract from soil matrix.
Soil wicking	Reduces moisture content and concurrently removes some contaminant mass, thus may decrease water and contaminant flux to groundwater. Removal of contaminant mass is permanent, but pore water wicking can only remove a small percentage of the water and associated contaminants. Long-term effectiveness and permanence of flux reduction depends upon limiting future recharge.								
	Low Sorption and presence of precipitated forms will hinder removal rate.	**Medium** High mobility is conducive to removal along with the pore water.	**Low** Sorption and presence of precipitated forms will hinder removal rate.	**Medium** High mobility is conducive to removal along with the pore water.	**Medium** High mobility is conducive to removal along with the pore water.	**Low** Sorption will hinder removal rate.	**Medium** High mobility is conducive to removal along with the pore water.	**Low** Sorption and presence of precipitated forms will hinder removal rate.	**Low** Difficult to extract from soil matrix.
Ex Situ Technologies									
Vitrification	**High** Vitrification reduces toxicity, mobility, and volume through treatment. Long-term protectiveness is achieved quickly in a short implementation timeframe. Vitrified logs/monoliths still require disposal in an appropriate facility. Heavy metals, inorganics, and radionuclides, are incorporated into the glass structure, which is generally a strong, durable material that is resistant to leaching.								**High** High temperatures (up to 1,200°C [2,200°F]) destroy organic constituents, with very few byproducts.
Solidification/ stabilization	**High** Solidification/stabilization reduces mobility and has proven effective for radionuclides and inorganics. Mix composition is specific to the soil conditions and COIs (and is determined during remedial design).								**Low** Solidification/ stabilization is not expected to be effective for volatile organic COIs.

Table 4-1. Evaluation of Technology Effectiveness by COI

Technology Category	COI								
	Uranium	Technetium-99	Iodine-129	Cr(VI)	Nitrate	Strontium-90	Cyanide	Carbon-14	Organics (MIBK, TCE)
Contaminant separation	The effectiveness of contaminant separation technologies including soil sorting and soil washing is dependent on the nature of co-mingled contaminants. Separated contaminants are treated to reduce toxicity, mobility, and/or volume. Complex mixtures of co-mingled contaminants are difficult to treat. Mixtures of contaminants with varying characteristics and heterogeneous soils require complex soil washing formulations and treatment trains. The effectiveness of soil sorting/screening is limited where contamination is distributed homogeneously in the soil matrix.								
	Medium Effectiveness of soil sorting has been demonstrated for separation of radionuclides.	**Medium** Effectiveness of soil sorting has been demonstrated for separation of radionuclides.	**Medium** Effectiveness of soil sorting has been demonstrated for separation of radionuclides.	**Medium** Soil washing is effective for high mobility COIs.	**Medium** Soil washing is effective for high mobility COIs.	**Medium** Effectiveness of soil sorting has been demonstrated for separation of radionuclides.	**Medium** Soil washing is effective for high mobility COIs.	**Medium** Effectiveness of soil sorting has been demonstrated for separation of radionuclides.	**Not Applicable** Ex situ contaminant separation not likely to be used for VOCs, due to volatilization losses.
Backfill with treated soil	Effectiveness of reusing treated soil for backfill depends on the effectiveness of ex situ treatment methods that are used on the soil (prior to backfill). Effectiveness is likely to be low where there are multiple co-mingled contaminants, and where contaminant concentrations are far above cleanup standards (i.e. requires high removal efficiency).								
	Low Higher contaminant concentrations and co-mingled contaminants likely reduce ability to meet low cleanup levels required for backfill.								**Medium** Ex situ thermal treatment methods can effectively treat volatile organics to meet cleanup levels prior to backfill. Co-mingled contaminants could reduce effectiveness.
Onsite landfill	**High** Effective and proven method of containment for all COIs. Waste material is placed in an onsite engineered landfill with physical and regulatory controls that reduce or eliminate COI mobility. Effectiveness maintained through monitoring, leachate collection and treatment. Risk-reduction achieved quickly (short implementation timeframe) by preventing exposure. Can be combined with ex situ treatment as needed (e.g., solidification/stabilization or micro-encapsulation) as needed to meet acceptance criteria. Generally, does not reduce volume of contaminated waste materials, and may actually increase volume (e.g., solidification/stabilization), but does consolidate waste into a single location.								
Offsite landfill/repository	**High** Effective and proven method of containment for all COIs. Waste material is placed in an offsite engineered landfill with physical and regulatory controls that reduce or eliminate COI mobility. Effectiveness maintained through monitoring, leachate collection, and treatment. Short-term effectiveness is low due implementation risk to the community due to potentially long transport distances. Risk-reduction achieved quickly (short implementation timeframe) by preventing exposure; however, longer timeframe likely compared to onsite landfill due to potential permitting and state/community acceptance issues. Can be combined with ex situ treatment as needed (e.g., solidification/stabilization or micro-encapsulation) as needed to meet acceptance criteria. Generally, does not reduce volume of contaminated waste materials, and may actually increase volume (e.g., solidification/stabilization), but does consolidate waste into a single location.								
Ex situ water treatment	Only applicable with technologies that remove soil pore water from perched (e.g., pore water extraction) or introduce water to flush contaminants prior to recapture (e.g., soil flushing). The aboveground treatment components of Hanford Site pump and treat systems have proved to be effective for multiple COIs. Aboveground treatment processes become less effective as COI concentrations decrease. Discharge of treated water through vertical injection wells can limit aboveground treatment system flow rates.								

Table 4-1. Evaluation of Technology Effectiveness by COI

Technology Category	COI								
	Uranium	Technetium-99	Iodine-129	Cr(VI)	Nitrate	Strontium-90	Cyanide	Carbon-14	Organics (MIBK, TCE)
	High Ion exchange resins have effectively removed uranium.	**High** Ion exchange resins have effectively removed Tc-99.	**Low** Currently available I-129 treatment technologies are not effective in treating water to applicable standards. Additional I-129 treatment technology evaluations and development are being performed for the 200-UP-1 OU.	**High** Cr(VI) treatment technologies have been proven effective.	**High** Effectiveness of biological nitrate treatment is proven.	**Medium** Effectiveness of ion exchange is proven.	**High** Ion exchange or biological processes are possible.	**Medium** Water treatment methods for C-14 are not well documented for environmental remediation. C-14 in aqueous liquid waste is usually in chemical forms of carbonate and/or bicarbonate, depending on the solution pH. Conventional water treatment processes, such as ion exchange, can therefore sufficiently remove C-14 as carbonate and bicarbonate from liquid streams.	**High** Multiple unit operations are proven for organics treatment.
In Situ Technologies									
In situ vitrification	**Low** Solidification process uses high temperatures to melt and convert waste materials into less mobile glass crystalline products. Various methods of starting the melt have been developed, some of which may be applicable for deeper contaminants. In situ vitrification uses a containment hood to capture off-gases, though vapor collection difficulties and control of the process may increase with depth of application. Effectiveness could be good for non-volatile contaminants based on producing a stable waste form but establishing an effective melt at depth is uncertain and a poor melt would have low effectiveness.								
Thermal water volatilization	**Not Applicable** Non-volatile contaminant	**Not Applicable** Non-volatile contaminant	**Not Applicable** Non-volatile contaminant	**Not Applicable** Non-volatile contaminant	**Not Applicable** Non-volatile contaminant	**Not Applicable** Non-volatile contaminant	**Not Applicable** Non-volatile contaminant	**Not Applicable** Non-volatile contaminant	**High** Elevated temperatures promote water removal in the vapor phase and associated volatile organic contaminant removal to reduce contaminant mass. Effective methods for heating have been commercially applied.
Thermal desorption/ destruction	**Not Applicable** Non-volatile contaminant	**Not Applicable** Non-volatile contaminant	**Not Applicable** Non-volatile contaminant	**Not Applicable** Non-volatile contaminant	**Not Applicable** Non-volatile contaminant	**Not Applicable** Non-volatile contaminant	**Not Applicable** Non-volatile contaminant	**Not Applicable** Non-volatile contaminant	**High** Elevated temperatures volatilize organic contaminants and can promote in situ degradation to reduce toxicity by hydrolysis or enhanced microbial activity. Effective methods for heating have been commercially applied.

Table 4-1. Evaluation of Technology Effectiveness by COI

Technology Category	COI								
	Uranium	Technetium-99	Iodine-129	Cr(VI)	Nitrate	Strontium-90	Cyanide	Carbon-14	Organics (MIBK, TCE)
Soil vapor extraction	**Not Applicable** Non-volatile contaminant.	**Not Applicable** Non-volatile contaminant.	**Not Applicable** Non-volatile contaminant.	**Not Applicable** Non-volatile contaminant.	**Not Applicable** Non-volatile contaminant.	**Not Applicable** Non-volatile contaminant.	**Not Applicable** Non-volatile contaminant.	**Not Applicable** Non-volatile contaminant.	**High** Highly effective for removal of VOCs. Already proven effective at the Hanford Site.
Encapsulation	**Medium** To effectively reduce contaminant mobility, encapsulation would require a high number of boreholes for injection points and heating elements for molten wax. Effective application depends on subsurface properties. Emplacement integrity and monitoring for verification of integrity are difficult in the vadose zone, where methods used in the saturated zone are not applicable. Long-term effectiveness and permanence are difficult to predict. Effective emplacement of the barrier over a large lateral areal extent would be difficult because of potential variability for the multiple injections required.								**Low** Encapsulation is not expected to be effective for volatile organic COIs.
Electrokinetic removal	**Low** Demonstrated process to move water and contaminants between subsurface electrodes where contaminant mass can be removed from the subsurface to reduce its volume. Effectiveness is low in drier soils, such as those at the Hanford Site. Technical challenges, including placement of the electrodes and control of the electrical potential, controlling undesired reactions in the subsurface, and maintaining permeability may limit effectiveness.								
Chemical oxidation	**Not Applicable** Oxidation does not reduce mobility or degrade the contaminant.	**Not Applicable** Oxidation does not reduce mobility or degrade the contaminant.	**Not Applicable** Oxidation does not reduce mobility or degrade the contaminant.	**Not Applicable** Oxidation does not reduce mobility or degrade the contaminant.	**Not Applicable** Oxidation does not reduce mobility or degrade the contaminant.	**Not Applicable** Oxidation does not reduce mobility or degrade the contaminant.	**Not Applicable** Oxidation does not reduce mobility or degrade the contaminant.	**Not Applicable** Oxidation does not reduce mobility or degrade the contaminant.	**Medium** Liquid or gas (ozone) oxidants can degrade organic contaminants if effectively delivered. Degradation of soil organic material consumes some of the reactive amendments.
Particulate chemical reduction	**Low** Uranium is reduced by materials such as zero valent iron; when reduced the uranium forms less mobile precipitates. Reoxidation will occur over time such that the treatment only delays uranium movement; there is little change in the eventual flux to groundwater.	**Low** Tc-99 is reduced by materials such as zero valent iron; when reduced the Tc-99 forms less mobile precipitates. Reoxidation will occur over time such that the treatment only delays Tc-99 movement; there is little change in the eventual flux to groundwater.	**Not Applicable** Reduction does not reduce mobility.	**High** Reduction is an effective method to decrease Cr(VI) mobility and toxicity. Cr(VI) can be reduced by particulates such as zero valent iron.	**Not Applicable** Chemical reduction is ineffective.	**Not Applicable** Reduction does not reduce mobility.	**Not Applicable** Reduction does not reduce mobility.	**Not Applicable** Reduction does not reduce mobility.	**Medium** Particles such as zero valent iron have been applied for dechlorination to reduce contaminant toxicity and are effective, if adequately delivered.

Table 4-1. Evaluation of Technology Effectiveness by COI

Technology Category	COI								
	Uranium	Technetium-99	Iodine-129	Cr(VI)	Nitrate	Strontium-90	Cyanide	Carbon-14	Organics (MIBK, TCE)
Gas-phase chemical reduction	**Low** Uranium is reduced, then forms less mobile precipitates. Reoxidation will occur over time such that the treatment only delays uranium movement; there is little change in the eventual flux to groundwater.	**Low** Tc-99 is reduced then forms less mobile precipitates. Reoxidation will occur over time such that the treatment only delays Tc-99 movement; there is little change in the eventual flux to groundwater.	**Not Applicable** Reduction does not reduce mobility.	**High** Reduction is an effective method to decrease Cr(VI) mobility and toxicity. Cr(VI) can be reduced by gas such as hydrogen sulfide. This approach has been commercially applied.	**Not Applicable** Chemical reduction is ineffective.	**Not Applicable** Reduction does not reduce mobility.	**Not Applicable** Reduction does not reduce mobility.	**Not Applicable** Reduction does not reduce mobility.	**Low** Dechlorination by indirect process induced by gas phase reduction is possible but not well demonstrated.
Particulate sequestration	**High** Sorptive materials such as phosphate have been shown to reduce uranium mobility via sequestration.	**Medium** Materials that sequester contaminants have been evaluated in the laboratory and may be suitable for in situ application.	**Medium** Materials that sequester contaminants have been evaluated in the laboratory and may be suitable for in situ application.	**Medium** Materials that sequester contaminants have been evaluated in the laboratory and may be suitable for in situ application.	**Not Applicable** Sequestration chemistries are ineffective.	**High** Sorptive materials such as phosphate have been shown to reduce Sr-90 mobility via sequestration.	**Not Applicable** Sequestration chemistries are ineffective.	**Not Applicable** Sequestration chemistries are ineffective.	**Not Applicable** Sequestration chemistries are ineffective.
Gas-phase chemical sequestration	**Medium** Use of ammonia to reduce uranium mobility via sequestration has been demonstrated in the laboratory and may be effective, depending on site conditions.	**Low** Use of ammonia for Tc-99 sequestration has been shown to be poor in the laboratory; other single-step sequestration options are also likely to be ineffective.	**Medium** Use of carbonate precipitation to reduce I-129 mobility via sequestration has been demonstrated in the laboratory and may be effective, depending on site conditions.	**Medium** Use of carbonate precipitation to reduce Cr(VI) mobility via sequestration has been demonstrated in the laboratory and may be effective depending on site conditions.	**Not Applicable** Sequestration chemistries are ineffective.	**Medium** Gas-phase sequestration has not been demonstrated in the laboratory, but may be possible, such as through carbonate precipitation.	**Not Applicable** Sequestration chemistries are ineffective.	**Low** Gas-phase sequestration has not been demonstrated in the laboratory, but may be possible, such as through carbonate precipitation.	**Not Applicable** Sequestration chemistries are ineffective.
Particulate-phase combined chemical reduction and sequestration	**Medium** [b] Use of phosphate to reduce uranium mobility via sequestration has been demonstrated in the laboratory and field, and may be effectively implemented as a particulate, depending on site conditions. Use of a combined reduction and sequestration may also be effective but has not been tested.	**Low** Use of a particle with a combined reduction and sequestration mechanism may be effective for Tc-99 sequestration but has not has been demonstrated for field applications.	**Not Applicable** Reduction hinders sequestration chemistry.	**High** [b] Reduction is an effective method to decrease Cr(VI) mobility and toxicity. Cr(VI) can be reduced by particles such as ZVI. Applying a subsequent sequestration step is not needed.	**Not Applicable** Reduction and sequestration chemistries are ineffective.	**High** [b] Reduction would have no effect on Sr-90 other than changing sorption sites. Particulate sequestration to reduce Sr-90 mobility has been demonstrated in the field.	**Not Applicable** Reduction and sequestration chemistries are ineffective.	**Not Applicable** Reduction and sequestration chemistries are ineffective.	**Not Applicable** Reduction and sequestration chemistries are ineffective.
Gas-phase combined chemical reduction and sequestration	**Medium** [b] Use of ammonia to reduce uranium mobility via sequestration has been demonstrated in the laboratory and may be effective, depending on site conditions. Use of a combined reduction and sequestration such as with combined hydrogen sulfide and ammonia gas would also likely be effective but has not been tested.	**Medium** Use of hydrogen sulfide combined with ammonia to reduce Tc-99 mobility via sequestration has been demonstrated in the laboratory and may be effective, depending on site conditions.	**Not Applicable** Reduction hinders sequestration chemistry.	**High** [b] Reduction is an effective method to decrease Cr(VI) mobility and toxicity. Cr(VI) can be reduced by gas such as hydrogen sulfide. Applying a subsequent sequestration step is not needed.	**Not Applicable** Reduction and sequestration chemistries are ineffective.	**Low** [b] Reduction would have no effect on Sr-90 other than changing sorption sites. Gas-phase sequestration has not been demonstrated in the laboratory but may be possible, such as through carbonate precipitation.	**Not Applicable** Reduction and sequestration chemistries are ineffective.	**Low** [b] Reduction would have no effect on C-14. Gas-phase sequestration has not been demonstrated in the laboratory but may be possible, such as through carbonate precipitation.	**Not Applicable** Reduction and sequestration chemistries are ineffective.

Table 4-1. Evaluation of Technology Effectiveness by COI

Technology Category	COI								
	Uranium	Technetium-99	Iodine-129	Cr(VI)	Nitrate	Strontium-90	Cyanide	Carbon-14	Organics (MIBK, TCE)
Gas-phase bioremediation	**Low** Field-scale biological reductive processes have been demonstrated using hydrogen gas and are likely to reduce uranium mobility. Reoxidation will occur over time such that the treatment only delays uranium movement, but there is little change in the eventual flux to groundwater.	**Low** Field-scale biological reductive processes have been demonstrated using hydrogen gas and are likely to reduce Tc-99 mobility. Reoxidation will occur over time such that the treatment only delays Tc-99 movement, but there is little change in the eventual flux to groundwater.	**Not Applicable** Oxidation or reduction does not cause a reduction in mobility.	**High** Field-scale biological reductive processes have been demonstrated using hydrogen gas and are likely to reduce Cr(VI) mobility.	**High** Field-scale biological reductive processes have been demonstrated using hydrogen gas and are likely to reduce nitrate mobility.	**Not Applicable** Cannot be biotransformed or degraded.	**Low** Gas-phase biological processes have not been demonstrated for CN.	**Not Applicable** Cannot be biotransformed or degraded.	**High** [c] Aerobic bioremediation of MIBK is robust and could be promoted with oxygen addition, as has been commercially applied for other aerobically degraded hydrocarbons. Field-scale biological reductive processes have been demonstrated using hydrogen gas and may be applicable to TCE, but likely at a low effectiveness.
Gas-phase combined bioreduction and chemical sequestration	**Medium** [b] Use of ammonia to reduce uranium mobility via sequestration has been demonstrated in the laboratory and may be effective, depending on site conditions. Use of a combined reduction and sequestration such as with combined bioreduction and ammonia gas would also likely be effective but has not been tested.	**Medium** Use of hydrogen sulfide combined with ammonia to reduce Tc-99 mobility via sequestration has been demonstrated in the laboratory and may be effective, depending on site conditions. It is likely that the chemical reduction step could be replaced by bioreduction, but this has not been tested.	**Not Applicable** Reduction hinders sequestration chemistry.	**High** [b] Field-scale biological reductive processes have been demonstrated using hydrogen gas and are likely to reduce Cr(VI) mobility. Applying a subsequent sequestration step is not needed.	**High** [b] Field-scale biological reductive processes have been demonstrated using hydrogen gas and are likely to reduce nitrate mobility. Applying a subsequent sequestration step is not needed.	**Low** [b] Reduction would have no effect on Sr-90 other than changing sorption sites. Gas-phase sequestration has not been demonstrated in the laboratory but may be possible, such as through carbonate precipitation.	**Not Applicable** Gas-phase biological processes have not been demonstrated for CN and sequestration would not be effective.	**Low** [b] Reduction would have no effect on C-14. Gas-phase sequestration has not been demonstrated in the laboratory but may be possible such as through carbonate precipitation.	**Low** [b,d] Field-scale biological reductive processes have been demonstrated using hydrogen gas and may be applicable to TCE, but likely at a low effectiveness. A subsequent sequestration step is not applicable.
Liquid chemical reduction	**Low** Liquid-phase chemical reductants have been applied at the field scale for saturated conditions and are likely effective for reducing uranium. Reoxidation will occur over time such that the treatment only delays uranium movement; there is little change in the eventual flux to groundwater.	**Low** Liquid-phase chemical reductants have been applied at the field scale for saturated conditions and are likely effective for reducing Tc-99. Reoxidation will occur over time such that the treatment only delays Tc-99 movement; there is little change in the eventual flux to groundwater.	**Not Applicable** Reduction does not lead to sequestration.	**High** Liquid-phase chemical reductants have been applied at the field scale for saturated conditions to reduce Cr(VI) mobility and toxicity.	**Not Applicable** Chemical reduction is ineffective.	**Not Applicable** Reduction does not reduce mobility.	**Not Applicable** Reduction does not reduce mobility.	**Not Applicable** Reduction does not reduce mobility.	**Low** [d] Dechlorination by indirect processes that are induced by liquid-phase reduction is possible, but not well demonstrated.

Table 4-1. Evaluation of Technology Effectiveness by COI

Technology Category	COI								
	Uranium	Technetium-99	Iodine-129	Cr(VI)	Nitrate	Strontium-90	Cyanide	Carbon-14	Organics (MIBK, TCE)
Liquid-phase chemical sequestration	**High** Sequestration of uranium to reduce mobility by liquid-phase phosphate has been demonstrated in the field.	**Low** Moderate sequestration at high pH for Tc-99 has been demonstrated in the laboratory; other single-step sequestration options are likely to be ineffective.	**Medium** Use of carbonate precipitation to reduce I-129 mobility via sequestration has been demonstrated in the laboratory and may be effective, depending on site conditions.	**Medium** Use of carbonate precipitation to reduce Cr(VI) mobility via sequestration has been demonstrated in the laboratory and may be effective depending on site conditions.	**Not Applicable** Sequestration chemistries are ineffective.	**High** Sequestration of Sr-90 to reduce mobility by liquid-phase phosphate (apatite) has been demonstrated in the field.	**Not Applicable** Sequestration chemistries are ineffective.	**Low** Liquid-phase sequestration has not been demonstrated in the laboratory but may be possible such as through carbonate precipitation.	**Not Applicable** Sequestration chemistries are ineffective.
Liquid-phase combined chemical reduction and sequestration	**Medium** [b] Use of phosphate to reduce uranium mobility via sequestration has been demonstrated in the laboratory and may be effective, depending on site conditions. Use of a combined chemical reduction and sequestration using phosphate gas may not be as effective as sequestration alone but has not been tested.	**Medium** Liquid-phase chemical reductants have been applied at the field scale for saturated conditions and are likely effective for reducing Tc-99 to a less mobile compound. Use of phosphate or other coatings may armor the Tc-99 and make it less susceptible to reoxidation, but this has not been tested in the laboratory.	**Not Applicable** Reduction hinders sequestration chemistry.	**High** [b] Liquid-phase chemical reductants have been applied at the field scale for saturated conditions to reduce Cr(VI) mobility. Applying a subsequent sequestration step is not needed.	**Not Applicable** Reduction and sequestration chemistries are ineffective.	**High** [b] Sequestration of Sr-90 to reduce mobility by liquid-phase phosphate (apatite) has been demonstrated in the field. Reduction would have no effect on Sr-90 other than changing sorption sites.	**Not Applicable** Reduction and sequestration chemistries are ineffective.	**Low** [b] Liquid-phase sequestration has not been demonstrated in the laboratory but may be possible such as through carbonate precipitation. Reduction would have no effect on C-14.	**Low** [b,d] Dechlorination by indirect process induced by liquid-phase reduction is possible, but not well demonstrated. A subsequent sequestration step is not applicable.
Liquid-phase bioremediation	**Low** Liquid-phase bioremediation has been applied at the field scale for saturated conditions and is likely effective for reducing uranium to a less mobile compound. Reoxidation will occur over time such that the treatment only delays uranium movement; there is little change in the eventual flux to groundwater.	**Low** Liquid-phase bioremediation has been applied at the field scale for saturated conditions and is likely effective for reducing Tc-99 to a less mobile compound. Reoxidation will occur over time such that the treatment only delays Tc-99 movement; there is little change in the eventual flux to groundwater.	**Not Applicable** Biological processes do not lead directly to sequestration needed for effective bioremediation.	**High** Liquid-phase bioremediation has been applied in the field for Cr(VI).	**High** Liquid-phase bioremediation has been applied in the field for nitrate.	**Not Applicable** No biological transformation processes.	**Medium** Liquid-phase bioremediation has been applied in the field for other contaminants and may be effective for CN, depending on the concentration.	**Not Applicable** No biological transformation processes.	**Not Applicable** There are no organic COCs in the perched water, and liquid-phase bioremediation is not used at the water table interface.

Table 4-1. Evaluation of Technology Effectiveness by COI

Technology Category	COI								
	Uranium	Technetium-99	Iodine-129	Cr(VI)	Nitrate	Strontium-90	Cyanide	Carbon-14	Organics (MIBK, TCE)
Liquid-phase combined bioreduction and chemical sequestration	**Medium** [b] Use of phosphate to reduce uranium mobility via sequestration has been demonstrated in the laboratory and may be effective depending on site conditions Use of combined bioreduction and sequestration using phosphate gas may not be as effective as sequestration alone but has not been tested.	**Medium** Liquid-phase bioremediation has been applied at the field scale for saturated conditions and is likely effective for reducing Tc-99 to a less mobile compound. Use of phosphate or other coatings may armor the Tc-99 and make it less susceptible to reoxidation, but this has not been tested in the laboratory.	**Not Applicable** Reduction hinders sequestration chemistry.	**High** [b] Liquid-phase bioremediation has been applied in the field to reduce Cr(VI) mobility. Applying a subsequent sequestration step is not needed.	**High** [b] Liquid-phase bioremediation has been applied in the field to reduce nitrate mobility. Applying a subsequent sequestration step is not needed.	**High** [b] Reduction would have no effect on Sr-90 other than changing sorption sites. Sequestration of Sr-90 to reduce mobility by liquid-phase phosphate (apatite) has been demonstrated in the field.	**Medium** [a] Liquid-phase bioremediation has been applied in the field for other contaminants and may be effective for CN, depending on the concentration. Applying a subsequent sequestration step is not applicable.	**Low** [b] Liquid-phase sequestration has not been demonstrated in the laboratory but may be possible such as through carbonate precipitation. Reduction would have no effect on C-14.	**Medium** [b,d] Liquid-phase bioremediation has been applied for dechlorination and can be effective under some conditions. Applying a subsequent sequestration step is not applicable.
Microbially facilitated volatilization	**Not Applicable** Only applicable to iodine.	**Not Applicable** Only applicable to iodine.	**Low** Transformation of iodine to volatile compounds has been demonstrated in the laboratory but has not been applied in the field to remove contaminant mass from the subsurface. Effectiveness may be low based on specific requirements for the transformation process.	**Not Applicable** Only applicable to iodine.	**Not Applicable** Only applicable to iodine.	**Not Applicable** Only applicable to iodine.	**Not Applicable** Only applicable to iodine.	**Not Applicable** Only applicable to iodine.	**Not Applicable** Only applicable to iodine.

a. While desiccation does not have an EIC gap, because it is deployed with a surface barrier and surface barriers have an EIC gap, this surface barrier gap will need to be resolved before consideration of desiccation in a feasibility study.

b. Technology has more steps than are required to achieve treatment but is effective for the contaminant at the stated rating.

c. High for aerobic gas-phase bioremediation of MIBK, low for TCE (anaerobic bioremediation).

d. Rating applies to listed organics, organics not listed are not applicable.

