

Draft

Corrective Measures Study

**Santa Susana Field Laboratory
Ventura County, California**

Prepared for:

U.S. Department of Energy
4100 Guardian Street
Suite 160
Simi Valley, California 93063

Prepared by:

CDM Federal Programs Corporation
555 17th Street, Suite 1100
Denver, Colorado 80202

Prepared under:

U.S. Department of Energy
EM Consolidated Business Center
Contract DE-EM0001128
CDM Smith Task Order DE-DT0003515

September, 2018

Draft
Corrective Measures Study
Santa Susana Field Laboratory
Ventura County, California

Contract DE-EM0001128
CDM Smith Task Order DE-DT0003515

Prepared by: _____
Dung (Zoom) Nguyen.
CDM Smith Geologist

Date

Reviewed by
Ryan Wymore: _____
CDM Smith

Date

John Wondolleck: _____
CDM Smith
Project Manager

Date

Table of Contents

1. Introduction	1-1
1.1 Background	1-2
1.2 CMS Content.....	1-3
2. Area IV Existing Ground Water Contamination Conditions.....	2-1
2.1 Former Sodium Disposal Facility.....	2-1
2.2 Building 56 Landfill.....	2-4
2.3 Buildings 4057/4059/4626.....	2-5
2.4 Hazardous Materials Storage Area/Building 4457	2-6
2.5 Tritium Plume	2-7
2.6 Radioactive Materials Handling Facility	2-8
2.7 Buildings 4030/4093 Leach Fields/DOE Leach Field 1	2-9
2.8 Building 4064 Leach Field	2-10
2.9 Old Conservation Yard.....	2-11
2.10 Building 4065 Metals Clarifier/DOE Leach Field 3.....	2-11
2.11 Building 4100 Trench.....	2-12
2.12 Building 4009 Leach Field.....	2-13
2.13 Building 4020 Rockwell International Hot Lab	2-14
2.14 Buildings 4133/4029 Hazardous Waste Management Facility	2-14
3. Development of Remedial Action Objectives.....	3-1
3.1 Corrective Action Objectives.....	3-1
3.2 Identification of ARARs and TBCs	3-2
3.3 Identification of Site Specific RAOs.....	3-4
4. Technology Description.....	4-1
4.1 No Action.....	4-1
4.1 Administrative and Legal Controls.....	4-1
4.3 Monitored Natural Attenuation.....	4-2
4.4 Containment.....	4-3
4.4.1 Physical Containment.....	4-3
4.4.2 In Situ Stabilization Solidification.....	4-4
4.4.3 Hydraulic Control.....	4-6
4.4.4 Capping.....	4-6
4.4.5 Grouting.....	4-7
4.4.6 Microbially-Induced Calcite Precipitation.....	4-7
4.5 <i>In Situ</i> Treatment	4-8
4.5.1 <i>In Situ</i> Reduction	4-8
4.5.1.1 In situ chemical and biological reduction.....	4-9
4.5.1.2 Low-temperature, thermally-enhanced bioremediation	4-9
4.5.2 <i>In Situ</i> Chemical Oxidation	4-12
4.5.3 Cometabolism.....	4-12
4.5.4 <i>In Situ</i> Soil Mixing.....	4-13

4.6 Source Removal	4-14
4.6.1 Excavation	4-14
4.6.2 Extraction	4-15
4.6.2.1 Pump and Treat.....	4-15
4.6.2.2 Soil Vapor Extraction	4-15
4.6.2.3 Air Sparging/Biosparting.....	4-16
4.6.2.4 In Situ Flushing.....	4-17
4.6.2.5 Dual-Phase Extraction/Multi-Phase-Extraction.....	4-18
4.6.3 <i>In Situ</i> Thermal Treatment.....	4-18
4.6.3.1 Electrical Resistive Heating.....	4-18
4.6.3.2 Thermal Conductive Heating.....	4-20
4.6.3.3 Steam Enhanced Extraction	4-22
4.6.3.4 Vitrification	4-24
4.6.3.5 Radio Frequency Heating.....	4-25
4.6.3.6 Hot Air Injection.....	4-25
4.6.3.7 Hot Water Injection	4-26
4.7 Ex Situ Treatment (Assuming Excavation)	4-26
4.8 Ex Situ Treatment (Assuming P&T).....	4-26
4.9 Preliminary Screening	4-27
5. Remedial Technology Evaluation Criteria	5-1
5.1 Threshold Criteria.....	5-1
5.1.1 Attain Relevant Groundwater Cleanup Standard.....	5-1
5.1.2 Control the Sources of Releases.....	5-2
5.1.3 Protect Human Health and the Environment.....	5-2
5.2 Balancing Criteria	5-2
5.2.1 Long Term Reliability and Effectiveness.....	5-2
5.2.2 Reduction of Toxicity, Mobility or Volumes of Wastes.....	5-2
5.2.3 Short Term Effectiveness.....	5-3
5.2.4 Implementability	5-3
5.2.5 Cost.....	5-3
5.3 Comparative Analysis of Remedial Technologies	5-3
6. Remedial Technology Evaluation.....	6-1
6.1 FSDF.....	6-1
6.1.1 Data Gaps	6-1
6.1.2 Conceptual Design and Implementation and Preliminary Analysis.....	6-2
6.1.2.1 Groundwater Extraction via Fracture Dewatering	6-2
6.1.2.2 Bedrock Vapor Extraction.....	6-4
6.1.2.3 <i>In Situ</i> Reduction.....	6-5
6.1.2.4 <i>In Situ</i> Reduction with Permeability Enhancement.....	6-7
6.1.2.5 <i>In Situ</i> Chemical Oxidation.....	6-9
6.1.2.6 <i>In Situ</i> Chemical Oxidation with Permeability Enhancement.....	6-10
6.1.2.7 Excavation.....	6-11
6.1.2.8 Enhanced Groundwater Extraction with Permeability Enhancement	6-13
6.1.2.9 <i>In situ</i> Thermal Remediation	6-14
6.1.3 Comparative Analysis.....	6-15

6.1.3.1 Long-Term Reliability and Effectiveness	6-16
6.1.3.2 Reduction of Toxicity, Mobility or Volume of Wastes.....	6-16
6.1.3.3 Short-Term Effectiveness	6-16
6.1.3.4 Implementability	6-17
6.1.3.5 Overall Score	6-17
6.1.3.6 Cost.....	6-17
6.1.4 Preferred Remedial Technologies	6-18
6.2 PCE Plume	6-18
6.2.1 Pump and Treat	6-18
6.2.2 Monitored Natural Attenuation	6-19
6.3 Hazardous Materials Storage Area.....	6-20
6.3.1 Data Gaps.....	6-20
6.3.2 Conceptual Design and Implementation.....	6-21
6.3.2.1 Pump and Test.....	6-21
6.3.2.2 <i>In Situ</i> Reduction.....	6-22
6.3.2.3 <i>In Situ</i> Chemical Oxidation	6-24
6.3.2.4 Low-Temperature Thermal Biological Treatment	6-25
6.3.2.5 Excavation	6-26
6.3.2.6 Air Sparging – Near-Surface Groundwater Zone	6-28
6.3.2.7 Monitored Natural Attenuation	6-29
6.3.3 Comparative Analysis.....	6-30
6.3.3.1 Long-Term Reliability and Effectiveness	6-30
6.3.3.2 Reduction of Toxicity, Mobility or Volume of Wastes.....	6-30
6.3.3.3 Short-Term Effectiveness	6-31
6.3.3.4 Implementability	6-31
6.3.3.5 Cost.....	6-31
6.3.3.6 Overall Score	6-32
6.3.3.7 Cost.....	6-32
6.3.4 Preferred Remedial Technologies	6-32
6.4 Tritium Plume	6-32
6.5 Radioactive Materials Handling Facility	6-33
6.5.1 Data Gaps.....	6-33
6.5.2 Conceptual Design and Implementation.....	6-34
6.5.2.1 Bedrock Fracture Grouting	6-34
6.5.2.2 Excavation	6-35
6.5.2.3 Groundwater Elevation Control.....	6-36
6.5.2.4 Monitored Natural Attenuation	6-37
6.5.3 Comparative Analysis.....	6-38
6.5.3.1 Long-Term Reliability and Effectiveness	6-38
6.5.3.2 Reduction of Toxicity, Mobility or Volume of Wastes.....	6-39
6.5.3.3 Short-Term Effectiveness	6-39
6.5.3.4 Implementability	6-39
6.5.3.5 Overall Score	6-40
6.5.3.6 Cost.....	6-40
6.5.4 Preferred Remedial Technologies	6-40
6.6 Metals Clarifier Laboratory Building 4065/DOE Leach Fields 3 RFI Site.....	6-40

7. Recommended Remedial Technologies	7-1
7.1 Former Sodium Disposal Facility	7-1
7.2 Building 4100/B56 Landfill TCE Plume	7-2
7.3 Buildings 4059/4057/4626 PCE Plume	7-2
7.4 HMSA TCE Plume	7-2
7.5 Tritium Plume.....	7-3
7.6 Radioactive Materials Handling Facility.....	7-3
7.6.1 RMHF TCE Impacted Groundwater	7-3
7.6.2 RMHF Leach Field Sr-90 Source.....	7-4
7.7 Metals Clarifier/DOE Leach Field 3 TCE Plume	7-4
8. Area IV Groundwater Remediation Schedule	8-1
9. Evaluation of Area IV Monitoring Well Network for Water Quality SAP Revision	9-1
10. References.....	10-1

List of Figures

- Figure 1-1 Area IV Groundwater Investigation Areas
- Figure 1-2. SSFL Site Area Designations
- Figure 2-1 Former Sodium Disposal Facility (FSDF) Layout 2016-2017 TCE Data
- Figure 2-2 Building 56 Landfill Layout – 2016/2017 TCE Data
- Figure 2-3 Buildings 4057/4059/4626 PCE Concentrations 2016/2017
- Figure 2-4 Hazardous Materials Storage Area Layout – 2016/2017 Data
- Figure 2-5 Tritium Plume Layout 2016/2017 Tritium Data
- Figure 2-6 RMHF Layout -TCE 2016/2017 Data
- Figure 2-7 Buildings 4029/4133 and 4030/4064/4093 Leach Fields Layout
- Figure 2-8 Old Conservation Yard Layout – 2016/2017 TCE Data
- Figure 2-9 Metals Clarifier/DOE Leach Fields 3 Layout – 2016/2017 TCE Data
- Figure 2-10 Building 4100 and Building 4009 Leach Field Layout
- Figure 4-1 Illustration of PRB Configurations (courtesy of SERPB 2000)
- Figure 4-2 Illustration of ISS (courtesy of Battelle 2004)
- Figure 4-3 Illustration of MICP (courtesy of De Muynck et al. 2010)
- Figure 4-4 Illustration of *In Situ* Soil Mixing (courtesy of Battelle 2004)
- Figure 4-5 Field Application of LDA (courtesy of FECC 2018)
- Figure 4-6 Illustration of a P & T System (courtesy of DOE 2015)
- Figure 4-7 Illustration of SVE and Air Sparging (courtesy of Clu-in 2008)
- Figure 4-8 Illustration of In Situ Flushing (courtesy of NAVFAC 2002)
- Figure 4-9 Conceptual Design of an ERH System (courtesy of ER-0314, 2010)
- Figure 4-10 Conceptual Design of a TCH System(courtesy of ER-0314, 2010)
- Figure 4-11 Typical Operational Phases of a TCH System (courtesy of ER-0314, 2010)
- Figure 4-12 Conceptual Design of an SEE System (courtesy of ER-0314, 2010)
- Figure 4-13 Typical SEE Operational Period (courtesy of ER-0314, 2010)

List of Tables

Table 3-1 Regulatory Standards Pertinent to Remedial Actions in Area IV

Table 3-2 Remedial Actions Objectives for Area IV Sites with Groundwater Impacts

Table 4-1 Potentially Applicable Remedial Technologies Under Consideration

Table 4-2 Preliminary Screening of Potentially Applicable Remedial Alternatives

Table 4-3 Association of Retained Remedial Technologies with Area IV Groundwater Impact Areas

Table 6-1 Remedial Technology Evaluation at the FSDF (VOCs in Near Surface Bedrock)

Table 6-2 Remedial Technology Evaluation at the HMSA (VOCs in Perched Zone)

Table 6-3 Remedial Technology Evaluation at the RMHF (Sr-90 in Bedrock)

Table 8-1 High Level Area IV Groundwater Remediation Schedule

Table 9-1 Summary of Purpose of each Area IV Well Under DOE Responsibility

Table 9-2 WQSAP Revision Recommendations

Table 9-3 Area IV Monitoring Well Network Evaluation

Acronyms and Abbreviations

1,1-DCE	1,1-dichloroethene
AFCEE	Air Force Center for Engineering and Environment
Ag	silver
Al	aluminum
As	arsenic
B	boron
Ba	barium
BEV	bedrock vapor extraction
bgs	below ground surface
BVE	Bedrock Vapor Extraction
Ca	calcium
CaO	calcium oxide
CCR	California Code of Regulation
Cd	cadmium
CFR	Code of Federal Regulation
CDM Smith	CDM Federal Programs Corporation
CEA	Classification Exemption Area
CEQA	California Environmental Policy Act
°C	degrees Celsius
<i>cis</i> -1,2-DCE	<i>cis</i> -1,2-dichloroethene
CMS	Corrective Measures Study
Co	cobalt
CO	Consent Order
COC	contaminant of concern
Cr	Chromium
Cs	cesium
CSM	conceptual site model
Cu	copper
CVOC	chlorinated volatile organic compounds
DCE	dichloroethene
DNAPL	dense non-aqueous phase liquid
DOE	United States Department of Energy
DPE/MPE	Dual-phase extraction/multi-phase extraction
DTSC	Department of Toxic Substances Control
EAB	enhanced anaerobic bioremediation
EPA	United States Environmental Protection Agency
ERH	electrical resistance heating
ESADA	Empire State Atomic Development Authority
ESTCP	Environmental Security Technology Certification Program
EVO	emulsified vegetable oil
eZVI	emulsified zero valent iron
F&G	funnel and gate
FSDF	Former Sodium Disposal Facility
ft	feet or foot
GAC	granular activated carbon
gpd	gallons per day

GWIM	groundwater interim measure
Hg	mercury
HMSA	Hazardous Materials Storage Area
HWMF	Hazardous Waste Management Facility
INEL	Idaho National Engineering Laboratory
ISCO	<i>in situ</i> chemical oxidation
ISCR	<i>in situ</i> chemical reduction
ISR	<i>in situ</i> reduction
ISEB	<i>in situ</i> enhanced bioremediation
ISS	<i>in situ</i> stabilization/solidification
ISTR	<i>in situ</i> thermal remediation
K	potassium
LDA	large-diameter augering
LNAPL	light non-aqueous phase liquid
MCL	maximum contaminant level
µg/kg	microgram per kilogram
µg/L	microgram per liter
MCL	maximum contaminant level
MCLGs	maximum contaminant level goals
mg/L	milligram per liter
Mn	manganese
MNA	monitored natural attenuation
Mo	molybdenum
MPE	multi-phase extraction
NASA	National Aeronautics and Space Administration
NAPL	Non-aqueous phase liquid
NBZ	Northern Buffer Zone
NEPA	National Environmental Policy Act
Ni	nickel
OCY	Old Conservation Yard
O&M	operations and maintenance
%	Percent
PAH	polyaromatic hydrocarbons
PCB	polychlorinated biphenyl
PCE	tetrachloroethene
pCi/L	picocuries per liter
PCU	power control unit
ppb	parts per billion
PRB	permeable reactive barrier
psi	pounds per square inch
P&T	pump and treat
RAO	remedial action objectives
RCRA	Resource Conservation and Recovery Act
RFC	Radio Frequency Company
RFH	radio frequency heating
RI	Remedial Investigation
RIHL	Rockwell International Hot Laboratory
RMHF	Radioactive Materials Handling Facility
ROI	radius of influence

RWQCB	Regional Water Quality Control Board
Sb	antimony
Se	selenium
SEE	steam enhanced extraction
SNAP	Systems Nuclear Auxiliary Power
Sr-90	Strontium-90
SRE	Sodium Reactor Experiment
SSFL	Santa Susana Field Laboratory
SVE	soil vapor extraction
SVOCs	semi-volatile organic compounds
SWMU	solid waste management unit
SWRCB	State Water Resources Control Board
TBC	to be considered
TCA	trichloroethane
TCE	Trichloroethene
TCH	Thermal conductive heating
TDS	total dissolved solids
Tl	thallium
TPH	total petroleum hydrocarbon
USACE	US Army Corps of Engineers
V	vanadium
VC	vinyl chloride
VOCs	volatile organic compounds
WQSAP	Water Quality Sampling and Analysis Plan
ZVI	zero-valent iron

Section 1

Introduction

This Corrective Measures Study (CMS) assesses and provides the rationale for identifying possible groundwater cleanup actions for solid waste management units (SWMUs) and areas of concern that are the responsibility of the U.S. Department of Energy (DOE) for Area IV of the Santa Susana Field Laboratory (SSFL) (**Figure 1-1**). The SWMUs and areas of concern are based on the listing in Attachment 4 of the Consent Order for Corrective Action (2007 CO) issued by the California Department of Toxic Substances Control (DTSC 2007). The processes used to conduct the CMS are based on US Environmental Protection Agency (EPA) guidance for conducting feasibility studies at hazardous waste sites. This CMS also complies with reporting requirements set forth in the 2007 CO (DTSC 2007).

The SWMUs addressed in this CMS are:

- 7.1 Building 56 Landfill
- 7.3 Building 4886 Former Sodium Disposal Facility (FSDF)
- 7.4 Old Conservation Yard (OCY)
- 7.5 Building 100 Trench
- 7.6 Radioactive Materials Handling Facility (RMHF, a portion of which is Resource Conservation and Recovery Act [RCRA] permitted)
- 7.7 Building 4020 (Rockwell International Hot Lab)

The Areas of Concern addressed in this CMS are:

- Building 4059 – Former SNAP Reactor Facility (combined with Buildings 057 and 626 groundwater investigation area)
- Building 4065 Metals Clarifier (combined with Buildings 353, 363, and 373 as a groundwater investigation area)
- Building 4457 Hazardous Materials Storage Area
- Leach Field AI-Z2 – Building 4064
- Leach Field AI-Z3 – Building 4030 (combined with Building 093 as DOE Leach Field 1)
- Leach Field AI-Z4 – Building 4093 (combined with Building 030 as DOE Leach Field 1)
- Leach Field AI-Z5 – Building 4021
- Leach Field AI-Z6 – Building 4028
- Leach Field AI-Z7 – Buildings 4010/4012 (Tritium Plume)
- Leach Field AI-Z10 – Building 4383
- Leach Field AI-Z11 – Building 4009
- Leach Field AI-Z12 – Building 4020 (Rockwell International Hot Lab)
- Leach Field AI-Z13 – Building 4373 (DOE Leach Field 2)

- Leach Field AI-Z14 – Building 4363 (DOE Leach Field 2)
- Leach Field AI-Z15 – Building 4353 (DOE Leach Field 2)

Figure 1-2 provides the locations of the SWMUs and areas of concern. Descriptions of the functions of these facilities, groundwater investigation activities, and groundwater impacts are provided in the *RCRA Facility Groundwater Remedial Investigation Report, Area IV* (CDM Smith 2018). **Section 2** of this CMS provides an overview of the groundwater issues associated with each location.

The Building 4133 Hazardous Waste Management Facility (SWMU 7.2) and the Building 029 Reactive Metals Yard (SWMU 7.11) were operated under a RCRA permit and are being closed under permit requirements. These two facilities are not addressed in this CMS and any impacted groundwater encountered during RCRA closure activities will be addressed as part of their RCRA closures.

1.1 Background

Area IV is situated in the western portion of SSFL (**Figure 1-2**). SSFL was established in 1947 for use in the testing or support of testing of rocket engines within what became Areas I, II, and III. Development of Area IV for energy research was started in the mid-1950s by predecessor agencies to the DOE. From the late 1950s through 1988, nuclear energy research, including the testing of 10 small reactors, occurred within Area IV. Area IV was also a center for liquid metals research. Not all the energy research performed in Area IV was conducted on the behalf of the federal government, as commercial company research also occurred.

At one time there were more than 200 numbered structures within Area IV supporting energy research. As the mission of each building ended, the building was decontaminated and demolished for off-site disposal of debris. Today only 18 structures remain. Over time, more than 50 soil cleanup actions have occurred in Area IV, initially addressing releases of radioactive materials, and then removal of debris and chemically impacted soils. Groundwater interim actions (primarily pump and treat) have occurred at the RMHF, at Building 059, and at the FSDF.

Since 2010, Area IV has been subject to two major soil investigations for characterization of contaminant extent. The characterization of the extent of radionuclides in soil was conducted by EPA during which 3,482 soil samples were collected. At the same time, DOE under DTSC oversight, collected 5,854 soil samples throughout Area IV for chemical contaminant characterization. Prior to 2010, 2,259 soil samples were collected under the RCRA facility investigation. In addition, soil gas samples have been collected and analyzed across Area IV.