COC = contaminant of concern
COI = contaminant of interest
EIC = effectiveness, implementability, and cost
ERDF = Environmental Restoration Disposal Facility
MIBK = methyl isobutyl ketone
VOC = volatile organic compound
TCE = trichloroethene

Table 4-2. Technology Implementability and Cost Evaluation

Technology Category	Implementability				Cost
	Unsaturated Higher Permeability Zones	Unsaturated Lower Permeability Zones	Perched Water Zones	Water Table Interface Zones	
	Containment				
Surface barrier	**High*** Well proven, mature technology. Uses conventional and readily available construction equipment and methods. Short implementation timeframe to install barrier. May need to be coupled with other technologies (e.g., desiccation) for DVZ contamination.		**Medium*** Uncertainties in size, shape, and location of perched water zone and nature of contributing surface water infiltration area present challenges to implementation of a surface barrier.	**Not Applicable** Would not be deployed at the water table interface to prevent future contaminant flux.	**Medium** Low capital cost compared to in situ technologies or removal. Low annual O&M cost, however duration of maintenance period increases cost. Cost of coupling with other technologies (e.g., desiccation) increases relative cost for DVZ sites.
Subsurface jet injection grouting	**Low** DVZ contamination extending to the water table would likely require vertical borings through the waste site rather than a "V-trough" arrangement using angled borings. Difficult to implement for large sites, where a large number of boreholes would be required. Large number of boreholes may not be feasible for sites with high concentrations of low-mobility high-dose radionuclides, due to implementation risk. Cobbles and preferential grout flow paths can lead to gaps in grout placement. Must be implemented in conjunction with a surface barrier.	**Low** DVZ contamination extending to the water table would likely require vertical borings through the waste site rather than a "V-trough" arrangement using angled borings. Difficult to implement for large sites, where a large number of boreholes would be required. Large number of boreholes may not be feasible for sites with high concentrations of low-mobility high-dose radionuclides near, due to implementation risk. Tighter spacing of injection boreholes is needed because the radius of influence decreases in low permeability formations. Must be implemented in conjunction with a surface barrier.	**Low** Low implementability due to large number of boreholes, large footprint of perched water zone, borehole placement, and obstructions from surface infrastructure. Horizontal barrier is not effective for the perched zone if source of recharge to the perched zone is not addressed.	**Not Applicable** Would not be deployed at the water table interface to prevent future contaminant flux.	**High** High cost due to depth and number of boreholes required.
Subsurface permeation grouting	**Low** Difficult to implement for large sites, where a large number of boreholes would be required. Large number of boreholes may not be feasible for sites with high concentrations of low-mobility high-dose radionuclides, due to implementation risk. Cobbles and preferential grout flow paths can lead to gaps in grout placement.	**Low** Difficult to implement for large sites, where a large number of boreholes would be required. Large number of boreholes may not be feasible for sites with high concentrations of low-mobility high-dose radionuclides near, due to implementation risk. Tighter spacing of injection boreholes is needed because the radius of influence decreases in low permeability formations.	**Low** Low implementability due to large number of boreholes, large footprint of perched water zone, and borehole placement obstructions from surface infrastructure. Horizontal barrier is not effective for the perched zone if source of recharge to the perched zone is not addressed.	**Not Applicable** Would not be deployed at the water table interface to prevent future contaminant flux.	**High** High cost due to depth and number of boreholes required.
Subsurface soil freezing	**Low** Difficult to implement due close spacing of wells. The application has not been proved at depths necessary for use in the DVZ. Low moisture content in the vadose zone must be overcome by addition of supplemental soil moisture, which may be difficult due to the presence of cobbles and gravel in the DVZ at the Hanford Site. Requires long-term O&M to maintain frozen conditions. Must be implemented in conjunction with a surface barrier.		**Low** Low implementability due to large number of boreholes, large footprint of perched water zone, and borehole placement obstructions from surface infrastructure.	**Not Applicable** Would not be deployed at the water table interface to prevent future contaminant flux.	**High** High capital cost due to large number and depth of boreholes. Energy intensive. High O&M cost to maintain frozen conditions over a long duration.
Desiccation	**High** Wider injection point spacing allows more flexibility to avoid high-risk boreholes through the center of highly contaminated waste sites. May need several cycles of air injection to achieve desired moisture reduction. Must be implemented in conjunction with a surface barrier.		**Not Applicable** Not applicable directly to the perched water but could be used above the perched water to reduce recharge in conjunction with a surface barrier – see surface barrier item above.	**Not Applicable** Would not be deployed at the water table interface to prevent future contaminant flux.	**Medium** Low cost due to wide spacing of injection points. May need several cycles of air injection to achieve desired moisture reduction.

Table 4-2. Technology Implementability and Cost Evaluation

Technology Category	Implementability				Cost
	Unsaturated Higher Permeability Zones	Unsaturated Lower Permeability Zones	Perched Water Zones	Water Table Interface Zones	
Removal					
Excavation with retaining walls	**Low** Implementability decreases at depth greater than 30 m (100 ft) for many vertical wall construction techniques. Stability of retaining walls needs to be carefully considered in cases with other waste sites or structures in close proximity (e.g., tank farms). Long duration of open excavation presents risk of stormwater infiltration, as well as infiltration of water used for dust suppression.		**Not Applicable** Perched water excavation would likely lead to draining of contaminants to the groundwater. Excavating soil in perched zone would require addressing source of recharge during excavation, treatment and backfill operations. Dewatering likely required. Located below B/BX Tank Farms.	**Not Applicable** Would not be deployed at the water table interface to prevent future contaminant flux.	**High** High cost due to very large volume of contaminated soil excavation, hauling and onsite disposal (ERDF). Could require construction of additional capacity at ERDF. High cost due to high surface area of retaining walls. Requires significant volume of clean backfill.
Excavation without retaining walls	**Low** Implementability decreases at depth greater than 30 m (100 ft) due to large volume of clean soil that must be excavated with sloping and benching. Not implementable for waste sites with nearby infrastructure and other waste sites (e.g., tank farms, canyon facilities) that may be closed in place due to large footprint of excavation. Long duration of open excavation presents risk of stormwater infiltration, as well as infiltration of water used for dust suppression. Large footprint of sloped and benched excavation increases likelihood of infiltration of precipitation and dust suppression water.		**Not Applicable** Perched water excavation would likely lead to draining of contaminants to the groundwater. Excavating soil in perched zone would require addressing source of recharge during excavation, treatment and backfill operations. Dewatering likely required. Located below B/BX Tank Farms.	**Not Applicable** Would not be deployed at the water table interface to prevent future contaminant flux.	**High** High cost due to very large volume of contaminated soil excavation, hauling and onsite disposal (ERDF). Could require construction of additional capacity at ERDF. Requires significant volume of excavation, stockpiling, and reuse of clean soil from side slopes.
Soil flushing/soil washing	**Low** Difficult to uniformly distribute water and/or chemical reagents. Need to ensure recapture of mobilized contaminants.	**Low** Low permeability soils increase difficulty of flushing contaminants. Need to ensure recapture of mobilized contaminants.	**Not Applicable** Perched water hydrogeologic configuration would make flushing flow path very difficult to manage.	**Not Applicable** Would not be deployed at the water table interface to prevent future contaminant flux.	**High** High cost due to amendments, number of boreholes, capture wells, and aboveground treatment.
Perched water removal	**Not Applicable** Only for perched water saturated zones.	**Not Applicable** Only for perched water saturated zones.	**Medium** Requires significant number of vertical wells (which have a low yield) to remove perched water from a thin saturated zone. Horizontal wells can increase effectiveness but are difficult to install in cobbles of Hanford formation. Several attempts to install horizontal, directionally drilled wells have been unsuccessful.	**Not Applicable** Would not be deployed at the water table interface to prevent future contaminant flux.	**Medium** Moderate capital cost due to number of vertical wells required, or higher cost of drilling deep horizontal well. Low O&M costs from low flow/volume of extracted water.
Pore water extraction	**Not Applicable** Only for zones with high moisture content.	**Low** May require long duration of operations, depending on spacing of wells used.	**Medium** Deployed in sequence from regular pumping to vacuum enhanced pumping to pore water extraction. May require additional wells to be effective across the full perched water zone.	**Not Applicable** Would not be deployed at the water table interface to prevent future contaminant flux.	**Medium** Moderate capital cost due to number of vertical wells required, or higher cost of drilling deep horizontal well. Low O&M cost from low flow/volume of extracted water.
Soil wicking	**Not Applicable** Only for non-saturated zones with high moisture content.	**Low** May require long duration of operations, depending on spacing of wells used.	**Not Applicable** Only for high moisture content materials in the vadose zone, not for saturated or near-saturated zones.	**Not Applicable** Would not be deployed at the water table interface to prevent future contaminant flux.	**Medium** Moderate capital cost due to number of vertical wells required, or higher cost of drilling deep horizontal well. Low O&M from low flow/volume of extracted water.

Table 4-2. Technology Implementability and Cost Evaluation

Technology Category	Implementability				Cost
	Unsaturated Higher Permeability Zones	Unsaturated Lower Permeability Zones	Perched Water Zones	Water Table Interface Zones	
Ex Situ Technologies					
Vitrification	**Low** Complex treatment technology. Gravel and cobbles larger than 60 mm (2.4 in.) need to be screened out, making implementation challenging for formation materials with significant fraction of large gravels and cobbles (e.g., Hanford formation soils).		**Not Applicable** Excavation of soil in perched water zone is not implementable.	**Not Applicable** Would not be deployed at the water table interface to prevent future contaminant flux.	**High** High implementation cost due to complex technological challenges. High O&M cost due to high energy cost. Vitrified logs require appropriate disposal.
Solidification/stabilization	**High** Well proven and mature technology. Can be implemented with commercially available equipment, materials, and methods. More difficult to implement if soil has cobbles.		**Not Applicable** Excavation of soil in perched water zone is not implementable.	**Not Applicable** Would not be deployed at the water table interface to prevent future contaminant flux.	**Medium** Likely requires disposal at ERDF.
Contaminant separation	**Low** Difficult to effectively screen and separate non-radiological contaminants, and therefore not implementable for sites with multiple COIs.		**Not Applicable** Excavation of soil in perched water zone is not implementable.	**Not Applicable** Would not be deployed at the water table interface to prevent future contaminant flux.	**Medium** Co-mingled COIs require sequential treatment steps, or complex wash fluid formations. Wash fluids also require treatment and disposal since this is a media transfer process. May require disposal at ERDF unless cleanup levels can be achieved prior to reuse of treated soils as backfill.
Backfill with treated soil	**Low** Requires stockpiling of large quantity of soils before and after treatment. Additional treatment duration could extend timeframe that excavation is left open, leading to higher potential for infiltration of stormwater or dust suppression water into the excavation. Treatment to levels required for backfill may be difficult for some COIs.		**Not Applicable** Excavation of soil in perched water zone is not implementable.	**Not Applicable** Would not be deployed at the water table interface to prevent future contaminant flux.	**High** Cost of treatment likely much higher than cost of onsite disposal and would not offset savings from procurement of clean backfill materials from an onsite or offsite source. Cost is additive with cost of excavation.
Onsite landfill	**High** Onsite landfill is already demonstrated and available. Additional landfill capacity may be needed if deep excavation is selected for multiple DVZ waste sites.		**Not Applicable** Excavation of soil in perched water zone is not implementable.	**Not Applicable** Would not be deployed at the water table interface to prevent future contaminant flux.	**Medium to High** Cost of disposal at existing ERDF is moderate. Cost would increase for large/high volume sites, if additional capacity is required at ERDF.
Offsite landfill/repository	**Low** Additional planning and risk due to hauling contaminated materials on public roads. Administrative feasibility may be limited due to availability of facilities permitted to accept the waste material, and State and Community acceptance of hauling contaminated materials long distances for permanent disposal.		**Not Applicable** Excavation of soil in perched water zone is not implementable.	**Not Applicable** Would not be deployed at the water table interface to prevent future contaminant flux.	**High** Cost of transport is added to removal cost. Cost of offsite disposal is likely to be much higher than ERDF.

Table 4-2. Technology Implementability and Cost Evaluation

Technology Category	Implementability				Cost
	Unsaturated Higher Permeability Zones	Unsaturated Lower Permeability Zones	Perched Water Zones	Water Table Interface Zones	
Ex situ water treatment	**High** Only applicable in unsaturated portions of vadose zone when used with technologies that inject water (soil flushing) and extract groundwater or those that collect pore water through extraction. Pump and treat systems are highly implementable due to use of readily available equipment, treatment technologies, and construction methods. Duration of pump and treat components of remedy need to be coordinated with Groundwater OU remedy pumping durations, if existing pump-and treat systems are employed for treatment. Availability of proven treatment technologies is limited for some COIs (e.g., I-129).		**High** Pump and treat is already being used at the Hanford Site to treat 200-DV-1 OU perched water at the 200 West Pump and Treat System. Pump and treat systems are highly implementable due to use of readily available equipment, treatment technologies, and construction methods. Duration of pump and treat components of remedy need to be coordinated with groundwater OU remedy pumping durations, if existing pump and treat systems are employed for treatment. Availability of proven treatment technologies is limited for some COIs (e.g., I-129).	**Not Applicable** Would not be deployed at the water table interface to prevent future contaminant flux.	**Medium** Low capital cost if existing pump and treat system is utilized for treatment. Higher capital cost if stand-alone pump and treat system is constructed. Long-term O&M costs are proportional to pumping duration and cleanup timeframe.
In Situ Technologies					
In situ vitrification	**Low** Design and implementation of off-gas treatment hood and a starter path would be very difficult for deep applications of in situ vitrification.			**Not Applicable** Would not be deployed at the water table interface to prevent future contaminant flux.	**High** Cost is high relative to other technologies due to energy and infrastructure requirements.
Thermal water volatilization	**Low** Heating requires close spacing of electrodes or heating units (<10 m [33 ft]). Vapor extraction wells also require close spacing.			**Not Applicable** Would not be deployed at the water table interface to prevent future contaminant flux.	**High** Cost is high relative to other technologies due to energy and infrastructure requirements.
Thermal desorption/ destruction	**Low:** Heating requires close spacing of electrodes or heating units (<10 m). Vapor extraction wells also require close spacing.			**Not Applicable** Would not be deployed at the water table interface to prevent future contaminant flux.	**High** Cost is high relative to other technologies due to energy and infrastructure requirements.
Soil vapor extraction	**High** Well proven and mature technology for vadose zone removal of VOCs. Easily implemented with readily available equipment, materials, and construction methods. Easily coupled with ex situ treatment technologies. History of successful implementation at Hanford. High permeability formations allow wider spacing of SVE wells and therefore fewer conflicts with surface infrastructure and need to install higher risk boreholes.	**Medium** Extraction is slow from lower permeability zones because it primarily depends on diffusion into higher permeability zones and then advective extraction.	**Not Applicable** Not implementable for saturated zones.	**Not Applicable** Would not be deployed at the water table interface to prevent future contaminant flux.	**Medium** Active treatment technology requiring aboveground systems and a suitable number of wells. Cost increases in lower permeability formations due to tighter SVE well spacing.
Encapsulation	**Low** Encapsulation grouting has a small radius of influence in unsaturated zones.	**Low** Encapsulation grouting has a small radius of influence in unsaturated zones.	**Medium** Encapsulation grouting has a small to moderate radius of influence in saturated zones.	**Not Applicable** Would not be deployed at the water table interface to prevent future contaminant flux.	**High** Cost is high relative to other technologies due to the large number of boreholes needed for injection.

Table 4-2. Technology Implementability and Cost Evaluation

Technology Category	Implementability				Cost
	Unsaturated Higher Permeability Zones	Unsaturated Lower Permeability Zones	Perched Water Zones	Water Table Interface Zones	
Electrokinetic removal	**Low** Relatively close spacing of electrodes would be needed (approximately 10 m [33 ft]). Design and implementation of contaminant/water collection process for deep, dry application is difficult.	**Low:** Relatively close spacing of electrodes would be needed (approximately 10 m [33 ft]). Design and implementation of contaminant/water collection process for deep application is difficult.	**Low** Relatively close spacing of electrodes would be needed (approximately 10 m [33 ft]).	**Not Applicable** Would not be deployed at the water table interface to prevent future contaminant flux.	**High** Relatively close spacing of electrodes would be needed (approximately 10 m [33 ft]). Design and implementation of contaminant/water collection process for deep, dry application is difficult.
Chemical oxidation	**Medium** Liquid oxidant delivery in the deep unsaturated zone would be limited. Gas-phase (ozone) may be delivered effectively.	**Medium** Liquid oxidant delivery in the deep unsaturated zone would be limited. Gas-phase (ozone) may be delivered effectively, but more difficult in low permeability materials.	**Medium** Liquid oxidant may be delivered effectively but low transmissivity and thin perched water zone may require close well spacing.	**Not Applicable** Would not be deployed at the water table interface to prevent future contaminant flux.	**High** Relative cost may be high depending on the oxidant demand for a specific site.
Particulate chemical reduction	**Low** Use of either liquid or gas injection carrier fluid would require very close injection well spacing in the vadose zone.	**Low** Use of either liquid or gas injection carrier fluid would require very close injection well spacing in the vadose zone. Delivery would be more difficult in low permeability materials.	**Medium** Use of liquid injection carrier fluid and nanoparticles may enable moderate injection well spacing in the perched water.	**Medium** Use of liquid injection carrier fluid and nanoparticles may enable moderate injection well spacing in the perched water.	**High** Relative cost would be high due to the close-to-moderate well spacing (best for saturated zone application) and high reagent (particle) cost.
Gas-phase chemical reduction	**Low** The technology has been implemented at full scale but use of a toxic gas will cause significant controls and administrative burden for implementation.	**Low** The technology has been implemented at full scale but use of a toxic gas will cause significant controls and administrative burden for implementation. Delivery would be more difficult in low permeability materials.	**Not Applicable** Not implementable for saturated zones.	**Not Applicable** Would not be deployed at the water table interface to prevent future contaminant flux.	**Medium** Cost is medium relative to other options with cost factors that include administrative and engineering controls with use of a toxic gas.
Particulate sequestration	**Low** Use of either liquid or gas injection carrier fluid would require very close injection well spacing in the vadose zone.	**Low** Use of either liquid or gas injection carrier fluid would require very close injection well spacing in the vadose zone. Delivery would be more difficult in low permeability materials.	**Medium** Use of liquid injection carrier fluid and nanoparticles may enable moderate injection well spacing in the perched water.	**Medium:** Use of liquid injection carrier fluid and nanoparticles may enable moderate injection well spacing in the perched water.	**High** Relative cost would be high due to the close-to-moderate well spacing (best for saturated zone application) and high reagent (particle) cost.
Gas-phase chemical sequestration	**Medium** The technology is being tested at the field scale for use of ammonia. Implementation difficulties include equipment compatibility with ammonia and significant controls and administrative burdens.	**Medium** The technology is being tested at the field scale for use of ammonia. Implementation difficulties include equipment compatibility with ammonia and significant controls and administrative burdens. Delivery would be more difficult in low permeability materials.	**Not Applicable** Not implementable for saturated zones.	**Not Applicable** Would not be deployed at the water table interface to prevent future contaminant flux.	**Medium** Cost is medium relative to other options with cost factors that include administrative and engineering controls with use of ammonia gas.
Particulate-phase combined chemical reduction and sequestration	**Low** Use of either liquid or gas injection carrier fluid would require very close injection well spacing in the vadose zone.	**Low** Use of either liquid or gas injection carrier fluid would require very close injection well spacing in the vadose zone. Delivery would be more difficult in low permeability materials.	**Medium** Use of liquid injection carrier fluid and nanoparticles may enable moderate injection well spacing in the perched water.	**Medium** Use of liquid injection carrier fluid and nanoparticles may enable moderate injection well spacing in the perched water.	**High** Relative cost would be high due to the close-to-moderate well spacing (best for saturated zone application) and high reagent (particle) cost.

Table 4-2. Technology Implementability and Cost Evaluation

Technology Category	Implementability				Cost
	Unsaturated Higher Permeability Zones	Unsaturated Lower Permeability Zones	Perched Water Zones	Water Table Interface Zones	
Gas-phase combined chemical reduction and sequestration	**Low** The reduction technology has been implemented at full scale but use of a toxic gas will cause significant controls and administrative burden for implementation. The ammonia sequestration technology is being tested at the field scale for use of ammonia. Implementation difficulties include equipment compatibility with ammonia and significant controls and administrative burdens.	**Low** The reduction technology has been implemented at full scale, but use of a toxic gas will cause significant controls and administrative burden for implementation. The ammonia sequestration technology is being tested at the field scale for use of ammonia. Implementation difficulties include equipment compatibility with ammonia and significant controls and administrative burdens. Delivery would be more difficult in low permeability materials.	**Not Applicable** Not implementable for saturated zones.	**Not Applicable** Would not be deployed at the water table interface to prevent future contaminant flux.	**Medium** Cost is medium relative to other options with cost factors that include administrative and engineering controls with use of hazardous gases.
Gas-phase bioremediation	**Medium** The use of hydrogen gas as a gas-phase bioremediation technology has been demonstrated at full scale. There will be some implementation issues with use of a flammable gas.	**Medium** The use of hydrogen gas as a gas-phase bioremediation technology has been demonstrated at full scale. There will be some implementation issues with use of a flammable gas. Delivery would be more difficult in low permeability materials.	**Not Applicable** Not implementable for saturated zones.	**Not Applicable** Would not be deployed at the water table interface to prevent future contaminant flux.	**Medium** Cost is medium relative to other options with cost factors that include administrative and engineering controls with use of hydrogen gas.
Gas-phase combined bioreduction and chemical sequestration	**Medium** The use of hydrogen gas as a gas-phase bioremediation technology has been demonstrated at full scale. There will be some implementation issues with use of a flammable gas. The sequestration technology is being tested at the field scale for use of ammonia. Implementation difficulties include equipment compatibility with ammonia and significant controls and administrative burdens.	**Medium** The use of hydrogen gas as a gas-phase bioremediation technology has been demonstrated at full scale. There will be some implementation issues with use of a flammable gas. The sequestration technology is being tested at the field scale for use of ammonia. Implementation difficulties include equipment compatibility with ammonia and significant controls and administrative burdens. Delivery would be more difficult in low permeability materials.	**Not Applicable** Not implementable for saturated zones.	**Not Applicable** Would not be deployed at the water table interface to prevent future contaminant flux.	**Medium** Cost is medium relative to other options with cost factors that include administrative and engineering controls with use of hazardous gases.
Liquid chemical reduction	**Not Applicable** Not implementable for saturated zones due to very poor distribution and potential to push contaminants ahead of the amendment.	**Not Applicable** Not implementable for saturated zones due to very poor distribution and potential to push contaminants ahead of the amendment.	**Medium** The technology has been used in the field for aquifers, but distribution in the thin perched water zone may be more difficult than in an aquifer because less hydraulic driving force is available.	**Medium** The technology has been used in the field for aquifers but the radius of influence is typically less than 5 m (16 ft).	**High** Cost is high relative to other options with cost factors related to spacing of wells. Reagent cost is moderate.
Liquid-phase chemical sequestration	**Not Applicable** Not implementable for saturated zones due to very poor distribution and potential to push contaminants ahead of the amendment.	**Not Applicable** Not implementable for saturated zones due to very poor distribution and potential to push contaminants ahead of the amendment.	**Medium** The technology has been used in the field for aquifers, but distribution in the thin perched water zone may be more difficult than in an aquifer because less hydraulic driving force is available.	**Medium** The technology has been used in the field for aquifers but the radius of influence is typically less than 5 m (16 ft).	**High** Cost is high relative to other options with cost factors related to spacing of wells. Reagent cost is moderate.
Liquid-phase combined chemical reduction and sequestration	**Not Applicable** Not implementable for saturated zones due to very poor distribution and potential to push contaminants ahead of the amendment.	**Not Applicable** Not implementable for saturated zones due to very poor distribution and potential to push contaminants ahead of the amendment.	**Medium** The technology components have been used in the field for aquifers, but distribution in the thin perched water zone may be more difficult than in an aquifer because less hydraulic driving force is available.	**Medium** The technology components have been used in the field for aquifers but the radius of influence is typically less than 5 m (16 ft).	**High** Cost is high relative to other options with cost factors related to spacing of wells. Reagent cost is moderate.

Table 4-2. Technology Implementability and Cost Evaluation

Technology Category	Implementability				Cost
	Unsaturated Higher Permeability Zones	Unsaturated Lower Permeability Zones	Perched Water Zones	Water Table Interface Zones	
Liquid-phase bioremediation	**Not Applicable** Not implementable for saturated zones due to very poor distribution and potential to push contaminants ahead of the amendment.	**Not Applicable** Not implementable for saturated zones due to very poor distribution and potential to push contaminants ahead of the amendment.	**Medium** The technology has been used in the field for aquifers, but distribution in the thin perched water zone may be more difficult than in an aquifer because less hydraulic driving force is available.	**Medium** The technology has been used in the field for aquifers with a radius of influence depending on the substrate selected, but typically better than for chemical treatments.	**Low** Cost is low relative to other options with cost factors related to spacing of wells. Reagent cost is low to moderate.
Liquid-phase combined bioreduction and chemical sequestration	**Not Applicable** Not implementable for saturated zones due to very poor distribution and potential to push contaminants ahead of the amendment.	**Not Applicable** Not implementable for saturated zones due to very poor distribution and potential to push contaminants ahead of the amendment.	**Medium** The technology has been used in the field for aquifers, but distribution in the thin perched water zone may be more difficult than in an aquifer because less hydraulic driving force is available.	**Medium** The technology has been used in the field for aquifers with a radius of influence depending on the bioreduction substrate selected, but typically better than for chemical treatments. However, the radius of influence may be limited to about 5 m (16 ft) based on the sequestration chemical used.	**High** Cost is high relative to other options with cost factors related to spacing of wells. Reagent cost is moderate.
Microbially facilitated volatilization	**Low** Information available is for liquid based substrates that would be difficult to distribute in the vadose zone. Potentially, gas-phase substrates could be used to improve implementation.	**Low** Information available is for liquid based substrates that would be difficult to distribute in the vadose zone. Potentially, gas-phase substrates could be used to improve implementation. Delivery would be more difficult in low permeability materials.	**Not Applicable** I-129 is not a contaminant issue in the perched water.	**Not Applicable** Would not be deployed at the water table interface to prevent future contaminant flux.	**Medium** Cost would be medium to high for use of liquid because of the close well spacing but would be lower if a gas-phase substrate were available.

*Surface barrier could have a potential conflict with the tank farms or other structures.

COI = contaminant of interest
DVZ = deep vadose zone
ERDF = Environmental Restoration Disposal Facility
O&M = operations & maintenance
OU = operable unit
SVE = soil vapor extraction
VOC = volatile organic compound

Table 4-3. Technology Effectiveness, Implementability and Cost Evaluation Summary

Technology Category	Effectiveness									Implementability				Cost
	U	Tc-99	I-129	Cr(VI)	NO_3	Sr-90	CN	C-14	Organics (TCE, MIBK)	Unsaturated Higher Permeability	Unsaturated Lower Permeability	Perched Water	Water Table Interface	
Containment														
Surface barrier	M	M	M	M	M	M	M	M	L	H [a]	H [a]	M [a]	N/A	M
Subsurface jet injection grouting	M	M	M	M	M	M	M	M	L	L	L	L	N/A	H
Subsurface permeation grouting	M	M	M	M	M	M	M	M	L	L	L	L	N/A	H
Subsurface soil freezing	L	L	L	L	L	L	L	L	L	L	L	L	N/A	H
Desiccation [b]	H	H	H	H	H	H	H	H	N/A	H	H	N/A	N/A	M
Removal														
Excavation with retaining walls	H	H	H	H	H	H	H	H	M	L	L	N/A	N/A	H
Excavation without retaining walls	H	H	H	H	H	H	H	H	M	L	L	N/A	N/A	H
Soil flushing/washing	M	M	M	M	M	M	M	M	M	L	L	N/A	N/A	H
Perched water removal	M	M	M	M	M	M	M	M	M	N/A	N/A	M	N/A	M
Pore water extraction	L	M	L	M	M	L	M	L	L	N/A	L	M	N/A	M
Soil wicking	L	M	L	M	M	L	M	L	L	N/A	L	NA	N/A	M
Ex Situ Technologies														
Vitrification	H	H	H	H	H	H	H	H	H	L	L	N/A	N/A	H
Solidification/Stabilization	H	H	H	H	H	H	H	H	L	H	H	N/A	N/A	M
Contaminant separation	M	M	M	M	M	M	M	M	N/A	L	L	N/A	N/A	M
Backfill with treated soil	L	L	L	L	L	L	L	L	M	L	L	N/A	N/A	H
Onsite landfill	H	H	H	H	H	H	H	H	H	H	H	N/A	N/A	M
Offsite landfill/repository	H	H	H	H	H	H	H	H	H	L	L	N/A	N/A	H
Ex situ water treatment	H	H	L	H	H	M	H	M	H	N/A	N/A	H	N/A	M

Table 4-3. Technology Effectiveness, Implementability and Cost Evaluation Summary

Technology Category	Effectiveness									Implementability				Cost
	U	Tc-99	I-129	Cr(VI)	NO_3	Sr-90	CN	C-14	Organics (TCE, MIBK)	Unsaturated Higher Permeability	Unsaturated Lower Permeability	Perched Water	Water Table Interface	
In Situ Technologies														
In situ vitrification	L	L	L	L	L	L	L	L	L	L	L	L	N/A	H
Thermal water volatilization	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	H	L	L	L	N/A	H
Thermal desorption/ destruction	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	H	L	L	L	N/A	H
Soil vapor extraction	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	H	H	M	N/A	N/A	M
Encapsulation	M	M	M	M	M	M	M	M	L	L	L	M	N/A	H
Electrokinetic removal	L	L	L	L	L	L	L	L	L	L	L	L	N/A	H
Chemical oxidation	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	M	M	M	M	N/A	H
Particulate chemical reduction	L	L	NA	H	N/A	N/A	N/A	NA	M [c] (TCE)	L	L	M	M	H
Gas-phase chemical reduction	L	L	N/A	H	N/A	N/A	N/A	N/A	L [c] (TCE)	L	L	N/A	N/A	M
Particulate sequestration	H	M	M	M	N/A	H	N/A	N/A	N/A	L	L	M	M	H
Gas-phase chemical sequestration	M	L	M	M	N/A	M	N/A	L	N/A	M	M	N/A	N/A	M
Particulate-phase combined chemical reduction and sequestration	M	L	NA	H	N/A	H	N/A	N/A	N/A	L	L	M	M	H
Gas-phase combined chemical reduction and sequestration	M [d]	M	N/A	H [d]	N/A	L [d]	N/A	L [d]	N/A	L	L	N/A	N/A	M
Gas-phase bioremediation	L	L	N/A	H	H	N/A	L	N/A	H [e]	M	M	N/A	N/A	M
Gas-phase combined bioreduction and chemical sequestration	M [d]	M	N/A	H [d]	H [d]	L [d]	N/A	L [d]	L [c,d] (TCE),	M	M	N/A	N/A	M

Table 4-3. Technology Effectiveness, Implementability and Cost Evaluation Summary

Technology Category	Effectiveness									Implementability				Cost
	U	Tc-99	I-129	Cr(VI)	NO_3	Sr-90	CN	C-14	Organics (TCE, MIBK)	Unsaturated Higher Permeability	Unsaturated Lower Permeability	Perched Water	Water Table Interface	
Liquid chemical reduction	L	L	N/A	H	N/A	N/A	N/A	N/A	L [c] (TCE)	N/A	N/A	M	M	H
Liquid-phase chemical sequestration	H	L	M	M	N/A	H	N/A	L	N/A	N/A	N/A	M	M	H
Liquid-phase combined chemical reduction and sequestration	M [d]	M	N/A	H [d]	N/A	H [d]	N/A	L [d]	L [c,d] (TCE)	N/A	N/A	M	M	H
Liquid-phase bioremediation	L	L	N/A	H	H	N/A	M	N/A	NA	N/A	N/A	M	M	L
Liquid-phase combined bioreduction and chemical sequestration	M [d]	M	N/A	H [d]	H [d]	H [d]	M [d]	L [d]	M [c,d] (TCE)	N/A	N/A	M	M	H
Microbially facilitated volatilization	N/A	N/A	L	N/A	N/A	N/A	N/A	N/A	N/A	L	L	N/A	N/A	M

a. Surface barrier could have a potential conflict with the tank farms or other structures.

b. While desiccation does not have an EIC gap, because it is deployed with a surface barrier and surface barriers have an EIC gap, this surface barrier EIC gap will need to be resolved before consideration of desiccation in a feasibility study.

c. Rating applies to listed organics, organics not listed are not applicable (N/A).

d. Technology has more steps than are required to achieve treatment but is effective for the contaminant at the stated rating.

e. High for aerobic gas-phase bioremediation of MIBK, low for TCE (anaerobic bioremediation).

EIC = effectiveness, implementability, and relative cost
H = high
L = low
M = medium
MIBK = methyl isobutyl ketone
N/A = not applicable
TCE = trichloroethene

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5 Deep Vadose Zone Treatability Study Assessment Conclusions and Recommendations

This chapter provides the conclusions of the DVZ technology evaluation presented in Chapter 4. The discussion also summarizes data gaps identified in those evaluations, and provides recommendations for additional treatability studies, where appropriate.

5.1 Deep Vadose Zone Treatability Study Assessment Determination

Technology data needs, and how a laboratory, modeling, or field treatability study could address those needs, were evaluated using the information compiled in Tables 4-1 through 4-3. Table 5-1 lists the outcome of that evaluation for technology process options/variants. Data needs were identified based on the EIC information in Tables 4-1 and 4-2 and the nature of technology information available in relation to the COIs and treatment areas. For instance, the mechanisms of some technologies were known and tested, but effectiveness for relevant contaminant mixtures or concentration levels has not been established. For some technologies, the remediation mechanism was known, but delivery of amendments for treatment areas had not been tested. Technologies designated as having no EIC data needs are ready to be evaluated as part of an FS based on available information. The FS would consider the EIC for each specific technology in the context of the site-specific condition for the waste sites included in the FS.

Based on the identified data need, the type of treatability study required to address this need was determined and listed in Table 5-1. The treatability study to address the need was determined based on what would be required for input to an FS. For instance, if there was good information about how a technology could be implemented, but the effectiveness for a COI or treatment area was not available, then laboratory studies to quantify effectiveness were identified as the necessary treatability action. For some of the technologies based on physical processes, treatability efforts were identified because an FS level design element was not currently well defined for the treatment areas (e.g., the relation of surface barrier size to depth of effectiveness).

Finally, treatability study recommendations were made for technologies with identified data needs based on expected effectiveness, implementability, and applicability relative to Central Plateau DVZ treatment areas and primary COIs. All recommended treatability studies address one or more primary COI(s). If a treatability need has been identified for a primary COI and information for this technology is needed for a secondary or tertiary COI, then that testing is included in the recommended study. If a treatability need was identified for a technology with low effectiveness or low implementability, then no treatability study was recommended. In some cases, a treatability study was not recommended because other available technologies within the same general response action have better effectiveness and implementability. For the perched water treatment area, some of the potential technologies are directly related to the current removal action and the recommendation is to pursue those options as part of the removal action rather than as a separate treatability study.

Table 5-2 provides summary-level information of the applicable DVZ technologies for each of the COI/treatment area scenarios to provide a relative rating of the DVZ technologies for use in future FSs. This summary provides context for the recommended studies in relation to the other potential technology options. The numerical ratings of each technology were derived from Table 4-3 by assigning numerical values to the qualitative ranks of high, medium, and low. For effectiveness and implementability, a high ranking was assigned a value of 1, medium was assigned 2, and low was assigned 3. For cost, high was assigned a value of 3, medium was assigned 2, and low was assigned 1. The sum of the numerical values was used as the numerical ratings in Table 5-2. Technologies that are recommended for treatability studies in Section 5.2 are underlined in Table 5-2. To highlight the better rated technologies and those

with low effectiveness or implementability, the numerical ratings of the applicable technologies for each treatment area and COI are color coded as follows:

- Red indicates that effectiveness and/or implementability is low (the rating range is from 6 to 9).
- Yellow indicates that effectiveness and implementability are medium or high and the rating is a 6 or 7.
- Green indicates that the effectiveness and implementability are medium or high and the rating is from 3 to 5.

Technologies color coded green are more effective and implementable and less costly than technologies color coded yellow. Technologies color coded red have a low rating for either effectiveness or implementability, therefore they are not viable for that COI and treatment area combination.

Table 5-3 provides a list of recommended technologies to consider for FSs of DVZ waste sites organized by treatment area and general response action. It includes technologies for which treatability studies are recommended, but only includes technologies that rate medium or high for both effectiveness and implementability. Table 5-3 uses the effectiveness and implementability rating from Table 5-2 to identify a list of viable technologies for each treatment area. This list of technologies does not supersede the technology screening and alternative development process in the FS, which considers waste site specific information derived from the RI/FS evaluations.

The layout of Table 5-3 emphasizes the range of viable DVZ technologies that could be evaluated in an FS for each COI/treatment area scenario. The underlined technologies indicate those that require treatability studies needed in order to use them in the FS evaluation. Each of these technologies have treatability data needs and are recommended for additional modeling or laboratory treatability studies. A review of Table 5-3 shows that there are limited DVZ treatment technologies for most of the COI/treatment area scenarios, and many of those require treatability studies to complete the FS evaluation.

Table 5-1. Treatability Study Determination

Technology Process Option	Technology Variant	What Data are Needed to Support an FS?	What Type of Treatability Study Would Address the Identified Data Need(s)?	Recommendation for a Treatability Study
Containment				
Surface barrier	All	Relation of barrier size and effective depth in the unsaturated zones and perched water	FS ready for shallow contamination sites. Modeling could address effective depth question. Implementation at the FS level is known based on other commercial sites.	Conduct modeling assessment for representative sites to define FS level design information. Information available from the Prototype Hanford Barrier and other surface barrier studies is sufficient for barrier construction information and no additional field test is currently recommended. Future phased implementation may be appropriate, pending modeling results.
Subsurface jet injection grouting	One variant	No EIC data needs	N/A	None recommended
Subsurface permeation grouting	One variant	Appropriate material and implementation approaches for the perched water	Paper study for materials and implementation (spacing) information	None recommended because of poor implementability (large number of wells needed).
Subsurface soil freezing	One variant	No EIC data needs	N/A	None recommended
Desiccation	One variant	No EIC data needs, data are sufficient from previous field testing	N/A	No desiccation treatability study needed, but need surface barrier design information to support FS evaluation of desiccation.
Removal				
Excavation with retaining walls	All	No EIC data needs	N/A	None recommended
Excavation without retaining walls	All	No EIC data needs	N/A	None recommended
Soil flushing	All	No EIC data needs	N/A	None recommended

Table 5-1. Treatability Study Determination

Technology Process Option	Technology Variant	What Data are Needed to Support an FS?	What Type of Treatability Study Would Address the Identified Data Need(s)?	Recommendation for a Treatability Study
Perched water removal	One variant	Field implementation using horizontal wells in the perched water	Evaluate installing horizontal wells in the perched water as part of the 200-DV-1 OU perched water removal action described in DOE/RL-2014-34.	No separate treatability study recommended. The horizontal well evaluation would be undertaken as part of the 200-DV-1 OU perched water removal described in Action Memorandum for 200-DV-1 Operable Unit Perched Water Pumping/Pore Water Extraction (DOE/RL-2014-34).
Pore water extraction	One variant	Field effectiveness in the perched water and low permeability unsaturated zone	Field testing of extraction effectiveness in perched water and low permeability materials	None recommended. EIC evaluation of pore water extraction is part of the Action Memorandum for 200-DV-1 Operable Unit Perched Water Pumping/Pore Water Extraction (DOE/RL-2014-34). Technology is not considered for other lower permeability zones because of poor implementability and availability of desiccation as an alternative.
Soil wicking	One variant	Field implementation for the low permeability unsaturated zone	Field testing in low permeability, wet material (not perched water)	Technology is not considered because of poor implementability and availability of desiccation as an alternative.
			Ex Situ	
Vitrification	One variant	No EIC data needs	N/A	None recommended
Solidification/ Stabilization	One variant	No EIC data needs	N/A	None recommended
Contaminant separation	One variant	No EIC data needs	N/A	None recommended
Backfill with treated soil	One variant	No EIC data needs	N/A	None recommended
Onsite landfill	One variant	No EIC data needs	N/A	None recommended

Table 5-1. Treatability Study Determination

Technology Process Option	Technology Variant	What Data are Needed to Support an FS?	What Type of Treatability Study Would Address the Identified Data Need(s)?	Recommendation for a Treatability Study
Offsite landfill/Repository	One variant	No EIC data needs	N/A	None recommended
Ex situ water treatment	All	No EIC data needs	N/A	None recommended
In Situ				
Vitrification	One variant	No EIC data needs	N/A	None recommended
Thermal water volatilization	One variant	No EIC data needs	N/A	None recommended
Thermal desorption/ Destruction	One variant	No EIC data needs	N/A	None recommended
Soil vapor extraction	One variant	No EIC data needs	N/A	None recommended
Encapsulation	One variant:	Appropriate material and implementation approaches for the perched water	Paper study for materials and implementation (spacing) information approaches	None recommended because of poor implementability (large number of wells needed).
Electrokinetic removal	One variant	No EIC data needs	N/A	None recommended
Chemical oxidation	One variant	No EIC data needs	N/A	None recommended
Particulate chemical reduction	One variant	Effectiveness and longevity for U, Tc-99, and Cr(VI) in the perched water and for a water table PRB	Laboratory testing of contaminant reaction and sequestration stability data. Implementation at FS level is known based on other commercial applications.	None recommended from lower effectiveness for U and Tc-99 than particulate approaches that include a sequestration component.
Gas-phase chemical reduction	One variant	No EIC data needs. Previous demonstration and commercial application are sufficient.	N/A	None recommended
Particulate-phase chemical sequestration	One variant	Effectiveness for U, Tc-99, Sr-90, I-129, and Cr(VI) in perched water and for a water table PRB	Laboratory testing of contaminant reaction and sequestration stability. Implementation at FS level is known based on other commercial applications.	Conduct laboratory testing to provide enough information about effectiveness to support remedial alternative evaluations in future FSs for the perched water or as a water table PRB.

Table 5-1. Treatability Study Determination

Technology Process Option	Technology Variant	What Data are Needed to Support an FS?	What Type of Treatability Study Would Address the Identified Data Need(s)?	Recommendation for a Treatability Study
Gas-phase chemical sequestration	Ammonia	Data needs were addressed in the URGS treatability study.	N/A, supporting site data needed for FS evaluation was identified in the URGS treatability study final report.	No additional testing recommended.
	CO_2	Effectiveness for I-129, Sr-90, and Cr(VI) in the unsaturated zones.	Laboratory testing for effectiveness and scale-up. Implementation at FS level is known based on other field testing.	Conduct laboratory study for effectiveness focused on I-129, considering impact on Sr-90, Cr(VI), and other co-contaminants (e.g., U). Laboratory studies to provide scale-up information for CO_2 injection. The RI/FS process will provide information about specific applications and identify if any additional information is needed.
Gas-phase combined chemical reduction and sequestration	One variant	No EIC data needs (laboratory data available for Tc-99, the primary target for this technology).	N/A	No additional testing recommended.
Particulate-phase combined chemical reduction and sequestration	All variants	Effectiveness in perched water geochemistry and delivery in the perched water and for a water table PRB.	Laboratory testing in perched water chemistry conditions and with delivery fluids that could be distributed in the perched water. Evaluate ability to incorporate Tc-99. Evaluate potential water table PRB applications relevant to Tc-99.	Laboratory study to determine effectiveness of candidate particles and ability to employ as particles for the perched water or as a water table PRB.
Gas-phase bioremediation	Oxygen	No EIC data needs. Known application based on other commercial aerobic sites.	N/A	None needed, only applicable to MIBK.
	H_2 or hydrocarbon gases	Effectiveness for NO_3, CN, and Cr(VI) in the unsaturated zones	Laboratory testing for bioreduction with H_2 or hydrocarbon gases. Implementation at FS level is known based on other commercial applications	Laboratory study to determine whether it is effective for NO_3, CN, and Cr(VI) and impact on U and Tc-99 co-contaminants.

Table 5-1. Treatability Study Determination

Technology Process Option	Technology Variant	What Data are Needed to Support an FS?	What Type of Treatability Study Would Address the Identified Data Need(s)?	Recommendation for a Treatability Study
Gas-phase combined bioreduction and chemical sequestration	One variant	Effectiveness for Tc-99 in the unsaturated zones	Laboratory testing for bioreduction with H_2 or hydrocarbon gases and to combine with an appropriate gas-phase sequestration approach (e.g., ammonia or CO_2). Implementation at FS level is known based on other commercial applications for bioreduction portion. Combined approach will need scale-up information.	Laboratory study to determine effectiveness for Tc-99 and impact on other co-contaminants (e.g., U, I-129, NO3, CN, C-14, and Cr(VI)) and to provide scale-up information.
Liquid-phase chemical reduction	All	Effectiveness for U and Tc-99 in perched water and delivery in the perched water.	Laboratory testing of candidate reductants in perched water chemistry conditions is needed along with testing of delivery fluids that could be distributed in the perched water conditions.	None recommended based on poor longevity for U and Tc-99.
Liquid-phase chemical sequestration	All variants	Effectiveness for U, Tc-99, I-129, Sr-90, C-14, and Cr(VI) in perched water geochemistry and delivery in the perched water and for water table PRB.	Phosphate sequestration shown to be effective for U and Sr-90. However, laboratory testing of phosphate-based sequestration and other candidate amendments in perched water chemistry is needed along with testing of delivery fluids that could be distributed in the perched water conditions. Evaluate ability to use for a water table PRB with effectiveness for the contaminants listed in the data need.	Laboratory study to determine effectiveness and to provide scale-up information for the perched water or as a water table PRB.
Liquid-phase combined chemical reduction and sequestration	All variants	Effectiveness for Tc-99 in perched water geochemistry and impact on other co-contaminants (e.g., U, Sr-90, I-129, C-14, and Cr(VI)) and delivery in the perched water and for water table PRB.	Phosphate sequestration shown to be effective for U and Sr-90. However, laboratory testing of combined reduction and candidate sequestration amendments in perched water chemistry is needed for Tc-99, testing of the effect on perched water co-contaminants, and for delivery mechanisms for distribution in the perched water conditions. Evaluate ability to use for a water table PRB with effectiveness for the contaminants listed in the data need.	Laboratory study to determine effectiveness for Tc-99, impact on other co-contaminants, and to provide scale-up information for the perched water or as a water table PRB.
Liquid-phase bioremediation	All variants	Effectiveness for U, Tc-99, NO_3, CN, and Cr(VI) in perched water and delivery in the perched water and for water table PRB.	Laboratory testing in perched water chemistry is needed along with testing of delivery mechanisms for distribution in the perched water conditions. Evaluate ability to use for a water table PRB with effectiveness for the contaminants listed in the data need.	None recommended based on poor longevity for U and Tc-99.

Table 5-1. Treatability Study Determination

Technology Process Option	Technology Variant	What Data are Needed to Support an FS?	What Type of Treatability Study Would Address the Identified Data Need(s)?	Recommendation for a Treatability Study
Liquid-phase combined bioreduction and chemical sequestration	All variants	Effectiveness for Tc-99 in perched water geochemistry and impact on other co-contaminants (e.g., U, NO_3, CN, Sr-90, I-129, C-14, and Cr(VI)) and delivery in the perched water and for water table PRB.	Phosphate sequestration shown to be effective for U and Sr-90. However, laboratory testing of combined reduction and candidate sequestration amendments in perched water chemistry is needed for Tc-99, testing of the effect on perched water co-contaminants, and for delivery mechanisms for distribution in the perched water conditions. Evaluate ability to use for a water table PRB with effectiveness for the contaminants listed in the data need.	Laboratory study to determine effectiveness for Tc-99, impact on other co-contaminants, and to provide scale-up information for delivery in perched water and for a water table PRB.
Microbially facilitated volatilization	Microbially facilitated volatilization	Field implementation and effectiveness for I-129 and delivery in unsaturated zones.	Laboratory testing of mechanisms to induce volatilization using bioremediation methods for the vadose zone.	None recommended based on poor effectiveness.

Reference: DOE/RL-2014-34, *Action Memorandum for 200-DV-1 Operable Unit Perched Water Pumping/Pore Water Extraction*.