The investigation for the presence of contaminants in groundwater was initiated in January 1986 with the installation of bedrock well RD-07. Since that time, 114 wells have been installed in and near Area IV. Three wells were subsequently abandoned leaving a network of 111 wells. This well network is used to describe the nature and extent of groundwater contamination associated with DOE's activities in Area IV. To conduct the groundwater investigations, Area IV was divided into 14 groundwater investigation areas that are DOE's responsibility per the 2007 CO. These investigation areas are illustrated in **Figure 1-2**. There are additional SWMUs and areas of concern that are the responsibility of the Boeing Company per the 2007 CO. Boeing is addressing

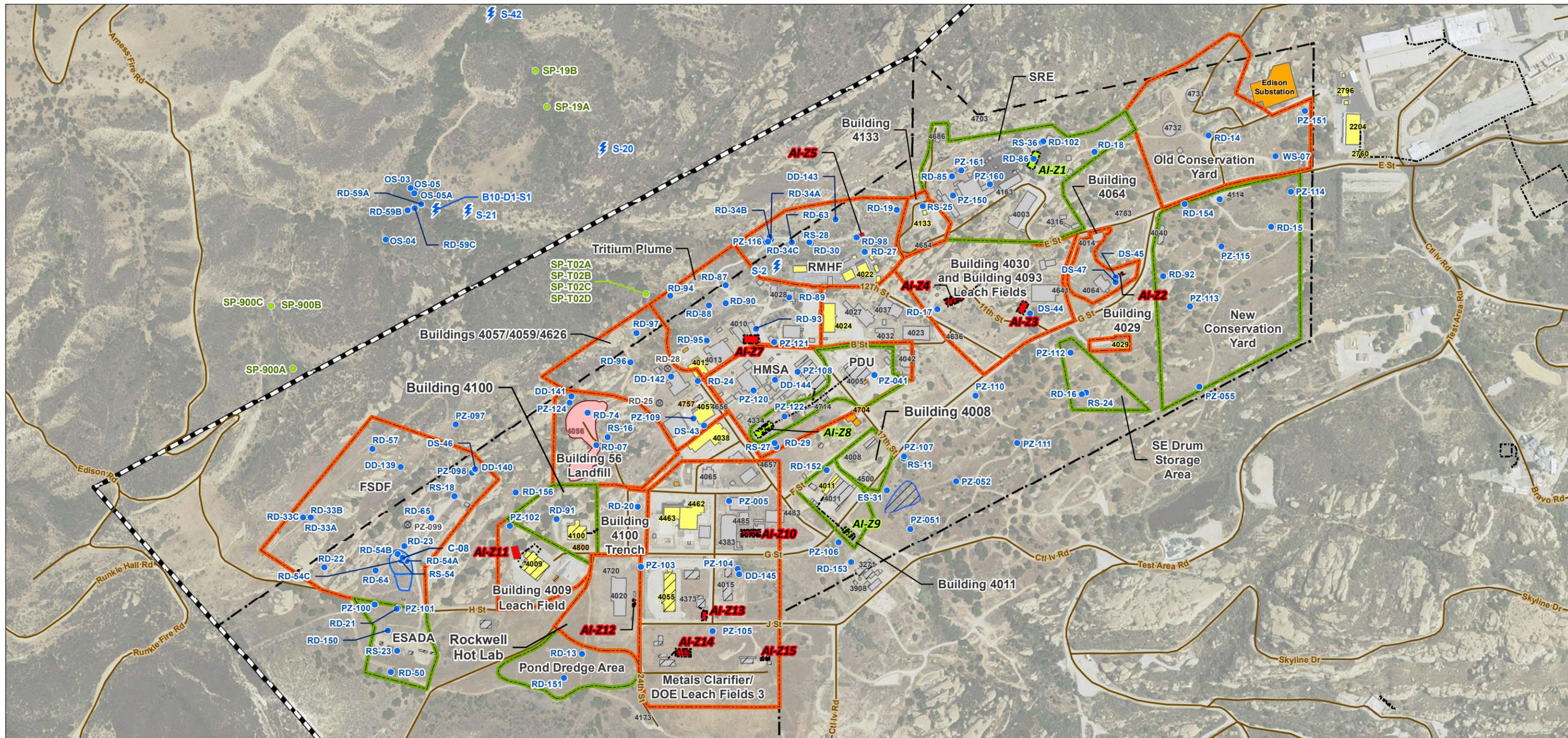
any impacted groundwater associated with its responsibilities in its separate CMS report. The Draft *RCRA Facility Groundwater Remedial Investigation Report, Area IV* (CDM Smith 2018a) provides details on the groundwater investigation history and the findings from the groundwater studies for the areas that are DOE's responsibility. The results of the groundwater investigations are summarized in Section 2.0 of this CMS.

1.2 CMS Content

The Area IV groundwater CMS contains the following sections.

- **Section 1 – Introduction** – provides an overview of the CMS basis and the portions of Area IV the CMS addresses
- **Section 2 – Existing Groundwater Contaminant Conditions** – provides summary information on the groundwater conditions in Area IV in relation to SWMUs and areas of concern with observed groundwater contamination
- **Section 3 – Development of Remedial Action Objectives** - presents the goals for groundwater restoration, timeframe for restoration, along with applicable, relevant, and appropriate requirements (ARARs)
- **Section 4 – Technology Description** – introduces groundwater remediation measures (technologies) potentially applicable to Area IV groundwater conditions
- **Section 5 – Remedial Technology Evaluation Criteria** – provides the evaluation of groundwater measures and their applicability to Area IV groundwater conditions
- **Section 6 – Remedial Technology Evaluation** – provides technical details on the proposed Area IV remediation measures, how the retained measures could be applied to address specific groundwater issues in Area IV, and an evaluation screening of the technologies based on effectiveness, implementability, and costs
- **Section 7 – Recommended Remedial Technologies** – provides CMS conclusions and recommendation for each area of concern within Area IV.
- **Section 8 – Area IV Groundwater Remediation Schedule** – provides a high level for the timeframe for initiation of groundwater remedies.
- **Section 9 – Evaluation of Area IV Monitoring Well Network for Water Quality Sampling and Analysis Plan Update** – provides recommendations for the revisions to the Water Quality Sampling and Analysis Plan (WQSAP) needed for future characterization and remedy effectiveness demonstration.
- **Section 10 – References** – provides a list of referenced used throughout the document.

This CMS was prepared by CDM Smith under contract with the DOE.



LEGEND

- | | | | | | | |
|-------------------|-------------------|------------------------|---------------------------------------|---------------------|----------------------|------------------------|
| ⊙ Abandoned Well | ⚡ Seep | Responsibility* | Groundwater Investigation Area | Existing Landfill | Former Pond | Former FSDF Pond |
| ● Well/Piezometer | — Road Centerline | AI-Zxx Boeing | Boeing | Existing Structure | Demolished Structure | Area IV Boundary |
| ● Seep Well | | AI-Zxx DOE | DOE | Existing Substation | Boeing Structure | SSFL Property Boundary |

Notes:
 - Original GIS layers provided by MWH/Boeing; updated by CDM Smith as needed.
 * - Leach Fields labeled using unique ID (AI-Zxx).

Service Layer Credits:
 - Aerial Source: Esri, DigitalGlobe, GeoEye, i-cubed, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community.
 - Road Centerline Source: Esri, TomTom.

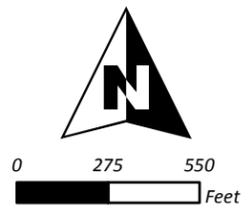
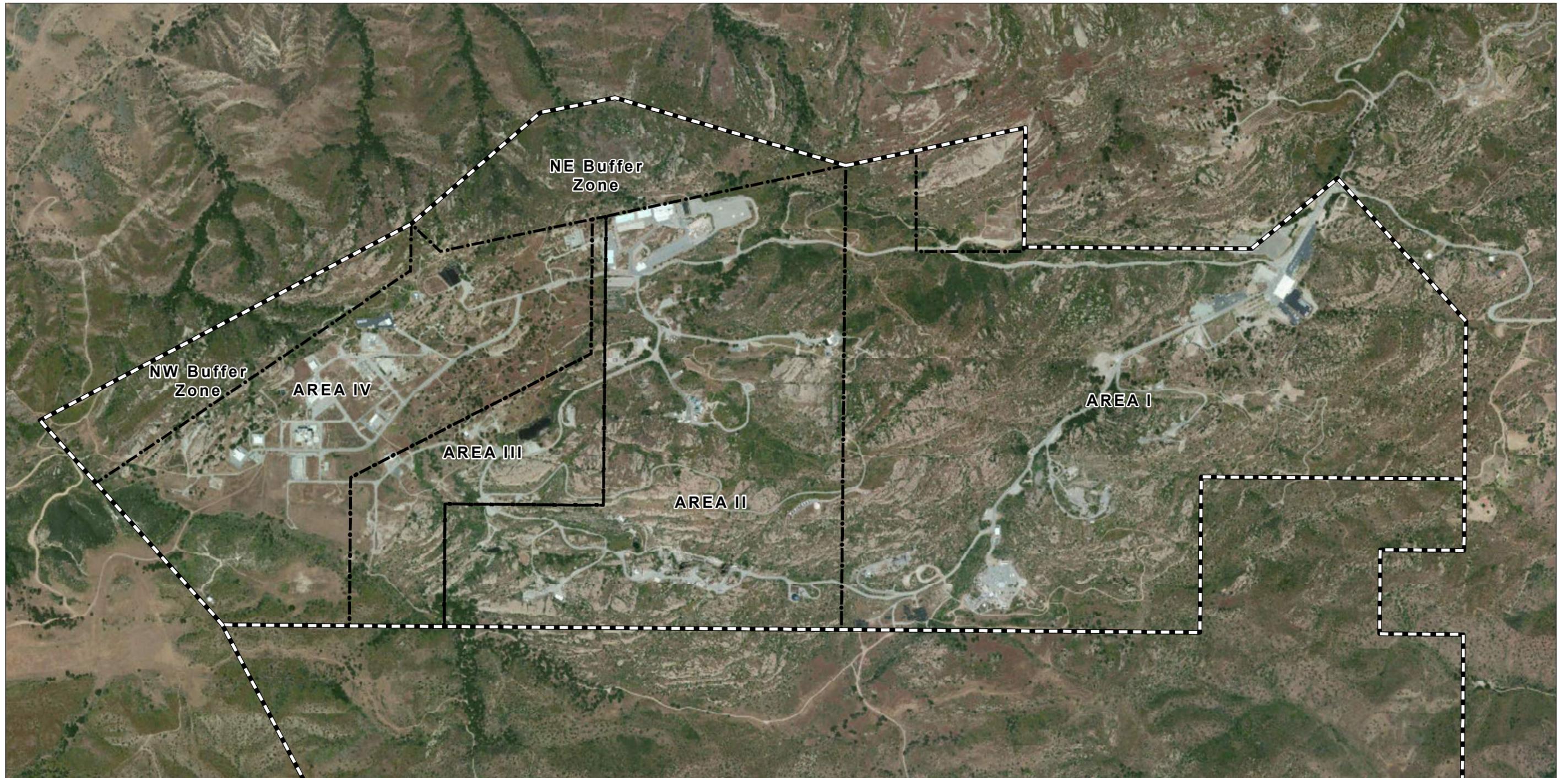
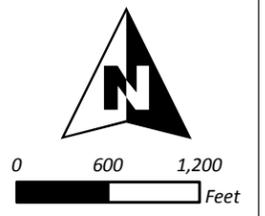


FIGURE 1-1
 Area IV Groundwater Investigation Areas



LEGEND
 Site Area Boundary  SSFL Property Boundary



Notes:
 - GIS Layers provided by MWH/Boeing.
 Service Layer Credits:
 - Aerial Source: Esri, DigitalGlobe, GeoEye, i-cubed, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community.

C:\projects\SantaSusana\GIS\MXD\EI\SSFL_Site_Areas_20150108.mxd 1/8/2015



FIGURE 1-2
SSFL Site Area Designations

Section 2

Area IV Existing Groundwater Contamination Conditions

This section summarizes the results of the groundwater investigation conducted for each of the 14 areas in Area IV under DOE responsibility, listed below, with respect to sources, nature and extent of groundwater contamination, hydrological setting, and groundwater issues that potentially require remediation. The information is primarily taken from the *RCRA Facility Investigation Groundwater Remedial Investigation Report* (CDM Smith 2018a). The Area IV groundwater investigation areas addressed in this CMS, which represent combinations of SWMUs and areas of concern introduced in **Section 1**, are:

- 1) Former Sodium Disposal Facility (FSDF)
- 2) Building 56 Landfill
- 3) Buildings 4057/4059/4626 Area
- 4) Hazardous Materials Storage Area (HMSA)/Building 4457
- 5) Tritium Plume
- 6) Radioactive Materials Handling Facility (RMHF)
- 7) Buildings 4030 and 4093 Leach Fields/DOE Leach Fields 1
- 8) Building 4064 Leach Field
- 9) Old Conservation Yard (OCY)
- 10) Building 4065 Metals Clarifier/DOE Leach Fields 3
- 11) Building 100 Trench
- 12) Building 4009 Leach Field
- 13) Rockwell International Hot Lab (RIHL)
- 14) Hazardous Waste Management Facility (HWMF) Building 4133/Building 4029

Figure 1-1 illustrates their locations.

2.1 Former Sodium Disposal Facility

Contaminants and Sources

Figure 2-1 illustrates the features and extent of groundwater contamination at the FSDF. Trichloroethene (TCE) and 1,1,1-Trichloroethane (1,1,1-TCA) along with their associated degradation (daughter products) are the main contaminants of concern for groundwater underlying the FSDF.

The FSDF, also known as the Sodium Burn Pit and Building 4886, was used from 1956 to 1978 to clean metallic components and materials of alkali metals (sodium and potassium/sodium mixtures). Rinsate from the process was disposed into two unlined ponds. The ponds also may have received liquid wastes from sodium metal tests conducted at the Empire State Atomic Development Authority (ESADA) facility due to a direct pipe connection with the FSDF (Building 4814; Boeing responsibility per the 2007 CO). The ponds were periodically dewatered, and dried sludge from the bottom of the ponds was disposed either locally in the western debris area or removed from the site. In addition to sodium-contaminated materials, the FSDF received chemical wastes including chlorinated solvents (mostly TCE and 1,1,1-TCA), polychlorinated biphenyl (PCBs), metals (mercury), and radionuclides (cesium-137 [Cs-137]). The land west of the FSDF was also reportedly used for drum and waste material storage. Another feature of the FSDF location is a former shooting range located immediately south of the former ponds.

Several soil and groundwater investigations were performed after operations ceased; soil was found to be contaminated with solvents, PCBs, mercury, and Cs-137, and groundwater was found to be contaminated with TCE, 1,1,1-TCA, metals, and perchlorate. As a result, soil, drums, and debris were removed and groundwater interim measures were conducted, including a pump and treat action using RD-21 and RD-54A. The current source of groundwater contamination at the FSDF consists of residual 1,1,1-TCA and TCE retained in the upper bedrock fractures.

Hydrogeologic Setting

The FSDF is located in the western portion of Area IV, within the northwest hydrogeologic zone (for purposes of the groundwater investigation, Area IV was divided into four hydrogeologic zones based on unique geologic characteristics of each zone). The Chatsworth Formation bedrock in this area is the tightest and least fractured in all of Area IV. The FSDF is underlain by the Upper Burro Flats member of the Chatsworth Formation. Fine-grained beds at the FSDF include the ELV member, which is approximately 170 feet deep at RD-54C, and the Lot bed, which may be close to ground surface at RD-23.

Near-surface groundwater, when present, occurs in fractures of weathered and competent bedrock; anticipated flow in the Near-surface groundwater is to the north, in the direction of surface topography. Near-surface groundwater is observed during average and above average rainfall years in well RS-54, installed approximately 46.5 feet below ground surface (bgs) into the upper bedrock, and RS-18 downgradient of RS-54. RS-54 has exhibited the highest TCE and 1,1,1-TCA concentrations for all wells in Area IV.

In November 2017, a groundwater interim measure (GWIM) was initiated using RS-54 as the pumping well. The GWIM involved pumping RS-54 dry and allowing the well to recover. Typically, the well was pumped dry in a 20-minute period and the well recovered to its maximum water level in about a 7- to 20-day period (CDM Smith 2018b). It was last pumped dry in June 2018 and it did not recover following the pumping event.

The depth to near-surface groundwater at RS-54 ranges 15 to 20 feet bgs under non-pumping conditions (in average or above average rainfall years). Groundwater is present in fractures in the Chatsworth Formation bedrock. Depth to deeper groundwater in the Chatsworth Formation bedrock varies greatly from approximately 100 to 310 feet bgs. Groundwater flow in the bedrock

at the FSDF is very slow. The hydraulic gradient is generally to the north/northwest, but actual flow is influenced locally by fracture flow. The vertical gradient in the Burro Flats area is generally downward but is upward near the base of the western slopes of the FSDF. The Santa Susana Formation and the east-west striking Burro Flats Fault are immediately south of the FSDF

Nature and Extent of Contamination

Groundwater at the FSDF is contaminated with 1,1,1-TCA and TCE from residual contamination retained in the weathered and upper competent bedrock. RS-54 has exhibited the highest volatile organic compound (VOC) concentrations in Area IV and the FSDF, with a maximum concentration of 15,000 microgram per liter ($\mu\text{g/L}$) reported for a sample collected in 1996; during the 2017-2018 GWIM, 1,1,1-TCA concentrations varied between 5,400 $\mu\text{g/L}$ and 11,000 $\mu\text{g/L}$ (CDM Smith 2018a). The maximum TCE concentration reported for RS-54 was 4,500 $\mu\text{g/L}$ for a 1994 sample; during the GWIM concentrations of TCE varied between 870 $\mu\text{g/L}$ and 2,000 $\mu\text{g/L}$. The metals boron, cadmium, chromium, cobalt, copper, manganese, molybdenum, and nickel have been frequently observed above groundwater screening levels in RS-54 samples.

Chatsworth Formation groundwater has exhibited elevated TCE concentrations, but not 1,1,1-TCA concentrations. Groundwater samples collected from bedrock wells RD-23 and RD-64 have produced TCE concentrations as high as 610 $\mu\text{g/L}$ (2000) and 680 $\mu\text{g/L}$ (2001), respectively. The concentrations of TCE in the adjacent bedrock wells appears to be related to the amount of rainfall and possibly leakage from the shallow perched groundwater zone. In 2017, following several years of drought, the concentrations of TCE decreased significantly to 25 and 34 $\mu\text{g/L}$ in RD-64 and RD-23, respectively. However, the tight nature and low conductivity of the Chatsworth bedrock limits VOC migration to thin fractures above and within Chatsworth Formation groundwater.

In wetter years when the Near-surface groundwater is more prevalent, bedrock fractures produce groundwater with VOCs. Fractures allow movement of VOCs laterally and downward depending on the orientation of the fractures. When Near-surface groundwater in fractures dries up in drier years such as the 2014 to 2017 drought, migration of VOCs is reduced.

Although the nature of the Chatsworth Formation limits VOC migration in bedrock, several open bedrock boreholes at the FSDF are a critical aspect of secondary contaminant flow and distribution in this area. These extended open boreholes provide conduits for water to be released from fractures, allowing for downward migration of contaminants in the well columns.

Groundwater Issues Potentially Requiring Remediation

The main groundwater issues at the FSDF include the following:

- RS-54 is the most-impacted Near-surface monitoring well at the FSDF; VOCs present in fractures that the well boring intercepts are also a source for deeper bedrock contamination.
- Open bedrock boreholes provide conduits for direct vertical migration of contaminants between contaminated and non-contaminated intervals in the bedrock

- Diffusion from residual 1,1,1-TCA and TCE retained in the weathered and upper competent bedrock provides an ongoing source to groundwater contamination during wet periods when Near-surface groundwater is present.
- Packer testing of bedrock coreholes have identified fractures bearing VOCs at depth. However, not all fractures are capable of producing water or harbor VOCs.

2.2 Building 56 Landfill

Contaminants and Sources

TCE is the main contaminant in bedrock groundwater underlying the Building 56 Landfill. The Building 56 Landfill, located southwest of the Building 56 basement excavation (**Figure 2-2**), consists of a 4-acre area in which surface depressions and drainages were filled with rock, soil, and construction debris (asphalt, concrete, and scrap metal), resulting in a relatively flat surface. The primary material in the landfill consists of excavated bedrock from the basement of Building 56 during its construction in the 1960s. Building debris was disposed at the landfill through the late 1970s. In the mid-1970s drums of waste (including grease, oils, alcohols, sodium, sodium reaction products, phosphoric acid, asbestos rags, and rope) were stored on the flat ground surface in the middle part of the landfill. Currently, the basement excavation is a circular vertical pit extending approximately 65 feet into the bedrock.

Based on soil and soil vapor data, there does not appear to be a VOC source associated with the Building 56 Landfill. TCE and its degradation product, *cis*-1,2- dichloroethene (*cis*-1-2 DCE), have been detected in one well at the landfill area (RD-07, a 300-foot deep open bedrock well). The source of this TCE is suspected to be located upgradient and along geologic strike from well RD-91, near Building 4100.

Hydrogeologic Setting

The Building 56 Landfill is located just northeast of the FSDF, and straddles both the northwestern and central Area IV hydrogeologic zones. The Building 56 Landfill is underlain by the Upper Burro Flats member of Chatsworth Formation. Fine-grained beds in the area include the ELV member, which is approximately 170 feet deep at RD-07, and the Lot bed, which is near ground surface at the center of the area.

Near-surface groundwater, when present, occurs as a perched zone above the bedrock; anticipated flow is to the north, in the direction of surface topography. Near-surface groundwater has been observed sporadically in PZ-124, at the northern edge of the area where topography drops off to the north. Closer to the center of the landfill, Near-surface groundwater was observed in RS-16 prior to 2012. Near-surface groundwater appears to be hydraulically connected to surface water in the excavation when it was actively dewatered from 1999 to 2004; however, it is not connected to the underlying Chatsworth Formation groundwater. Groundwater flow in the Chatsworth Formation bedrock is slow. The groundwater flow direction is generally to the north/northwest, but actual flow is influenced locally by fracture flow. The vertical gradient in the area is generally downward, however, there are no data that document vertical gradients within this part of the Chatsworth Formation.