Cr(VI) = hexavalent chromium
EIC = effectiveness, implementability, and relative cost
FS = feasibility study
N/A = not applicable
OU = operable unit
PRB = permeable reactive barrier
RI = remedial investigation
URGS = Uranium Reactive Gas Sequestration

Table 5-2. Technology Applicability

Technology Category (underlined technologies recommended for treatability testing)	Unsaturated Higher Permeability Zones									Unsaturated Lower Permeability Zones									Perched Water Zones				Water Table Interface Zones					
	U	Tc-99	I-129	Cr(VI)	NO_3	Sr-90	CN	C-14	Organics	U	Tc-99	I-129	Cr(VI)	NO_3	Sr-90	CN	C-14	Organics	U	Tc-99	NO_3	C-14	U	Tc-99	I-129	Cr(VI)	NO_3	CN
Containment																												
Surface barrier	5	5	5	5	5	5	5	5	6	5	5	5	5	5	5	5	5	6	6	6	6	6	—	—	—	—	—	—
Subsurface jet injection grouting	8	8	8	8	8	8	8	8	9	8	8	8	8	8	8	8	8	9	8	8	8	8	—	—	—	—	—	—
Subsurface permeation grouting	8	8	8	8	8	8	8	8	9	8	8	8	8	8	8	8	8	9	8	8	8	8	—	—	—	—	—	—
Subsurface soil freezing	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	—	—	—	—	—	—
Desiccation	4	4	4	4	4	4	4	4	—	4	4	4	4	4	4	4	4	—	—	—	—	—	—	—	—	—	—	—
Removal																												
Excavation with retaining walls	7	7	7	7	7	7	7	7	8	7	7	7	7	7	7	7	7	8	—	—	—	—	—	—	—	—	—	—
Excavation without retaining walls	7	7	7	7	7	7	7	7	8	7	7	7	7	7	7	7	7	8	—	—	—	—	—	—	—	—	—	—
Soil flushing/washing	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	—	—	—	—	—	—	—	—	—	—
Perched water removal	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	6	6	6	6	—	—	—	—	—	—
Pore water extraction	—	—	—	—	—	—	—	—	—	8	7	8	7	7	8	7	8	8	7	6	6	7	—	—	—	—	—	—
Soil wicking	—	—	—	—	—	—	—	—	—	8	7	8	7	7	8	7	8	8	—	—	—	—	—	—	—	—	—	—
Ex Situ Technologies																												
Vitrification	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	—	—	—	—	—	—	—	—	—	—
Solidification/Stabilization	4	4	4	4	4	4	4	4	6	4	4	4	4	4	4	4	4	6	—	—	—	—	—	—	—	—	—	—
Contaminant Separation	7	7	7	7	7	7	7	7	—	7	7	7	7	7	7	7	7	—	—	—	—	—	—	—	—	—	—	—
Backfill with treated soil	9	9	9	9	9	9	9	9	8	9	9	9	9	9	9	9	9	8	—	—	—	—	—	—	—	—	—	—
Onsite landfill	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	—	—	—	—	—	—	—	—	—	—
Offsite landfill/repository	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	—	—	—	—	—	—	—	—	—	—
Ex situ water treatment	4	4	6	4	4	5	4	5	4	4	4	6	4	4	5	4	5	4	4	4	4	5	—	—	—	—	—	—
In Situ Technologies																												
In situ vitrification	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	—	—	—	—	—	—
Thermal water volatilization	—	—	—	—	—	—	—	—	7	—	—	—	—	—	—	—	—	7	—	—	—	—	—	—	—	—	—	—
Thermal desorption/destruction	—	—	—	—	—	—	—	—	7	—	—	—	—	—	—	—	—	7	—	—	—	—	—	—	—	—	—	—
Soil vapor extraction	—	—	—	—	—	—	—	—	4	—	—	—	—	—	—	—	—	5	—	—	—	—	—	—	—	—	—	—
Encapsulation	8	8	8	8	8	8	8	8	9	8	8	8	8	8	8	8	8	9	7	7	7	7	—	—	—	—	—	—
Electrokinetic removal	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	—	—	—	—	—	—
Chemical oxidation	—	—	—	—	—	—	—	—	7	—	—	—	—	—	—	—	—	7	—	—	—	—	—	—	—	—	—	—
Particulate chemical reduction	9	9	—	7	—	—	—	—	8	9	9	—	7	—	—	—	—	8	8	8	—	—	8	8	—	6	—	—
Gas-phase chemical reduction	8	8	—	6	—	—	—	—	8	8	8	—	6	—	—	—	—	8	—	—	—	—	—	—	—	—	—	—
Particulate sequestration	7	8	8	8	—	7	—	—	—	7	8	8	8	—	7	—	—	—	6	7	—	—	6	7	7	7	—	—
Gas-phase chemical sequestration	6	7	6	6	—	6	—	7	—	6	7	6	6	—	6	—	7	—	—	—	—	—	—	—	—	—	—	—

Table 5-2. Technology Applicability

Technology Category (underlined technologies recommended for treatability testing)	Unsaturated Higher Permeability Zones									Unsaturated Lower Permeability Zones									Perched Water Zones				Water Table Interface Zones					
	U	Tc-99	I-129	Cr(VI)	NO_3	Sr-90	CN	C-14	Organics	U	Tc-99	I-129	Cr(VI)	NO_3	Sr-90	CN	C-14	Organics	U	Tc-99	NO_3	C-14	U	Tc-99	I-129	Cr(VI)	NO_3	CN
Particulate-phase combined chemical reduction & sequestration	8	9	—	7	—	7	—	—	—	8	9	—	7	—	7	—	—	—	7	8	—	—	7	8	—	6	—	—
Gas-phase combined chemical reduction and sequestration	7	7	—	6	—	8	—	8	—	7	7	—	6	—	8	—	8	—	—	—	—	—	—	—	—	—	—	—
Gas-phase bioremediation	7	7	—	5	5	—	7	—	5	7	7	—	5	5	—	7	—	5	—	—	—	—	—	—	—	—	—	—
Gas-phase combined bioreduction and chemical sequestration	6	6	—	5	5	7	—	7	7	6	6	—	5	5	7	—	7	7	—	—	—	—	—	—	—	—	—	—
Liquid chemical reduction	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	8	8	—	—	8	8	—	6	—	—
Liquid-phase chemical sequestration	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	6	8	—	8	6	8	7	7	—	—
Liquid-phase combined chemical reduction and sequestration	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	7	7	—	8	7	7	—	6	—	—
Liquid-phase bioremediation	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	6	6	4	—	6	6	—	4	4	5
Liquid-phase combined bioreduction and chemical sequestration	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	7	7	6	8	7	7	—	6	6	7
Microbially facilitated volatilization	—	—	3	—	—	—	—	—	—	—	—	3	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—

Notes: Underlined technologies are recommended for treatability studies.
Green indicates total rating is 3, 4, or 5 effectiveness and implementability are not low.
Yellow indicates total rating is 6 or 7, effectiveness and implementability are not low.
Red indicates effectiveness or implementability are low (the rating range is 6 to 9).
— = not applicable
Cr(VI) = hexavalent chromium

Table 5-3. Recommended Technologies to Consider for Feasibility Studies

Treatment Area	General Response Action			
	Containment	Removal	Ex Situ Treatment	In Situ Treatment [a]
Unsaturated (both higher and lower permeability)	Desiccation [b] Surface barrier	Excavation of <30 m (100 ft)	Solidification/Stabilization Onsite landfill	Gas-phase chemical sequestration (I-129, U, Cr(VI), Sr-90) Gas-phase combined bioreduction and chemical sequestration (Tc-99 [c], U, Cr(VI), NO_3) Gas-phase chemical reduction (Cr(VI)) Gas-phase bioremediation (Cr(VI), NO_3, CN, MIBK) Soil vapor extraction (TCE, MIBK) Chemical oxidation (TCE, MIBK)
Perched Water [d]	Surface barrier	Perched water removal (and related pore water extraction in the removal action)	Ex situ water treatment	Liquid-phase chemical sequestration Particulate sequestration Particulate-phase combined chemical reduction and sequestration Liquid-phase combined chemical reduction and sequestration Liquid-phase combined bioreduction and chemical sequestration Liquid-phase bioremediation Liquid-phase chemical reduction Particulate chemical reduction
Water Table Interface [e]	N/A	N/A	N/A	Liquid-phase chemical sequestration Particulate sequestration Particulate-phase combined chemical reduction and sequestration Liquid-phase combined chemical reduction and sequestration Liquid-phase combined bioreduction and chemical sequestration Liquid-phase bioremediation Liquid-phase chemical reduction Particulate chemical reduction

Notes: Underlined technologies are recommended for treatability studies and underlined COIs are the primary targets of those studies.

a. Access and delivery approaches are listed in Table B-2. The access and delivery assessment should be considered in conjunction with the listings in this table.

b. Desiccation itself does not have an EIC data gap. However, because desiccation is deployed with a surface barrier, the EIC data gap associated with the surface barrier would need to be resolved before consideration of desiccation in a feasibility study.

c. Denotes a combined technology where the combined approach is applicable to Tc-99 and with the consideration of the effect on co-contaminants.

d. In situ treatment technologies for the perched water will be based on the water quality from the 200-DV-1 OU perched water body located in the B Farm Complex.

e. Water table potential applications are expected to include primary COIs (U, Tc-99, and NO3 [the perched water COIs]) and contaminants (Cr(VI), I-129, and CN) that may also be groundwater or source-zone co-contaminants with near-term groundwater impact.

COI = contaminant of interest
Cr(VI) = hexavalent chromium
EIC = effectiveness, implementability, and costs
MIBK = methyl isobutyl ketone
N/A = not applicable
OU = operable unit

5.2 Recommendations for Additional Treatability Studies

This section provides additional detail for the treatability study recommendations shown in Table 5-1. These recommendations were derived from the results and conclusions of the testing programs completed to date summarized in Section 3.1, the DVZ technology evaluation performed in Chapter 4, the updated treatability study assessment conclusions provided in Section 5.1, and associated data gaps or uncertainties identified. A summary of recommendations categorized as modeling, laboratory testing, or field studies is provided in Table 5-4. In addition, the table provides examples of waste sites in 200-DV-1 and other Hanford Central Plateau OUs that these technologies could be applied to if the studies show they are effective and implementable. The 200-DV-1 OU perched water and BY Cribs are likely continuing sources of technetium-99 and uranium to groundwater, but these waste sites and the other listed waste sites need to be evaluated in the RI (and RFI) process to assess impacts to groundwater.

The recommended laboratory and modeling treatability studies will likely provide enough information to perform remedial alternative evaluations in the FS. The information obtained for technology effectiveness from the treatability studies, when combined with the other available technology information, will likely be sufficient for evaluating these technologies in the FS. After completing the laboratory studies and the 200-DV-1 OU RI (and RFI), results will be evaluated to determine whether field studies are needed to provide additional information on effectiveness, implementability, or costs for evaluating these technologies in the FS.

While the need for field studies was considered for all technologies, no additional field studies are recommended at this time because either the technology:

- Is already sufficiently mature for consideration in a future FS
- Has poor effectiveness or implementability for the identified Hanford Site DVZ remediation scenarios
- Has limited applicability that requires identification of a waste site during the RI evaluation process with specific performance criteria and a risk to groundwater before a field study is warranted
- Has identified data gaps that can be addressed through laboratory or modeling studies to enable their consideration in an FS

While no field studies are recommended at this time as described above, the need for field studies will be evaluated based on the results of the recommended laboratory studies and completion of the remedial investigations of the waste sites.

Table 5-4. Recommended Studies and Potential Site Applications

Technology Process Option	COI to Study	Examples of Potentially Applicable 200-DV-1 Waste Sites	Examples of Other Potentially Applicable Waste Sites
Laboratory quantification of effectiveness is needed for use in combination with existing field-scale information from other sites to evaluate these technologies in a feasibility study			
Technologies for Unsaturated Zone Applications			
Gas-phase combined bioreduction and chemical sequestration	Tc-99	BY Cribs [a]	BC Cribs and Trenches [b]

Table 5-4. Recommended Studies and Potential Site Applications

Technology Process Option	COI to Study	Examples of Potentially Applicable 200-DV-1 Waste Sites	Examples of Other Potentially Applicable Waste Sites
Gas-phase bioremediation	**Nitrate**	Unknown [b]	Unknown [b]
	CN	BY Cribs [a]	Unknown [b]
	Cr(VI)	Unknown [b]	216-S-10 [b], 216-S-8 [b], 216-T-4a [b]
Gas-phase chemical sequestration	**I-129**	Unknown [b]	216-A-10 [b], 216-A-5 [b], 216-S-7 [b]
Technologies for the 200-DV-1 Perched Water and Use as a Horizontal Permeable Reactive Barrier at the Water Table			
Particulate-phase chemical sequestration	**U and Tc-99**	Perched Water [a], below Perched Water [a], and below BY Cribs [a]	216-U-1&2 [a], S-SX Tank Farm [a], C Tank Farm [a], BC Cribs and Trenches [b]
	Cr(VI)	Unknown [b]	216-S-10 [b], 216-S-8 [b], 216-T-4a [b]
	I-129	Unknown [b]	216-A-10 [b], 216-A-5 [b], 216-S-7 [b]
Particulate-phase combined chemical reduction and sequestration	**U and Tc-99**	Perched Water [a], below Perched Water [a], and below BY Cribs [a]	216-U-1&2 [a], S-SX Tank Farm [a], C Tank Farm [a], BC Cribs and Trenches [b]
Liquid-phase chemical sequestration	**U and Tc-99**	Perched Water [a], below Perched Water [a], and below BY Cribs [a]	216-U-1&2 [a], S-SX Tank Farm [a], C Tank Farm [a], BC Cribs and Trenches [b]
	Cr(VI)	Unknown [b]	216-S-10 [b], 216-S-8 [b], 216-T-4a [b]
	I-129	Unknown [b]	216-A-10 [b], 216-A-5 [b], 216-S-7 [b]
Liquid-phase combined chemical reduction and sequestration	**U and Tc-99**	Perched Water [a], below Perched Water [a], and below BY Cribs [a]	216-U-1&2 [a], S-SX Tank Farm [a], C Tank Farm [a], BC Cribs and Trenches [b]
Liquid-phase combined bioreduction and chemical sequestration	**U, Tc-99, nitrate**	Perched Water [a], below Perched Water [a], and below BY Cribs [a]	216-U-1&2 [a], S-SX Tank Farm [a], C Tank Farm [a], BC Cribs and Trenches [b]
	CN	BY Cribs [a]	Unknown [b]
Model/Paper Study to support barrier design			
Surface barrier: relate surface barrier size to depth of barrier effectiveness	All	Unknown [b]	Unknown [b]
No field studies are recommended at this time. The need for field studies will be evaluated based on results of above treatability studies and waste site investigations			
None identified	N/A	N/A	N/A

Note: Bolded COIs are primary known contaminant targets. Other COIs are potential co-contaminants to evaluate with primary COIs.

a. These are likely continuing sources of contaminants to groundwater.

b. The remedial investigation evaluation will determine the waste sites that impact groundwater.

COI = contaminant of interest

N/A = not applicable

Additional details for recommended treatability studies are discussed in the following sections, organized by general response actions. For recommended treatability studies, a test plan to describe details of the testing will be required.

5.2.1 Containment Technologies

Surface Barriers: Containment technologies may be an important component of vadose zone remedial alternatives for the Central Plateau because they mitigate the driving force (infiltration) for contaminant flux to groundwater. Surface barriers are a robust and commonly applied approach for infiltration control, reducing mobility of the contaminants. Surface barrier technology is mature and there are Hanford Site-specific studies providing information on design elements and surface monitoring. However, to use surface barriers for DVZ contamination, additional design information is required. The relationship between barrier size and effectiveness versus depth is important design information needed to conduct an FS. It is also important to identify suitable monitoring approaches to verify performance with respect to mitigating contaminant flux from the vadose zone to groundwater. The information available for these surface barrier implementation elements is currently insufficient to provide suitable input to future FSs. This same type of information is relevant to implementing surface barriers in conjunction with desiccation. Thus, while desiccation itself does not have any additional treatability study needs, the treatability study for surface barriers will be used to support consideration of desiccation in future FSs. The recommended treatability study for surface barriers a modeling study to relate barrier size to depth of effectiveness as a resource for future FSs. The treatability study would build from the surface barrier evaluation published as part of the Deep Vadose Zone Treatability Test Program in Section 3.1 of PNNL-18661. In addition, the modeling study would include an element defining appropriate monitoring approaches and provide information about relevant monitoring technologies and monitoring development programs. All the contaminants listed in Section 2.2.1 should be investigated in the treatability study.

5.2.2 Removal Technologies

No treatability studies are recommended for removal technologies. These technologies were all deemed sufficiently mature for consideration in a future FS or as part of other remedy implementation programs. However, Table 5-1 includes several recommendations for technology activities as part of the existing perched water removal action (DOE/RL-2014-34), which would be more appropriate to administer under that program rather than as a treatability study.

5.2.3 Ex Situ Technologies

No treatability studies are recommended for ex situ technologies. These technologies were all deemed sufficiently mature for consideration in a future FS.

5.2.4 In Situ Technologies

Particulate Sequestration or Combined Reduction and Sequestration: Particulates such as sulfur-modified iron have been developed as reactive materials that can be deployed in situ to produce stable precipitates of some inorganic contaminants. These particles could induce sequestration reactions or induce a combination of reduction and sequestration reactions to achieve a long-lasting reduction in contaminant mobility. Deployment by injection of nanoparticles, and in some cases micron-sized particles, may be effective for direct treatment of targeted hot spots or for creation of a horizontal PRB for saturated zone applications (though not for unsaturated-zone applications). Particles can be used to emplace a relatively high mass of reactants that also have good longevity in the subsurface. Reactive particles may be suitable to create a water table PRB or for perched aquifer treatment. However, the emplaced reactive particles need to support suitable reactions, result in stable contaminant forms, and be effectively distributed in situ via a limited number of injection locations. The recommended treatability study is a laboratory study to determine effectiveness of candidate particles and scale-up information on particle distribution in the

subsurface (as compared to the radius of influence for liquid amendments). The treatability study should investigate effectiveness for uranium, technetium-99, iodine-129, Cr(VI), strontium-90, and carbon-14. The treatability study should consider perched aquifer and water table water chemistry, contaminant concentrations, and co-contaminant interactions.

Gas-Phase Sequestration: Gas-phase sequestration, such as ammonia treatment, can be deployed in the vadose zone to produce less mobile precipitates of some inorganic contaminants. Ammonia as a reactive gas for contaminant sequestration has already been investigated in a treatability study (PNNL-27773). However, recent laboratory information has shown that iodate (an important chemical form of iodine-129) can be co-precipitated with carbonates (PNNL-24709, *Conceptual Model of Iodine Behavior in the Subsurface at the Hanford Site*). Iodine association with carbonate precipitates has also been observed in recent vadose zone characterization studies (PNNL-26208, PNNL-26266). Thus, there is sufficient information to suggest that creating conditions for carbonate precipitation may provide in situ treatment for iodine-129 contamination. Gas-phase carbon dioxide injection could induce carbonate precipitation, resulting in iodate co-precipitation and reducing iodine-129 mobility. The technology may also reduce the mobility of uranium, Cr(VI), and strontium-90 (PNNL-18879; SGW-58416, *Persistent Source Investigation at 100-D Area*; Mucci and Morse, 1983, "The incorporation of Mg2+ and Sr2+ into calcite overgrowths: influences of growth rate and solution composition"). The recommended treatability study is a laboratory study to determine effectiveness of carbon dioxide injection for reducing the mobility of iodine-129, including evaluation of the effect of the treatment on common co-contaminants including uranium, strontium-90, technetium-99, and Cr(VI).

Gas-Phase Bioremediation: Use of gas-phase amendments, such as hydrogen and hydrocarbons, for vadose zone bioremediation has been successfully demonstrated for perchlorate and nitrate treatment as part of the U.S. Department of Defense Environmental Security Technology Certification Program (ESTCP) (www.serdp-estcp.org, ER-0511). This approach is also described in a U.S. Patent (GEDIT; U.S. Patent No. 7,282,149). Based on the ESTCP demonstration results, nitrate, chromate, and (potentially) cyanide may be biodegraded with this method to reduce contaminant mass (nitrate and cyanide) or mobility and toxicity (chromate). However, Hanford Site-specific information is needed to determine the most appropriate gas-phase amendments and technology effectiveness. The recommended treatability study is a laboratory study to quantify biodegradation effectiveness and to develop Hanford Site-specific scale-up parameters that can be used in conjunction with the field-scale information from the ESTCP demonstration to support future FS evaluations of this technology. The laboratory study will need to use Hanford Site sediments and associated microbial populations, pore water chemistry, and moisture content. Contaminants investigated in the study should include nitrate, chromate, and cyanide.

Gas-Phase Combined Bioreduction and Sequestration: Use of gas-phase amendments, such as hydrogen and hydrocarbons, for vadose zone bioremediation has been successfully demonstrated for perchlorate and nitrate biodegradation as part of the U.S. Department of Defense ESTCP program (www.serdp-estcp.org, ER-0511). This approach is also described in a U.S. Patent (GEDIT; U.S. Patent No. 7,282,149). Based on the ESTCP demonstration results, technetium-99 may be bioreduced with this method. If technetium-99 can be bioreduced, then it may be amenable to long-term sequestration to reduce its mobility as has been demonstrated in the laboratory with combined hydrogen sulfide (reductant) and ammonia (sequestration) treatment (Szecsody et al., 2015). Hanford Site-specific information is needed to determine the most appropriate gas-phase amendments and technology effectiveness. The recommended treatability study is a laboratory study to quantify biodegradation effectiveness and biodegradation/sequestration effectiveness and to develop Hanford Site-specific scale-up parameters that can be used in conjunction with the field scale information in the ESTCP demonstration and the URGS project (Section 3.1) to support future FS evaluations of this technology. The laboratory study will need to use Hanford Site sediments and associated microbial populations, pore

water chemistry, and moisture content. Contaminants investigated in the study should include technetium-99, but with consideration of potential co-contaminant effects.

Liquid-Phase Chemical Sequestration: Chemical sequestration using liquid-phase amendments to facilitate sequestration of uranium or strontium-90 has been successfully demonstrated and applied at the Hanford Site with polyphosphate and apatite amendments (SGW-59614, *300-FF-5 Operable Unit Enhanced Attenuation Stage A Delivery Performance Report*; DOE/RL-2016-68, *Calendar Year 2016 Annual Summary Report for the 100-HR-3 and 100-KR-4 Pump and Treat Operations, and 100-NR-2 Groundwater Remediation*). To apply these methods to the Central Plateau, information is needed about whether candidate sequestration approaches will work to reduce contaminant mobility for the contaminant concentration and geochemical conditions of the targeted applications in the perched water and as a water table PRB. In addition, delivery of liquid-phase sequestration chemicals needs to be evaluated because the same techniques used for previous applications at the Hanford Site may not be viable for the perched water (low hydraulic driving forces available) or the water table PRB (where large lateral areas may need to be treated). The recommended treatability study is a laboratory study to quantify sequestration effectiveness for Central Plateau treatment areas (perched water and water table PRB) and to develop Hanford Site-specific scale-up parameters for potential delivery methods for these targets. This information can be used in conjunction with the field scale information in previous Hanford Site applications to support future FS evaluations of this technology. The laboratory study will need to use Hanford Site sediments and associated water biogeochemistry. Contaminants investigated in the study should include uranium, technetium-99, iodine-129, Cr(VI), strontium-90, and carbon-14. The treatability study should consider perched aquifer and water table water chemistry, contaminant concentrations, and co-contaminant interactions with nitrate.

Liquid-Phase Combined Chemical Reduction and Sequestration: Direct chemical sequestration has been applied for uranium and strontium-90 and may be appropriate for iodine-129, Cr(VI), and carbon-14. However, treatment of technetium-99 may require an initial reduction step prior to sequestration. To apply this method to the Central Plateau, information is needed about whether candidate reduction/sequestration approaches will work to reduce contaminant mobility for the contaminant concentration and geochemical conditions of the targeted applications in the perched water and as a water table PRB. In addition, delivery of liquid-phase reduction/sequestration chemicals needs to be evaluated for the perched water (low hydraulic driving forces available) and the water table PRB (where large areas may need to be treated). The recommended treatability study is a laboratory study to quantify reduction/sequestration effectiveness for targeted Central Plateau treatment areas (perched water and water table PRB) and to develop Hanford Site-specific scale-up parameters for potential delivery methods for these treatment areas. This information can be used in conjunction with the field scale information in previous Hanford Site applications to support future FS evaluations of this technology. The laboratory study will need to use Hanford Site sediments and associated water biogeochemistry. Contaminants investigated in the study should include technetium-99 and co-contaminants, especially uranium and nitrate, considering concentrations and water chemistry of the perched water and water table applications.

Liquid-Phase Combined Bioreduction and Chemical Sequestration: Direct chemical sequestration has been applied for uranium and strontium-90 and may be appropriate for iodine-129, Cr(VI), and carbon-14. However, treatment of technetium-99 may require an initial reduction step prior to sequestration. If technetium-99 can be bioreduced, then it may be amenable to long-term sequestration to reduce contaminant mobility as has been demonstrated in the laboratory with combined hydrogen sulfide (reductant) and ammonia (sequestration) treatment (Szecsody et al., 2015). In addition, bioreduction may be suitable to treat nitrate, Cr(VI), and potentially cyanide. Thus, combined bioreduction and sequestration may be effective for use in the perched water or, with long-duration substrates, as a water table PRB. To apply this method to the Central Plateau, information is needed about whether candidate

bioreduction/sequestration approaches will work for the contaminant concentration and geochemical conditions of the targeted applications in the perched water and as a water table PRB. In addition, delivery of liquid-phase bioreduction/sequestration chemicals needs to be evaluated for the perched water (low hydraulic driving forces available) and the water table PRB (where large areas may need to be treated). The recommended treatability study is a laboratory study to quantify bioreduction/sequestration effectiveness for targeted Central Plateau treatment areas (perched water and water table PRB) and to develop Hanford Site-specific scale-up parameters for potential delivery methods for these targets. This information can be used in conjunction with the field scale information in previous Hanford Site applications to support future FS evaluations of this technology. The laboratory study will need to use Hanford Site sediments and associated water biogeochemistry. Contaminants investigated in the study should include technetium-99 and co-contaminants, especially uranium and nitrate, considering concentrations and water chemistry of the perched water and for water table applications.

5.3 Conclusion

This document summarizes the results and recommendations from the treatability studies performed under the DVZ Treatability Test Plan (DOE/RL-2007-56), provides recommendations for use of these technologies in an FS, and fulfills the requirement of the test plan for a final evaluation of the treatability effort.

Because only limited laboratory and modeling studies were identified in this technology evaluation and treatability study assessment, it is recommended that the 200-DV-1 OU RI/FS and RFI/CMS WP (DOE/RL-2011-102) and the recommended laboratory and modeling studies be conducted concurrently. The remedial investigation of the 20-DV-1 OU waste sites should be completed as scheduled to determine which waste sites and contaminants pose a risk to groundwater.

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Appendix A

Deep Vadose Zone Science and Technology Advances

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Contents

A1 Science and Technology Advances **A-1**

A2 References **A-6**

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Terms

CHPRC	CH2M HILL Plateau Remediation Company
DOE	U.S. Department of Energy
DVZ	deep vadose zone
EPA	U.S. Environmental Protection Agency
ORP	DOE Office of River Protection
PNNL	Pacific Northwest National Laboratory
RL	DOE Richland Operations Office
WRPS	Washington River Protection Solutions

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A1 Science and Technology Advances

This appendix summarizes specific elements of science and technology activities relevant to the Hanford Central Plateau. These have been recent national and international efforts providing updated relevant information for science and technology and integration with remediation efforts. These efforts include the U.S. Environmental Protection Agency's (EPA) Groundwater Road Map (EPA, 2011, *Groundwater Road Map: Recommended Process for Restoring Contaminated Groundwater at Superfund Sites*) and the EPA Groundwater Remedy Completion Strategy (EPA, 2014, *Groundwater Remedy Completion Strategy: Moving Forward with the End in Mind*) that recommend establishing an initial plan for the overall groundwater restoration process. EPA has recently updated and clarified the use of monitored natural attenuation for inorganic and radionuclide contaminants (EPA, 2015, *Use of Monitored Natural Attenuation for Inorganic Contaminants in Groundwater at Superfund Sites*). EPA has also clarified the technical impracticability waiver process (EPA, 2016, *Memorandum: Clarification of the Consultation Process for Evaluating the Technical Impracticability of Groundwater Restoration at CERCLA Sites*). The International Atomic Energy Agency has also been recently publishing documents relevant to attenuation remedies and other remediation considerations (http://www.iaea.org). In addition, the Interstate Technology & Regulatory Council has published relevant guidance for natural attenuation, specific types of characterization and analysis tools, remediation management of complex sites, and aspects of the remedy selection and implementation process (http://itrcweb.org). Consistent with these updated national and international guidance documents and advances in information, efforts more specific to the vadose zone and 200-DV-1 Operable Unit conditions have been conducted as outlined in this appendix.

A primary product of these more site-specific activities relevant to the waste sites on the Central Plateau is a structured approach for evaluating vadose zone contaminant transport and effect on groundwater. This approach uses targeted lines of evidence from characterization and monitoring data that are incorporated into analyses to quantify the features and processes controlling contaminant transport. The analyses are then used to develop defensible estimates of contaminant flux in the vadose zone and resulting groundwater contaminant concentrations. Previous and ongoing efforts to improve understanding of the mechanisms underlying the important controlling features and processes has improved the transport analyses and provides a foundation for remedial alternative analysis. Another primary emphasis of previous and ongoing science and technology activities has been in providing information on additional characterization, remediation, and monitoring approaches that may be considered in the Feasibility Study/Corrective Measures Study. This appendix provides a listing of science and technology activities.

Published in 2008, DOE/RL-2007-56, *Deep Vadose Zone Treatability Test Plan for the Hanford Central Plateau*, defined a program of technology testing and evaluation for the deep vadose zone (DVZ). The following elements of the DVZ treatability test plan (DOE/RL-2007-56) have been completed:

- A DVZ ***remediation technology review***, which was included as part of the DVZ treatability test plan (DOE/RL-2007-56), identified soil desiccation and gas-phase remediation technologies as the highest priority for development and testing at the field scale. The review also identified efforts needed to evaluate the role of surface infiltration barriers for DVZ contaminants, soil flushing as an extraction technique, and in situ grouting of vadose zone contaminants.

- A treatability test of ***desiccation*** was completed on the Central Plateau as reported in PNNL-26902, *Deep Vadose Zone Treatability Test of Soil Desiccation for the Hanford Central Plateau: Final Report*. The following reports and articles describe specific elements of the effort:
  - The following laboratory and modeling assessments of the desiccation process and design elements have been completed:
    - Oostrom et al., 2009, "Desiccation of Unsaturated Porous Media: Intermediate-Scale Experiments and Numerical Simulation"
    - Oostrom et al., 2011, "Determination of Water Saturation in Relatively Dry Porous Media Using Gas-Phase Partitioning Trace Tests"
    - Oostrom et al., 2012a, "Sensor and Numerical Simulator Evaluation by Porous Medium Desiccation and Rewetting at the Intermediate Laboratory Scale"
    - Oostrom et al., 2012b, "Effects of Porous Medium Heterogeneity on Vadose Zone Desiccation: Intermediate-Scale Laboratory Experiments and Simulations"
    - PNNL-20146, *Laboratory and Modeling Evaluations in Support of Field Testing for Desiccation at the Hanford Site*
    - PNNL-17274, *Experimental and Numerical Investigations of Soil Desiccation for Vadose Zone Remediation: Report for Fiscal Year 2007*
    - PNNL-20507, *Pore-Water Extraction Intermediate-Scale Laboratory Experiments and Numerical Simulations*
    - Truex et al., 2012a, "Technical Basis for Gas-Phase Vadose Zone Remediation Technologies at Hanford: A Review"
  - The active portion of desiccation field testing has been completed, as described in the following publications:
    - PNNL-18800, *Characterization of Sediments from the Soil Desiccation Pilot Test (SDPT) Site in the BC Cribs and Trenches Area*
    - PNNL-21369, *Deep Vadose Zone Treatability Test for the Hanford Central Plateau: Soil Desiccation Pilot Test Results*
    - Truex et al., 2012b, "Field-Scale Assessment of Desiccation Implementation for Deep Vadose Zone Contaminants"
    - DOE/RL-2010-04, *Field Test Plan for the Soil Desiccation Pilot Test*
    - DOE/RL-2010-83, Rev. 1, *Sampling and Analysis Plan for the Soil Desiccation Pilot Test*
  - Long-term performance monitoring of field testing has been completed, as described in the following publications:
    - PNNL-22826, *Deep Vadose Zone Treatability Test for the Hanford Central Plateau: Interim Post-Desiccation Monitoring Results*
    - PNNL-23731, *Deep Vadose Zone Treatability Test for the Hanford Central Plateau: Interim Post-Desiccation Monitoring Results, Fiscal Year 2014*

    - PNNL-24706, *Deep Vadose Zone Treatability Test for the Hanford Central Plateau: Interim Post-Desiccation Monitoring Results, Fiscal Year 2015*

  - Electrical resistivity tomography and ground-penetrating radar methods for remedy monitoring were tested as part of the desiccation field test, as described in the following publications:
    - PNNL-21369
    - Truex et al., 2013, "Monitoring Vadose Zone Desiccation with Geophysical Models"

  - In situ sensors for remedy monitoring were tested as part of the desiccation field test, as described in the following publications:
    - Oostrom et al., 2012a
    - PNNL-21369
    - Truex et al., 2013

  - Numerical modeling using the Subsurface Transport Over Multiple Phases code was applied for remedy design, as described in the following publications:
    - PNNL-21369
    - Truex et al., 2013

- A ***uranium reactive gas sequestration treatability test*** was completed, including laboratory testing, field test planning (DOE/RL-2010-87, *Field Test Plan for the Uranium Sequestration Pilot Test*; DOE/RL-2010-88, *Sampling and Analysis Plan for the Uranium Sequestration Pilot Test*), and field test design and construction at the 216-U-8 site. However, laboratory tests of sediment samples obtained from the 216-U-8 field test site showed that ammonia treatment did not reduce uranium mobility as intended. Because of these tests results, field testing activities were stopped and ammonia injection was not conducted. A final treatability test was published (PNNL-27773, *Deep Vadose Zone Treatability Test of Uranium Reactive Gas Sequestration for the Hanford Central Plateau: Final Report*). In addition, three reports and two journal articles describing the laboratory results have been published (PNNL-18879, *Remediation of Uranium in the Hanford Vadose Zone Using Gas-Transported Reactants: Laboratory-Scale Experiments*; PNNL-20004, *Remediation of Uranium in the Hanford Vadose Zone Using Ammonia Gas: FY 2010 Laboratory-Scale Experiments*; PNNL-23699, *Scale-Up Information for Gas-Phase Ammonia Treatment of Uranium in the Vadose Zone at the Hanford Site Central Plateau*; Szecsody et al., 2012, "Geochemical and Geophysical Changes During Ammonia Gas Treatment of Vadose Zone Sediments for Uranium Remediation"; Zhong et al., 2015, "Ammonia Gas Transport and Reactions in Unsaturated Sediments: Implications for Use as an Amendment to Immobilize Inorganic Contaminants").

- A ***soil flushing assessment*** was completed, including a review of potential flushing solution formulations and modeling of the process relevant to application in the Central Plateau (PNNL-19938, *Evaluation of Soil Flushing for Applications to the Deep Vadose Zone in the Hanford Central Plateau*).

- An assessment of ***in situ grouting*** was completed, including a review of injectable grouting materials and techniques to estimate injection performance (PNNL-20051, *Evaluation of In Situ Grouting as a Potential Remediation Method for the Hanford Central Plateau Deep Vadose Zone*).

- A review of ***surface barrier applicability*** and data gaps for DVZ contaminants was conducted (PNNL-18661, *Technical Basis for Evaluating Surface Barriers to Protect Groundwater from Deep Vadose Zone Contamination*).

- In response to observations from the desiccation field testing, initial development and testing of two technologies (***pore water extraction*** using applied vacuum, and ***soil wicking*** using super absorbent polymers) that have the potential to extract contaminated water from the vadose zone have been initiated. Proof-of-principle evaluations were conducted by Pacific Northwest National Laboratory (PNNL) in collaboration with the U.S. Department of Energy (DOE), Richland Operations Office (RL); CH2M HILL Plateau Remediation Company (CHPRC); DOE Office of River Protection (ORP); and Washington River Protection Solutions (WRPS) (Oostrom et al., 2011; Oostrom et al., 2012c, "Vadose Zone Soil Moisture Wicking Using Super Absorbent Polymers").

The DVZ Applied Field Research Initiative has been jointly funded by RL and the DOE Office of Environmental Management, Office of Soil and Groundwater Remediation. A review of DVZ remediation was competed and published in the *Environmental Science and Technology* journal as a critical review article (PNNL-18114, *Remediation of Deep Vadose Zone Radionuclide and Metal Contamination: Status and Issues*; Dresel et al., 2011, "Review: Technical and Policy Challenges in Deep Vadose Zone Remediation of Metals and Radionuclides").

- The ***impact of disposed waste chemistry on the fate of uranium*** in the vadose zone was evaluated with important ramifications in assessing the potential future impact to groundwater (PNNL-23666, *Conceptual Model of Uranium in the Vadose Zone for Acidic and Alkaline Wastes Discharged at the Hanford Site Central Plateau*; Szecsody et al., 2013, "Influence of Acidic and Alkaline Waste Solution Properties on Uranium Migration in Subsurface Sediments"; Gartman et al., 2015, "Uranium fate in Hanford sediment altered by simulated acid waste solutions").

- A ***contaminant flux/natural attenuation-based remedy evaluation approach*** for the vadose zone was developed as a means to structure the assessment of vadose zone contamination to support remedy decisions for protection of groundwater (PNNL-21815, *Remedy Evaluation Framework for Inorganic, Non-Volatile Contaminants in the Vadose Zone*; PNNL-23737, *Evaluating Contaminant Flux from the Vadose Zone to the Groundwater in the Hanford Central Plateau: SX Tank Farms Case Study*; PNNL-24731, *Evaluating Transport and Attenuation of Inorganic Contaminants in the Vadose Zone for Aqueous Waste Disposal Sites*; Oostrom et al., 2016, "Evaluation of Deep Vadose Zone Contaminant Flux into Groundwater: Approach and Case Study"; Oostrom et al., 2017, "Deep vadose zone contaminant flux evaluation at the Hanford BY-Cribs Site using forward and imposed concentration modeling approaches").

- An ***analysis of the B Complex perched water system*** was conducted to support the evaluation of future contaminant flux to groundwater and related monitoring approaches (PNNL-22499, *Perched-Water Evaluation for the Deep Vadose Zone Beneath the B, BX, and BY Tank Farms Area of the Hanford Site*; Oostrom et al., 2013, "Perched-Water Analysis Related to Deep Vadose Zone Contaminant Transport and Impact to Groundwater"; DOE/RL-2016-69, *Calendar Year 2016 Summary Report for the 200-ZP-1 and 200-UP-1 Operable Unit Pump-and-Treat Operations*).

- ***Pore water extraction*** technologies were evaluated and experiments and modeling were performed to support a WRPS-led field test at the SX Tank Farm in collaboration with ORP/WRPS (PNNL-21882, *Pore-Water Extraction Scale-Up Study for the SX Tank Farm*; Truex et al., 2013; PNNL-22662, *Field Test Design Simulations of Pore-Water Extraction for the SX Tank Farm*; and

Oostrom et al., 2014, "Pore-Water Extraction from Unsaturated Porous Media: Intermediate-Scale Laboratory Experiments and Simulations").

- A ***technetium sequestration*** laboratory investigation was conducted to evaluate candidate techniques, with continued development of combined hydrogen sulfide and ammonia vapor treatment as the most promising approach (Szecsody et al., 2014, "Influence of Alkaline Co-Contaminants on Technetium Mobility in Vadose Zone Sediments"; PNNL-23665, *Gas-Phase Treatment of Technetium in the Vadose Zone at the Hanford Site Central Plateau;* Szecsody et al., 2015, "Remediation of Technetium in Vadose Zone Sediments Using Ammonia and Hydrogen Sulfide Gases").

- ***Iodine speciation and biogeochemistry*** has been evaluated (PNNL-24709, *Conceptual Model of Iodine Behavior in the Subsurface at the Hanford Site*; SRNL-STI-2012-00592, *Laboratory report on iodine (^{129}I and ^{127}I) speciation, transformation and mobility in Hanford groundwater, suspended particles and sediments*; SRNL-STI-2012-00425, *Biogeochemical Considerations Related to the Remediation of ^{129}I Plumes*; Kaplan et al., 2014, "Radioiodine Biogeochemistry and Prevalence in Groundwater"; Xu et al., 2015, "Radioiodine sorption/desorption and speciation transformation by subsurface sediments from the Hanford Site"). A significant element of this effort is the ROD-specified remedy evaluation for I-129 at the 200-UP-1 Operable Unit (DOE/RL-2015-69, *UP-1 Evaluation Plan for Iodine*).

- ***Technetium speciation and biogeochemistry*** has been evaluated (PNNL-18139, *The Geochemistry of Technetium: A Summary of the Behavior of an Artificial Element in the Natural Environment*; Icenhower et al., 2010, "The Biogeochemistry of Technetium: Review of the Behavior of an Artificial Element in the Natural Environment").

- Monitoring data at the ***Hanford prototype barrier*** were reviewed and quality control applied. Summaries of the data and monitoring results for ***performance of the Hanford prototype barrier*** have been published (PNNL-28039, *Monitoring the Prototype Hanford Barrier – Fiscal Year 2018 Report*; PNNL-26953, *Monitoring the Prototype Hanford Barrier – Fiscal Year 2017 Report*; and DOE/RL-2016-37, *Prototype Hanford Barrier 1994 to 2015*).

- An ***improved electrical resistivity tomography software*** for subsurface characterization and monitoring has been completed by PNNL. Aspects of this effort include the following:

  - The software (E4D) was tested and documented to NQA-1 Level B safety software standards in 2014 and released with an open source license (see https://e4d.pnnl.gov).

  - A new capability to account for subsurface metallic infrastructure is included in the software (Johnson and Wellman, 2014, "Parallel Modeling and Inversion of Electrical Resistivity Data in the Presence of Metallic Infrastructure"), which enables effective imaging in the presence of tanks, pipes, and well casings.

  - The software is designed to operate on supercomputers to optimize electrical resistivity tomography imaging and time-lapse monitoring capabilities.

  - Methods to quantify and monitor moisture content distribution in the vadose zone to identify zones impacted by waste discharges and to determine the rate of contaminated water movement toward the groundwater (Johnson et al., 2013, "Determination of Water Saturation Using Gas Phase Partitioning Tracers and Time-Lapse Electrical Conductivity Measurements").

  - A refined approach for characterization of contaminant extent within the vadose zone (PNNL-22520, *Re-Inversion of Surface Electrical Resistivity Tomography Data from the*

Hanford Site B-Complex; Johnson et al., 2011, "Characterization and Monitoring of Subsurface Processes Using Parallel Computing and Electrical Resistivity Imaging").

- A document defining a ***framework for improved monitoring technologies and approaches*** (including the vadose zone) was published in support of DOE Headquarters, with the collaboration of scientists across the DOE complex (PNNL-21379, *Scientific Opportunities for Monitoring at Environmental Remediation Sites (SOMERS) Integrated Systems-Based Approaches to Monitoring*). The collaboration between CHPRC, RL, and PNNL is establishing the technical basis for transition of Hanford Site groundwater monitoring plans from point-source-based monitoring to systems-based monitoring, accounting for integration with expected plume behavior and remedy characteristics.

- ***Foam delivery technology*** was evaluated as a method to deliver remedial amendments into vadose zone environments. However, some key limitations were identified (Zhong et al., 2009, "Foam Delivery of Calcium Polysulfide to the Vadose Zone for Chromium(VI) Immobilization: A Laboratory Evaluation"; Zhong et al., 2010, "Foam Delivery of Amendments for Vadose Zone Remediation: Propagation Performance in Unsaturated Sediments"; Zhang et al., 2012a, "Experimental Investigation of the Effective Foam Viscosity in Unsaturated Porous Media").

Remedy activity support includes the following:

- CHPRC expanded ***pumping from the B-Complex perched water zone***. This effort includes characterization and monitoring to improve understanding of the perched water system and remedy performance.

- ***Interim surface infiltration barriers*** have been installed and are being monitored to examine impact on vadose zone flow (PNNL-19772, *T-TY Tank Farm Interim Surface Barrier Demonstration – Vadose Zone Monitoring Plan*; PNNL-20144, *T-TY Tank Farm Interim Surface Barrier Demonstration – Vadose Zone Monitoring FY10 Report*). A method to evaluate the performance of a surface barrier was developed in collaboration with ORP/WRPS (Zhang et al., 2012b, "Evaluating the Performance of a Surface Barrier for Reducing Soil-Water Flow").

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Appendix B

Deep Vadose Zone Technology Summary Tables

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B1 Deep Vadose Zone Technology Summary Tables

This appendix provides the technology summary tables for contaminants in the deep vadose zone of the Hanford Site Central Plateau identified in Sections 3.2 and 3.3 of the main text.

Table B-1 provides a broad list of deep vadose zone remedial technologies. The remedial technologies are grouped into four general response action categories: containment, removal, ex situ treatment, and in situ treatment. The remedial technology types are general categories of technologies, such as surface barrier or chemical treatment. The remedial technology types are broken down into specific process options, as described in EPA/540/R-92/071a, *Guide for Conducting Treatability Studies under CERCLA: Final*. The process options are differentiated into technology variants to show the variations of technologies with specific modes of applications to a subset of contaminants of interest or treatment areas. Table B-1 describes each technology, applicable contaminants of interest, state of development, maturity of the technology, and reference documents.

Access and delivery or enabling technologies are presented in Table B-2. These technologies are not stand-alone technologies, but must be coupled with the remediation technologies identified in Table B-1. Table B-2 describes each technology, applicable contaminants of interest, state of development, maturity of the technology, and reference documents.

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Table B-1. Deep Vadose Zone Remediation Technologies

General Response Actions	Technology Type	Technology Process Option	Technology Variant	Description	COIs Addressed	State of Development/Maturity	Applicable Reports and Studies
Containment	Surface barrier	Surface barrier	Asphalt/concrete cap	Asphalt-concrete caps consist of asphalt and aggregate that are heated, mixed, and then placed to form a surface barrier between the waste area and the environment.	All contaminants	Technology is well established. Asphalt/concrete caps are simple to construct. Ratio of areal size to depth of effectiveness is a key design/cost factor.	PNNL-18661, 2010, *Technical Basis for Evaluating Surface Barriers to Protect Groundwater from Deep Vadose Zone Contamination*, Pacific Northwest National Laboratory, Richland, Washington. SGW-34059, 2007, *Effect of Waste Depth on Barrier Effectiveness*, Rev. 0, Fluor Hanford, Inc., Richland, Washington. PNNL-17176, 2007, *200-BP-1 Prototype Hanford Barrier Annual Monitoring Report for Fiscal Years 2005 Through 2007*, Pacific Northwest National Laboratory, Richland, Washington. PNNL-14907, 2004, *Vadose Zone Contaminant Fate-and-Transport Analysis for the 216-B-26 Trench*, Pacific Northwest National Laboratory, Richland, Washington. Field demonstration. Ongoing interim barrier effort by the Office of River Protection.
			Modified RCRA Subtitle C barrier	A multilayer surface barrier that generally consists of an upper vegetative (topsoil) layer, a drainage layer, and a low-permeability layer consisting of a synthetic liner over compacted clay.	All contaminants	Technology is well established. Multiple barrier designs have been developed and implemented. Ratio of size to effective treatment depth is a key design/cost factor.	Same as cited above for asphalt/concrete caps.
			Hanford barrier	A prototype multilayer earthen barrier constructed in 1994 over an existing waste site to provide long-term protection of radioactive wastes in a semiarid environment.	All contaminants	Technology is well established, although its use has been limited to the Hanford Site. Ratio of size to effective treatment depth is a key design/cost factor.	Same as cited above for asphalt/concrete caps. PNNL-28039, 2018, *Monitoring the Prototype Hanford Barrier – Fiscal Year 2018 Report*, Pacific Northwest National Laboratory, Richland, Washington. PNNL-26953, 2017, *Monitoring the Prototype Hanford Barrier – Fiscal Year 2017 Report*, Pacific Northwest National Laboratory, Richland, Washington. DOE/RL-2016-37, 2016, *Prototype Hanford Barrier 1994 to 2015*, Rev. 0, and appendices, U.S. Department of Energy, Richland Operations Office, Richland, Washington.
			Vegetative cap (evapotranspi-ration cap/cover)	A capillary barrier consisting of a fine-grained soil layer overlying a relatively coarse-grained soil layer, creating a distinct textural interface that increases the water-holding capacity of the fine-grained soil over that associated with unimpeded vertical drainage.	All contaminants	Technology is well established. Vegetative caps are simple to construct. Ratio of size to effective treatment depth is a key design/cost factor.	Same as cited above for asphalt/concrete caps.
	Subsurface barrier	Subsurface grout injection	Jet grouting	Jet grouting is the injection of a grout mixture at very high pressures and velocities into the pore space of the soil or rock through small orifices located in the drill pipe above the drill bit. The demonstration grouted around and beneath waste, not above to minimize infiltration.	All contaminants	Commercially available. Field-scale application is fully deployable and has been performed to depths of 91 m (300 ft). A full-scale demonstration using jet grouting was conducted by installing a double close-couple barrier around and beneath a buried tank in the 400 Area at the Hanford Site.	SAND97-1193, 1997, *Demonstration of Close-Coupled Barriers for Subsurface Containment of Buried Waste*, Sandia National Laboratories, Albuquerque, New Mexico.
			Permeation grouting	Permeation grouting is the injection of a liquid grout that fills the natural porosity of unsaturated soils and then gels to form a solid, void-filling material. Multiple types of grouting materials are available (e.g., silica, polymer, molten wax)	All contaminants	Commercially available. Field-scale application is fully deployable. Development conducted at Idaho National Laboratory for radiologically contaminated environments.	PNNL-20051, 2011, *Evaluation of In situ Grouting as a Potential Remediation Method for the Hanford Central Plateau Deep Vadose Zone*, Pacific Northwest National Laboratory, Richland, Washington.
		Subsurface soil freezing	Soil freezing	Frozen soil barriers (or cryogenic barriers) are constructed by freezing the soil pore water. The cited demonstration froze the soil around and beneath the waste.	All contaminants	Commercially available. Proven application for temporary containment for dewatering during construction. Could potentially be used as containment barrier for environmental remediation.	DOE/EM-0273, 1995, *Frozen Soil Barrier Technology, Innovative Technology Summary Report*. U.S. Department of Energy, Oak Ridge Operation. TEPCO, "Land-side Impermeable Wall (Frozen Soil Wall)" (website). Available at: http://www.tepco.co.jp/en/decommision/planaction/landwardwall/index-e.html (accessed 4/30/2018).
		Desiccation	Desiccation	Soil desiccation removes water from the vadose zone to create a horizontal capillary barrier to vertical water infiltration.	All except organics	Basic concepts are well proved. Results of a field demonstration of the technology are provided in the cited reference document.	PNNL-26902, 2018, *Deep Vadose Zone Treatability Test of Soil Desiccation for the Hanford Central Plateau: Final Report*, Pacific Northwest National Laboratory, Richland, Washington.

Table B-1. Deep Vadose Zone Remediation Technologies

General Response Actions	Technology Type	Technology Process Option	Technology Variant	Description	COIs Addressed	State of Development/Maturity	Applicable Reports and Studies
Removal	Deep excavation	Deep excavation without retaining walls	Deep excavation without retaining walls	Deep excavation using sloping, benching, dragline, or drilling and soil replacement. See Table 3-2 for detailed descriptions and the state of development of the specific deep excavation without retaining walls technology variants.	All contaminants	Commercially available, fully mature technologies. Full-scale implementation to over 24 m (80 ft) along the river corridor.	Appendix A in SGW-50712, 2011, *Excavation Depth Techniques Study*, Rev. 0, CH2M HILL Plateau Remediation Company, Richland, Washington. Doornbos, M. and J. Morse, 2012, "Remediation Technologies Screening Report for the Deep Vadose Zone, Hanford's Central Plateau," Paper #12414, WM2012 Conference, February 26-March 1, Phoenix, Arizona. Ouellette, G. and G. Greenberg, 2016, *Mining Engineering and Technology*, Academic Studio, New York. PNL-9335, 1994, *Review of Potential Subsurface Permeable Barrier Emplacement and Monitoring Technologies*, Pacific Northwest Laboratory, Richland, Washington.
		Deep excavation with retaining walls	Deep excavation with retaining walls	Deep excavation using sheet pile, soldier piling, lagging, diaphragm, soil nail, secant/tangent pile, reinforced concrete, and jet grout walls, and using tunneling. See Table 3-2 for detailed descriptions and the state of development of the specific deep excavation with retaining walls technology variants.	All contaminants	Commercially available, fully mature technologies.	Appendix A in SGW-50712, 2011, *Excavation Depth Techniques Study*, Rev. 0, CH2M HILL Plateau Remediation Company, Richland, Washington. Chowdhury, A.K., T.R. Stolzenburg, R.R. Stanforth, M.A. Warner, and M.E. LaRowe, 1996, "Underwater Treatment of Lead-Contaminated Sediment," *Remediation J.*, 6(2):15-21. Mair, R.J., 1998, "Recent Experiences of Tunneling and Deep Excavations in London," *International Conference on Case Histories in Geotechnical Engineering*, St. Louis, Missouri. Doornbos, M. and J. Morse, 2012, "Remediation Technologies Screening Report for the Deep Vadose Zone, Hanford's Central Plateau," Paper #12414, WM2012 Conference, February 26-March 1, Phoenix, Arizona.
	Contaminated water removal	Perched water removal	Perched water removal	Water that is perched within the vadose zone is pumped to the surface before it migrates to the regional water table.	All contaminants	Technology is well developed and in use. Most effective for mobile contaminants.	DOE/RL-2011-40, 2011, *Field Test Plan for the Perched Water Pumping/Pore Water Extraction Treatability Test*, Rev. 0, U.S. Department of Energy, Richland Operations Office, Richland, Washington; DOE/RL-2014-34, 2014, *Action Memorandum for 200-DV-1 Operable Unit Perched Water Pumping / Pore Water Extraction*, Rev. 0, U.S. Department of Energy, Richland Operations Office, Richland, Washington; and DOE/RL-2014-37, 2015, *Removal Action Work Plan for 200-DV-1 Operable Unit Perched Water Pumping / Pore Water Extraction*, Rev. 0, U.S. Department of Energy, Richland Operations Office, Richland, Washington. DOE/RL-2016-69, Rev. 0, *Calendar Year 2016 Annual Summary Report for the 200-ZP-1 and 200-UP-1 Operable Unit Pump-and-Treat Operations*, Rev. 0, U.S. Department of Energy, Richland Operations Office, Richland, Washington.
		Pore water extraction	Pore water extraction	Subsurface water within the unsaturated zone containing mobile contaminants is extracted using high vacuum to overcome capillary forces.	All contaminants	Has been evaluated in laboratory and modeling efforts and a WRPS field effort. Most effective for mobile contaminants.	PNNL-20507, 2011, *Pore-Water Extraction Intermediate-Scale Laboratory Experiments and Numerical Simulations*, Pacific Northwest National Laboratory, Richland, Washington. Truex, M.J. and M. Oostrom, 2014, "Technical Basis for Contaminated Pore-Water Extraction from the Vadose Zone," Paper #14052, WM2012 Conference, March 2-6, Phoenix, Arizona. PNNL-22662, 2013, *Field Test Design Simulations of Pore-Water Extraction for the SX Tank Farm*, Pacific Northwest National Laboratory, Richland, Washington. PNNL-21882, 2013, *Pore-Water Extraction Scale-Up Study for the SX Tank Farm*, Pacific Northwest National Laboratory, Richland, Washington. DOE/RL-2011-40, 2011, *Field Test Plan for the Perched Water Pumping/Pore Water Extraction Treatability Test*, Rev. 0, U.S. Department of Energy, Richland Operations Office, Richland, Washington; DOE/RL-2014-34, 2014, *Action Memorandum for 200-DV-1 Operable Unit Perched Water Pumping / Pore Water Extraction*, Rev. 0, U.S. Department of Energy, Richland Operations Office, Richland, Washington; and DOE/RL-2014-37, 2015, *Removal Action Work Plan for 200-DV-1 Operable Unit Perched Water Pumping / Pore Water Extraction*, Rev. 0, U.S. Department of Energy, Richland Operations Office, Richland, Washington.