Nature and Extent of Contamination

Groundwater at the Building 56 Landfill area is contaminated with TCE, although it has only been detected in RD-07. TCE levels in this well have decreased from 130 µg/L in 1997 to 29 µg/L in 2017. Cis-1,2-DCE has also been detected in RD-07, at levels up to 5.6 µg/L. Since contamination has not been detected in the downgradient bedrock well (DD-141) to the northwest, the leading edge of the plume appears to be within the landfill boundary. Based on packer testing data from 2016, the highest TCE levels were detected in fractures approximately 120 feet bgs. TCE was also detected in fractures as deep as 280 feet bgs (6 µg/L), below the ELV Member.

Groundwater Issues Potentially Requiring Remediation

The main groundwater issue at the Building 56 Landfill is that the source of TCE and cis-1,2-DCE contamination in RD-07 has not been determined, but is suspected to be upgradient of the landfill, near Building 4100.

2.3 Buildings 4057/4059/4626

Contaminants and Sources

Tetrachloroethene (PCE)-contaminated groundwater in Area IV has been identified near former Buildings 4059 and 4626, and existing Building 4057 (**Figure 2-3**). This is the only location in Area IV with PCE contamination above its maximum contaminant level (MCL).

Two potential sources were located in this area - former Building 4059 and the area between Buildings 4057 and 4626. Building 4059 was part of the SNAP facility in the western part of Area IV. In 1964, a French drain was constructed below the foundation of Building 4059 to collect and remove groundwater infiltrating from test cells of the reaction vault. From 1986 through 1992, water collected in the drainage system was found to be contaminated with PCE, TCE, and their degradation products, and tritium (CH2M Hill 2008). Water from the French drain was temporarily stored in a holding tank, screened for radioactivity, and then discharged through carbon treatment vessels to the storm drain. Building 4059, the French drain, and storage tanks were removed in 2003 and 2004.

Former Building 4626 was used for equipment storage; soil samples collected in 2005 on the south side of the building contained VOCs, including PCE at 37 micrograms per kilogram (µg/kg) at 9 feet bgs. Existing Building 4057 supported the liquid metals testing program.

Hydrogeologic Setting

Buildings 4057/4059/4626 are located adjacent to and northwest of the Building 56 Landfill and straddle the northwestern and central hydrogeologic zones. The area is underlain by up to 12 feet of native soil and the Upper Burro Flats member of the Chatsworth Formation. Fine-grained beds in the area include the ELV member, which is approximately 100 feet deep at DS-43, and the Lot bed, which is near ground surface at RD-24.

Near-surface groundwater is present at Building 4057 at piezometer PZ-109 which is installed into the weathered Chatsworth Formation. The Near-surface groundwater at PZ-109 is likely the western edge of the localized groundwater “mound” observed to the immediate east-northeast in

central Area IV. Near-surface groundwater at PZ-109 is not connected to the underlying Chatsworth Formation groundwater. Groundwater flow in the Chatsworth Formation bedrock is slow. The groundwater flow direction is generally to the north/ northwest, but actual flow is influenced locally by fracture flow. The vertical gradient in the area is generally downward.

Nature and Extent of Contamination

Recent results indicate that PCE exceeds its MCL only in well PZ-109 (42 µg/L in 2017; 79 and 42 µg/L in February and May 2018, respectively). The vertical extent of PCE contamination in groundwater near Building 4057 is less than 80 feet bgs, as determined by results in DS-43 (0.57 µg/L). In 2017, the result for Chatsworth Formation well DD-142 at former Building 4059 was 0.2 µg/L.

Groundwater data collected since 2000 indicates that PCE levels in groundwater are declining, and that the area of PCE-impacted groundwater is not migrating with predicted groundwater flow direction.

Groundwater Issues Potentially Requiring Remediation

PCE concentrations have been steadily declining, and the plume is not migrating. Continued groundwater monitoring will document further degradation to levels below the MCL. A review of the contaminant degradation rate for PZ-109 indicates that PCE concentration in this well could be below the MCL within approximately 30-35 years. Remedial timeframe could be reduced through an interim measure.

2.4 Hazardous Materials Storage Area/Building 4457

Contaminants and Sources

TCE is the main contaminant of concern for groundwater underlying the HMSA. The HMSA consisted of several structures, including: laboratories, reactor testing buildings, chemical storage buildings, sumps, and several tanks which were used to store various forms of sodium or ammonia, fuels, lubricants, sulfuric acid and acid rinse waters, sodium hydroxide, and caustic rinse waters. Several spills of sulfuric acid, ammonia, and sodium hydroxide have been documented. Building 4457 was used for testing of sodium-lubricated bearings for large sodium pumps in the 1960s, and later, for storage of a variety of chemicals including waste oils, acids, bases, solvents, petroleum hydrocarbon oils, and other lubricants. A 1,000-gallon sulfuric acid storage tank and two sumps were located within the building.

With the exception of Buildings 4024, 4019, 4038, and 4057 (**Figure 2-4**), all buildings, tanks and sumps and appurtenances in this area have been removed. No centralized VOC source area has been identified at the HMSA; rather, groundwater contamination likely resulted from spills or releases at multiple locations, particularly near Buildings 4457, 4026, and 4357, where VOCs were detected in soil vapor samples. The contaminated bedrock matrix and fractures likely act as an ongoing source of TCE contamination in groundwater.

Hydrogeologic Setting

The HMSA is located immediately east of Buildings 4057/4059/4626, within the central hydrogeologic zone. The HMSA is underlain by up to 11 feet of soil and the Upper Burro Flats member of the Chatsworth Formation. The fine-grained ELV member is either exposed at the surface or subcrops beneath the soils between RD-29 and PZ-122.

In some dry years, Near-surface groundwater at the HMSA is discontinuous and perched above the Chatsworth Formation groundwater. In 2017 and 2018, the Near-surface groundwater was continuous with Chatsworth Formation groundwater. The ELV member may be providing a barrier to the downward infiltration of precipitation, causing perched conditions, particularly in the eastern portions of the HMSA. Groundwater flow direction in the Near-surface groundwater varies considerably. The HMSA is located on the northwestern edge of the groundwater mound within the Chatsworth Formation; bedrock groundwater flows radially outward, predominantly to the east, southeast, southwest, and west. Potentiometric head differences between the Near-surface groundwater and the Chatsworth Formation groundwater over much of the HMSA indicates a downward vertical gradient. Groundwater may be semi-confined in the bedrock beneath the ELV member.

Nature and Extent of Contamination

TCE-contaminated groundwater is located in the center of the HMSA, in the area of DD-144, PZ-108, and PZ-120; concentrations in these wells in 2017 ranged from 13 to 170 µg/L. Concentrations in wells surrounding this area were either below the MCL or non-detect, indicating that the horizontal extent of contamination is confined to the HMSA. TCE contamination at DD-144 (a bedrock well open to 71 feet bgs) in the March 2018 sample was 200 µg/L. Deeper bedrock well DD-146 (open 120 to 140 feet bgs) was installed at the DD-144 location in June 2018. The July 2018 sample collected from DD-146 was non-detect for TCE, indicating the vertical depth has been defined.

Groundwater Issues Potentially Requiring Remediation

TCE concentrations in the center of the HMSA in both near-surface and deep bedrock groundwater continue to exceed 50 µg/L.

2.5 Tritium Plume

Contaminants and Sources

Tritium has impacted Chatsworth Formation groundwater in the north central portion of Area IV (**Figure 2-5**), near buildings 4059, west of the RMHF, and centered near former building 4010, where reactor experiments were conducted during the 1960s and early 1970s. The source of the tritium has not been determined but has partially been attributed to the absorption of neutrons captured in lithium in the concrete in former buildings 4059 and 4010, both of which have been removed. Radiologically impacted bedrock adjacent to reactor vaults for these two buildings also has been removed.

Hydrogeologic Setting

The Tritium Plume is located within the northwest hydrogeologic zone, north of the HMSA, east of Buildings 4059. This area is underlain by up to 11 feet of native soil and the Upper Burro Flats member of the Chatsworth Formation. The top of the fine-grained Lot Bed occurs at depths ranging from approximately 30 feet bgs at RD-93 to 85 feet bgs at RD-90.

Depth to groundwater in this area varies between 30 and 90 feet bgs. Groundwater flow in the Chatsworth Formation bedrock is slow. The hydraulic gradient is generally to the northwest, but actual flow is influenced locally by fracture flow.

Nature and Extent of Contamination

The approximate horizontal extent of the tritium plume is confined within the boundary of the tritium plume area. Tritium concentrations have steadily decreased over time, consistent with its approximate 12.5-year half-life. The spring 2018 sampling results confirmed that tritium exceeded its MCL of 20,000 picocuries per liter (pCi/L) in two wells, RD-95 at 33,000 pCi/L (North Wind 2018) and RD-95 at 31,600 pCi/L; tritium concentrations in these wells will likely degrade below the MCL within the next 10 years. Seep well SP-T02D to the west/northwest, had a concentration of 1,119.7 pCi/L in 2018.

Groundwater Issues Potentially Requiring Remediation

Tritium is present above its MCL by the levels have been steadily declining. Continued groundwater monitoring will document further degradation to levels below the MCL.

2.6 Radioactive Materials Handling Facility

Contaminants and Sources

Groundwater at the RMHF is contaminated with TCE and strontium-90 (Sr-90). The RMHF was used for processing, packaging, and shipping of solid and liquid radioactive wastes and materials. The main source of groundwater contamination is a leach field that was constructed into fractured bedrock in the drainage north of the RMHF (**Figure 2-6**). Although intended for discharge of domestic wastes, the leach field was also connected to radioactive liquid wastes hold up tanks. Liquid wastes in the tanks, which also contained TCE, were discharged to the leach field and fractured bedrock.

In 1978, contaminated soil from the leach field was excavated to bedrock, and radioactive materials observed in the upper portion of the bedrock were removed by hydraulic hammering excavation. Following removal of bedrock materials, the bedrock was sealed with bituminous asphalt mastic and the excavation backfilled with 4 to 10 feet of soil.

Well RD-63 was installed in 1994 and pumped intermittently for nearly 10 years. The specific objectives of the groundwater extraction were not documented but it is assumed to be due to elevated TCE concentrations in nearby wells; approximately 4.3 million gallons of groundwater extracted, and TCE levels in RD-63 decreased from 20 to 4.9 µg/L during the pumping period.

Hydrogeologic Setting

The RMHF is located adjacent to and northeast of the Tritium Plume, within the northwestern hydrogeologic zone. The area is underlain by a thin veneer of soil and the Upper Burro Flats member of the Chatsworth Formation. Fine-grained beds in the area include the ELV member, which ranges from approximately 150 feet bgs in RD-63 to 190 feet bgs at the RD-34 well cluster, and the ELV member, which is approximately 400 feet deep at the RD-34 cluster.

Groundwater elevations vary significantly in wells near the RMHF leach field, with Near-surface groundwater wells showing greater variability than bedrock wells. Near-surface groundwater flow is more westerly than the expected northerly trend for Chatsworth Formation groundwater in this area, possibly due to east-west trending fractures in weathered bedrock that direct Near-surface groundwater to the west. The hydraulic gradient in the Chatsworth Formation bedrock groundwater is to the northwest, but actual flow is influenced locally by fracture flow. Groundwater elevation differences in the RD-34 well cluster suggest a small downward vertical hydraulic gradient in the shallower part of the Upper Burro Flats member and a moderate upward hydraulic gradient between the lower and upper strata of the Upper Burro Flats member.

Nature and Extent of Contamination

TCE has been detected in RD-63 at concentrations below or just slightly above its MCL of 5 µg/L; the 2017 concentration was 6.2 µg/L. TCE concentrations in the remaining wells at the RMHF are below the MCL. The vertical extent of TCE contamination is just over 200 feet bgs. Sr-90 was reported in RD-98 at 183 pCi/L in 2011 (a wet rainfall period) and at 114 pCi/L in 2017 following several years of drought. The vertical depth of Sr-90 impacted bedrock is between 35 and 45 feet bgs.

Groundwater Issues Potentially Requiring Remediation

Sr-90 in bedrock fractures remains a threat to groundwater quality. Using the maximum observed groundwater concentration for Sr-90 of 183 pCi/L, this threat could last for up to 150 years. The flushing of TCE from the leach field location by rainfall infiltration, coupled with the 10 years of groundwater pumping and natural degradation, has reduced TCE concentrations in this area to its MCL. The average TCE concentration for wells RD-63, RD-34A, RD-30, and RD-98 in 2017 was 3.2 µg/L.

2.7 Buildings 4030/4093 Leach Fields/DOE Leach Field 1

Contaminants and Sources

Buildings 4030 and 4093 (**Figure 2-7**) were former test reactor buildings, where nuclear waste releases were reported. The leach fields associated with Buildings 4030 (AI-Z3) and 4093 (AI-Z4) received waste from septic tanks from 1958 to 1961.

TCE has been detected in bedrock well RD-17 at levels below the MCL (0.71 µg/L in 2017). TCE is not known to have been used or released at these buildings and is not associated with the leach fields. Rather, this well likely monitors the eastern edge of the TCE plume at the HMSA.

Hydrogeologic Setting

Buildings 4030 and 4093 and their associated leach fields are located northeast of the HMSA, within the eastern hydrogeologic zone. The area is underlain by up to 10 feet of soil and the Upper Burro Flats member of the Chatsworth Formation. Fine-grained units in the area include the ELV member, which is approximately 100 feet bgs near Building 4030 and DS-44, and the Lot bed, which outcrops near Building 4093 and RD-17.

The presence of near-surface groundwater in the area is uncertain. The area is located southeast of the center of the bedrock groundwater mound, and therefore groundwater is expected to flow to the southeast.

Nature and Extent of Contamination

There is no significant groundwater contamination in this groundwater investigation area. It is likely that the TCE observed in well RD-17 is the eastern boundary of the HMSA TCE plume.

Groundwater Issues Potentially Requiring Remediation

There are no issues in this area that require groundwater remediation.

2.8 Building 4064 Leach Field

Contaminants and Sources

Building 4064 was used as the former Nuclear Materials Storage Facility to store packaged source material, including depleted uranium and thorium and enriched uranium-233. The leach field received waste from a 750-gallon septic tank. There were documented releases of radiological materials at the building. There was no reported chemical use at the building.

An area of Cs-137 impacted soil was excavated during demolition of the building in 1993. Methylene chloride and acetone were also detected in the soil at 40 and 130 µg/kg, respectively.

Hydrogeologic Setting

Building 4064 and its associated leach field are located adjacent to and east of Buildings 4030/4093 leach fields (**Figure 2-7**), within the eastern hydrogeologic zone. The area is underlain by less than a foot of soil and the Upper Burro Flats member of the Chatsworth Formation and the ELV member. The leach field was located above the subcropping ELV member, which dips beneath Building 4064.

The presence of Near-surface groundwater in the area is uncertain. Well DS-45, which was installed in 2016 into the top of the ELV at depth of 75 feet bgs, has been dry. The area is located near the northeastern edge of the bedrock groundwater mound, and therefore groundwater is expected to flow to the northeast and southeast.

Nature and Extent of Contamination

No chlorinated solvent contamination has been identified in groundwater in this area.

Groundwater Issues Potentially Requiring Remediation

There are no issues in this area that require groundwater remediation.

2.9 Old Conservation Yard

Contaminants and Sources

Low levels of TCE (13 µg/L maximum in 1990, estimated value of 0.43 µg/L in 2017) have been detected in well RD-14 at the OCY. The OCY was used from 1952 to 1977 to store salvageable metal objects and other materials in drums. All materials were removed in 1977 and the site was converted for vehicle storage. Subsequent investigations identified PCBs, metals, and Cs-137 in area soil; impacted soil was removed.

Hydrogeologic Setting

The OCY is located in the northeast corner of Area IV (**Figures 1-1, 2-8**), within the eastern hydrogeologic zone. Soils in the area consist of up to 10 feet of native soil and fill placed following soil and structure removal actions. Soils are underlain by the Upper Burro Flats member of the Chatsworth Formation. The fine-grained Lot bed subcrops below soils just north of RD-14.

Near-surface groundwater is discontinuous and perched above the Chatsworth Formation groundwater when present. The hydraulic gradient is generally to the north, but actual flow in the bedrock is influenced locally by fractures.

Nature and Extent of Contamination

Bedrock well RD-14 is the only well at the OCY used to monitor groundwater quality. TCE concentrations above the MCL were last observed in 2011 and concentrations have been below the MCL since then. The metals beryllium, cadmium, cobalt, selenium, and vanadium have been sporadically detected, but typically at their screening levels.

Groundwater Issues Potentially Requiring Remediation

Per the analysis of metals hotspots presented in the Area IV Groundwater Remedial Investigation (RI) Report, the single well may not be sufficient to determine presence of metals contamination at the OCY

2.10 Building 4065 Metals Clarifier/DOE Leach Fields 3

Contaminants and Sources

TCE is the main contaminant detected in groundwater in this area.

The Metals Clarifier/DOE Leach Fields 3 Site has been combined into one groundwater investigation area (**Figure 2-9**). Building 4065 was used as a vacuum test facility from 1963 to 1972. From 1973 until it was demolished in 1999, the building was used as the Chemical and Metallographic Analysis Laboratory. The DOE Leach Fields 3 site includes four leach fields associated with Buildings 4353 (AI-Z15), 4363 (AI-Z14), 4373 (AI-Z13), and 4383 (AI-Z10)

The Metals Clarifier Laboratory Building 4065 and several former structures are where TCE may have been used and released to the environment.

Hydrogeologic Setting

The Building 4065 Metals Clarifier and DOE Leach Fields 3 area is located south of the Building 56 Landfill, Buildings 4057/4059/4626 area, and the HMSA, within the central hydrogeologic zone. Soils in this area are up to approximately 20 feet thick. The area is primarily underlain by the Lower Burro Flats member of the Chatsworth Formation, although the fine-grained SPA member and the Silvernale Member occur in the far southeast corner of the area. The fine-grained SPA member occurs at approximately 20 feet bgs at PZ-105.

Groundwater in this area occurs in the weathered and competent bedrock. The area is near the southwestern edge of the groundwater mound, and therefore groundwater is expected to flow northwest and southwest; however, actual flow is influenced locally by fractures.

Nature and Extent of Contamination

Four piezometers (PZ-005, PZ-103, PZ-104, and PZ-105) monitor TCE concentrations in the weathered bedrock; recent (2017) concentrations range from 1.8 µg/L (PZ-104) to 7.9 µg/L (PZ-105). Chatsworth Formation well DD-145 showed 0.92 µg/L in 2017 indicating that the vertical extent in this area has been defined. Trend data for this location starting in 2002 show a steady decline in concentrations. The maximum concentrations observed were 12 µg/L for PZ-105 (2002), 8 µg/L for PZ-005 in 2002 (1.5 µg/L in 2017), 3 µg/L for PZ-103 in 2003 (estimated value of 0.53 µg/L in 2017), 9 µg/L for PZ-104 in 2003 (1.8 µg/L in 2017).

Groundwater Issues Potentially Requiring Remediation

Trend data for this location illustrate a steady decline in TCE concentrations. Further monitoring will be performed to confirm this trend.

2.11 Building 4100 Trench

Contaminants and Sources

There is no contamination or sources of contamination related to the Building 4100 Trench. The Building 100 Trench, labelled as such due to its proximity to Building 4100 (**Figure 2-10**), was used from 1960 through 1966 to burn and dispose of building debris. All materials were removed. The trenches were filled and partially paved over in 1971. In 2003, the trenches were excavated and approximately 330 cubic yards of soil and debris removed. The trenches were then backfilled.

Hydrogeologic Setting

The Building 4100 Trench area is located west of the Building 4065 Metals Clarifier/DOE Leach Fields 3 area, within the central hydrogeologic zone. The hydraulic gradient is generally to the northwest, but actual flow in the bedrock is influenced locally by fractures.

Nature and Extent of Contamination

There is no significant groundwater contamination in this groundwater investigation area.

Groundwater Issues Potentially Requiring Remediation

There are no issues in this area that require groundwater remediation.

2.12 Building 4009 Leach Field

Contaminants and Sources

TCE is the primary contaminant reported at the Building 4009 Leach Field, based on results from PZ-109 in 2003. Building 4009 was used as a nuclear testing and in-service inspection facility for high-energy rate forging, and for non-nuclear research. The building was connected to a sanitary leach field (AI-Z11; **Figure 2-10**), which may have received liquid process wastes after 1961.

The source of TCE in PZ-102 is not known; however, it is likely from the Building 4100 source than from former operations in Building 4009 but it is proximate to Building 4100. A 2018 soil gas investigation of the Building 4009 showed no detectable VOCs at or downgradient of the leach field (CDM Smith 2018b). Therefore, the TCE detected in piezometer PZ-102 is not associated with the leach field. Chatsworth Formation well RD-91 near Building 4100 had a reported concentration of 200 µg/L TCE in 2014.

Hydrogeologic Setting

The Building 4009 Leach Field area straddles the eastern and central hydrogeologic areas, located between the FSDF and the Building 4065 Metals Clarifier/DOE Leach Field 3. Soils range from 1 to 5 feet thick and overlie the Upper and Lower Burro Flats members of the Upper Chatsworth Formation.

PZ-102 is the only well near the Building 4009 Leach Field; it has been dry since 2014. The groundwater flow direction is generally to the northwest, but actual flow in the bedrock is influenced locally by fractures.

Nature and Extent of Contamination

There is no significant groundwater contamination in this groundwater investigation area. In 2003, TCE was detected in PZ-102 at 6 µg/L, but the well has been dry since 2014. Recent soil gas study results indicated that TCE is not present at the leach field site.

Groundwater Issues Potentially Requiring Remediation

There are no issues for the leach field site that require groundwater remediation.

2.13 Building 4020 Rockwell International Hot Lab

Contaminants and Sources

TCE is the primary contaminant reported at the RIHL, based on recent results from piezometer PZ-103 (**Figure 2-10**). TCE was reported at an estimated value of 3 µg/L in 2003 and at an estimated value of 0.53 µg/L in 2017. The RIHL was used from 1959 through 1987 for the examination and preparation of irradiated nuclear fuel, and decladding, cleaning, and packaging of nuclear fuel for reuse. Chemicals, including solvents, semi-volatile organic compounds (SVOCs), PCBs, and metals, were stored in drums in a machine shop. Building 4020 also had a leach field (AI-Z12).

Soil contaminated with radionuclides and chemicals was removed between 1986 and 1998. Based on soil data for the RIHL, there is no remaining source of contamination to groundwater.

Hydrogeologic Setting

The RIHL is located in the southern portion of Area IV, on the western side of the Building 4065 Metals Clarifier/DOE Leach Field 3 (**Figures 1-1, 2-10**), within the central hydrogeologic zone. Soils range from 6 to 14 feet thick and overlie the Lower Burro Flats member of the Upper Chatsworth Formation.

The groundwater flow direction is generally to the northwest, but actual flow in the bedrock is influenced locally by fractures.

Nature and Extent of Contamination

There is no significant groundwater contamination in this groundwater investigation area. PZ-103 on northeastern corner of the RIHL site monitors groundwater in the weathered bedrock on western edge of the Metals Clarifier plume. TCE levels have historically been below the MCL; the most recent concentration in 2017 was estimated at 0.53 µg/L.

Groundwater Issues Potentially Requiring Remediation

There are no issues in this area that require groundwater remediation.

2.14 Buildings 4133/4029 Hazardous Waste Management Facility

Contaminants and Sources

The HWMF is comprised of Building 4133 and Building 4029 (**Figure 1-1**). Building 4133 was actively used from 1978 to 1997 to treat reactive metals such as sodium and potassium for subsequent reaction with air. Building 4029 was originally used from 1959 to 1974 for the storage of radioactive materials; and then for the storage of reactive metals until 1997.

These buildings are RCRA-regulated facilities that have been combined under the same RCRA permit. The HWMF was permitted under RCRA in 1983 and a RCRA closure plan was developed

following cessation of operations in 1997. Therefore, these buildings were not evaluated further as part of the Area IV Groundwater RI Report.

Hydrogeologic Setting

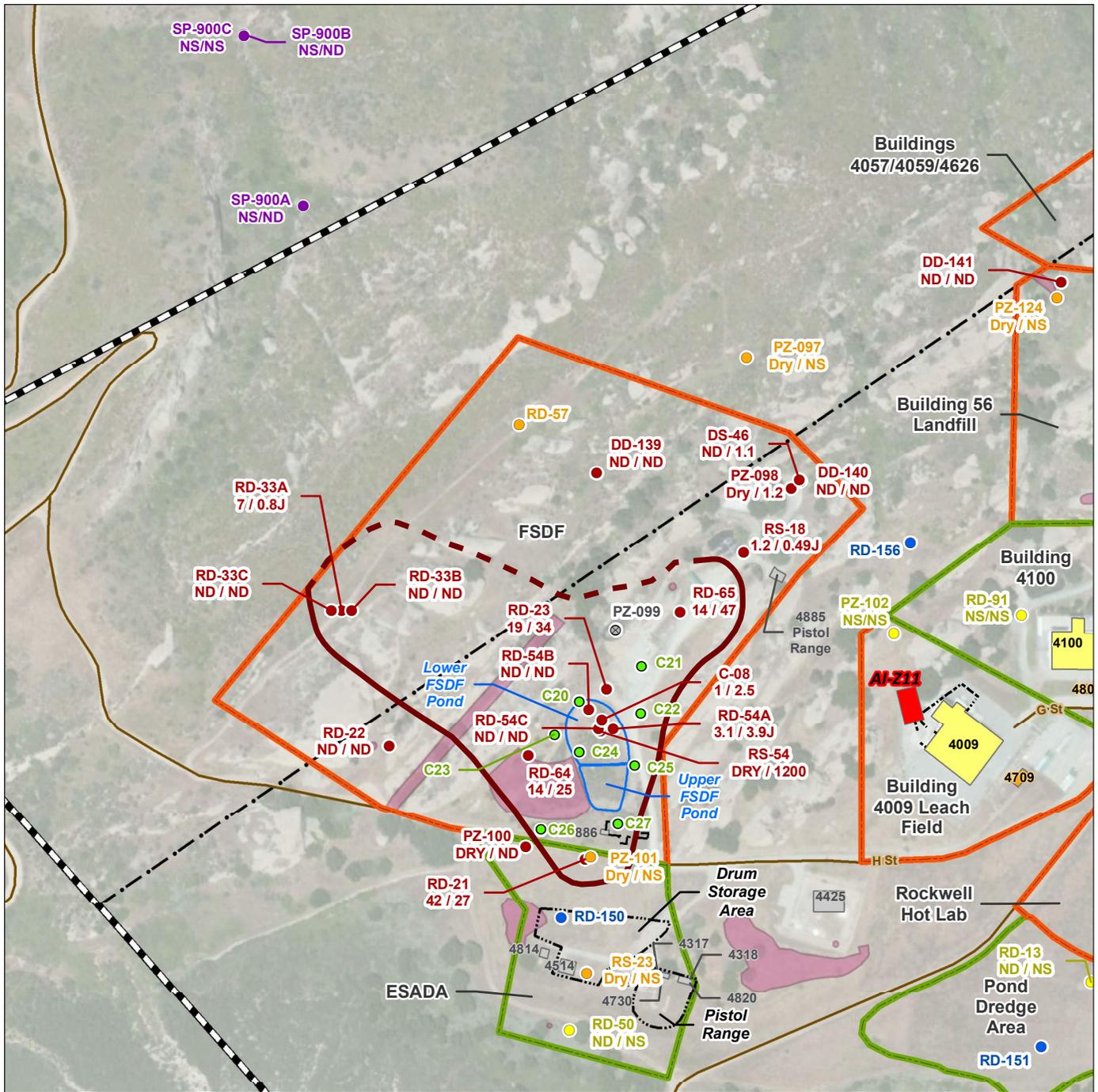
Building 4133 is located on the northwest side of the Buildings 4030 and 4093 Leach Fields, within the northwest hydrogeologic zone. Building 4029 is located on the eastern side of the Buildings 4030 and 4093 Leach Fields, within the eastern hydrogeologic zone.

Nature and Extent of Contamination

The RCRA closure action will involve monitoring well installation to evaluate the potential for groundwater contamination. Any detected contamination will be addressed as part of the closure action. These buildings were not evaluated in the Area IV Groundwater RFI Report.

Groundwater Issues Potentially Requiring Remediation

Any groundwater issues will be addressed as part of the RCRA closure action.



LEGEND

● Sampled Well - Dry well or insufficient water for purging/sampling ● (<3 feet of water in well designated for low-flow purging)	● Not Sampled	⊗ Abandoned Well	● Boeing Well	● Corehole Location	● Seep Well	⊖ TCE at 5 ug/L	--- Former Concrete Pool	— Road Centerline	⊕ Former FSDF Pond	■ Chemical Use Areas Debris Responsibility* Boeing DOE	■ Groundwater Investigation Area Boeing DOE Existing Structure	■ Existing Substation	■ Demolished Structure	⊞ SSFL Property Boundary	⊞ Area IV Boundary
---	---------------	------------------	---------------	---------------------	-------------	-----------------	--------------------------	-------------------	--------------------	--	---	-----------------------	------------------------	--------------------------	--------------------

Notes:
 - Original GIS layers provided by MWH/Boeing; updated by CDM Smith as needed.
 * - Leach Fields labeled using unique ID (AI-Zxx).
 - Plume boundary dashed where inferred.
 - 2016/2017 TCE results are ug/L or ppb.
 - U or ND - Non-detected result.
 - J - Estimated Result.

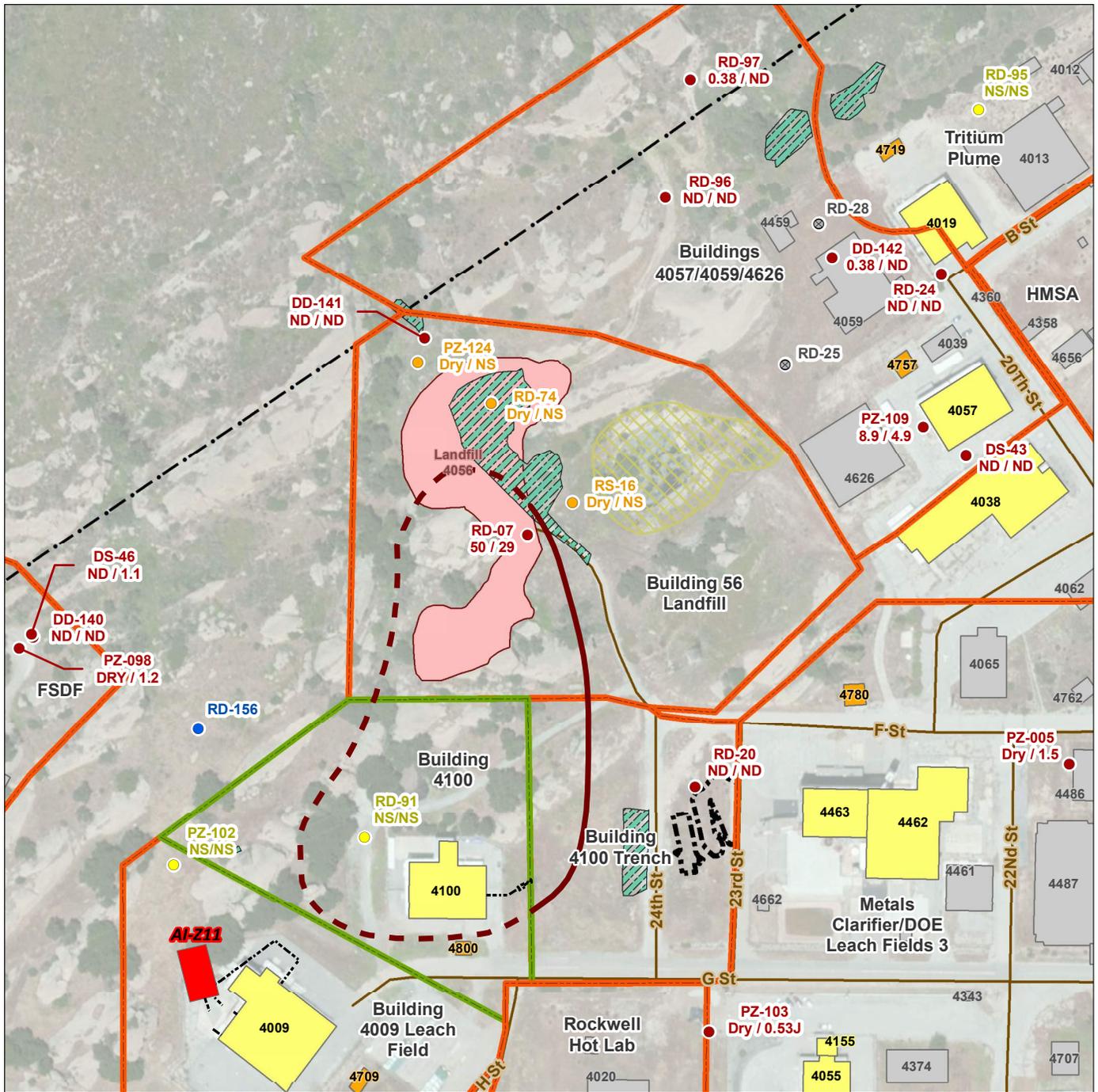
Service Layer Credits:
 - Aerial Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community.
 - Road Centerline Source: Esri, TomTom.

0 150 300 Feet

C:\projects\SantaSusana\GIS\MXD\Groundwater\RI\2018\SSFL_GWRI_FSDF_Layout_20180919.mxd 9/19/2018



FIGURE 2-1
Former Sodium Disposal Facility (FSDF) Layout



- Sampled Well
- - Dry well or insufficient water for purging/sampling (<3 feet of water in well designated for low-flow purging)
- Not Sampled
- ⊙ Abandoned Well
- Boeing Well
- ⊙ Responsibility*
 - Boeing
 - DOE
- ⊙ Boeing
- ⊙ DOE
- ⊙ Boeing
- ⊙ DOE

- Road Centerline
- Building 56 Excavated Area
- Debris Area
- Existing Landfill
- Existing Structure
- Existing Substation
- Demolished Structure
- Area IV Boundary
- SSFL Property Boundary
- B100 Trench Outline

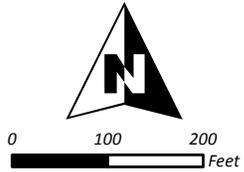
- LEGEND**
- Boeing
 - Boeing
 - DOE

Notes:

- Original GIS layers provided by MWH/Boeing; updated by CDM Smith as needed.
- * - Leach Fields labeled using unique ID (AI-Zxx).
- Plume boundary dashed where inferred.
- 2016/2017 TCE results are ug/L or ppb.
- U or ND - Non-detected result.
- J - Estimated Result.

Service Layer Credits:

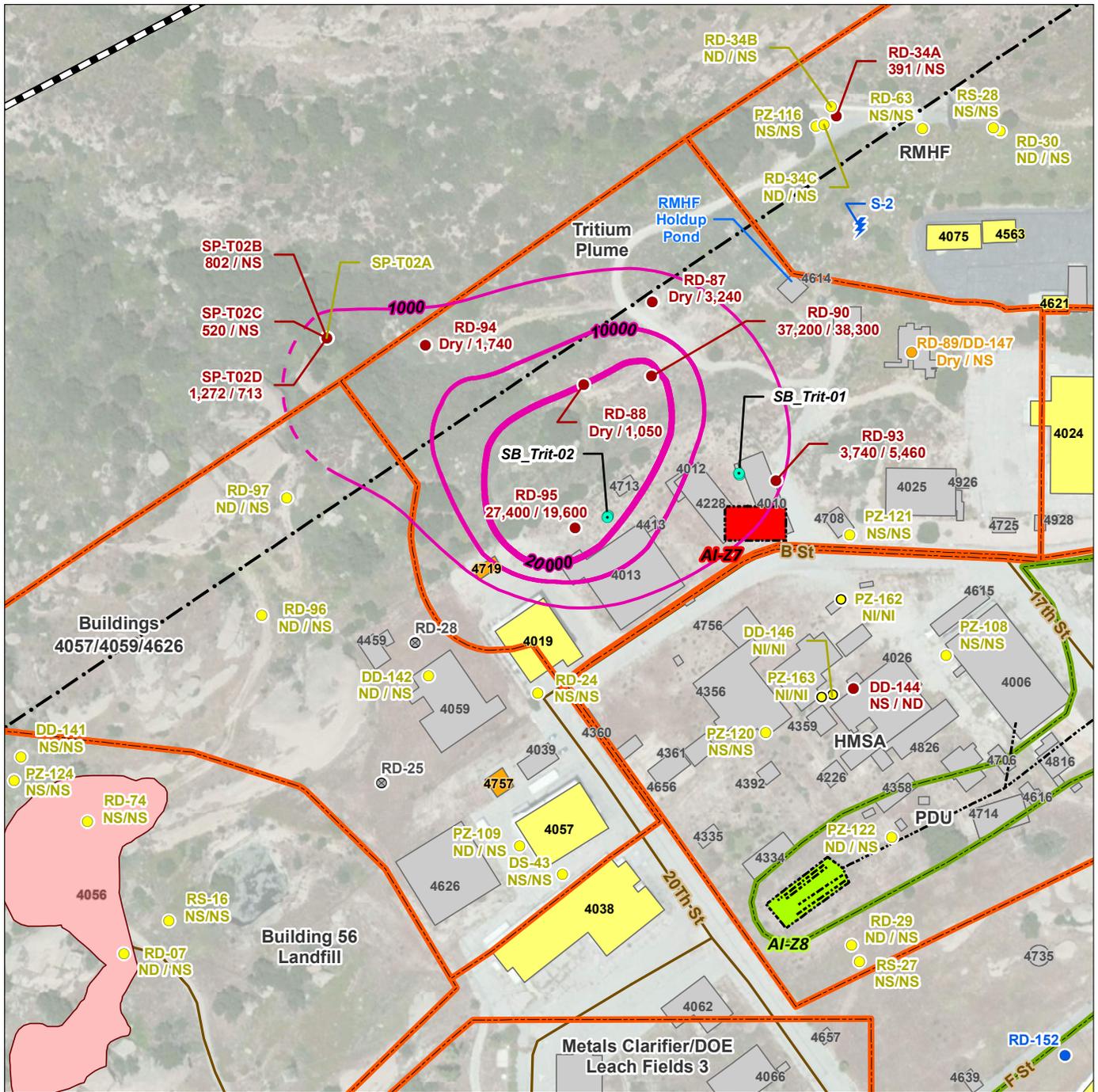
- Aerial Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community.
- Road Centerline Source: Esri, TomTom.



C:\projects\SantaSusana\GIS\MXD\Groundwater\RI\2018\SSFL_GWR1_Bldg56_Landfill_Layout_20180824.mxd 8/24/2018



FIGURE 2-2
Building 56 Landfill Layout



LEGEND

● Sampled Well - Dry well or insufficient water for purging/sampling - (<3 feet of water in wells designated for low-flow purging)	● Not Sampled	● Tritium Soil Boring Location	Responsibility* Groundwater Investigation Area	■ Existing Landfill	▭ Area IV Boundary
● Boeig Well	● Abandoned Well	⚡ Seep	■ Boeing	■ Existing Structure	▭ SSFL Property Boundary
● Tritium at 20,000 Picocuries/L	— Road Centerline		■ DOE	■ Existing Substation	■ Demolished Structure

Notes:

- Original GIS layers provided by MWH/Boeing; updated by CDM Smith as needed.
- * - Leach Fields labeled using unique ID (AI-Zxx).
- Plume boundary dashed where inferred.
- 2016/2017 Tritium results are picocuries/L.
- U or ND - Non-detected result.
- J - Estimated Result.
- NI = Not Installed.

Service Layer Credits:

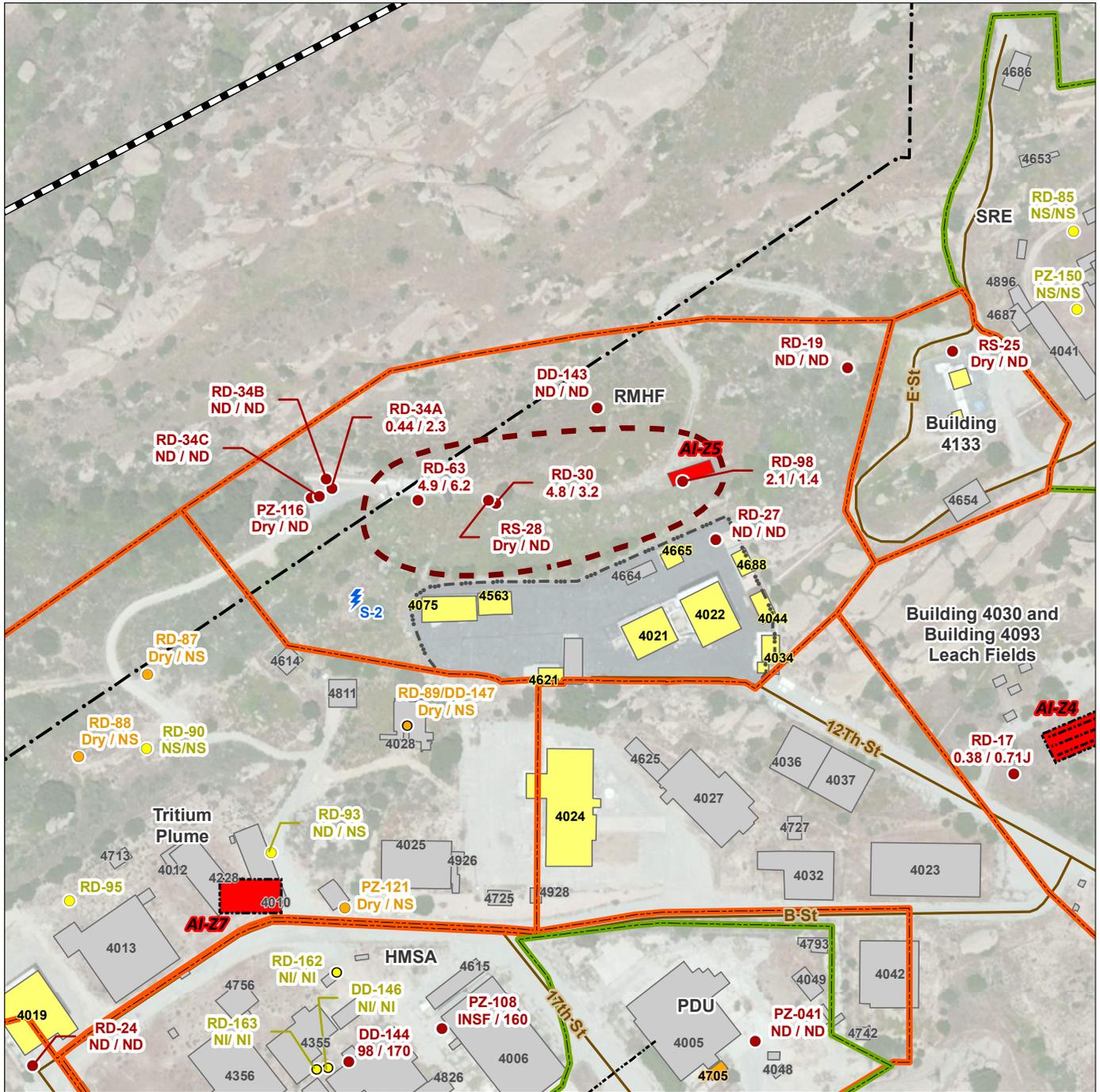
- Aerial Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community.
- Road Centerline Source: Esri, TomTom.