Table B-1. Deep Vadose Zone Remediation Technologies

General Response Actions	Technology Type	Technology Process Option	Technology Variant	Description	COIs Addressed	State of Development/Maturity	Applicable Reports and Studies
		Soil wicking	Soil wicking	Placement of absorbents in well bores that wick contaminated pore water out of the subsurface.	All contaminants	Demonstrated in the laboratory. Most effective for mobile contaminants.	Oostrom, M., K.V. Smoot, T.W. Wietsma, M.J. Truex, M.D. Benecke, and G.B. Chronister, 2012, "Soil Moisture Wicking Using Super Absorbent Polymers: A Novel Method for Water and Contaminant Removal from the Vadose Zone," *Vadose Zone J.*, 11(4).
	Soil flushing and contaminant recovery	Soil flushing vadose zone with water/chemicals	Soil flushing vadose zone with water/chemicals	Mobilization of contaminants with water so they can be removed and treated or disposed.	Tc-99, Cr(VI), nitrate	Mature technology for shallow vadose zone. Most effective for mobile contaminants.	PNNL-19938, 2010, *Evaluation of Soil Flushing for Application to the Deep Vadose Zone in the Hanford Central Plateau*, Pacific Northwest National Laboratory, Richland, Washington. PNNL-20322, 2011, *100-NR-2 Apatite Treatability Test: Fall 2010 Tracer Infiltration Test*, Pacific Northwest National Laboratory, Richland, Washington. SGW-59614, 2016, *300-FF-5 Operable Unit Enhanced Attenuation Stage A Delivery Performance Report*, Rev. 0, CH2M HILL Plateau Remediation Company, Richland, Washington. DOE/RL-2017-30, 2018, *KW Soil Flushing/Infiltration Treatability Test Plan*, Rev. 0, U.S. Department of Energy, Richland Operations Office, Richland, Washington.
			Soil washing	Lixiviant/surfactant in an aquesous solution is applied to desorb contaminants from soil for transport to groundwater extraction wells.	U, I-129, Sr-90, C-14, CN, organics	Mature technology for shallow vadose zone. Most effective for mobile contaminants.	Same as cited above for soil flushing.
			In situ uranium recovery	In situ leaching, sometimes termed in situ recovery or "solution mining," consists of injecting a leaching solution into an ore zone, dissolving uranium, pumping the uranium-bearing solution out of the aquifer, and processing the solution to recover uranium.	U	This technology is currently being deployed in the uranium mining industry in the United States, Kazakhstan, and Australia under saturated conditions.	PNNL-19938, 2010, *Evaluation of Soil Flushing for Application to the Deep Vadose Zone in the Hanford Central Plateau*, Pacific Northwest National Laboratory, Richland, Washington. World Nuclear Association, 2017, "In Situ Leach Mining of Uranium" (website). Available at: http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/mining-of-uranium/in-situ-leach-mining-of-uranium.aspx (accessed 4/30/2018). U.S. Nuclear Regulatory Commission, 2016, "In Situ Recovery Facilities" (website). Available at: https://www.nrc.gov/materials/uranium-recovery/extraction-methods/isl-recovery-facilities.html (accessed 4/30/2018).
Ex situ treatment and disposal	Thermal treatment	Ex situ vitrification	Ex situ vitrification	Process that converts excavated soil and other materials into stable glass substances using high temperatures.	All contaminants	Commercially available. Uses furnaces that have evolved from the glass industry. Implementability is higher than for in situ application given use of proven technology.	WSRC-MS-95-0422P, 1998, *Waste Vitrification Projects Throughout the U.S. Initiated by SRS*, Westinghouse Savannah River Company, Aiken, South Carolina.
	Physical/ chemical treatment	Solidification/ stabilization	Solidification/ stabilization	Treatment process that eliminates or minimizes the mobility of inorganic and organic contaminants by physical or chemical retention.	U, Tc-99, Cr(VI), NO3, I-129, Sr-90, CN, C-14	Commercially available. Well established technology for shallow applications. Site-specific studies need to be completed to evaluate equipment required and appropriate binding agent.	EPA 542-F-12/019, 2012, *A Citizen's Guide to Solidification and Stabilization*, U.S. Environmental Protection Agency, Washington, D.C. Tajudin, S.A.A., M.A.M. Azmi, and A.T.A. Nabila, 2016, "Stabilization/Solidification Remediation Method for Contaminated Soil: A Review," *IOP Conference Series: Mater. Sci. Eng.*, 136:012043. Wiles, C.C., 1987, "A Review of Solidification/Stabilization Technology," *J. Haz. Mater*, 14(1):5-21. ITRC, 2012, "Solidification/Stabilization" (website). Available at: https://www.itrcweb.org/team/Public?teamID=15 (accessed 4/30/2018). FRTR, 2002, "Solidification/Stabilization" (website). Available at: https://frtr.gov/matrix2/section4/4-8.html (accessed 4/30/2018). CPEO, 2010, "Solidification/Stabilization Physical" (website). Available at: http://www.cpeo.org/techtree/ttdescript/solidsta.htm (accessed 4/30/2018).
		Contaminant separation	Soil washing	Water-based treatment technology for excavated soils that removes contaminants by dissolving or suspending the contaminants in the wash solution or by concentrating the soil particles by size.	U, Tc-99, Cr(VI), NO3, I-129, Sr-90, CN, C-14	Commercially available. Conventional aggregate washing and screening technology is used to separate soil particles. Mobile contaminants are captured in the wash water.	WHC-SD-EN-TI-268, 1994, *100 Area Soil Washing: Bench-Scale Tests on 116-F-4 Pluto Crib Soil*, Rev. 0, Westinghouse Hanford Company, Richland, Washington.

Table B-1. Deep Vadose Zone Remediation Technologies

General Response Actions	Technology Type	Technology Process Option	Technology Variant	Description	COIs Addressed	State of Development/Maturity	Applicable Reports and Studies
			Soil sorting/ screening	Clean soil is separated from contaminated soil based upon radioactive energy emissions from the soil.	U, Tc-99, I-129, Sr-90, C-14	Commercially available. Fully functional prototype has been developed and deployed. Sorting is being performed at the river corridor.	Patteson, R., D. Maynor, and C. Callan, 2000, *The Accelerated Site Technology Deployment Program Presents the Segmented Gate System*, WM2000 Conference, February 27-March 2, Tucson, Arizona.
			Molecular sieves	Industrial effluent and other aqueous waste streams are passed through molecular sieves, which function as an ion-exchange media. Sieves can be heated to create a stable disposal form.	Cr(VI), Sr-90	Laboratory-scale tests are being performed by Sandia National Laboratories.	Honeywell, 2016, "Cleaning Up At Fukushima: Honeywell Adsorbents are Making a Difference" (website). Available at: https://www.honeywell.com/newsroom/news/2016/05/cleaning-up-after-fukushima-honeywell-adsorbents-are-making-a-difference. Tranter, T.J., R.D. Tillotson, and T.A. Todd, 2006, "Laboratory-Scale Column Testing Using Crystalline Silicotitanate (IONSIV™ IE-911) for Removing Cesium from Acidic Tank Waste Simulant. 1: Cesium Exchange Capacity of a 15-cm^3 Column and Dynamic Stability of the Exchange Media," *Solvent Extr. Ion Exch.* 23(4):583-593. SAND2016-0521, 2016, *Evaluation of Strontium Selectivity by Sandia Octahedral Molecular Sieves (SOMS)*, Sandia National Laboratories, Albuquerque, New Mexico. Fletcher-Wood, R., 2014, *Zeolites and Other Molecular Sieves for Chromate Remediation*. Thesis, University of Birmingham, Birmingham, UK.
	Onsite	Backfill with treated soil	Backfill with treated soil	Excavation and ex situ treatment of soil followed by onsite disposal of the treated soil (backfill).	All contaminants	Fully mature technology.	No Hanford Site-specific reports.
		Onsite landfill	Onsite landfill	Disposal of excavated soil at onsite landfill (e.g., ERDF).	All contaminants	Fully mature technology.	ERDF-00011, 2016, *Environmental Restoration Disposal Facility Waste Acceptance Criteria, formerly WCH-191 Rev 4*, Rev. 0, CH2M HILL Plateau Remediation Company, Richland, Washington. *Resource Conservation and Recovery Act of 1976,* as amended, 42 USC 6901, et seq.
	Offsite	Offsite landfill/ repository	Offsite landfill/ repository	Disposal of excavated soil at offsite landfill. Required for wastes for which onsite disposal is not acceptable.	All contaminants	Fully mature technology.	No Hanford Site-specific reports.
	Contaminated water treatment	Ex situ treatment	Existing 200W P&T Facility	Existing treatment processes for radionuclides and chemical contaminants. Treatment of perched water.	U, Tc-99, Cr(VI), NO3	Currently in operation at full scale.	DOE/RL-2008-78, *200 West Area 200-ZP-1 Pump-and-Treat Remedial Design/Remedial Action Work Plan*, U.S. Department of Energy, Richland Operations Office, Richland, Washington.
			Alternative P&T system	Treatment processes for COI not included in the existing facility, as needed. Treatment of perched water.	I-129, Sr-90, CN, C-14, TCE, and MIBK	Mature technologies available, except for I-129. I-129 technologies are currently being evaluated as part of efforts for the 200-UP-1 Operable Unit.	DOE/RL-2015-69, Rev. 0, *UP-1 Evaluation Plan for Iodine*, U.S. Department of Energy, Richland Operations Office, Richland, Washington.
In Situ Treatment	Thermal treatment	In situ vitrification	In situ vitrification	Solidification process that uses high temperatures to melt and convert waste materials into glass crystalline products. Treatment of contaminated zone in unsaturated or saturated zone.	All contaminants	In situ vitrification has been the subject of several pilot studies to test its effectiveness.	RPP-ENV-34028, *Central Plateau Vadose Zone Remediation Technology Screening Evaluation*, CH2M HILL Plateau Remediation Company, Richland, Washington. PNL-8281, *In Situ Vitrification of a Mixed-Waste Contaminated Soil Site: The 116-B-6A Crib at Hanford*, Pacific Northwest Laboratory, Richland, Washington.
		Thermal water volatilization	Thermal water volatilization	In situ thermal treatment to volatilize water, with vapor extraction and aboveground condensation. Heat can be applied through multiple methods, including electrical resistance heating or conductance heating. This technology will remove volatile COIs if present, but the purpose is water removal. Treatment of perched water.	Perched-water removal	Commercially applied for numerous contaminants, properties of the technology are suitable to boil water.	EPA, 2018, "Thermal Treatment: In Situ" (website). Available at: https://clu-in.org/techfocus/default.focus/sec/Thermal_Treatment%3A_In_Situ/cat/Overview/ (accessed 4/30/2018). NAVFAC, "Heating In Situ" (website). Available at: https://www.navfac.navy.mil/navfac_worldwide/specialty_centers/exwc/products_and_services/ev/erb/tech/rem/heat-insitu.html (accessed 4/30/2018). EnviroWiki, 2018, "Thermal Remediation." (website). Available at: https://www.enviro.wiki/index.php?title=Thermal_Remediation.

Table B-1. Deep Vadose Zone Remediation Technologies

General Response Actions	Technology Type	Technology Process Option	Technology Variant	Description	COIs Addressed	State of Development/Maturity	Applicable Reports and Studies
		In situ thermal desorption/ destruction	In situ thermal desorption/ destruction	In situ thermal treatment that uses direct application of heat to increase the temperature of soil and destroy or volatilize organic compounds, with extraction in the vapor phase. Heat can be applied through multiple methods, including electrical resistance heating, conductance heating, hot air injection, or steam injection. Treatment of contaminated zone in unsaturated or saturated zone.	TCE, MIBK	Commercially applied for numerous contaminants.	DOE/RL-2007-28, *Feasibility Study Report for the 200-ZP-1 Groundwater Operable Unit*, U.S. Department of Energy, Richland Operations Office, Richland, Washington. ITRC, 1998, "Thermal Desorption Documents" (website). https://www.itrcweb.org/Guidance/ListDocuments?TopicID=45&SubTopicID=37 (accessed 4/30/2018). USACE, 2014, *Design: In Situ Thermal Remediation*. EM 200-1-21, U.S. Army Corps of Engineers, Washington, D.C. Same as cited above for thermal water volatilization.
	Physical treatment	Soil vapor extraction	Soil vapor extraction	Soil vapor extraction applies a vacuum to the soil to induce a controlled flow of air for the removal of volatile and some semivolatile contaminants from the soil. Heat can be applied to enhance extraction. Treatment of contaminated zone in unsaturated zone.	TCE, MIBK	Technology is proved for remediating soils contaminated by volatile organics.	SGW-51807, Rev. 0, *Performance Evaluation Report for Soil Vapor Extraction Operations at the 200-PW-1 Operable Unit Carbon Tetrachloride Site, Calendar Year 2011*, CH2M HILL Plateau Remediation Company, Richland, Washington. DOE/RL-2014-48, Rev. 0, *Response Action Report for the 200-PW-1 Operable Unit Soil Vapor Extraction Remediation*, U.S. Department of Energy, Richland Operations Office, Richland, Washington.
		Encapsulation	Permeation grouting	Permeation grouting is the injection of a liquid grout that fills the natural porosity of unsaturated soils and then gels to form a solid, void-filling material that encapsulates contaminants within the grouted zone. Multiple types of grouting materials are available (e.g., silica, polymer, molten wax). Treatment of contaminated zone in unsaturated or saturated zone.	All contaminants	Commercially available. Field-scale application is fully deployable. Development conducted at Idaho National Laboratory for radiologically contaminated environments.	PNNL-20051, *Evaluation of In situ Grouting as a Potential Remediation Method for the Hanford Central Plateau Deep Vadose Zone*, Pacific Northwest National Laboratory, Richland, Washington. PNNL-28054, *Evaluation of Perched Water Post-Extraction Remedy Technologies: Interim Status Report*, Pacific Northwest National Laboratory, Richland, Washington.
		Electrokinetic mobilization and recovery	Electrokinetic mobilization and recovery	Electrokinetic mobilization and recovery uses electrodes to create a low-voltage, direct-current electric field across contaminated soil to help mobilize contaminants (charged and polar species). Treatment of contaminated zone in unsaturated or saturated zone.	U, Tc-99, Cr(VI), NO3, I-129, Sr-90, CN	Method has been implemented in a limited number of shallow vadose zone contaminant areas. Most effective for mobile contaminants.	Reddy, K.R. and C. Cameselle, 2009, *Electrochemical Remediation Technologies for Polluted Soils, Sediments, and Groundwater*, John Wiley & Sons, Hoboken, New Jersey. Virkutyte, J., M. Sillanpää, and P. Latostenmaa, 2002, "Electrokinetic Soil Remediation—Critical Overview," *Sci. Total Environ.* 289:97-121. EPA, 2018, "Electrokinetics: Electric Current Technologies" (website). Available at: https://clu-in.org/techfocus/default.focus/sec/Electrokinetics%3A_Electric_Current_Technologies/cat/Overview/ (accessed 4/30/2018). NAVFAC, "Electrokinetic Extraction" (website). Available at: https://www.navfac.navy.mil/navfac_worldwide/specialty_centers/exwc/products_and_services/ev/erb/tech/rem/ekextract.html (accessed 4/30/2018). FRTR, 2002, "Electrokinetic Separation" (website). Available at: https://frtr.gov/matrix2/section4/4-4.html (accessed 4/30/2018). CPEO, 2010, "Electrokinetics" (website). Available at: http://www.cpeo.org/techtree/ttdescript/elctro.htm (accessed 4/30/2018).
	Chemical treatment, particulate and gas phase	Chemical oxidation, gas phase	Chemical oxidation, gas phase	Chemical oxidation uses oxidation reactions for chemical conversion of hazardous contaminants to nonhazardous or less toxic compounds that are more stable, less mobile, or inert. Oxidants include ozone. Treatment of contaminated zone in unsaturated zone.	TCE, MIBK, CN	Technology is proved for deployment in fairly homogeneous soils. Chemical oxidants can be delivered using soil mixing, horizontal injections wells, or vertical injection wells.	ITRC, 2005, *Technical and Regulatory Guidance for In Situ Chemical Oxidation of Contaminated Soil and Groundwater, Second Edition*, Interstate Technology & Regulatory Council, Washington, D.C.

Table B-1. Deep Vadose Zone Remediation Technologies

General Response Actions	Technology Type	Technology Process Option	Technology Variant	Description	COIs Addressed	State of Development/Maturity	Applicable Reports and Studies
		Particulate chemical reduction	Micron and nano-scale materials	Injected particles, such as zero valent iron (sometimes in combination with catalysts such as sulfur modified iron [SMI]), induce chemical and biological reactivity that can chemically reduce contaminants. Treatment of contaminated zone or PRB for unsaturated or saturated zones.	U, Tc-99, Cr(VI)	Field treatability testing of ZVI has been performed in saturated conditions at the Hanford Site. Commercially available for some applications. Some Hanford Site-specific laboratory testing has been conducted.	PNNL-28054, *Evaluation of Perched Water Post-Extraction Remedy Technologies: Interim Status Report*, Pacific Northwest National Laboratory, Richland, Washington. PNNL-26957, 2017, *Evaluation of Iodine Remediation Technologies in Subsurface Sediments: Interim Status Report*, Pacific Northwest National Laboratory, Richland, Washington. DOE/RL-2009-35, Rev. 1, *Treatability Test Report on Mending the In Situ Redox Manipulation Barrier Using Nano-Size Zero Valent Iron*, U.S. Department of Energy, Richland Operations Office, Richland, Washington.
		Gas-phase chemical reduction	Gas-phase chemical reduction	Gaseous reduction uses a gaseous reagent in the subsurface to reduce contaminants to a less mobile and/or less toxic form. H_2S and SO_2 are the primary gaseous reductants that have been evaluated. Treatment of contaminated zone in unsaturated zone or PRB application.	U, Tc-99, Cr(VI)	Field-scale demonstration of hexavalent chromium remediation in the vadose zone has been successful. Commercially applied for hexavalent chromium. Modeling evaluation conducted for remediation of uranium and Tc-99 in the Hanford Site vadose zone.	Hitchens, B.R., A.C. Bird, and K. Craig, 2016, "Full-Scale In Situ Gaseous Reduction of Hexavalent Chromium in Vadose Zone Soils with H_2S Gas," Geosyntec Consultants, Session D9, May 26, Tenth International Conference on Remediation of Chlorinated and Recalcitrant Compounds. DOE/EM-0521, *Innovative Technology Summary Report: In Situ Gaseous Reduction System*, U.S. Department of Energy, Office of Environmental Management, Washington, D.C. PNNL-12121, 1999, *In Situ Gaseous Reduction Pilot Demonstration - Final Report*, Pacific Northwest National Laboratory, Richland, Washington. Thornton, E.C., T.J. Gilmore, K.B. Olsen, J.T. Giblin, and J.M. Phelan, 2007, "Treatment of a Chromate-Contaminated Soil Site by In Situ Gaseous Reduction," *Ground Water Monitoring & Remediation* 27(1):56-64. Thornton, E.C., L. Zhong, M. Oostrom, and B. Deng, 2007, "Experimental and Theoretical Assessment of the Lifetime of a Gaseous-Reduced Vadose Zone Permeable Reactive Barrier," *Vadose Zone J.* 6(4):1050-1056. PNNL-18879, 2010, *Remediation of Uranium in the Hanford Vadose Zone Using Gas-Transported Reactants: Laboratory-Scale Experiments*, Pacific Northwest National Laboratory, Richland, Washington.
		Particulate chemical sequestration	Apatite particle injection	Phosphate sequestration is used to stabilize metals by chemically binding them into new stable phosphate mineral phases (e.g., apatite minerals) and other relatively insoluble phases in the soil. Solid-phase apatite can be injected to create a treatment zone or PRB in situ. Treatment of contaminated zone or PRB for unsaturated or saturated zones.	U, Sr-90, Tc-99, I-129	Field treatability testing of jet-injected apatite has been performed at the Hanford Site for Sr-90. Limited laboratory testing has been applied for other contaminants.	SGW-47062, 2010, *Treatability Test Report for Field-Scale Apatite Jet Injection Demonstration for the 100-NR-2 Operable Unit*, Rev. 0, CH2M HILL Plateau Remediation Company, Richland, Washington.
		Gas-phase chemical sequestration	Gaseous ammonia	An ammonia gas mixture is injected into the subsurface to increase the pH sufficiently to dissolve silica. During the subsequent decrease in pH, the aluminosilicates will precipitate and will coat or bind the mobile contaminants. Treatment of contaminated zone in unsaturated zone.	U, Cr(VI)	Laboratory treatability test conducted at the Hanford Site (sediment from 216-U-8 Crib).	PNNL-27773, *Deep Vadose Zone Treatability Test of Uranium Reactive Gas Sequestration for the Hanford Central Plateau: Final Report*, Pacific Northwest National Laboratory, Richland, Washington. PNNL-20004, 2010, *Remediation of Uranium in the Hanford Vadose Zone Using Ammonia Gas: FY 2010 Laboratory-Scale Experiments*, Pacific Northwest National Laboratory, Richland, Washington. DOE/RL-2010-87, 2015, *Field Test Plan for the Uranium Sequestration Pilot Test*, Rev. 0, U.S. Department of Energy, Richland Operations Office, Richland, Washington. Zhong L., J.E. Szecsody, M.J. Truex, and M.D. Williams, 2014, "Ammonia Gas Transport and Reactions in Unsaturated Sediments: Implications for Use as an Amendment to Immobilize Inorganic Contaminants," *J. Haz. Materials*, 289:118-129.

Table B-1. Deep Vadose Zone Remediation Technologies

General Response Actions	Technology Type	Technology Process Option	Technology Variant	Description	COIs Addressed	State of Development/Maturity	Applicable Reports and Studies
			CO_2	Injected CO_2 alters the carbonate system in the pore water, causing precipitation reactions that can bind contaminants and reduce their mobility. Treatment of contaminated zone in unsaturated zone.	U, Tc-99, Cr(VI), I-129, Sr-90, C-14	Laboratory tested for Hanford Site applications.	PNNL-18879, 2010, *Remediation of Uranium in the Hanford Vadose Zone Using Gas-Transported Reactants: Laboratory-Scale Experiments*, Pacific Northwest National Laboratory, Richland, Washington. PNNL-26957, 2017, *Evaluation of Iodine Remediation Technologies in Subsurface Sediments: Interim Status Report*, Pacific Northwest National Laboratory, Richland, Washington.
		Gas-phase combined chemical reduction and sequestration	Gas-phase reduction by H_2S or SO_2 and sequestration by ammonia, or CO_2	Use of a reductant and subsequent or in-parallel sequestration to induce reduced contaminant mobility. Treatment of contaminated zone in unsaturated zone.	U, Tc-99, Cr(VI)	Laboratory tested at the Hanford Site. Components have been individually tested from laboratory to field scale at Hanford and other sites.	Szecsody, J.E., L. Zhong, M.J. Truex, and N. Qafoku, 2015, "Remediation of Technetium in Vadose Zone Sediments Using Ammonia and Hydrogen Sulfide Gases," *Vadose Zone J.* 14(7):1-12.
		Gas-phase bioremediation	Aerobic bioremediation	Applying oxygen flow to the vadose zone to enhance aerobic bioremediation rates. Also referred to as bioventing. Treatment of contaminated zone in unsaturated zone.	MIBK	Field-tested and commercially applied at other sites for other contaminants. Laboratory tests showing aerobic MIBK degradation at other sites.	No Hanford Site-specific reports. EPA/540/R-95/534a, 1995, *Bioventing Principles and Practices, Volume I: Bioventing Principles*, U.S. Environmental Protection Agency, Washington, D.C. EPA, 2018, "Aerobic Bioremediation (Direct)" (website). Available at: https://clu-in.org/TechFocus/default.focus/sec/bioremediation/cat/Aerobic_Bioremediation_(Direct)/ (accessed 4/30/2018).
			Gas-phase in situ biological reduction	Addition of a gas-phase substrate (e.g., hydrogen) to induce in situ biological reductive metabolic processes that will result in a less mobile and/or less toxic form. Treatment of contaminated zone in unsaturated zone.	NO3, Cr(VI), CN, U, Tc-99, TCE	Scientific literature on vadose zone biological reduction applications is available for some contaminants.	PNNL-28055, *Central Plateau Remediation Alternatives: Interim Status Report*, Pacific Northwest National Laboratory, Richland, Washington. Höhener, P. and V. Ponsin, 2014, "In Situ Vadose Zone Bioremediation," *Current Opinion in Biotechnology* 27:1-7. Evans, P.J. and M.M. Trute, 2006, "In Situ Bioremediation of Nitrate and Perchlorate in Vadose Zone Soil for Groundwater Protection Using Gaseous Electron Donor Injection Technology," *Water Environment Research* 78(13):2436-2446. Brockman, F.J., W. Payne, D.J. Workman, A. Soong, S. Manley, and T.C. Hazen, 1995, "Effect of Gaseous Nitrogen and Phosphorus Injection on In Situ Bioremediation of a Trichloroethylene-contaminated Site," *J. Haz. Mater* 41(2-3):287-298.
		Gas-phase combined bioreduction and chemical sequestration	Gas-phase bioreduction and sequestration by ammonia or CO_2	Use of a reductant and subsequent or in parallel sequestration to induce reduced contaminant mobility. Treatment of contaminated zone in unsaturated zone.	U, Tc-99, Cr(VI), NO3	Laboratory tested at the Hanford Site. Components have been individually testing from laboratory to field scale at Hanford and other sites.	PNNL-28055, *Central Plateau Remediation Alternatives: Interim Status Report*, Pacific Northwest National Laboratory, Richland, Washington.
	Chemical treatment, liquid phase	Chemical oxidation, liquid phase	Chemical oxidation, liquid phase	Chemical oxidation uses reduction/oxidation reactions for chemical conversion of hazardous contaminants to nonhazardous or less toxic compounds that are more stable, less mobile, or inert. Oxidants include Fenton's reagent, ozone, hydrogen peroxide, permanganate, and others. Treatment of contaminated zone in saturated zone.	TCE, MIBK, CN	Technology is proved for shallow deployment in fairly homogeneous soils. Chemical oxidants can be delivered using soil mixing, horizontal injections wells, or vertical injection wells.	ITRC, 2005, *Technical and Regulatory Guidance for In Situ Chemical Oxidation of Contaminated Soil and Groundwater, Second Edition*, Interstate Technology & Regulatory Council, Washington, D.C. Siegrist, R.L., M. Crimi, and T.J. Simpkin, 2011, *In Situ Chemical Oxidation for Groundwater Remediation*, Springer-Verlag New York. EPA/600/R-06/072, 2007, *In-Situ Chemical Oxidation—Engineering Issue*, U.S. Environmental Protection Agency, Cincinnati, Ohio. Devi, P., U. Das, and A.K. Dalai, 2016, "In-situ Chemical Oxidation: Principle and Applications of Peroxide and Persulfate Treatments in Wastewater Systems," *Sci. Total Environ.* 571:643-657. Hesemann, J.R. and M. Hildebrandt, 2009, "Successful Unsaturated Zone Treatment of PCE with Sodium Permanganate," *Remediation J.* 19(2):37-48.

Table B-1. Deep Vadose Zone Remediation Technologies

General Response Actions	Technology Type	Technology Process Option	Technology Variant	Description	COIs Addressed	State of Development/Maturity	Applicable Reports and Studies
		Liquid-phase chemical reduction	Sodium dithionite	Sodium dithionite is injected into the subsurface for chemical reduction of contaminants into a less mobile and/or less toxic form. Treatment of perched water or water-table horizontal PRB.	U, Tc-99, Cr(VI)	Applied in the Hanford Site 100 Area for chromate contamination in groundwater.	PNNL-13349, 2000, *100-D Area in Situ Redox Treatability Test for Chromate-Contaminated Groundwater*, Pacific Northwest National Laboratory, Richland, Washington. DOE/RL-2008-10, 2007, *In Situ Redox Manipulation (ISRM) Annual Report Fiscal Year 2007*, Rev. 0, U.S. Department of Energy, Richland Operations Office, Richland, Washington.
			Sulfide salts and minerals	Calcium polysulfide is injected into the subsurface for chemical reduction of contaminants into a less mobile and/or less toxic form. Treatment of perched water.	U, Tc-99, Cr(VI)	Field deployment for hexavalent chromium remediation has taken place at several sites. Tested in the 100 Area for chromate contamination in Hanford Site groundwater.	PNNL-28054, *Evaluation of Perched Water Post-Extraction Remedy Technologies: Interim Status Report*, Pacific Northwest National Laboratory, Richland, Washington. DOE/RL-2006-17, 2006, *Treatability Test Report for Calcium Polysulfide in the 100-K Area*, Rev. 0, U.S. Department of Energy, Richland Operations Office, Richland, Washington. SGW-38255, 2008, *Chromium Treatment Technology Information Exchange for Remediation of Chromium in Groundwater at the Department of Energy Hanford Site*, Rev. 0, Fluor, Richland, Washington.
			Ferrous iron	Ferrous iron in aqueous solution is injected into the subsurface to reduce mobile contaminants such as hexavalent chromium and other contaminants to less mobile forms. Treatment of perched water.	U, Tc-99, Cr(VI)	Laboratory and field-tested for Cr(VI).	No Hanford Site-specific reports. PNNL-18114, 2008, *Remediation of Deep Vadose Zone Radionuclide and Metal Contamination: Status and Issues*, Pacific Northwest National Laboratory, Richland, Washington. Ludwig, R. D., C. M. Su, T. R. Lee, R. T. Wilkin, S. D. Acree, R. R. Ross, and A. Keeley, 2007, "In Situ Chemical Reduction of Cr(VI) in Groundwater Using a Combination of Ferrous Sulfate and Sodium Dithionite: A Field Investigation," *Environ. Sci. Technol.* 41(15):5299-5305.
		Liquid-phase chemical sequestration	Phosphate sequestration (e.g., apatite)	Phosphate sequestration is used to stabilize metals by chemically binding them into new stable phosphate mineral phases (e.g., apatite minerals) and other relatively insoluble phases in the soil. Liquid reagents can be injected to form apatite in situ. Treatment of perched water or water-table horizontal PRB.	U, Sr-90, Tc-99, I-129	Applied at the Hanford Site for Sr-90 and uranium contamination in the groundwater and shallow vadose zone.	PNNL-28054, *Evaluation of Perched Water Post-Extraction Remedy Technologies: Interim Status Report*, Pacific Northwest National Laboratory, Richland, Washington. SGW-59614, 2016, *300-FF-5 Operable Unit Enhanced Attenuation Stage A Delivery Performance Report*, Rev. 0, CH2M HILL Plateau Remediation Company, Richland, Washington. DOE/RL-2016-68, 2017, *Calendar Year 2016 Annual Summary Report for the 100-HR-3 and 100-KR-4 Pump and Treat Operations, and 100-NR-2 Groundwater Remediation*, Rev. 0, U.S. Department of Energy, Richland Operations Office, Richland, Washington. SGW-56970, 2015, *Performance Report for the 2011 Apatite Permeable Reactive Barrier Extension for the 100-NR-2 Operable Unit*, Rev. 0, CH2M HILL Plateau Remediation Company, Richland, Washington.
			Carbonate sequestration	Carbonate sequestration is used to stabilize contaminants by substituting the metals into the carbonate mineral phases to reduce their mobility. Liquid reagents can be injected to form carbonates in situ. Treatment of perched water.	U, Tc-99, Cr(VI), I-129, Sr-90, C-14	Substitution of strontium, uranium, and chromium into carbonates has been demonstrated in the laboratory and observed in contaminated-site sediments, but the approach has not yet been developed into a field-scale remediation technology.	PNNL-28054, *Evaluation of Perched Water Post-Extraction Remedy Technologies: Interim Status Report*, Pacific Northwest National Laboratory, Richland, Washington. PNNL-26934, 2017, *Identification of Promising Remediation Technologies for Iodine in the UP-1 Operable Unit*, Pacific Northwest National Laboratory, Richland, Washington. PNNL-26957, 2017, *Evaluation of Iodine Remediation Technologies in Subsurface Sediments: Interim Status Report*, Pacific Northwest National Laboratory, Richland, Washington. PNNL-18114, 2008, *Remediation of Deep Vadose Zone Radionuclide and Metal Contamination: Status and Issues*, Pacific Northwest National Laboratory, Richland, Washington.

Table B-1. Deep Vadose Zone Remediation Technologies

General Response Actions	Technology Type	Technology Process Option	Technology Variant	Description	COIs Addressed	State of Development/Maturity	Applicable Reports and Studies
			Alkaline sequestration	High pH solutions introduced to the vadose zone are buffered by dissolving sediment silicates and other mineral phases. When the constituents re-precipitate, contaminants can be bound into the solid phase, becoming sequestered and reducing their mobility. Treatment of perched water.	U, Cr(VI)	Laboratory tested for Hanford Site applications.	PNNL-18879, 2010, *Remediation of Uranium in the Hanford Vadose Zone Using Gas-Transported Reactants: Laboratory-Scale Experiments*, Pacific Northwest National Laboratory, Richland, Washington.
			Iron oxide sequestration	Iron oxide can adsorb, and incorporate, some contaminants during precipitation. Liquid reagents can be injected to form iron oxides in situ. Treatment of perched water.	U, I-129	Laboratory tested for Hanford Site applications.	PNNL-26957, 2017, *Evaluation of Iodine Remediation Technologies in Subsurface Sediments: Interim Status Report*, Pacific Northwest National Laboratory, Richland, Washington. PNNL-28064, *Evaluation of Remediation Technologies for Iodine-129: FY18 Bench Scale Results*, Pacific Northwest National Laboratory, Richland, Washington.
		Liquid or particulate phase combined chemical reduction and sequestration	Liquid phase reduction by dithionite, calcium poly-sulfide, or ferrous iron and sequestration by phosphate, bases, carbonate, iron oxide, or silica	Use of a reductant and subsequent or in-parallel sequestration to induce reduced contaminant mobility. Treatment of perched water.	U, Tc-99, Cr(VI), Sr-90	Laboratory tested at the Hanford Site. Components have been individually tested from laboratory to field scale at Hanford and other sites.	PNNL-28054, *Evaluation of Perched Water Post-Extraction Remedy Technologies: Interim Status Report*, Pacific Northwest National Laboratory, Richland, Washington.
			Particulate or liquid-phase reduction by ZVI or SMI and sequestration by phosphate, bases, carbonate, iron oxide, or silica	Use of a reductant and subsequent or in-parallel sequestration to induce reduced contaminant mobility. Treatment of perched water.	U, Tc-99 Cr(VI), Sr-90	Laboratory tested at the Hanford Site. Components have been individually tested from laboratory to field scale at Hanford and other sites.	PNNL-28054, *Evaluation of Perched Water Post-Extraction Remedy Technologies: Interim Status Report*, Pacific Northwest National Laboratory, Richland, Washington.
	Biological treatment, liquid phase	Liquid-phase bioremediation	Long-duration substrate for reductive bioremediation	Addition of a liquid-phase substrate (vegetable oil or slow-release compounds) to induce in situ biological reductive metabolic processes that will result in a less mobile and/or less toxic form. Treatment of perched water or water-table horizontal PRB.	NO3, Cr(VI), CN, U, Tc-99	Commercially available for uranium, hexavalent chromium, and nitrate in saturated zones. Field-tested for Cr(VI) in 100 Area Hanford Site groundwater. Scientific literature on vadose zone biological reduction applications for some contaminants using aqueous-phase amendments.	PNNL-18784, 2009, *Hanford 100-D Area Biostimulation Treatability Test Results*, Pacific Northwest National Laboratory, Richland, Washington. Faybishenko B., T.C. Hazen, P.E. Long, E.L. Brodie, M.E. Conrad, et al., 2008, "In Situ Long-Term Reductive Bioimmobilization of Cr(VI) in Groundwater Using Hydrogen Release Compound," *Environ. Sci. Technol.* 42:8478-8485. AFCEE, 2007, *Protocol for In Situ Bioremediation of Chlorinated Solvents Using Edible Oil*. Air Force Center for Engineering and the Environment, Brooks AFB, San Antonio, Texas.
			Short-duration substrate for reductive bioremediation	Addition of a liquid-phase substrate (organic acids or sugars) to induce in situ biological reductive metabolic processes that will result in a less mobile and/or less toxic form. Treatment of perched water.	NO3, Cr(VI), CN, U, Tc-99	Commercially available for uranium, hexavalent chromium, and nitrate in saturated zones. Field-tested for Cr(VI) in 100 Area Hanford Site groundwater. Scientific literature on vadose zone biological reduction applications for some contaminants using aqueous-phase amendments.	PNNL-18784, 2009, *Hanford 100-D Area Biostimulation Treatability Test Results*, Pacific Northwest National Laboratory, Richland, Washington. Faybishenko B., T.C. Hazen, P.E. Long, E.L. Brodie, M.E. Conrad, et al., 2008, "In Situ Long-Term Reductive Bioimmobilization of Cr(VI) in Groundwater Using Hydrogen Release Compound," *Environ. Sci. Technol.* 42:8478-8485.

Table B-1. Deep Vadose Zone Remediation Technologies

General Response Actions	Technology Type	Technology Process Option	Technology Variant	Description	COIs Addressed	State of Development/Maturity	Applicable Reports and Studies
			Combined chemical/ biological reduction	Chemical reductant (e.g., calcium polysulfide, hydrogen sulfide gas, ferrous sulfate, or zero-valent iron) and biological carbon source (molasses, sodium lactate, or emulsified oil) are applied in combinations to the treat contaminants within the vadose zone. Treatment of perched water or water-table horizontal PRB.	NO3, Cr(VI), CN, U, Tc-99	Has been conceptually described for application at the Hanford Site (DOE/RL-2010-96). Commercially available for groundwater (e.g., ZVI) and other contaminants (chlorinated solvents/DNAPLs).	DOE/RL-2010-96, *Remedial Investigation/Feasibility Study for the 100-BC-1, 100-BC-2, and 100-BC-5 Operable Units,* Draft A, U.S. Department of Energy, Richland Operations Office, Richland, WA. Krug, T., S. O'Hara, M. Watling, and J. Quinn, 2010, "Emulsified Zero-Valent Nano-Scale Iron Treatment of Chlorinated Solvent DNAPL Source Areas," ER-200431, Environmental Security Technology Certification Program, Alexandria, Virginia. Quinn, J., C. Geiger, C. Clausen, K. Brooks, C. Coon, S. O'Hara, T. Krug, D. Major, W.S. Yoon, A. Gavaskar, T. Holdsworth, 2005, "Field Demonstration of DNAPL Dehalogenation Using Emulsified Zero-Valent Iron," *Environ. Sci. Technol.* 39(5):1309-1318.
		Microbial facilitated volatilization in the vadose zone	Microbial facilitated volatilization in the vadose zone	Stimulation of microbes to promote iodine methylation, plus SVE capture of the volatile methyl iodide. Treatment of perched water.	I-129	Literature is available showing a basis for the conceptual remediation technology.	No Hanford Site-specific reports for remediation. Described in Hanford Site-specific reports PNNL-24709, Rev. 2, *Conceptual Model of Iodine Behavior in the Subsurface at the Hanford Site*, Pacific Northwest National Laboratory, Richland, Washington; PNNL-26934, *Identification of Promising Remediation Technologies for Iodine in the UP-1 Operable Unit*, Pacific Northwest National Laboratory, Richland, Washington; and PNNL-28053, *Conceptual Model of Subsurface Processes for Iodine at the Hanford Site*, Pacific Northwest National Laboratory, Richland, Washington.
		Liquid-phase combined bioreduction and chemical sequestration	Reduction by bioremediation and sequestration by phosphate, bases, carbonate, iron oxide, or silica	Use of a reductant and subsequent or in parallel sequestration to induce reduced contaminant mobility. Treatment of perched water.	U, Tc-99 Cr(VI), Sr-90	Laboratory tested at the Hanford Site. Components have been individually testing from laboratory to field scale at Hanford and other sites.	PNNL-28054, *Evaluation of Perched Water Post-Extraction Remedy Technologies: Interim Status Report*, Pacific Northwest National Laboratory, Richland, Washington.
	Monitored natural attenuation	Monitored natural attenuation	Monitored natural attenuation	Monitored natural attenuation relies on natural processes to achieve remediation objectives within a designated time frame and uses monitoring to track progress and ensure that contamination does not spread or increase.	All contaminants	Mature technology.	Hanford Site applications for groundwater and ongoing efforts for vadose zone operable units. EPA, 1999, "Use of Monitored Natural Attenuation at Superfund, RCRA Corrective Action, and Underground Storage Tank Sites" (memorandum), OSWER Directive 9200.4-17P, U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Washington, D.C., April 21.

COI = contaminant of interest
DNAPLS = dense nonaqueous-phase liquid
ERDF = Environmental Restoration Disposal Facility
PNNL = Pacific Northwest National Laboratory
PRB = permeable reactive barrier
P&T = pump and treat
SMI = sulfur modified iron
SVE = soil vapor extraction
WRPS = Washington River Protection Solutions
ZVI = zero valent iron

Table B-2. Deep Vadose Zone Access and Delivery Technologies

Technology Type	Technology Process Option	Technology Variant	Description	COIs Addressed	State of Development/Maturity	Applicable Reports and Studies
Access method	Boreholes and wells	Vertical boreholes/wells	Vertical borings and wells are used to extract soil vapor or groundwater from the subsurface or to inject water, chemical reagents, gases, particulates, or biological substrates into the subsurface to address contaminated regions.	Reactant/ contaminant dependent	Commercially available. Technology is well proved. Injection in unsaturated conditions can be more challenging compared with saturated conditions. Gravelly and cobbly lithologies make distribution of injection amendments challenging, although injection effectiveness is a function of the nature of the fluid (i.e., liquid, foam, or gas).	Multiple Hanford Site applications.
		Angle borings	Angled borings and wells are used to extract soil vapor or groundwater from the subsurface or to inject water, chemical reagents, gases, particulates, or biological substrates into the subsurface to address contaminated regions. Angled borings facilitate subsurface access in situations where conditions such as surface obstructions or shallow vadose zone contamination constrain ability to use vertical borings.	Reactant/ contaminant dependent	Commercially available. Technology is well proved. Injection in unsaturated conditions can be more challenging compared with saturated conditions. Gravelly and cobbly lithologies make distribution of injection amendments challenging, although injection effectiveness is a function of the nature of the fluid (i.e., liquid, foam, or gas).	BHI-00105, 1995, *FY 1993 Wellfield Enhancement Status Report and Data Package for the 200 West Area Carbon Tetrachloride Expedited Response Action*, Rev. 00, Bechtel Hanford, Inc., Richland, Washington. WMP-30566, 2007, *Borehole Summary Report for Slant Well 299-W15-48 (Borehole C3427) Drilled at the 216-Z-9 Trench*, Rev. 0, Fluor, Richland, Washington.
		Horizontal wells	Horizontal wells are typically directionally drilled and can be used to extract soil vapor or groundwater from the subsurface or to inject water, chemical reagents, gases, particulates, or biological substrates into the subsurface to address contaminated regions.	Reactant/ contaminant dependent	Commercially available. Technology is well proved at shallow depths and for certain geological conditions. Implementation is challenging in gravelly and cobbly lithologies. Pilot testing at moderate depths (23 m [75 ft]) in the 100-D Area has encountered significant challenges in strata containing cobbles.	SGW-45974, 2010, *Treatability Demonstration Report for Directional Drilling in the 100-D Area*, Rev. 0, CH2M HILL Plateau Remediation Company, Richland, Washington.
	Deep excavation without retaining walls	Deep soil/auger mixing	Deep soil mixing uses large-diameter augers, or horizontally rotating mechanical or hydraulic mixing tools, to blend in reactants and homogenize soil.	Reactant/ contaminant dependent	Commercially available. Technology is proved for shallow deployment in fairly homogeneous soils. May be effective in combination with other technologies (e.g., excavation). Although deep soil mixing has been performed to depths of 30 m (100 ft), most field applications have been limited to approximately 15 m (50 ft). Implementation is challenging in gravelly and cobbly lithologies.	Appendix A in SGW-50712, 2011, *Excavation Depth Techniques Study*, Rev. 0, CH2M HILL Plateau Remediation Company, Richland, Washington.
		Deep excavation using drilling and soil replacement	Drilling and soil replacement involves constructing hollow spaces using drilling techniques and then replacing the existing soil with fill materials.	All contaminants	Commercially available. Drilling and soil replacement is a standard technique used in the construction industry throughout the world. Large-diameter borings have been drilled to over 61 m (200 ft) at sites that included large cobbles.	Appendix A in SGW-50712, 2011, *Excavation Depth Techniques Study*, Rev. 0, CH2M HILL Plateau Remediation Company, Richland, Washington.
		Deep excavation with sloping and/or benching (open-pit excavation)	Sloping and benching support systems cut back the excavation walls an angle designed to maintain the stability of the sidewalls.	All contaminants	Commercially available. Excavation with sloping and/or benching is a fully mature technology. Significant laybacks or a combination of innovative and mature technologies are required for deep excavations. Full-scale implementation to over 24 m (80 ft) has taken place along the river corridor.	Appendix A in SGW-50712, 2011, *Excavation Depth Techniques Study*, Rev. 0, CH2M HILL Plateau Remediation Company, Richland, Washington.
		Deep excavation using dragline excavators	Dragline excavators use large buckets and cables to move large volumes of loose material. Used as a primary excavating method in many surface mining operations.	All contaminants	Commercially available. Fully mature technology in the construction industry. May require detailed evaluation of applicability at each specific waste site.	Doornbos, M. and J. Morse, 2012, "Remediation Technologies Screening Report for the Deep Vadose Zone, Hanford's Central Plateau," Paper #12414, WM2012 Conference, February 26-March 1, Phoenix, Arizona. Ouellette, G. and G. Greenberg, 2016, *Mining Engineering and Technology*, Academic Studio, New York. PNL-9335, 1994, *Review of Potential Subsurface Permeable Barrier Emplacement and Monitoring Technologies*, Pacific Northwest National Laboratory, Richland, Washington.
	Deep excavation with retaining walls	Deep excavation using sheet piling or sheet pile walls	Sheet pile walls are thin interlocking steel sections that are driven into soil by hammering or vibrating to provide side-slope stability.	All contaminants	Commercially available. Fully mature technology in the construction industry. May require detailed evaluation of applicability at each specific waste site. Difficult to drive deeply in soils with large cobbles.	Appendix A in SGW-50712, 2011, *Excavation Depth Techniques Study*, Rev. 0, CH2M HILL Plateau Remediation Company, Richland, Washington.

Table B-2. Deep Vadose Zone Access and Delivery Technologies

Technology Type	Technology Process Option	Technology Variant	Description	COIs Addressed	State of Development/Maturity	Applicable Reports and Studies
		Deep excavation using soldier pile and lagging wall	Soldier piles are steel "H"- or "I"-shaped piles that are driven into the ground to support lagging walls for side-slope stability.	All contaminants	Commercially available. Fully mature technology in the construction industry. May require detailed evaluation of applicability at each specific waste site.	Appendix A in SGW-50712, 2011, *Excavation Depth Techniques Study*, Rev. 0, CH2M HILL Plateau Remediation Company, Richland, Washington.
		Deep excavation using diaphragm walls	Diaphragm walls are underground structures formed by filling trenches with slurry that solidifies to provide side-slope stability.	All contaminants	Commercially available. Fully mature technology in the construction industry. May require detailed evaluation of applicability at each specific waste site.	Appendix A in SGW-50712, 2011, *Excavation Depth Techniques Study*, Rev. 0, CH2M HILL Plateau Remediation Company, Richland, Washington.
		Deep excavation using soil nail walls	Soil nail walls use steel bars, wire mesh, and concrete installed in the side of the excavation to provide side-slope stability.	All contaminants	Commercially available. Fully mature technology in the construction industry. May require detailed evaluation of applicability at each specific waste site.	Appendix A in SGW-50712, 2011, *Excavation Depth Techniques Study*, Rev. 0, CH2M HILL Plateau Remediation Company, Richland, Washington.
		Deep excavation using secant/ tangent pile wall	Secant/tangent pile walls are formed by drilling boreholes and constructing overlapping, reinforced concrete piles to provide side-slope stability. Tangent pile walls are a variation of secant pile walls but with no overlap of the piles.	All contaminants	Commercially available. Fully mature technology in the construction industry. May require detailed evaluation of applicability at each specific waste site.	Appendix A in SGW-50712, 2011, *Excavation Depth Techniques Study*, Rev. 0, CH2M HILL Plateau Remediation Company, Richland, Washington.
		Deep excavation using caissons	A caisson is an open-ended concrete cylinder that is lowered into position during excavation to provide side-slope stability.	All contaminants	Commercially available. Fully mature technology in the construction industry. May require detailed evaluation of applicability at each specific waste site.	Appendix A in SGW-50712, 2011, *Excavation Depth Techniques Study*, Rev. 0, CH2M HILL Plateau Remediation Company, Richland, Washington.
		Deep excavation using jet grout walls	Jet grout walls are retaining walls that are constructed by emplacing single to triple rows of jet grout columns or deep mixed columns to provide side-slope stability.	All contaminants	Commercially available. Fully mature technology in the construction industry. May require detailed evaluation of applicability at each specific waste site.	Appendix A in SGW-50712, 2011, *Excavation Depth Techniques Study*, Rev. 0, CH2M HILL Plateau Remediation Company, Richland, Washington.
		Deep excavation using deep mixed walls	Deep mixed walls are constructed by mixing in situ soils with cement to increase strength, control deformation, and reduce permeability of unconsolidated sediments.	All contaminants	Commercially available. Fully mature technology in the construction industry. May require detailed evaluation of applicability at each specific waste site.	Appendix A in SGW-50712, 2011, *Excavation Depth Techniques Study*, Rev. 0, CH2M HILL Plateau Remediation Company, Richland, Washington.
		Deep excavation using reinforced concrete walls	Reinforced concrete walls are staged excavation walls that are usually supported by ground anchors to provide side-slope stability.	All contaminants	Commercially available. Fully mature technology in the construction industry. May require detailed evaluation of applicability at each specific waste site.	Appendix A in SGW-50712, 2011, *Excavation Depth Techniques Study*, Rev. 0, CH2M HILL Plateau Remediation Company, Richland, Washington.
		Deep excavation using cofferdams	Cofferdams are temporary earth-retaining structures to enable excavation during construction activities, typically used near water bodies.	All contaminants	Commercially available. Fully mature technology in the construction industry. May require detailed evaluation of applicability at each specific waste site. Technology is not likely to be applicable to the Central Plateau.	Chowdhury, A.K., T.R. Stolzenburg, R.R. Stanforth, M.A. Warner, and M.E. LaRowe, 1996, "Underwater Treatment of Lead-Contaminated Sediment," *Remediation J.* 6(2):15-21.
		Deep excavation using tunneling	Tunneling is a completely enclosed excavation with opening for egress.	All contaminants	Commercially available. Fully mature technology in the construction industry. May require detailed evaluation of applicability at each specific waste site.	Mair, R.J., 1998, "Recent Experiences of Tunneling and Deep Excavations in London," International Conference on Case Histories in Geotechnical Engineering. 9. Doornbos, M. and J. Morse, 2012, "Remediation Technologies Screening Report for the Deep Vadose Zone, Hanford's Central Plateau," Paper #12414, WM2012 Conference, February 26-March 1, Phoenix, Arizona.
Delivery methods	Reagent delivery method	Jet injection	Jet injection is the injection of a reagent at very high pressures and velocities into the pore space of the soil or rock through small orifices located in the drill pipe above the drill bit.	Reactant/ contaminant dependent	Commercially available. Field-scale application is fully deployable and has been performed to depths of 91 m (300 ft). A full-scale demonstration using jet grouting was conducted by installing a closed-couple barrier around and beneath a buried tank in the 400 Area at the Hanford Site. The close-coupled barrier is produced by installing a cement grout curtain followed by a thin inner lining of polymer grout. The radius of influence may be limited in soils with lower permeability. May require evaluation of impacts on the vadose zone surrounding the targeted area.	SAND97-1193, 1997, *Demonstration of Close-Coupled Barriers for Subsurface Containment of Buried Waste*, Sandia National Laboratories, Albuquerque, New Mexico. 100-NR-2 apatite jet grouting, SGW-56970, 2015, *Performance Report for the 2011 Apatite Permeable Reactive Barrier Extension for the 100-NR-2 Operable Unit*, Rev. 0, CH2M HILL Plateau Remediation Company, Richland, Washington.