0 100 200 Feet

C:\projects\SantaSusana\GIS\MXD\Groundwater\RI\2018\SSFL_GWR1_Tritium_Plume_Layout_20180824.mxd 8/27/2018



FIGURE 2-5
Tritium Plume Layout



LEGEND

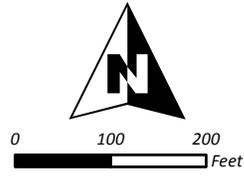
● Sampled Well	● Not Sampled	⚡ Seep	Responsibility*	Groundwater Investigation Area	■ Existing Structure	⊞ Area IV Boundary
○ Dry well or insufficient water for purging/sampling (<3 feet of water in well designated for low-flow purging)	⊙ Abandoned Well	⌋ TCE at 5 ug/L	■ Boeig	■ Boeig	■ Existing Substation	⊞ SSFL Property Boundary
● Boeig Well	— Road Centerline	— Road Centerline	■ DOE	■ DOE	■ Demolished Structure	
			■ RMHF Boundary			

Notes:

- Original GIS layers provided by MWH/Boeing; updated by CDM Smith as needed.
- * - Leach Fields labeled using unique ID (AI-Zxx).
- Plume boundary dashed where inferred.
- 2016/2017 TCE results are ug/L or ppb.
- U or ND - Non-detected result.
- J - Estimated Result.
- NI = Not Installed.

Service Layer Credits:

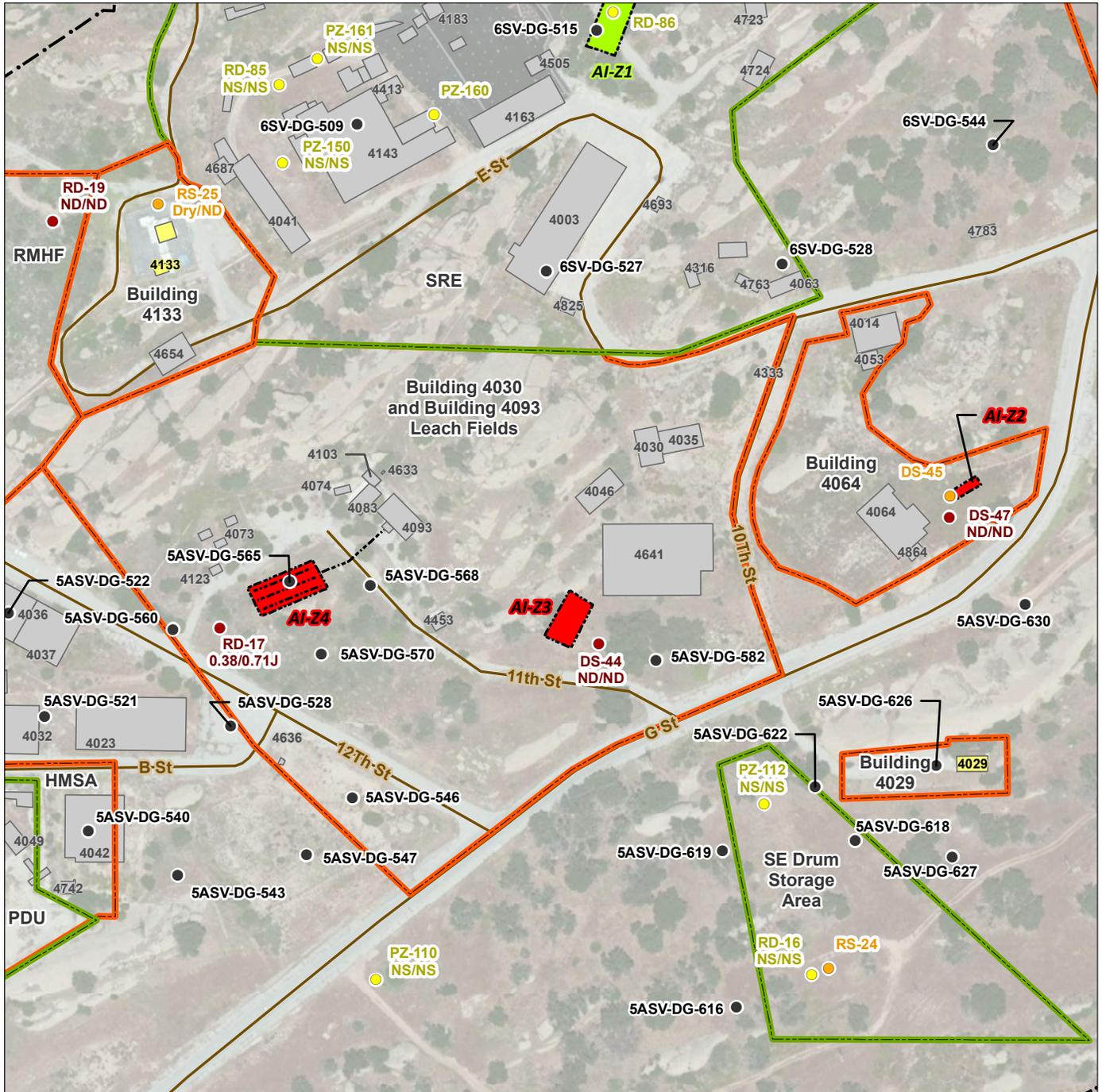
- Aerial Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community.
- Road Centerline Source: Esri, TomTom.



C:\projects\SantaSusana\GIS\MXD\Groundwater\RI\2018\SSFL_GWRI_RMHF_Layout_20180824.mxd 8/24/2018



FIGURE 2-6
Radioactive Materials Handling Facility Layout

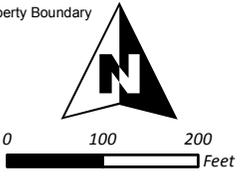


LEGEND

● Sampled Well - Dry well or insufficient water for purging/sampling	● Not Sampled	— Road Centerline	Groundwater Investigation Area	■ Existing Substation
● Abandoned Well	● Boeing Well	Responsibility*	■ Boeing	■ Demolished Structure
● Soil Vapor Location	● DOE	■ Boeing	■ DOE	■ Area IV Boundary
		■ DOE	■ Existing Structure	■ SSFL Property Boundary

Notes:
 - Original GIS layers provided by MWH/Boeing; updated by CDM Smith as needed.
 * - Leach Fields labeled using unique ID (AI-Zxx).
 - Soil Vapor Data Gap locations provided by MWH (2014).
 - 2016/2017 TCE results are ug/L or ppb.
 - U or ND - Non-detected result.
 - J - Estimated Result.

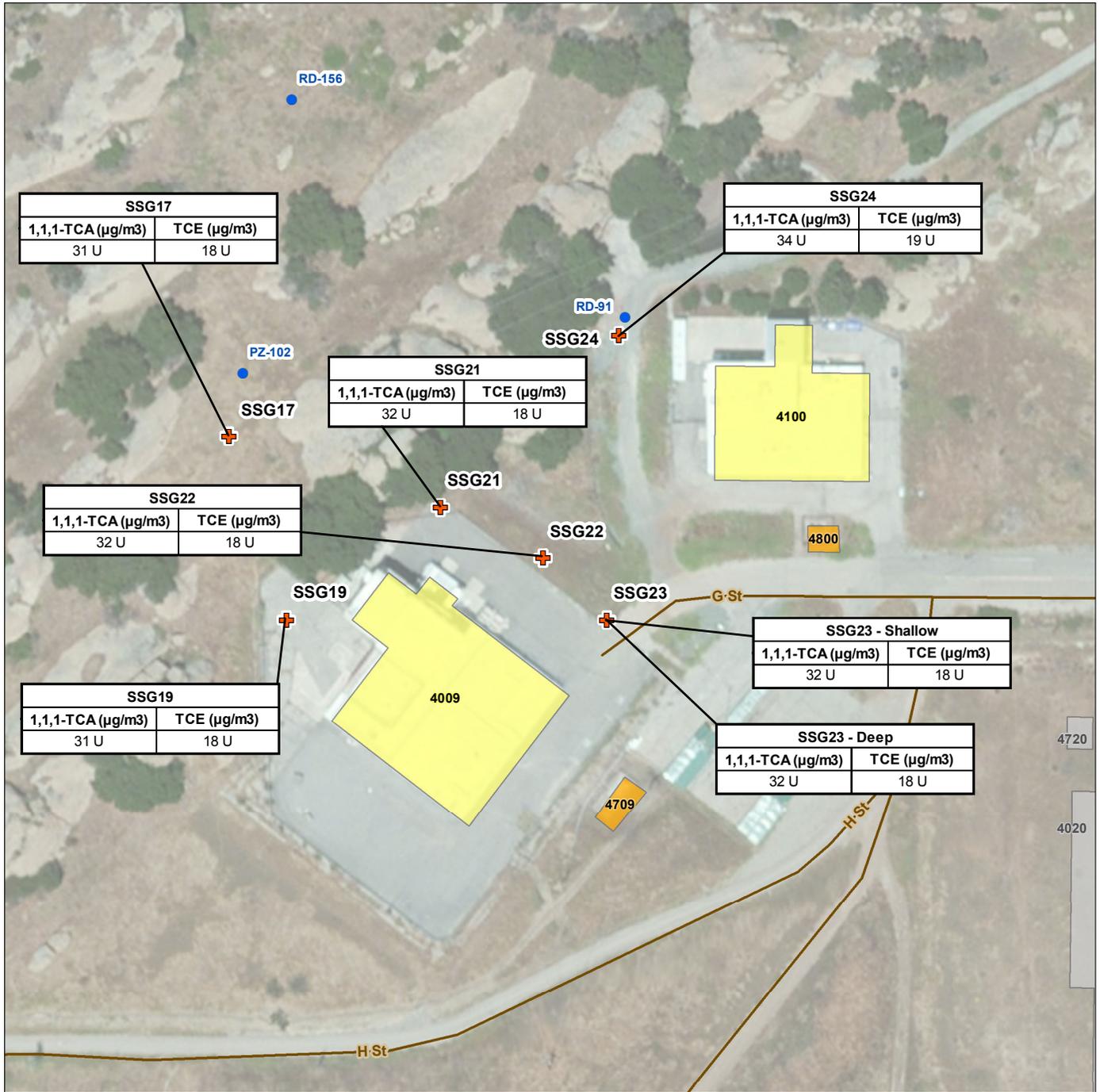
Service Layer Credits:
 - Aerial Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community.
 - Road Centerline Source: Esri, TomTom.



C:\projects\SantaSusana\GIS\MXD\Groundwater\RI\2018\SSFL_GWR1_4029_4030_4064_4093_SEDrum_Layout_20180624.mxd 8/26/2018



FIGURE 2-7
Buildings 4030/4064/4093 Leach Fields Layout



LEGEND

- Soil Gas Location
- Road Centerline
- Existing Structure
- SSFL Property Boundary
- Corehole Location
- Former FSDF Pond
- Existing Substation
- Area IV Boundary
- Existing Well/Piezometer
- Existing Landfill
- Demolished Structure
- Abandoned Well/Piezometer

Notes:
 - Original GIS layers provided by MWH/Boeing; updated by CDM Smith as needed.
 - 1,1,1-TCA = 1,1,1-Trichloroethane.
 - TCE = Trichloroethene.
 - All results ug/m3.
 - J = Estimated result.
 - U = Non-detected result.

Service Layer Credits:
 - Aerial Source: Esri, DigitalGlobe, GeoEye, i-cubed, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community.
 - Road Centerline Source: Esri, TomTom.

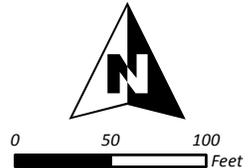
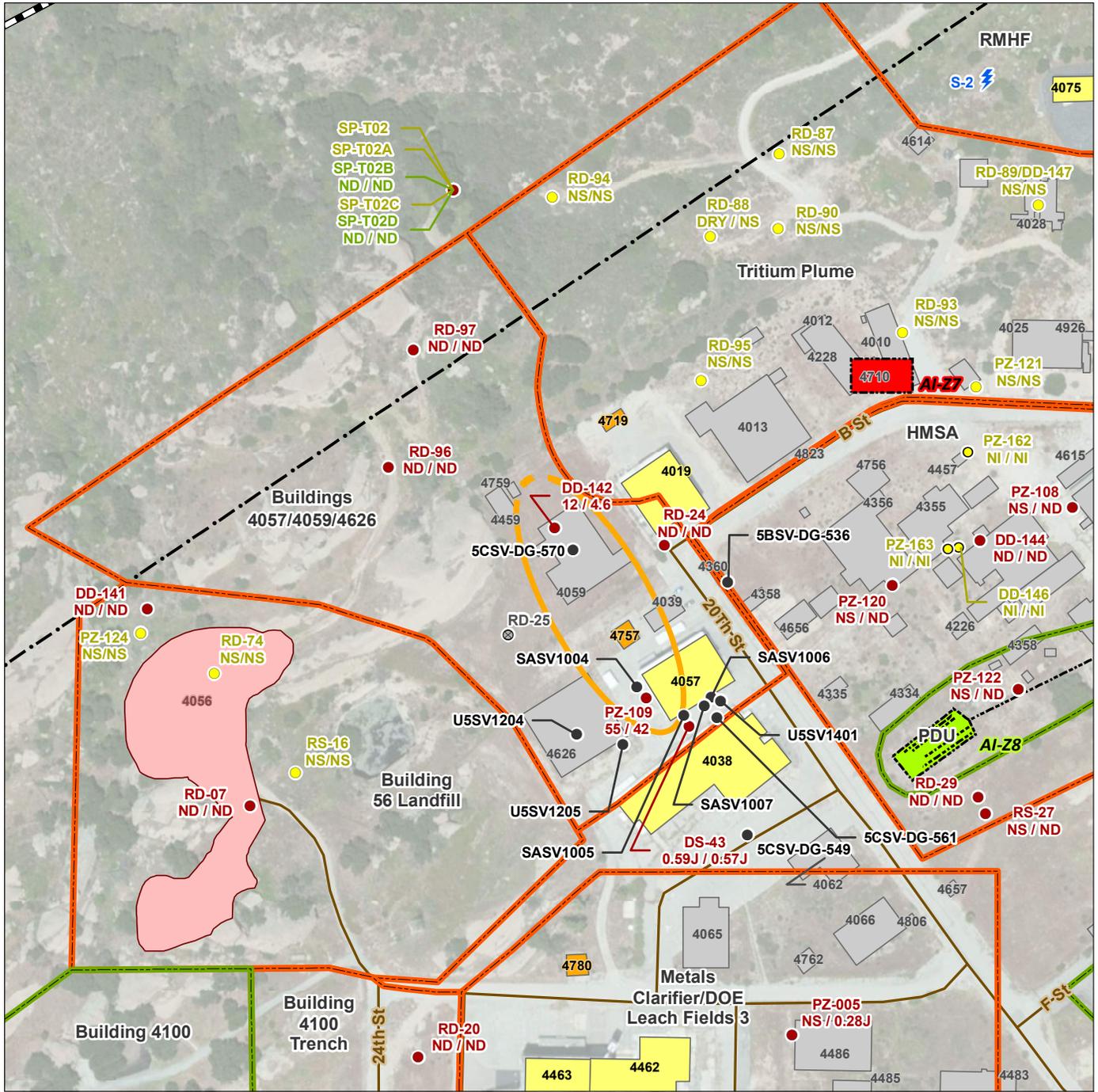


FIGURE 2-10
Building 4009 Soil Gas 1,1,1-Trichloroethane and Trichloroethene Results - 2018



LEGEND

● Sampled Well	⊗ Abandoned Well	— Road Centerline	Groundwater Investigation Area	Existing Structure	Area IV Boundary
● Not Sampled	● Soil Vapor Location	~ PCE above 5 ug/L	Boeing	Existing Substation	SSFL Property Boundary
⚡ Seep			Responsibility*	Demolished Structure	
			Boeing		
			DOE		
			Existing Landfill		

Notes:

- Original GIS layers provided by MWH/Boeing; updated by CDM Smith as needed.
- Leach Fields labeled using unique ID (AI-Zxx).
- Soil Vapor Data Gap locations provided by MWH (2014).
- Plume boundary dashed where inferred.
- 2016/2017 PCE results are ug/L.
- U or ND - Non-detected result.
- NI = Not Installed.

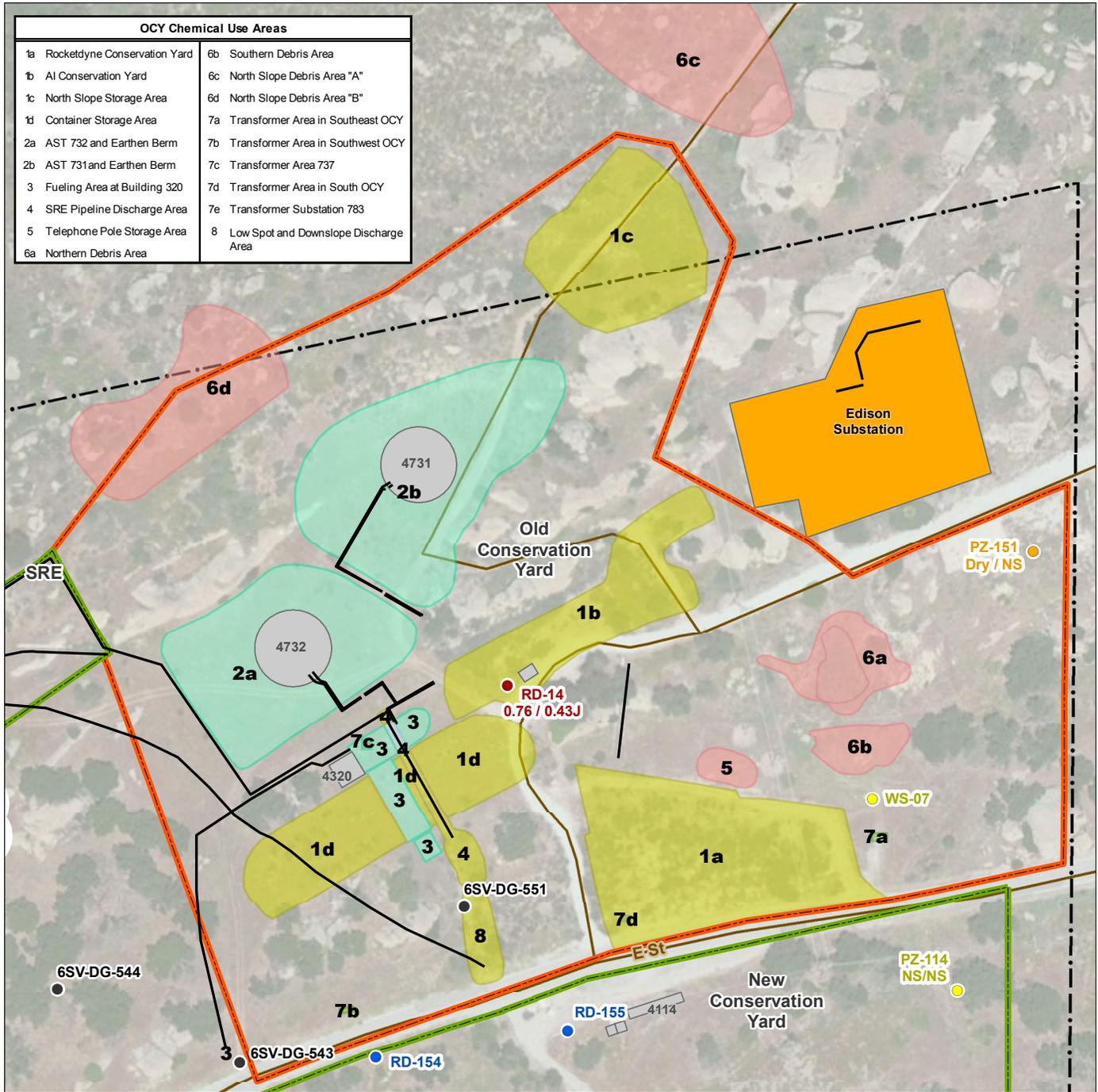
Service Layer Credits:

- Aerial Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community.
- Road Centerline Source: Esri, TomTom.

C:\projects\SantaSusana\GIS\MXD\Groundwater\RI\2018\SSFL_GWR1_Bldg57_Bldg59_Layout_20180824.mxd 8/24/2018



FIGURE 2-3
Buildings 4057/4059/4626 PCE Concentrations - 2016 and 2017



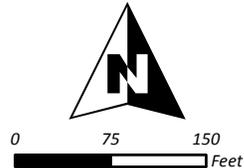
- | | | |
|--|---|--|
| <ul style="list-style-type: none"> ● Sampled Well ○ Dry well or insufficient water for purging/sampling ○ (<3 feet of water in well designated for low-flow purging) ● Not Sampled ○ Abandoned Well ● Boeig Well ● Soil Vapor Location | <ul style="list-style-type: none"> — Pipe — Road Centerline Chemical Use Areas Debris | <p>LEGEND</p> <ul style="list-style-type: none"> Oil PCB Petroleum Potential Screening Groundwater Investigation Area Boeing DOE Existing Structure Existing Substation Demolished Structure Area IV Boundary SSFL Property Boundary |
|--|---|--|

Notes:

- Original GIS layers provided by MWH/Boeing; updated by CDM Smith as needed.
- Soil Vapor Data Gap locations provided by MWH (2014).
- 2016/2017 TCE results are ug/L or ppb.
- U or ND - Non-detected result.
- J - Estimated Result.