Table B-2. Deep Vadose Zone Access and Delivery Technologies

Technology Type	Technology Process Option	Technology Variant	Description	COIs Addressed	State of Development/Maturity	Applicable Reports and Studies
		Surface infiltration	Surface infiltration uses drip irrigation, trenches, and shallow basin systems to apply reagent to the ground surface for infiltration into the underlying vadose zone.	Reactant/ contaminant dependent	Tested and applied in the Hanford Site 300 Area.	PNNL-19938, 2010, *Evaluation of Soil Flushing for Application to the Deep Vadose Zone in the Hanford Central Plateau*, Pacific Northwest National Laboratory, Richland, Washington. SGW-59614, 2016, *300-FF-5 Operable Unit Enhanced Attenuation Stage A Delivery Performance Report*, Rev. 0, CH2M HILL Plateau Remediation Company, Richland, Washington.
		Electrokinetic mobilization and recovery	Electrokinetic mobilization and recovery uses electrodes to create a low-voltage, direct-current electric field across contaminated soil to distribute charged/polar reagents.	Reactant/ contaminant dependent	Method has been implemented in selected shallow vadose zone contaminant areas.	Reddy, K.R. and C. Cameselle, 2009, *Electrochemical Remediation Technologies for Polluted Soils, Sediments, and Groundwater*, John Wiley & Sons, Hoboken, New Jersey. Virkutyte, J., M. Sillanpää, and P. Latostenmaa, 2002, "Electrokinetic Soil Remediation—Critical Overview," *Sci. Total Environ*. 289:97-121. EPA, 2018, "Electrokinetics: Electric Current Technologies" (website). Available at: https://clu-in.org/techfocus/default.focus/sec/Electrokinetics%3A_Electric_Current_Technologies/cat/Overview/ (accessed 4/30/2018). NAVFAC, "Electrokinetic Extraction" (website). Available at: https://www.navfac.navy.mil/navfac_worldwide/specialty_centers/exwc/products_and_services/ev/erb/tech/rem/ekextract.html (accessed 4/30/2018). FRTR, 2002, "Electrokinetic Separation" (website). Available at: https://frtr.gov/matrix2/section4/4-4.html (accessed 4/30/2018). CPEO, 2010, "Electrokinetics" (website). Available at: http://www.cpeo.org/techtree/ttdescript/elctro.htm (accessed 4/30/2018).
		Electrokinetic delivery of treatment chemicals	Electrodes are used to create a low-voltage, direct-current electric field across contaminated soil to cause chemical amendments (supplied via wells/electrode penetrations) to migrate to target areas. Moves liquid amendments in saturated or unsaturated conditions to achieve volumetric application.	Reactant/ contaminant dependent	Field-tested at other sites.	No Hanford Site-specific reports. PNNL-18114, 2008, *Remediation of Deep Vadose Zone Radionuclide and Metal Contamination: Status and Issues*, Pacific Northwest National Laboratory, Richland, Washington. Gill, R.T., M.J. Harbottle, J.W.N. Smith, and S.F. Thornton, 2014, "Electrokinetic-enhanced Bioremediation of Organic Contaminants: A Review of Processes and Environmental Applications," *Chemosphere* 107:31-42.
	Reagent media	Liquid-phase delivery	Liquid-phase delivery is defined here as using vertical, angled, or horizontal injection wells to introduce aqueous reagents into the subsurface to treat contaminants within the underlying vadose zone.	Reactant/ contaminant dependent	Liquid-phase delivery is a mature technology with numerous proven applications.	Multiple Hanford Site applications.
		Gas-phase delivery	Gas-phase delivery uses vertical or horizontal injection wells and extraction wells to introduce and draw gaseous chemical reagents through the vadose zone.	Reactant/ contaminant dependent	Field treatability tests and laboratory studies have been conducted at the Hanford Site. Laboratory and field tests are also available in the scientific literature (e.g., ESTCP).	PNNL-26902, 2018, *Deep Vadose Zone Treatability Test of Soil Desiccation for the Hanford Central Plateau: Final Report*, Pacific Northwest National Laboratory, Richland, Washington. DOE/RL-2010-87, 2015, *Field Test Plan for the Uranium Sequestration Pilot Test*, Rev. 0, U.S. Department of Energy, Richland Operations Office, Richland, Washington. PNNL-20004, 2010, *Remediation of Uranium in the Hanford Vadose Zone Using Ammonia Gas: FY10 Laboratory-Scale Experiments*, Pacific Northwest National Laboratory, Richland, Washington.
		Particulate-phase delivery	Particulate-phase delivery uses vertical, angled, or horizontal injection wells to introduce particulate reagents (e.g., ZVI) into the subsurface for vadose zone or saturated zone treatment.	Reactant/ contaminant dependent	Field treatability testing of ZVI has been performed in saturated conditions at the Hanford Site. Commercially available for some applications. Some Hanford Site-specific laboratory testing has been conducted.	PNNL-26957, 2017, *Evaluation of Iodine Remediation Technologies in Subsurface Sediments: Interim Status Report*, Pacific Northwest National Laboratory, Richland, Washington. DOE/RL-2009-35, 2011, *Treatability Test Report on Mending the In Situ Redox Manipulation Barrier Using Nano-Size Zero Valent Iron*, Rev. 1, U.S. Department of Energy, Richland Operations Office, Richland, Washington. 100-NR-2 apatite jet grouting, SGW-56970, 2015, *Performance Report for the 2011 Apatite Permeable Reactive Barrier Extension for the 100-NR-2 Operable Unit*, Rev. 0, CH2M HILL Plateau Remediation Company, Richland, Washington.

Table B-2. Deep Vadose Zone Access and Delivery Technologies

Technology Type	Technology Process Option	Technology Variant	Description	COIs Addressed	State of Development/Maturity	Applicable Reports and Studies
		Oil-phase delivery	Use of LNAPL as a substrate (e.g., vegetable oil) or carrier to deliver other amendments miscible in the oil.	Reactant/ contaminant dependent	Laboratory and field tested/deployed as a bioremediation substrate.	SRNL-STI-2012-00290, 2012, *Treatability Study for Edible Oil Deployment for Enhanced cVOC Attenuation for T-Area, Savannah River Site*, Rev. 0, Savannah River National Laboratory, Aiken, South Carolina. No Hanford Site-specific reports.
		Shear thinning fluid injection	A shear thinning fluid, which decreases in viscosity with increasing shear stress, will enhance the uniformity of amendment distribution in the vadose zone.	Reactant/ contaminant dependent	Tested by ESTCP and used commercially for groundwater and fracture emplacement methods.	Truex, M.J., V.R. Vermeul, D.P. Mendoza, B.G. Fritz, R.D. Mackley, M. Oostrom, T.W. Wietsma, and T.W. Macbeth, 2011, "Injection of Zero Valent Iron into an Unconfined Aquifer Using Shear-Thinning Fluids," *Ground Water Monitoring and Remediation* 31(1):50-58. Oostrom, M., M.J. Truex, V.R. Vermeul, L. Zhong, G.D. Tartakovsky, and T.W. Wietsma, 2014, "Remedial amendment delivery near the water table using shear thinning fluids: Experiments and numerical simulations," *Environmental Processes* 1(4):1-21 Zhong, L., J.E. Szecsody, M. Oostrom, M.J. Truex, X. Shen, X. Li, 2011, "Enhanced remedial amendment delivery to subsurface using shear thinning fluid and aqueous foam," *J. Hazard. Mater* 1(3):249-257.
		Foam delivery	Foam, which is a dispersed phase of gas in a liquid, can be used for lateral flushing or delivery of liquid chemical reagents through the vadose zone.	Reactant/ contaminant dependent	Tested in DOE research that revealed limitations for large-scale applications.	Mattigod, S., L. Zhong, D. Jansik, M. Foote, A. Hart, and D. Wellman, 2010, "Reactant Carrier Microfoam Technology for In Situ Remediation of Radionuclide and Metallic Contaminants in Deep Vadose Zone," WM2010 Conference, March 7-11, Phoenix, Arizona. Foote, M., A. Hart, D. Wellman, S. Mattigod, L. Zhong, 2010, "Scale-Up Testing—Foam as a Remedial Amendment Carrier," WM2010 Conference, March 7-11, Phoenix, Arizona. Shen, X., L. Zhao, Y. Ding, B. Liu, H. Zeng, L. Zhong, and X. Li, 2011, "Foam, a promising vehicle to deliver nanoparticles for vadose zone remediation," *Journal of Hazardous Materials* 186(2-3): 173-1780. Zhong, L., J. Szecsody, M. Oostrom, M. Truex, X. Shen, and X. Li, 2011, "Enhanced remedial amendment delivery to subsurface using shear thinning fluid and aqueous foam," *Journal of Hazardous Materials* 191(1-3): 249-257. Zhong, L., J. Szecsody, Z. Zhang, and S. Mattigod, 2010, "Foam Delivery of Amendments for Vadose Zone Remediation: Propagation Performance in Unsaturated Sediments," *Vadose Zone Journal* 9(3): 757-767. PNNL-18918, 2009, *Foam Transport in Porous Media - A Review*, Pacific Northwest National Laboratory, Richland, Washington. Zhong, L., N. Qafoku, J. Szecsody, P. Dresel, and Z. Zhang, 2009, "Foam Delivery of Calcium Polysulfide to the Vadose Zone for Chromium(VI) Immobilization: A Laboratory Evaluation, *Vadose Zone Journal* 8(4): 976-985

COI = contaminant of interest
DOE = U.S. Department of Energy
ESTCP = Environmental Security Technology Certification Program
LNAPL = light non-aqueous phase liquid
ZVI = zero valent iron

Review Comment Record			August 21, 2019
Document: *Technology Evaluation and Treatability Studies Assessment for the Hanford Central Plateau Deep Vadose Zone*, DOE/RL-58, Draft A **Comment Response to State of Washington Department of Ecology letter to RL, 19-NWP-076, dated April 24, 2019**			
ID	**Comment**	**Disposition**	**Response to Comment**
0	The Department of Ecology (Ecology) request that you submit a draft change to the work Plan schedule ([DOE/RL-2011-102], Figure 6-1), in accordance with the change procedures in the Hanford Federal Facility Agreement and Consent Order (Tri-Party Agreement), Section 9.3, "**Document Revisions.**" Ecology disagrees with the USDOE conclusion (p. 5-12) **that "no additional field studies are recommend at this time."** Ecology requests that the update to the schedule identify those additional laboratory studies the USDOE proposes, followed by the revised dates to "**Initiate** Additional Treatability Test **Field Work**" (emphasis added).	Partially accept with change	The Figure 6-1 Schedule in the RI/FS and RFI/CMS Work Plan for the 200-DV-1 OU (DOE/RL-2011-102) will be revised to include the decision point "**Evaluate Need for Potential Additional Treatability Tests**" after "**Prepare Cumulative Impacts Evaluation** (200-DV-1)". USDOE understands and appreciates the importance and value of field studies. To clarify that, the following 2 statements were added in 2 places each, in: • the Executive Summary, page v, lines 14 through 17, replace last sentence with: • section 5.2, page 5-12, lines 15 through 17, replace last sentence with: "After completing the laboratory studies and the 200-DV-1 OU RI (and RFI), results will be evaluated to determine whether field studies are needed to provide additional information on effectiveness, implementability or costs for evaluating these technologies in the FS." And: • the Executive Summary, page v, line 26 (after the 4 bullets) and • section 5.2, page 5-12, after line 26 (after the 4 bullets): "**While no field studies are recommended at this time as describe**d above, the need for field studies will be evaluated based on the results of the recommended laboratory studies and completion of the remedial investigations of the waste sites." As described in DOE/RL-2017-58, *Technology Evaluation and Treatability Studies Assessment for the Hanford Central Plateau Deep Vadose Zone*, (DVZ TTER), no additional field studies are recommended at this time because either the technology: • Is already sufficiently mature for consideration in an FS • Has poor effectiveness or implementability • Has limited applicability that requires identification of an appropriate waste site during the RI (and RFI) process • Has identified data gaps that can be addressed through the recommended laboratory or modeling studies to enable their consideration in a feasibility study None of the technologies with recommended lab studies are good candidates for field studies at this time because effectiveness needs to be proven first. The 200-DV-1 Laboratory Treatability Test Plan is being prepared to evaluate these technologies for possible application at Hanford. If results of the recommended laboratory treatability studies indicate that the technology is effective and the remedial technology screening and alternative evaluations in the 200-DV-1 OU Feasibility Study indicate the need, then Figure 6-1 Schedule in DOE/RL-2011-102 will be revised and the field treatability studies performed.

1	1. <u>Technology Evaluation does not meet the expectation for treatment</u> 40 CFR 300.430(a)(1)(iii)(A); "EPA expects to use treatment to address the principal threats posed by a site, wherever practicable. Principal threats for which treatment is most likely to be appropriate include liquids, areas contaminated with high concentrations of toxic compounds, and highly mobile materials." DOE/RL-2017-58 does not identify in-situ treatment technologies that are ready to be evaluated in a Feasibility Study. We note in particular that almost all technologies in Table 5-2 are marked red because "effectiveness and/or implementability is low."	Reject, but with change	USDOE disagrees with Ecology's statement: "DOE/RL-2017-58 does not identify in-situ treatment technologies that are ready to be evaluated in a Feasibility Study." Technologies listed in Table 5-1 that have "no EIC data needs" in column 3 (What Data are Needed to Support a Feasibility Study) are ready to be evaluated in a feasibility study. There are 9 in situ technologies with that designation. To clarify this in the document, the following was added to the end of the first paragraph describing Table 5-1 in section 5.1, page 5-1, line 14: "Technologies designated as having no EIC data needs are ready to be evaluated as part of an FS based on available information. The FS would consider the EIC for each specific technology in the context of the site-specific conditions for the waste sites included in the FS." DOE/RL-2017-58, DVZ TTER: • Provides a comprehensive evaluation of currently available DVZ technologies, • Identifies data needed to support remedial technology screening and alternative evaluation, and • Recommends additional treatability studies for the most promising DVZ technologies. Tables 4-1 and 4-2 provide the evaluations for each technology relative to the effectiveness on the contaminants of interest and the implementability in the treatment areas, respectively. The results of this evaluation are summarized in table 4-3, then combined into an overall rating in Table 5-2. As noted, many of in situ technologies have low effectiveness, implementability or both. However, Table 5-3 lists a range of recommended technologies to consider for feasibility studies of DVZ waste sites organized by treatment area and general response action. This table includes innovative technologies that have data gaps and have been recommended for treatability studies (these have been underlined in Table 5-3) and remedial technologies with adequate data for an FS evaluation. Note that table 5-3 does not replace the technology screening and alternative development process in the FS, which considers waste site specific information derived from the RI/FS evaluations.
1a	For example, Ecology disagrees with the low ranking for: • Soil flushing in area where we can take advantage of the existing 200 West (200-ZP-1 Operable Unit) Pump & Treat System.	Partially accept, no change	While soil flushing is considered to have medium effectiveness for all the contaminants of interest, it has low implementability in the unsaturated zones and high relative costs, as described in Table 4-2. PNNL-19938 (published in 2010 as part of the Deep Vadose Zone Treatability Test Plan efforts) provided an evaluation of soil flushing (summarized in section 3.1.6 of DOE/RL-2017-58, DVZ TTER). Soil flushing for the Central Plateau would require large flushing volumes, must consider near surface contamination for implementing infiltration, must consider near-surface conditions and the potential for ponding of water, must consider the effect of the Cold Creek Unit upon infiltration, and has uncertainties in movement of infiltrating water that drive a need for an expensive capture system. At the screening level assessment in the document, these factors drive implementability low and costs high. Soil flushing for a Central Plateau application would need to consider the above factors and the potential impacts to the full range of contaminants at these sites (e.g., the BY Cribs contains many

			contaminants). This situation is in contrast to the conditions in the 100K area where Cr(VI) is the only contaminant of concern and a focused test of soil flushing can be conducted with little risk of unintended consequences. The USGS affirmed the assessment of the challenges of using soil flushing in the DVZ in their review of the report. In their comments sent to Craig Cameron in a letter dated June 17, 2019, they stated: "*The aridity of the Hanford Site is an environmental condition that will likely persist for centuries, and that condition is generally favorable to limiting groundwater contamination and should not be readily overlooked. Soil flushing seems to be a risky remediation strategy due to the limitations described, and the follow-up pump and treat step that could linger out for decades/centuries due to the long-term drainage of the water/solution used for flushing. Agreed that it can be (very carefully) considered with no further treatability studies.*"
1b	• Soil desiccation, where preliminary tests at the 200-BC-1 Operable Unit (BC Cribs & Trenches) showed promising results	No change	Soil desiccation did show promising results in the field tests at the 200-BC-1 OU. Therefore, it was rated high for effectiveness on all COIs, except organics and was rated high for implementability in the unsaturated zones. See summary in Table 4-3 and detailed evaluation in Tables 4-1 and 4-2. Based on this evaluation, it is given a numerical rating of 4, highlighted green in Table 5-2 for the high ranking for COIs and treatment zones (16 cells). Soil desiccation is considered a viable technology for remediation of most contaminants of interest, has no EIC data needs, requires no further treatability studies, and is ready for feasibility study evaluations, as summarized in Tables ES-2 and 3-1.
1c	Ecology request that USDOE plan and schedule field tests for these two technologies [**soil flushing** and **desiccation**], and allow contingency for a **third field test** based on the additional laboratory test recommended by USDOE	Partially agree, with change	**Soil Flushing** does not require additional treatability tests, because the previous evaluation sufficiently described soil flushing for its consideration in a feasibility study. **Soil Desiccation** does not require additional field tests, because those performed at the 200-BC-1 OU (described in PNNL-26902, *Deep Vadose Zone Treatability Test of Soil Desiccation for the Hanford Central Plateau: Final Report*) provide adequate information to fully evaluate soil desiccation as part of a remedial alternative in future Feasibility Studies. It is recommended that desiccation be implemented in conjunction with a surface barrier to improve effectiveness and longevity. **Ecology Recommendation for Third Field Test:** USDOE provides option for possible field tests, if needed, after the laboratory studies are performed. See response and change provided to comment #0.
2	2. Technology Evaluation does not meet the expectation for innovative technologies 40 CFR 300.430(a)(1)(iii)(E); "EPA expects to consider using innovative technology when such technology offers the potential for comparable or superior treatment performance or implementability, fewer or lesser adverse impacts than other available	Partially agree, with change	The DVZ TTER considers many innovative technologies in the evaluations performed for this report and recommends additional laboratory treatability studies on 8 of these innovative technologies so they can be evaluated in future Feasibility Studies. The 8 technologies proposed for testing are innovative and have not been used before for key Hanford contaminants. These innovative technologies and all technologies evaluated in this technology treatability evaluation report will be considered in future feasibility studies. To clarify this in the report, the following was added to the Purpose sub-sections in: • the Executive Summary, page iii, line 25 and

	approaches, or lower costs for similar levels of performance than demonstrated technologies."		• section 1.1, page 1-4, beginning of line 1 (before section 1.2): "The technology evaluations performed herein do not screen out any remedial technologies for consideration in future FS/CMSs and the fact that technologies are not recommended for treatability studies (e.g. excavation) does not imply these are considered poor remedial technologies. All applicable DVZ remediation technologies will be included in the FS evaluations for DVZ waste sites."
2a	DOE/RL-2017-58 includes the statement (p. 4-3): "Promising innovative technologies that are not mature enough to be developed within the timeframe needed for inclusion in the 200-DV-1 FS/CMS evaluation may still warrant consideration for other long-term technology development initiatives associated with the Hanford Site."	Accept, with change	The DVZ TTER evaluates current remedial technologies, including innovative technologies that have a potential for near-term maturity based on similar applications for other contaminants/site conditions. USDOE evaluates and implements commercially available technologies, and does not have an active program to develop new technologies. However, innovative technologies will be evaluated at key decision points in the cleanup process. The intent of this sentence was to acknowledge that: • remedial technologies continue to evolve, improve, and gain wider applicability, • it is likely better technologies will be available in the coming decades and centuries, and • USDOE will continue to monitor the progress of remedial technologies and evaluate the applicability of these for contamination at the Hanford Site. However, USDOE considers it prudent to move ahead with addressing the DVZ contamination that poses a risk to groundwater by completing the 200-DV-1 Remedial Investigation (and RFI) and initiating the Feasibility Study (and CMS) in parallel with performing the recommended treatability studies described in DOE/RL-2017-58. The quoted statement does not provide any additional value to the report and is prone to misunderstanding, therefore it was deleted.
2b	In response to the statement: • USDOE should identify promising innovative technologies that are not mature, and should propose additional laboratory as well as field studies for those technologies.	Clarify, with change	This report has identified all promising innovative technologies and has proposed laboratory studies to assess their effectiveness. No field tests are proposed at this time, as explained in the report. All technologies selected for laboratory treatability studies are innovative technologies with respect to their application to the targeted COI identified in the document. These technologies are sufficiently mature that testing can provide suitable information to meet 200-DV-1 OU needs and schedule. The purpose of a treatability test is not for technology development, thus conceptual technologies without an existing basis for applicability are not part of a treatability test evaluation. See response to comment 2a for change to DVZ TTER.
2c	• If the development of those technologies extend beyond the timeframe defined by the M-15-110b Milestone, then USDOE should propose a Tri-Party Agreement extension to allow adequate time to bring the technologies to maturity.	Clarify, with change	The DVZ TTER did not identify any promising technologies for long-term development other than those recommended for laboratory treatability studies. USDOE considers it prudent to move ahead with addressing the DVZ contamination that poses a risk to groundwater by completing the 200-DV-1 Remedial Investigation (and RFI) and initiating the Feasibility Study (and CMS) in parallel with performing the recommended treatability studies described in DOE/RL-2017-58. See response to comment 2a for change to DVZ TTER.

2d	• Ecology is not aware of "other long-term technology development initiatives associated with the Hanford Site" and requests that USDOE identify those other initiatives.	Clarify, with change	USDOE monitors industry trends of remedial technologies and if any show promise, USDOE will evaluate the applicability of these for contamination at the Hanford Site as part of FS efforts. See response to comment 2a for change to the DVZ TTER.
3	3. <u>Technology Evaluation does not match approved work plan schedule</u> Figure 6-1 is the schedule in the approved work plan [DOE/RL-2011-102]. One line item in the schedule is "Initiate Additional Treatability Test **Field Work**" (emphasis added). A footnote in the table stipulates, "DOE may elect (**with agency approval**) to not implement additional treatability studies if the evaluation above demonstrates they are not necessary" (emphasis added). Ecology does not grant agency approval to forgo the Additional Treatability Test Field Work.	Partially agree, with change	The Figure 6-1 Schedule in the RI/FS and RFI/CMS Work Plan for the 200-DV-1 OU (DOE/RL-2011-102) will be revised to include a decision point to "Evaluate Need for Additional Treatability Tests" after "Prepare Cumulative Impacts Evaluation (200-DV-1)". The DVZ TTER does recommend additional treatability studies. If any of these lab studies prove effective and the need is identified in the feasibility study, then implementation of the field studies will be evaluated. If a technology is deemed ineffective or not implementable, there is no need to perform field work. As described in DOE/RL-2017-58, no additional field studies are recommended at this time because either the technology: • Is already sufficiently mature for consideration in an FS • Has poor effectiveness or implementability • Has limited applicability that requires identification of an appropriate waste site during the RI (and RFI) process • Has identified data gaps that can be addressed through the recommended laboratory or modeling studies to enable their consideration in a feasibility study If results of the recommended laboratory treatability studies indicate that the technology is effective and the remedial technology screening and alternative evaluations in the 200-DV-1 OU Feasibility Study indicate the need, the Figure 6-1 Schedule in DOE/RL-2011-102 will be revised and the field treatability studies performed.
	<u>United States Geological Society (USGS) comment:</u> **Page v, lines 1-6:** Three in situ technologies to sequester/degrade contaminants were identified for use in the DVZ, but it was stated that data are not available to determine their effectiveness for specific Hanford Site applications. With regard to Uranium Reactive Gas Sequestration (URGS), laboratory studies have been completed that indicate the potential effectiveness of URGS at suitable waste sites, and data from those studies also indicate where URGS would likely NOT be successful. Following through with a field pilot test at a non-acidic uranium waste site would provide the testing information originally sought; the 241-BX-102 and 216-B-12 sites are two good candidate sites (PNNL 27773). Technically, this field test (along with the needed preliminary lab tests) could be conducted now or later in the FS process. Regardless of the	Accept, with change	The two potential uranium treatability test locations at Site 241-BX-102 have access problems due to being in congested areas of the BX Tank Farm and the deeper test location is associated with the perched water where other more suitable technologies are being evaluated in laboratory treatability tests. Site 216-B-12 has not yet been adequately characterized. The other potential sites have similar poor access or would require additional characterization to collect samples for laboratory studies to determine which site would be best for field studies. After applicable waste sites have been identified during the remedial investigation (and RFI), laboratory studies could be performed during the FS, if needed to select between remedial alternatives. The following sentence was added to section 3.1.3.4: "An evaluation will be conducted to determine whether a field study of the URGS ammonia treatment technology is warranted where the site-specific laboratory testing shows positive results with a decrease in uranium mobility that will meet groundwater protection needs."

	timing, URGS appears to be a promising remediation strategy at perhaps 5 of the 11 uranium waste sites of interest.		
	<u>USGS comment:</u> **Page v, lines 12-17:** There will always be site-specific implementation design needs for these technologies, but enough should be known about characteristics of a suitable site up-front to determine likely effectiveness. Results from a field test (and additional lab tests) would better inform this process.	Clarify, with change	The RI/FS (and RFI/CMS) will be used to identify appropriate waste sites for these technologies. Once the laboratory studies are completed, then a path forward will be evaluated. The last sentence was revised as follows: "After completing the laboratory studies and the 200-DV-1 OU RI (and RFI), results will be evaluated to determine whether field studies are needed to provide additional information on effectiveness, implementability or costs for evaluating these technologies in the FS."