Service Layer Credits:

- Aerial Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community.
- Road Centerline Source: Esri, TomTom.



C:\projects\SantaSusana\GIS\MXD\Groundwater\RI\2018\SSFL_GWRI_OCY_Layout_20180824.mxd 8/28/2018

FIGURE 2-8
Old Conservation Yard Layout

Section 3

Development of Remedial Action Objectives

This section outlines the remedial action objectives (RAOs) for Area IV groundwater RCRA Corrective Action sites that are the responsibility of DOE. RAOs are statements of the overarching cleanup goals and timeframes for remediating groundwater, and ARARs, or other requirements to be considered (TBCs) driving the scope of remediation. RAOs are developed to meet the overall objective of protecting human health and the environment by addressing both chemical concentrations and potential exposure pathways. The overall goal for Area IV sites under DOE responsibility is to remediate impacted groundwater to drinking water standards in a timely and cost-effective manner that results in final regulatory closure of the sites.

This goal can be achieved by reducing the contaminant mass, volume, toxicity, or mobility; controlling contaminant migration; performing groundwater monitoring to demonstrate improvement of groundwater conditions; or by a combination of these approaches. Achieving these objectives will require that remedies be hydraulically consistent with those in adjacent areas (i.e., implementation of a remedy at one location should not interfere with a remedy being implemented at a nearby location).

3.1 Corrective Action Objectives

Corrective action objectives are the media-specific goals required to protect human health and the environment. Corrective action objectives have been developed to address protection of human health and environmental receptors, and regulatory policies for groundwater restoration (i.e., protection of the beneficial uses of groundwater). Boeing has entered into a land use covenant (Ventura County 2017) that prevents on-site use of groundwater. However, groundwater beneath Area IV migrates laterally and can surface at seeps and springs adjacent to Area IV. Preventing consumption and contact of groundwater containing contaminants by human and ecological receptors becomes a primary corrective action objective. Reducing contaminant concentrations in groundwater and preventing migration of contaminated groundwater are actions that can be taken to meet the objectives.

DOE considered the promulgated MCL and EPA's risk management range of 1×10^{-4} to 1×10^{-6} , and a hazard index of 1, to establish a risk-based objective for human receptors, and a hazard index of 1 for ecological receptors as a basis for groundwater cleanup. Risk-based cleanup would be considered for any chemical where the MCL is greater than a 1×10^{-4} risk, or the combined chemical risk exceeds 1×10^{-4} . Otherwise, the MCL is DOE's groundwater cleanup objective.

The primary corrective action objectives, listed below, were established for the basis of evaluating corrective action measures described in **Sections 4** and **5**.

- Reduce contaminant concentrations in groundwater to levels that are protective of beneficial uses (i.e., contaminant concentrations are reduced to levels less than or equal to MCLs for drinking water per State Water Resource Control Board [SWRCB] criteria for

potential drinking water) to the extent practicable and within a reasonable timeframe to remain protective.

- Control of migration of contaminated groundwater to seeps and springs preventing off-site human and ecological exposure until contaminants are reduced to non-risk concentrations.

Secondary corrective action objectives were developed to aid in the comparison of groundwater remedial technologies. The secondary objectives are:

- Reduce contaminant concentrations to protective levels in a timely and cost-effective manner, using technologies that consider the degree of groundwater impact.
- Recognize and protect the unique biological and cultural resources present in Area IV as part of any surface disturbance activity.

3.2 Identification of ARARs and TBCs

In order for remedial actions to be protective of human health and the environment, they must attain the levels or standards of control for hazardous substances, pollutants, or contaminants specified by ARARs based on federal and state environmental laws, rules, and regulations.

According to EPA guidance, remedial actions also must take into account non-promulgated TBC criteria or guidelines if the ARARs do not address a particular situation. TBCs pertain to federal and state criteria, advisories, guidelines, or proposed standards that are not generally enforceable but are advisory and that do not have the status of potential ARARs. Guidance documents or advisory TBCs may be used where no specific ARARs exist for a chemical or situation, or where such ARARs are not sufficient to be protective, to determine the necessary level of remediation to be protective of human health or the environment.

The 2007 Consent Order for Corrective Action (DTSC 2007) is considered an ARAR for groundwater remediation as it sets forth the process and procedures for groundwater investigation, reporting, assessment, and this Corrective Action Measures Plan.

ARARs are defined as chemical-, location-, or action-specific, as described below.

- Chemical-specific ARARs include laws and regulations governing the release of materials possessing certain chemical or physical characteristics or containing specified chemical compounds. These ARARs and TBCs usually are numerical values that are health- or risk-based values or methodologies. They establish acceptable amounts or concentration of chemicals that may be found in, or discharged to, the ambient environment. They also may define acceptable exposure levels for a specific contaminant in an environmental medium. They may be actual concentration-based cleanup levels, or they may provide the basis for calculating such levels. Chemical-specific ARARs include federal and state MCLs specified for public drinking water that are applicable to groundwater aquifers used for drinking water. The main contaminants of concern in groundwater in Area IV include VOCs such as TCE, 1,1,1-TCA and PCE, and their degradation products, as well as the radionuclides tritium and Sr-90.
- Location-specific ARARs are design requirements or activity restrictions based on the geographical or physical positions of the site and its surrounding area. Location-specific requirements may set restrictions on the types of remedial activities that can be performed based on site-specific characteristics or location. For example, Area IV includes federally

designated habitat for a listed endangered species and habitat for a state listed endangered species. Avoidance of these areas or siting treatment facilities within these areas is a design and implementation concern.

- Action-specific ARARs are technology-based, establishing performance, design, or other similar action-specific controls that may provide restrictions on particular remedial actions. Action-specific ARARs are considered in the screening and evaluation of various technologies and process options discussed in **Section 5** of this report.

DOE considers the majority of the location and action-specific ARARs/TBCs to be design and siting criteria for remedial actions. Therefore, the regulatory standards for chemicals released into the environment provide the primary basis for remedy evaluation at this stage of CMS development. **Table 3-1** summarizes the basis for regulatory standards for groundwater cleanup in Area IV.

Operations Conducted	Chemicals Known/Potentially Used or Released
Federal Safe Drinking Water Act (CFR40.141)	Sets MCLs and Maximum Contaminant Level Goals (MCLGs) for drinking water
State California Safe Drinking Water Act (CCR Title 22, Division 4, Chapter 15)	Sets California MCLs for drinking water
State Porter-Cologne Water Quality Control Act (California Water Code, Division 7)	Adopts Water Quality Control Plans (South Coast Basin Plan) that establish beneficial uses of state waters and sets water quality objectives for those areas

The State Water Resources Control Board (SWRCB) has established policies potentially affecting groundwater cleanup. These policies include:

- Resolution 68-16 “Statement of Policy with Respect to Maintaining the High Quality Waters in California” (non-degradation policy) requires that for waters for which water quality objectives are set by Basin Plans or the Porter-Cologne Water Quality Control Act, existing water quality must be maintained. This resolution implies that non-detect or background levels must be maintained except in specific circumstances. DOE believes that the resolution is pertinent to groundwater that emanates at seeps and springs.
- Resolution 88-63, “Sources of Drinking Water Policy,” indicates that, except under specifically detailed circumstances, all surface waters and groundwaters are to be protected as existing or potential sources of municipal and domestic supply. DOE believes that the resolution is pertinent to identifying MCLs and MCLGs as RAOs.
- Resolution 92-94, “Policies and Procedures for Investigation and Cleanup Abatement of Discharges under the Water Code 13304”, requires regional boards to meet the highest levels reasonably attainable, where, at a minimum, water quality objectives established in

the Basin Plans must be met. However, it does permit specification of case-by-case cleanup levels where restoration of background levels is not a reasonable objective.

The California Regional Water Quality Control Board (RWQCB) *Water Quality Control Plan, Los Angeles Region, Basin Plan for the Coastal Watershed of Los Angeles and Ventura Counties* (Basin Plan) does not include the SSFL property within a defined regional groundwater basin. Therefore, there are no designated beneficial uses for groundwater beneath Area IV. However, the land use covenant entered by Boeing establishes restrictions on groundwater usage and identifies future land use as open space. Any future usage of groundwater would be based on recreational and ecological considerations at seeps and springs.

SWRCB Resolution No. 88-63 specifies that all groundwaters of the State are considered suitable, or potentially suitable, for municipal or domestic water supply with the following exceptions: 1) the water source does not provide sufficient water supply capable of producing an average sustained yield of 200 gallons per day (gpd); 2) total dissolved solids (TDS) exceed 3,000 milligrams per liter (mg/L); or 3) contamination that cannot reasonably be treated for domestic use for either Best Management Practices or best economically achievable treatment practices. DOE believes only the first criterion may apply to Area IV groundwater. Many of the near-surface wells exhibiting contamination cannot sustain a 200 gpd pumping rate over time. Nevertheless, DOE's RAO is to return groundwater beneath Area IV to drinking water standards, the maximum beneficial use.

3.3 Identification of Site Specific RAOs

Table 3-2 presents the specific RAOs for each of the areas with groundwater impacts in Area IV under DOE responsibility. These sites include: the FSDF, Building 56 Landfill, Buildings 4057/4059/4626, HMSA, RMHF, Tritium Plume, and the Metals Clarifier/DOE Leach Field 3.

For sites with no groundwater impacts, the ultimate RAO is their removal from the list of RFI sites and receipt of closure through the completion of the RCRA process. These sites include: Building 4100 Trench, Building 4009 Leach Field, Building 4064 Leach Field, Buildings 4030/4093/DOE Leach Field 1, Old Conservation Yard, and Rockwell International Hot Lab. This CMS does not address any actions at the HWMF (Buildings 4133 and 4029), which will be subject to closure through the interim RCRA permit process.

Area	Groundwater Issues	RAOs	ARARs	Actions to Meet RAOs
FSDf	<ul style="list-style-type: none"> ▪ Near surface bedrock fractures harboring VOCs greater than 1,000 µg/L ▪ Release of VOCs from fractures during wet periods results in migration of VOCs to deeper bedrock groundwater. ▪ Open bedrock boreholes that may provide conduits for direct vertical migration of contaminants. ▪ Metals above screening levels 	<ul style="list-style-type: none"> ▪ Reduce TCE and 1,1,1-TCA contaminant mass and groundwater concentrations in shallow fractured bedrock to levels that do not threaten underlying groundwater. ▪ Control contaminant migration from shallow fractured bedrock groundwater into deeper bedrock groundwater. 	<p>TCE MCL = 5 µg/L</p> <p>1,1,1-TCA MCL = 200 µg/L</p>	<ul style="list-style-type: none"> ▪ Assess effectiveness of interim groundwater remedial action at RS-54 ▪ Conduct remedial action to reduce contaminant mass and concentrations. ▪ Address open bedrock wells that may enable lateral and downward contaminant migration ▪ Continue groundwater monitoring.
Building 56 Landfill	<ul style="list-style-type: none"> ▪ The source of TCE and cis-1,2-DCE contamination in RD-07 has not been determined, but is suspected to be upgradient of the landfill, near Building 4100. The leading edge of the plume appears to be at the landfill. 	<ul style="list-style-type: none"> ▪ Control any further movement of impacted groundwater from landfill area. ▪ Address higher concentrations of VOCs at source location. 	TCE MCL = 5 µg/L	<ul style="list-style-type: none"> ▪ Additional investigation to determine if Building 4100 is the source of TCE contamination. ▪ Continue groundwater monitoring to assess migration of TCE beyond the landfill.
Buildings 4057/4059/4626	<ul style="list-style-type: none"> ▪ Near-surface groundwater in this area is contaminated with PCE, however concentrations are declining, and the plume is not migrating. 	<ul style="list-style-type: none"> ▪ Reduce PCE contaminant mass and groundwater concentrations in near-surface groundwater at PZ-109 to below the MCL. 	PCE MCL = 5 µg/L	<ul style="list-style-type: none"> ▪ Conduct short-term remedial action to reduce contaminant mass and concentrations. ▪ Continue to monitor declining PCE concentrations and estimate time to decline below the MCL.
HMSA	<ul style="list-style-type: none"> ▪ TCE concentrations in near-surface and bedrock groundwater exceeding 50 µg/L that do not appear to be declining. 	<ul style="list-style-type: none"> ▪ Reduce TCE contaminant mass in perched groundwater and bedrock groundwater to below the MCL. 	TCE MCL = 5 µg/L	<ul style="list-style-type: none"> ▪ Conduct remedial action to reduce contaminant mass and concentrations. ▪ Continue groundwater monitoring.
Tritium Plume	<ul style="list-style-type: none"> ▪ Groundwater in north-central portion of Area IV is contaminated with tritium. Degradation is consistent with its half-life; concentrations are expected to be below the MCL in 10 years. 	<ul style="list-style-type: none"> ▪ Reduce tritium concentrations to below the MCL. 	Tritium MCL = 20,000 pCi/L	<ul style="list-style-type: none"> ▪ Continue to monitor declining tritium concentrations to below the MCL.
RHMF Leach Field	<ul style="list-style-type: none"> ▪ TCE near its 5 µg/L MCL ▪ Strontium-90 elevated above its 8 pCi/L MCL in near-surface bedrock fractures, and underlying near surface groundwater 	<ul style="list-style-type: none"> ▪ Reduce TCE to below its MCL ▪ Remove mass of Strontium 90 	<p>TCE MCL = 5 µg/L</p> <p>Strontium 90 MCL 8 pCi/L</p>	<ul style="list-style-type: none"> ▪ Continue monitoring TCE concentrations ▪ Remove mass of Strontium-90 threatening underlying groundwater

<p>Metals Clarifier/DOE Leach Field 3</p>	<ul style="list-style-type: none"> ▪ TCE at concentrations near its MCL. ▪ TCE concentrations appear to be diminishing naturally. 	<ul style="list-style-type: none"> ▪ Reduce TCE concentrations to below the MCL. 	<p>TCE MCL = 5 µg/L</p>	<ul style="list-style-type: none"> ▪ Continue to monitor declining TCE concentrations to below the MCL.
---	---	---	-------------------------	--

Section 4

Technology Description

The range of potential remedial technologies that are being initially considered to address groundwater areas of interest in Area IV are categorized in **Table 4-1**. The six categories, listed herein in the order of increased treatment aggressiveness, include (1) no action, (2) administrative and legal controls, (3) monitored natural attenuation (MNA), (4) containment, (5) in situ treatment, and (6) source removal. It should be noted that in some instances, multiple methodologies could be employed for each remedial technology. For example, *in situ* chemical oxidation (ISCO) could be implemented in a grid-injection or permeable reactive barrier (PRB) configuration. In addition, the ISCO injection itself could be performed using permeation injection through permanent injection wells or hydraulic permeability enhancement (i.e., hydraulic fracturing). PRB could also be implemented using conventional injection wells, trenching, or direct-push injection. Therefore, any number of combinations of remedial technologies and associated implementation methodologies could be possible. A brief description of the individual groups of remedial technologies potentially applicable is provided in the following subsections. A preliminary screening to remove remedial technologies, that from a technical, practical or economic standpoint would be difficult to implement in Area IV, is presented at the end of this section and summarized in **Table 4-2**.

The description of technologies in this section are generic in nature. Applicability of the technologies relative to site-specific hydrogeology, including fractured sandstone bedrock and thin (less than 15 feet) alluvial layer, are discussed in **Section 4.9** and summarized in **Table 4-1** and **Table 4-2**. The inability to use a technology in Area IV is one of the initial screening criteria used to eliminate technologies based on geological conditions. **Section 5** provides the screening criteria for the retained technologies and **Section 6.0** provides the evaluation of the technologies with site-specific hydrogeology.

4.1 No Action

No action provides the baseline against which the positive effects of the various remedial technologies can be compared. Under a no action alternative, no remedial measures would be undertaken to address contaminated media or control exposure to potential receptors. There would be no intentional change in the soil and groundwater contaminant concentrations because no treatment, containment, or removal of contaminated material would be included as part of No Action.

4.2 Administrative and Legal Controls

Administrative and legal controls would consist of a combination of governmental controls, proprietary controls, and/or informational devices. “Layering” of institutional controls may be required to enhance the overall protectiveness of institutional controls. Issuance and periodic review and update of a comprehensive institutional control plan likely would be required to keep track of the various institutional control measures taken. A Deed Notice for soil and a groundwater Classification Exemption Area (CEA) are often required administrative/legal

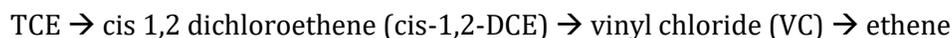
controls when impacted soil or groundwater is left in place. DOE notes that administrative control measures are already in place at Area IV to restrict the use of groundwater via the Boeing land use covenant (Ventura County 2017).

4.3 Monitored Natural Attenuation

Monitored Natural Attenuation differs from No Action and Administrative and Legal Controls alternatives in that the mechanisms that result in contaminant degradation are identified and understood prior to its selection as a remedy. During application of MNA, the degradation mechanisms and contaminant concentration trends are monitored over time. Should monitoring data indicate that attenuation is not occurring as predicted, then enhancement of MNA or other treatment technologies may need to be considered to meet the remedial action objectives.

MNA in groundwater systems results from the integration of several subsurface attenuation mechanisms classified as either destructive or nondestructive. Biodegradation is typically the most significant destructive attenuation mechanism, although destruction of some compounds may occur via abiotic pathways such as biogeochemical transformation with iron sulfide minerals. Common nondestructive attenuation mechanisms include dispersion, dilution, sorption, diffusion, and volatilization.

Biodegradation via reductive dechlorination (i.e., biologically-mediated reactions where chlorine atoms are sequentially removed from chlorinated VOCs) is typically the most significant destructive attenuation mechanism, although destruction of some compounds may occur via abiotic pathways such as biogeochemical transformation with iron sulfide minerals or via biologically-mediated cometabolic pathways. Each of these biodegradation mechanisms are described in further detail below. In many cases, natural attenuation processes will reduce dissolved contaminant concentrations to below regulatory standards before the contaminant plume reaches potential receptors. The efficacy of MNA as a remedy component is based on the site-specific assessment of these mechanisms in the context of transport to receptors. Overall, biodegradation via reductive dechlorination is typically the most important natural attenuation mechanism that is protective of downgradient receptors. Through biologically-mediated reactions, chlorinated solvents such as TCE are transformed via sequential removal of chlorine atoms. The following reaction sequence depicts the primary reductive dechlorination pathway for TCE to non-toxic ethene, which is the terminal reductive dechlorination end-product:



Although trans-1,2-DCE and 1,1-DCE may be generated during the reductive dechlorination of TCE, they are typically only minor components in the dechlorination pathway and can be further degraded to VC and ethene. In this process, the TCE (or daughter product) acts as an electron acceptor, while an electron donor is required to provide energy for this process. Hydrogen is ultimately the direct electron donor for reductive dechlorination reactions, and in an MNA application, it is typically produced from the anaerobic oxidation or fermentation of naturally occurring carbon.

In situ biogeochemical transformation (i.e., abiotic degradation) involves biological formation of reactive minerals that can destroy chlorinated solvents such as TCE, resulting in production of

acetylene and carbon dioxide as end-products without accumulation of toxic intermediates such as VC. Iron sulfides are one class of minerals that have been identified as being reactive with chlorinated solvents. These minerals are formed via anaerobic reduction of sulfate to sulfide followed by reaction of sulfide with solid-phase iron oxides or soluble ferrous ion. These minerals are formed under conditions that are favorable for biological reductive dechlorination because iron and sulfate reduction are required. While sulfate is elevated at Area IV, the lack of reducible iron likely renders biogeochemical transformation of TCE a minor attenuation mechanism, and thus it is not discussed further.

Cometabolism of chlorinated compounds is an additional mechanism that should be evaluated when considering potential natural attenuation mechanisms. In aerobic cometabolism, bacterial enzymes that typically utilize compounds including methane, ethene, ethane, toluene, phenol, ammonia, propane, and propene as electron donors can also fortuitously transform chlorinated solvents under aerobic conditions. One difficulty in assessing the importance of cometabolism is that, unlike reductive dechlorination, daughter products are not produced. The cometabolic oxidation essentially mineralizes the VOCs into chloride, carbon dioxide, and water. Similar to in situ biogeochemical transformation, cometabolic reactions likely represent a minor degradation mechanism compared to reductive dechlorination in Area IV groundwater.

MNA would require a groundwater monitoring program that would be implemented to track and evaluate progression of reductions in contaminant concentrations between the source and the receptor over time. The groundwater monitoring would be used to evaluate the long-term performance to verify a stable and retracting groundwater plume with stable and declining contaminant concentration trends. Sufficient data would be required to demonstrate that natural processes can achieve the remediation objectives for groundwater in a reasonable timeframe. Administrative and/or legal controls are also assumed to be implemented under this alternative.

4.4 Containment

Containment refers to a group of remedial technologies implemented in situ to minimize contaminant migration via physical or biological means or a combination thereof. Note that some containment technologies are intended to “lock” the contaminants in place by reducing the hydraulic permeability of the matrix of interest, whereas some other technologies are intended to contain and treat contaminants in situ. A brief description of the six containment technologies including physical containment, in situ stabilization/solidification (ISS), hydraulic control, capping, in situ grouting, and microbially-induced calcite precipitation (MICP) is provided in the following subsections.

4.4.1 Physical Containment

This remedial technology involves the use of a vertical, passive barrier wall to intercept and treat contaminants migrating in groundwater. It is primarily applied to groundwater within alluvial systems. A variety of commercially available biological and chemical reagents can be used in the construction of these PRBs. PRBs can be installed in a variety of configurations depending on site-specific lithology, treatment depth, contaminants of concern, and plume dimensions as shown in **Figure 4-1**. Specifically, at sites where the treatment depth is less than 25 feet below ground surface (bgs), a PRB may be constructed via trenching and subsequent backfilling with the appropriate solid/liquid treatment amendments. At sites with deeper treatment zone of interest

that may not be amenable to trenching, permanent injection wells, direct-push points, or environmental fracturing techniques may be used to facilitate introducing the treatment amendments into the subsurface and create a free-standing reactive treatment zone. The plume width also influences selection of the appropriate PRB configuration. Specifically, a PRB may be constructed in a funnel and gate (F&G) configuration to overcome challenges associated with a very wide groundwater plume. In an F&G PRB, a slurry wall or sheet piles may be constructed to route groundwater through a small area (i.e., the gate) amended with the appropriate treatment chemicals to react with and subsequently treat the flow-through groundwater plume. Regardless of the configuration, one common denominator for efficient and effective implementation of PRBs is a sufficient groundwater flux; PRBs should not be implemented at sites with a stagnant groundwater flow regime.

Depending on the site-specific contaminants of interest, a variety of treatment chemicals may be used to construct a PRB. The majority of PRBs installed via trenching employ zero-valent iron (ZVI) as the reactive medium. As a mild reductant, ZVI can be used to reductively dehalogenate (i.e., remove the chlorine atoms) many halogenated hydrocarbons, energetics, and metals. Other materials that may be employed for PRB construction include mulch or other vegetative materials. The Air Force biowall protocol (Air Force Center for Engineering and the Environment [AFCEE] 2008) provides guidance for the use of these permeable biowalls for treatment of variety of common groundwater contaminants including chlorinated solvents, perchlorate, and energetics. The mulch and other biodegradable vegetative materials used during construction of the PRB may serve as a long-term carbon resource, rendering frequent amendment replenishment unnecessary. Where applicable, physical containment represents an attractive remedial technique because very little operation and maintenance (O&M) effort is likely required besides periodic performance monitoring and amendment replenishment.

4.4.2 *In Situ* Stabilization/Solidification

In situ stabilization/solidification (ISS) involves *in situ* introduction of chemical reagents to create a soil-reagent composite with improved properties relative to the native soil requiring treatment. ISS generally applies to alluvial groundwater systems. This remedial alternative is akin to locking contaminants in place via physical encapsulation or fixation. The most common objectives in implementation of ISS include increased compressive strength, decreased permeability, increased seismic shear resistance, and decreased leachability. Although Portland cement is the most commonly used reagent in ISS, other reagents such as furnace slag, fly ash, cement kiln dust, bentonite, and proprietary carbon-based binding reagents such as organophilic clay and activated carbon may also be used; some of these additives provide treatment mechanisms in combination with stabilization. For typical environmental applications, ISS is often performed with a large-diameter auger, ranging between 3 and 12 feet in diameter, equipped with mixing paddles and grout ports. Generally, the amendment fluid is added to and mixed with the native soil as the soil mixing auger is advanced to the subsurface. The end-product resulting from ISS is essentially a monolithic block with high structural integrity that nearly completely limits the solubility and/or mobility of the encapsulated waste. Note that in addition to chemical stabilization, other treatment reagents including ZVI, specialty clays, granular activated carbon, and chemical oxidants can also be used to facilitate contaminant treatment *in situ*. An illustration of the ISS process is depicted in **Figure 4-2**.

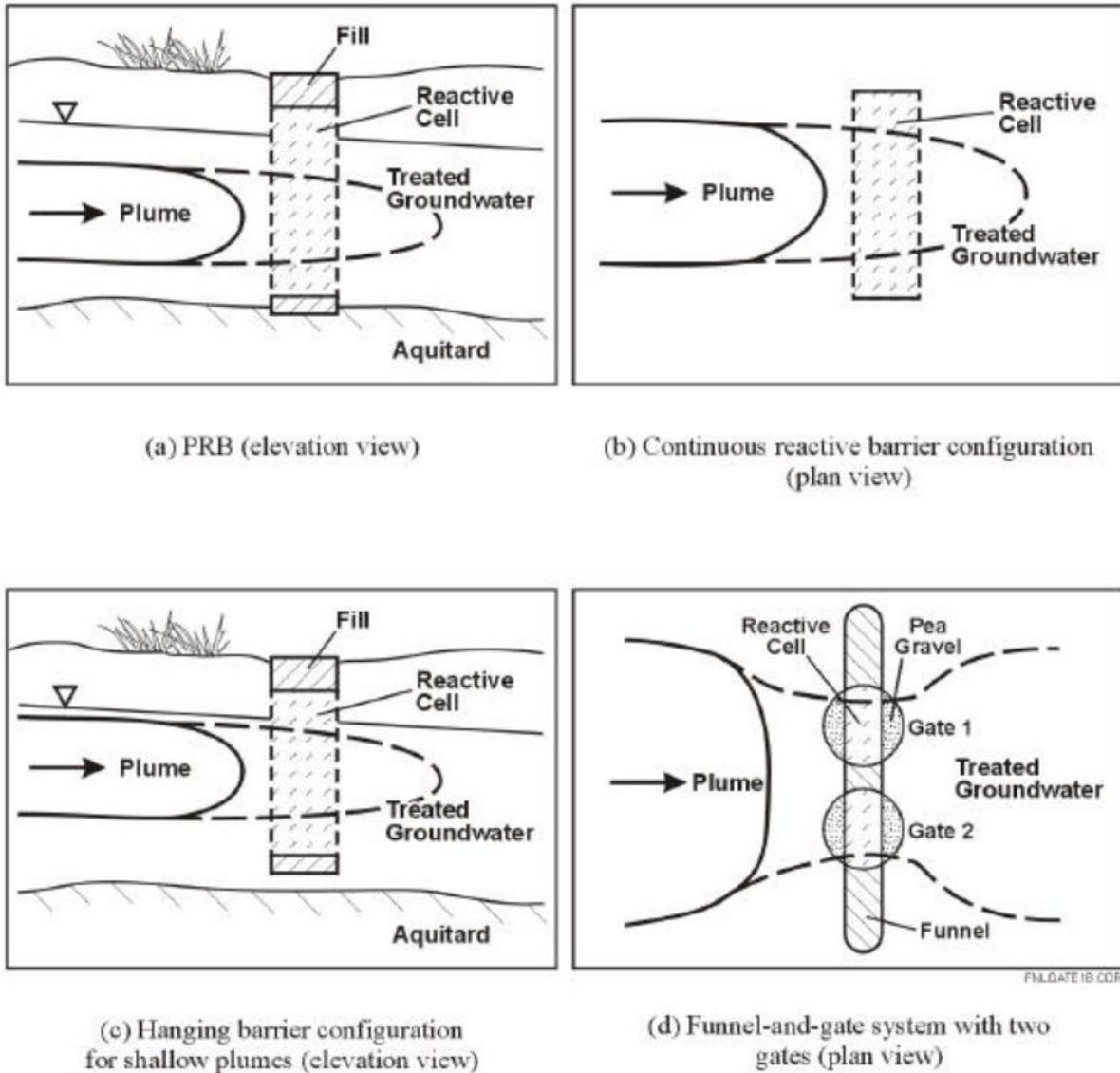


Figure 4-1. Illustration of PRB Configurations (courtesy of Strategic Environmental Research and Development Program [SERDP] 2000)

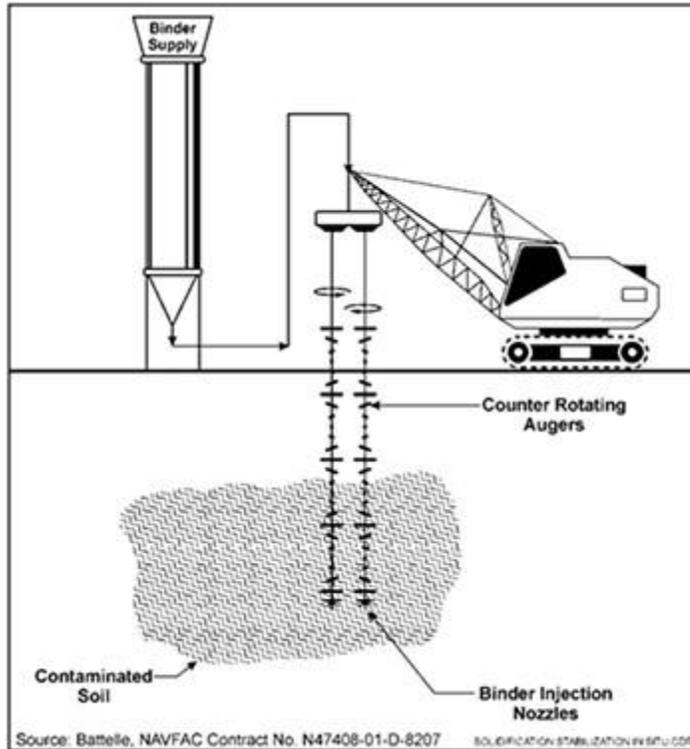


Figure 4-2. Illustration of ISS (courtesy of Battelle 2004)

4.4.3 Hydraulic Control

This remedial technology involves the use of a well field to control and/or alter the natural groundwater flow regime that could halt/reverse contaminant migration or to minimize contaminant contact with groundwater. Hydraulic control is usually implemented using extraction wells to pump groundwater to either lower the water table or change the hydraulic gradient. Hydraulic control via phytoremediation can also be implemented where poplar or cottonwood trees, for example, which can uptake hundreds of gallons of water per day with their extensive root structure, are planted to aid controlling groundwater movement. Unlike phytoremediation where no groundwater is transferred aboveground, containment and subsequent treatment and proper disposal of groundwater extracted via active groundwater pumping must be implemented.

4.4.4 Capping

Capping refers to the placement of a cover over contaminated materials to isolate and minimize contaminant migration via infiltration surface water runoff, groundwater percolation, wind affects, volatilization, and ecological contacts. Note that capping simply keeps the contaminants in place and is not intended for contamination destruction. It would need to be combined with MNA in order to demonstrate effectiveness and ultimate contaminant degradation. The design of the cap depends on a number of factors including the nature and extent of the contaminants of interest, future land use, and site-specific lithologic, hydrogeological, and meteorological settings. A cap design can be as simply as placing a single layer of material over the contaminated soil or

employing multiple layers including a vegetative layer, drainage layer, geomembrane, and clay layer to address hazardous waste.

4.4.5 *In Situ* Grouting

This remedial technology involves *in situ* delivery of a cement/bentonite slurry to facilitate in-place grouting of high-permeability fractures and subsequently minimize contaminant migration via matrix diffusion. Pressure grouting has primarily been used for geotechnical purposes such as *in situ* dam foundation repair, elevating foundations or slabs that have settled, enhancing underlying soils that are weak, stabilizing sinkholes, and improving expansive or collapsible soils. Its application in the remediation industry to seal off fractures in a fracture bedrock system to minimize contaminant migration has been very limited. One field trial of pressure grouting in fractured basalt to reduce the hydraulic conductivity was conducted by the Idaho National Engineering Laboratory (INEL) in 1996 (INEL 1996). Results from this field trial indicate that a reduction in hydraulic conductivity ranging between 3- and 105-fold may be achieved using pressure grouting of cementitious materials. However, in basalt cores collected 1 year following the initial pressure grouting, only 22 percent (%) of the fractures showed evidence of cement penetration. In addition, the top-to-bottom grout distribution indicates that the injected grout flowed downward through the open channels gravitationally following the high-pressure injection and that targeted grouting of select fractures may be very difficult to achieve. Other studies have also investigated the use of pressure grouting with bentonite to reduce the hydraulic conductivity of the matrix of interest requiring treatment (Chapuis 2002). However, such application was only done in sand.

In summary, pressure grouting to reduce hydraulic conductivity in fractured bedrock for remediation purposes was not found in abundance in contemporary literature, indicating that the technique may only be appropriate for geotechnical applications and that, if to be implemented in fractured bedrock for remediation purposes, a feasibility study/pilot study may be warranted given the lack of demonstrated success in a full-scale setting.

4.4.6 Microbial Induced Calcite Precipitation

Microbial-induced calcite precipitation (MICP) is a biogeochemical process that induces calcium carbonate precipitation within the soil matrix as shown in Figure 4-3. Such induction is often facilitated via microbially-mediated mechanisms including urea hydrolysis, denitrification, sulfate reduction, and iron-reduction. There are multiple applications of MICP in geotechnical and environmental engineering including soil strength improvement, permeability reduction, seismic remediation, and surface corrosion control. Specifically, MICP has been used in geotechnical engineering applications to prevent or stabilize surface erosion and increase slope stability. It was reported that such bioconsolidation can lead to an order of magnitude improvement in the primary properties of a typical sand including permeability, stiffness, compressibility, and shear strength (DeJong et al. 2010). The application of MICP to soil types other than sand has been very limited (Soon et al. 2014). MICP has also been used in remediation of concrete cracks.

In the field of environmental engineering, MICP has been evaluated as a potentially applicable remedial technology for sequestration of radionuclides and heavy metals, as well as organic compounds including PCBs. Contemporary literature indicates that MICP may be potentially applicable for remediating copper (Achal et al. 2011, Li et al. 2013), cadmium (Kang et al. 2014,

Ma et al. 2009, and Li et al. 2013), chromium (Hua et al. 2007 and Achal et al. 2013), lead (Li et al. 2013), and arsenic (Achal et al. 2012b). In addition, coprecipitation of radionuclides such as strontium using MICP has been reported with relatively good removal efficiency, ranging between 80 and 90% (Kang et al. 2014, Achal 2012c); this is the primary potential application for Area IV.

There are several limitations regarding the use of MICP as a remedial technology. First, MICP implementation may result in elevated concentrations of ammonium and nitrate introduced the ureolysis-driven process, which may be above regulatory limits. Next, because it is driven by microbially-mediated processes, MICP is usually slower and more complex than other chemical processes. Successful implementation of MICP predicated largely on attaining and maintaining the appropriate geochemical and microbiological conditions, rendering MICP implementation very challenging at a commercial scale. Note that the calcite generated during microbially-mediated processes may be susceptible to dissolution when significant changes in geochemical conditions occur. Finally, high concentrations of contaminants targeted for treatment such as toxic heavy metals may result in microbial inhibition. Collectively, additional investigations are needed to reduce cost, mitigate unwanted products, and demonstrate the potential applicability of MICP on a commercial scale.

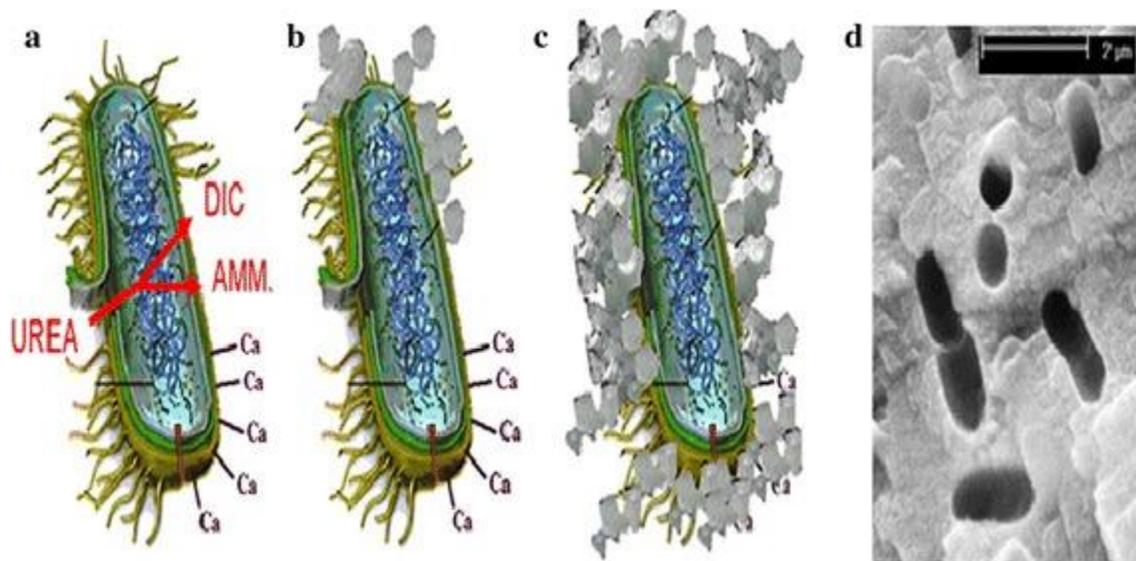


Figure 4-3. Illustration of MICP (courtesy of De Muynck et al. 2010)

4.5 *In Situ* Treatment

Descriptions of potentially applicable *in situ* treatment techniques that rely on physical, chemical, or biological processes, or a combination thereof, are provided in the subsequent sections.

4.5.1 *In Situ* Reduction

This group of remedial technologies includes *in situ* treatment techniques using oxidation, reduction, cometabolism, or a combination thereof, to promote contaminant degradation. Details pertinent to the individual technologies are provided.

4.5.1.1 In situ chemical and biological reduction

In situ reduction technologies are technologies that would accomplish reductive degradation of VOCs including in situ chemical reduction (ISCR) (abiotic) and enhanced anaerobic bioremediation (EAB) (biotic). ISCR uses an abiotic reductive pathway and relies on introducing a reducing agent (e.g., ZVI) to enhance abiotic reduction of groundwater contaminants. The reducing agent can be applied in several configurations including PRBs and permeation injection through permanent injection wells.

EAB relies on delivery of a carbon source and appropriate microbial organisms into the subsurface to promote microbially-facilitated reductive degradation of VOCs. Common electron donors for biotic degradation include lactate, molasses, whey, emulsified vegetable oil (EVO), and carbon integrated with ZVI. EAB can be applied as source area treatment but can also be applied as a biobarrier to limit exposure to downgradient receptors. Additives are often combined with amendments to increase the effectiveness of EAB, and in some cases, ISCR. The pH can be buffered by adding sodium bicarbonate, as EAB often results in an abundance of metabolic acid production, which may drive down the pH without a pH buffer present. Shear thinning fluids such as xanthan gum can also be mixed with amendment to change the properties of the injected fluid. As the injectant is mixed and pumped at a high shear rate, the xanthan keeps the viscosity of the mixed amendment liquid low. Also, when the injectant is distributed into a heterogeneous aquifer, the viscosity remains low as it is forced into lower permeability units, but the viscosity will increase in higher permeability units where the flow becomes more dispersed (and shear decreases). Lastly, after the injection is stopped, the viscosity of the amendment will increase, allowing the amendment to remain in place instead of flowing downgradient with the natural flow path. This allows the amendment to both be injected uniformly in heterogeneous aquifers and to remain in the targeted treatment area. A more aggressive delivery technique called hydraulic permeability enhancement, which involves sand emplacement at relatively high pressure [between 100 and 500 pounds per square inch (psi)] to create permanent sand-filled, high-permeability pathways, can also be implemented to facilitate uniform amendment delivery and distribution. Note that EAB is often augmented by adding a commercially-available bacterial culture capable of degrading PCE and TCE to ethene. For purposes of consideration of EAB and ISCR for Area IV groundwater, they are discussed together as in situ reduction (ISR); the actual amendment used (whether carbon, iron, or both) would be determined during the design phase.

4.5.1.2 Low-temperature, thermally-enhanced bioremediation

Traditional *in situ* thermal remediation (ISTR) technologies rely on the heating of the subsurface, either via resistive or conductive energy transfer, to a temperature near or far exceeding steaming/boiling point to promote volatilization, desorption, and/or destruction of contaminants. ISTR can be applied with excellent efficiency and effectiveness at a variety of sites with differing lithologic and hydrogeological settings as well as contaminant profile and distribution. However, the capital costs associated with ISTR are very high when compared to other in situ treatment techniques. At sites where the remedial timeframe is not the primary driver, operating ISTR at a low energy and temperature to promote biotic and abiotic degradation processes rather than the physical removal and/or destruction of the contaminants of concern in the subsurface may represent an attractive remedial alternative.

Low-temperature, thermally-enhanced remediation refers to the heating of the subsurface to approximately 50 degrees Celsius (°C) or less with electrical resistance heating to promote enhanced reaction kinetics in the subsurface via several physical, chemical, and microbiological processes. Compared to traditional ISTR, advantages associated with this low-temperature, thermally-enhanced remediation technique include the following:

- Microbiological reactions generally follow Arrhenius-type behavior; reaction kinetics are expected to increase from temperatures typical of most groundwater systems (10 – 12 °C) to reach a maximum at approximately 50 °C then decline with further temperature increases. This relationship between reaction kinetics and subsurface temperature is well documented for general microbiological processes (Atlas and Bartha 1987, Suyama et al. 2002), biological reductive dechlorination, and abiotic dechlorination via ZVI-aided beta elimination (Kohring et al. 1989, Holliger 1993, He 2003).
- At sites with source-level contaminant concentrations, application of low-temperature heating can facilitate enhanced mass transfer of residual dense non-aqueous phase liquid (DNAPL) to the aqueous phase thus making the contaminants available and suitable for microbiological, chemical, and/or physical reactions. Contaminant dissolution and volatilization generally increase with increasing subsurface temperature (Yaws et al. 2009, Sleep and Ma 1997, Horvath 1982). Imhoff et al. (1997) empirically and predicatively demonstrated that moderate temperature applications of hot water flushing for chlorinated solvent treatment can result in an increase of mass transfer rate of residual DNAPL by a factor of four to five when temperatures were increased from 5°C to 6°C. Therefore, combining moderate heating of the subsurface with a proven *in situ* treatment technique such as enhanced anaerobic bioremediation or *in situ* chemical reduction may eliminate the requirement for vapor recovery and treatment (which often represents a large fraction of ISTR implementation) and thus reduce the overall remedy cost.
- Low-temperature heating of the subsurface results in increased hydrolysis rates associated with chlorinated solvents, petroleum products, pesticides, and several energetic compounds. At sites where DNAPL is present, the concentration gradient between the DNAPL and water interface (Yang 2000) can be increased. This concentration gradient allows for more soluble degradation daughter products to be present in the aqueous phase and available for treatment (Carr 2000). Additionally, because the subsurface heating can be achieved with a great degree of control and uniformity, remediation of the aforementioned compounds can be performed in a variety of matrix including sand, silt, clay, and bedrock.
- Elevated temperatures increase the hydrolysis rate of non-soluble humic and fulvic acids (also known as total organic carbon) and increase the dissolved organic carbon by up to two orders of magnitude (SERDP 2014). Therefore, by simply heating the subsurface, additional electron donors required by subsurface microorganisms for microbial respiration and contamination transformation/destruction are fortuitously generated. Because non-soluble humic and fluvic acids are often well distributed in the matrix, application of low-temperature heating may result in relatively uniform distribution of electron donors even in low-permeability zones; uniform delivery of electron donors in a

matrix with a high degree of heterogeneity often represents the one of the most challenging aspects of *in situ* remediation.

- Due to the lower temperature and thus lower energy requirements compared to traditional ISTR, smaller diameter electrodes could be used in low-temperature, thermally-enhanced remediation. Installation of such smaller electrodes may be performed using direct-push drilling technology at unconsolidated sites, which generates significantly less investigation-derived waste than other drilling techniques and thus reduces overall remedy cost.

Low-temperature heating of the subsurface to aid *in situ* remediation has not been widely implemented in a field-scale setting. The two most prominent studies performed to date using this technology include a field research project funded by the Department of Defense's Environmental Security Technology Certification Program (ESTCP) entitled "Combining Low-Energy Electrical Resistance Heating with Biotic and Abiotic Reactions for Treatment of Chlorinated Solvent DNAPL Source Areas", and a pilot study funded by the EPA Region 10 entitled "Applying Electrical Resistance Heating at Below Steaming Temperatures to Enhance Bioremediation Kinetics at the Well 12A Superfund Site".

ESTCP project ER-200719 was intended to evaluate the use of low-temperature resistance heating coupled with EAB and ISCR to accelerate the dissolution, desorption, and degradation of residual TCE contamination. Electrical resistance heating was applied to both the EAB and ISCR test cells to increase the subsurface temperature to approximately 30°C to 45°C and 40°C to 55°C, respectively. The elevated temperatures increased the dissolution of contaminant into the groundwater and increased the rate and extent of dechlorination in both test cells. During this demonstration, the total contaminant mass discharge increased by a factor of 4 to 16 within the ISCR test cell, and consisted primarily of the reductive daughter products (ethene and ethane) as the degradation kinetics were sufficiently high to keep the TCE concentrations low. For the EAB test cell, the total contaminant mass discharge increased by a factor of approximately 4 to 5 and the fraction of the total mass present as ethene increased dramatically compared to baseline conditions.

Most recently at the Well 12A Superfund Site (ESTCP 2007), a pilot study was performed to evaluate the effectiveness of low-temperature, thermally-enhanced reductive dechlorination for treatment of chlorinated ethanes and chlorinated ethenes existing as DNAPL at two hot spots, EAB-1 and INJ-30. Three heating electrodes with an anticipated heating radius of influence of approximately 10 feet and spanning the depth intervals of interest (approximately 40 to 50 feet bgs) were installed to aid subsurface heating from the ambient groundwater temperature of approximately 10°C to 45°C surrounding each of the hot spot monitoring wells. Groundwater monitoring and temperature measurements were performed periodically at EAB-1, INJ-30, and nearby monitoring wells to facilitate system optimization and performance evaluation. Near EAB-1, which represents a very localized DNAPL hot spot, the most recent sampling results show that VOC concentrations have declined substantially since heating, and total VOC mass and molar concentrations have decreased by more than 99 percent (%) from maximum concentrations observed immediately prior to heating and by 93% since baseline sampling in 2013. Substantial reductions have also been observed at nearby monitoring well EAB-2, with a greater than 98% decrease in molar concentration from the peak and 96% from baseline conditions.

4.5.2 *In Situ* Chemical Oxidation

In situ chemical oxidation involves the use of chemical oxidants such as permanganate, persulfate, hydrogen peroxide, ozone, or combination thereof, and other chemical activators to promote chemical oxidation reactions in the subsurface. ISCO is most often implemented at sites with highly elevated contaminant concentrations. Note that the soil and its associated organic content rather than the contaminants themselves often represent the predominant oxidant demand at many ISCO sites. Therefore, ISCO technology may be subject to a high frequency of amendment re-injections and contaminant rebound. Like other *in situ* techniques, amendment delivery is essential in achieving optimal remedial performance. ISCO implementation may result in adverse changes in geochemical conditions; while some effects may be transient, others are permanent. Injection of hydrogen peroxide in a limestone bedrock formation may result in significant carbon dioxide gas generation. Injection of persulfate may result in drastic pH depression as the persulfate is degraded and sulfuric acid generated. This is especially true at sites with a low pH-buffering capacity. Such pH depression may, in turn, result in dissolution of metals above applicable regulatory limit. However, it should be noted that these changes in geochemical conditions are generally transient and confined to the target treatment zone. Geochemical conditions generally revert to background levels once the oxidant is consumed. Unlike persulfate, the use of the ISCO reagent permanganate may result in permanent changes in the aquifer of interest. Manganese dioxide precipitation during ISCO applications using permanganate may result in a permanent reduction in hydraulic conductivity.

The Boeing Company conducted a pilot study of the ISCO technology in Area I of SSFL in 2015. The study involved the injection of potassium permanganate (the oxidant) into a single well and using five wells to monitor for performance (CH2M 2016). Tracer tests using fluorescein dye and bromide were also performed. Seven injection events were conducted involving the use of gravity to move the permanganate down into the well and bedrock fractures, at a flow rate of 2 gallons per minute. Each injection event lasted for an 8-hour period over 5 consecutive days. In all, approximately 6,000 pounds of chemical were injected to the subsurface.

The study demonstrated that although it was possible to have the oxidant move with the groundwater in fractures, not all fractures in the monitoring wells showed evidence of permanganate. The presence of permanganate was short-lived, probably the result of the natural oxidant demand of the local geology consuming the oxidant. Although VOC concentrations temporarily declined in some monitoring wells, there was a rebound in concentrations following cessation of oxidant injection. The study concluded that although it was possible to inject the oxidant into fractures, the limited hydraulic connection between fractures limited oxidant contact with contaminants. The rebound of VOCs probably reflected back-diffusion of VOCs from the bedrock matrix that did not meet the oxidant. The study authors were also concerned about the water quality impacts of permanganate, as it was observed in groundwater at the end of the monitoring period (CH2M 2016).

4.5.3 Cometabolism

Cometabolism of chlorinated compounds is an additional mechanism that should be evaluated when considering potential natural attenuation mechanisms. In addition, it can also be implemented under engineered conditions where multiple substrates are injected to stimulate cometabolic degradation. In aerobic cometabolism, bacterial enzymes that typically utilize

compounds including methane, ethene, ethane, toluene, phenol, ammonia, propane, and propene as electron donors can also fortuitously transform chlorinated solvents under aerobic conditions. One difficulty in assessing the importance of cometabolism is that unlike reductive dechlorination, daughter products are not produced. The cometabolic oxidation essentially mineralizes the VOCs into chloride, carbon dioxide, and water. Similar to *in situ* biogeochemical transformation, cometabolic reactions likely represent a minor MNA mechanism compared to reductive dechlorination.

Cometabolic bioremediation has been used to address a number of groundwater contaminants including polyaromatic hydrocarbons (PAHs), explosives, 1,4-dioxane, PCBs, pesticides, chlorinated alkanes and alkenes, and petroleum hydrocarbons. Successful implementation of cometabolism hinges on uniform delivery of a suitable substrate to the target treatment interval to stimulate the appropriate reactions under a particular set of geochemical conditions. The high degree of difficulty in achieving these objectives represents the inherent disadvantage of cometabolism as an engineered remedy.

4.5.4 *In Situ* Soil Mixing

In situ soil mixing is performed in the same manner as ISS, with the exception that the chemical reagents used in large-diameter augering (LDA) soil mixing are intended to promote contaminant degradation rather than immobilization. Typically, a chemical oxidant such as persulfate or permanganate, or a chemical reducing reagent such as ZVI or emulsified ZVI (eZVI), is used. eZVI consists of nano-scale ZVI that is encapsulated by a surfactant-stabilized, biodegradable oil-in-water emulsion. In addition to chemical reduction, the biodegradable emulsion can serve as a long-term electron donor and promote biologically-mediated reductive dechlorination reactions. An illustration of the ISS process is depicted in **Figure 4-4**.

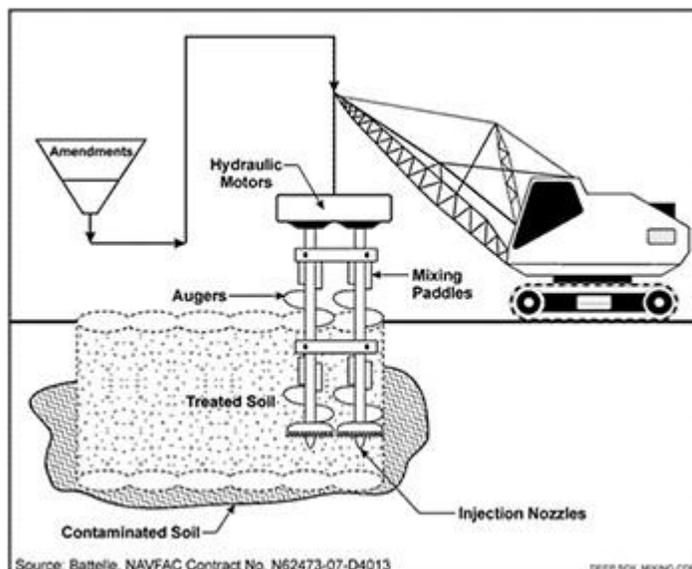


Figure 4-4. Illustration of *In Situ* Soil Mixing (courtesy of Battelle 2004)

4.6 Source Removal

Source removal reflects the most aggressive group of remedial technologies, as the source of the contamination is addressed directly via processes including physical removal, chemical treatment, or thermal treatment.

4.6.1 Excavation

Excavation utilizes conventional civil engineering methods to remove overlying soils to expose the source area for removal by mechanical excavation. The techniques employed are commonly used for deep excavations where horizontal extents are constrained and a shallow water table is present. Specifically, this technology involves installing steel sheeting along the maximum lateral perimeter of the source area and a sloped access road, followed by dewatering and mechanically excavating soils therein. Groundwater within the sheeting is extracted, treated, and discharged to groundwater at a point outside the excavation. Soils are excavated, segregated and characterized at the surface for onsite re-use or offsite disposal.

Large diameter auger techniques could also be used for source material excavation. This remedial technology involves advancing large-diameter casings (approximately 8 feet in diameter) into an area of interest with the appropriate vibratory equipment, followed by removing the impacted soil with a hydraulic drill rig as shown in **Figure 4-5**. In general, LDA applications are limited to unconsolidated or poorly-cemented materials and thus LDA is not suitable for bedrock remediation. In addition, LDA excavation may not be appropriate for every site. Specifically, LDA does not likely represent the most economical remedial alternative to address a shallow and/or small source area. LDA implementation will be very challenging or impossible at sites with significant above- and under-ground utilities. LDA is also very cost-, energy-, and water-intensive although the remedial timeframe is generally very short.



Figure 4-5. Field Application of LDA (courtesy of FECC 2018)

4.6.2 Extraction

This group of remedial technologies relies on physical and/or chemical processes to remove, capture, and treat contaminant. A brief description of each individual technology is provided.

4.6.2.1 Pump and Treat

Pump and treat (P&T) is perhaps the most commonly implemented remedial technology to address groundwater contamination. This technology involves extraction of the contaminated groundwater followed by *ex situ* treatment and subsequent reinjection or disposal of the treated water. Specifically, P&T applications generally involve installing one or more extraction wells screened appropriately within the target treatment zone of interest, followed by collecting the groundwater extracted from the wells in an aboveground holding tank with subsequent treatment via physical, biological, or chemical means, or by a combination thereof. Subsequently, the treated groundwater may be reinjected underground, discharged into a nearby drainage, sprayed aboveground, or disposed of offsite. Other waste streams generated as part of the treatment processes including spent activated carbon or sludge are generally disposed of offsite. An illustration of a P&T system is shown in **Figure 4-6**. This figure also illustrates how groundwater pumping can be used for hydraulic control of a groundwater plume (described in Section 4.4.3). The primary difference in using P&T for source removal is that the system is designed to directly remove contaminant mass from high concentration areas, whereas hydraulic control is designed to limit plume migration.

Several limitations are often associated with the implementation of the P&T technology. First, potentially long remedial timeframes in the order of decades may be encountered in P&T applications to reduce contaminant levels to MCLs due to effects of back diffusion. For some project sites there is a potential for high capital cost to construct the necessary above- and underground infrastructure. Potential long-term costs could reflect the extended remedial timeframe and associated O&M and waste disposal requirements. Some P&T applications may be effective for only a short period as the pumping only addresses immediately available source removal, and not contaminants within the matrix; contaminant rebounds may occur because of matrix back-diffusion effects. P&T applications are also only applicable at sites with relatively homogeneous lithology and high hydraulic conductivity that favor uniform and effective groundwater pumping.

4.6.2.2 Soil Vapor Extraction

Soil vapor extraction involves application of a vacuum to facilitate extracting volatile or semi-volatile contaminants in a vadose zone followed by *ex situ* treatment of the extracted vapor. Specifically, SVE applications generally involve installing one or more extraction wells within the vadose zone targeted for treatment. In addition to such underground infrastructure, aboveground equipment including blowers and vacuum pumps are used to apply a vacuum to subsequently collect the vapor containing the volatile or semi-volatile contaminants to an aboveground treatment system. The aboveground treatment system generally consists of an air-water separator to remove excess moisture followed by treating the contaminated vapor using granular activated carbon.

The limitations associated with P&T applications are also encountered in implementing SVE technology. For example, SVE efficiency and effectiveness are limited at sites of low permeability

and high organic content. SVE is generally not effective in low-permeability materials and in bedrock systems as primarily addresses VOCs in fractures, not the matrix. In addition, higher vacuums are required at sites with a high moisture content. SVE is also not effective for removing long-chain hydrocarbons, heavy oils, metals, and other organic contaminants including dioxins and PCBs. Groundwater elevation may occur because of the applied vacuum; groundwater extraction may be required to minimize the groundwater rising. SVE is often applied in combination with other technologies such as pump and treat or air sparging and is a common component of ISTR systems.

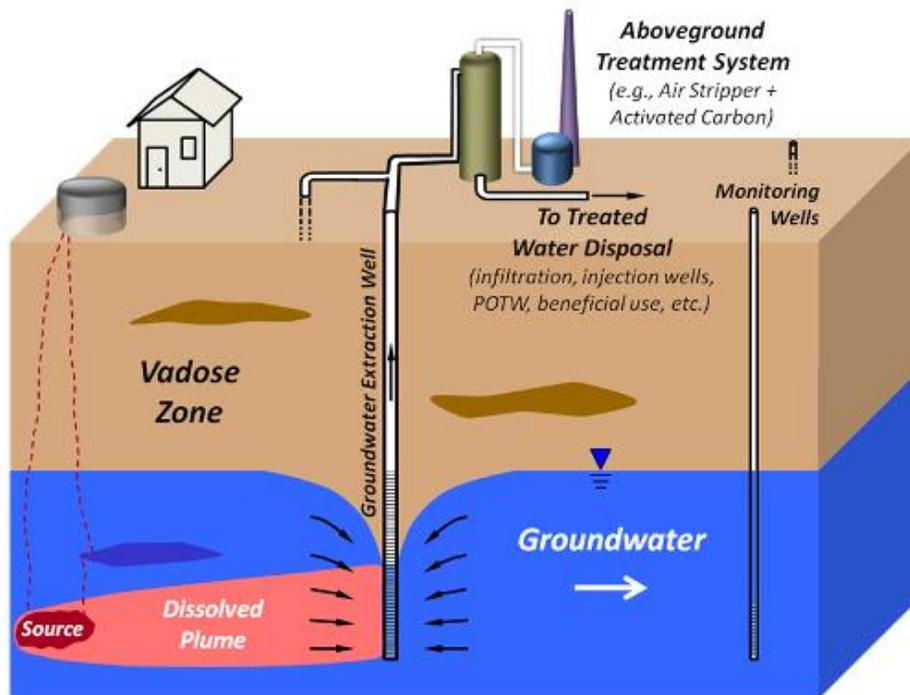


Figure 4-6. Illustration of a P&T System (courtesy of DOE 2015)

4.6.2.3 Air Sparging/Biosparging

Air sparging (also referred to as *in situ* air stripping) and biosparging involves injection of air or gaseous amendments to promote volatilization and degradation of volatile contaminants in saturated soil and groundwater. The typical air sparging/biosparging remedial action often involves installing one or more injection wells within the saturated zone of interest. An air compressor is then used to facilitate injecting air into the contaminated groundwater to drive volatile and semi-volatile contaminants into the overlying vadose zone via volatilization. Note that some contaminant destruction via aerobic degradation may also occur because of this sparging process. SVE technology is then used to capture, collect, and treat the vapor containing the contaminants of interest.

Like SVE, air sparging and biosparging may not be effective at sites of low permeability or with a high degree of lithologic heterogeneity. The latter may result in uneven air flow through the saturated zone and therefore nonuniform treatment. Uncontrolled movement of potentially

harmful vapors may occur in improper SVE design and implementation, resulting in elevated risk of vapor intrusion in aboveground infrastructure. An illustration of SVE and air sparging is shown in **Figure 4-7**.

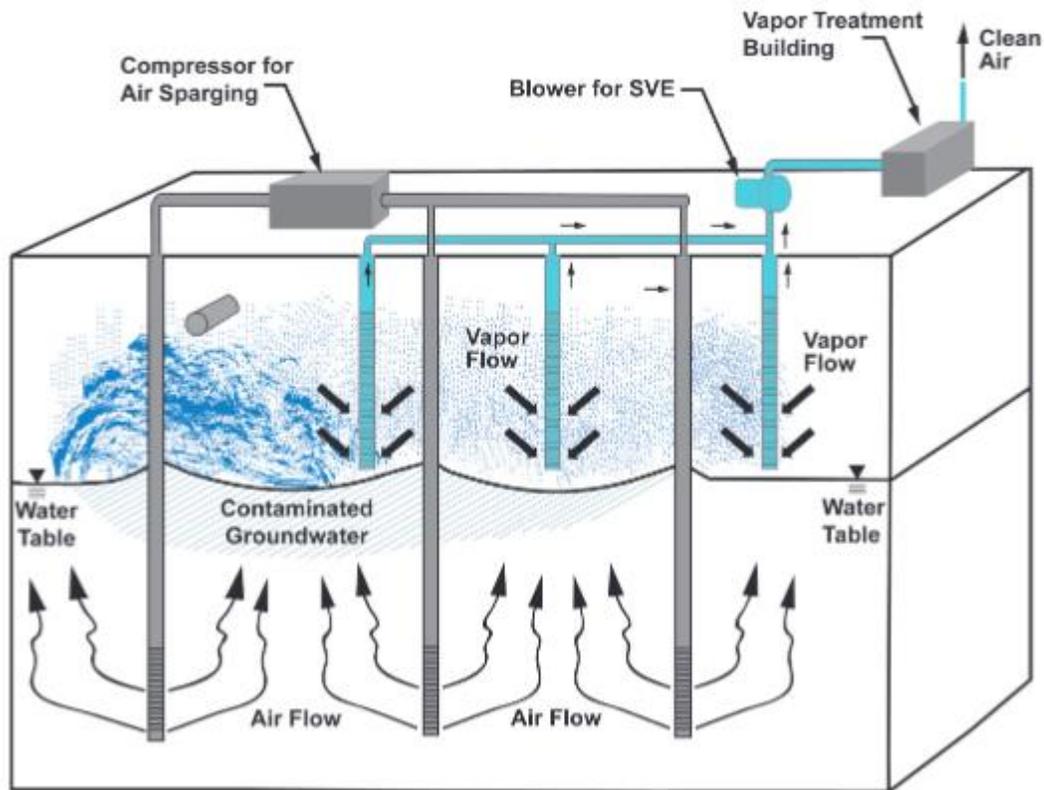


Figure 4-7. Illustration of SVE and Air Sparging (courtesy of Clu-in 2008)

4.6.2.4 In Situ Flushing

This remedial technology involves flooding the saturated or unsaturated zone of interest with an appropriate surfactant or co-solvent to promote enhanced dissolution and subsequent removal of the contaminants from the soil matrix. Subsequently, water is injected into the flooded area and the contaminated fluid is collected and conveyed aboveground for treatment, reinjection, or onsite or offsite disposal. *In situ* flushing technique relies on the ability to uniformly deliver and distribute the surfactant/co-solvent into the zone of interest as well as the ability to recover the flushing fluid. Therefore, *in situ* flushing is typically used in conjunction with P&T. Because of this limitations inherent to P&T are generally observed in *in situ* flushing applications. In addition, extensive bench-scale laboratory testing may be required to optimize the flushing formulation. *In situ* flushing may potentially result in contaminant spreading beyond the capture zone laterally and vertically if the recovery system is not designed and implemented adequately. Due to concerns associated with contaminant migration, it may be difficult to gain regulatory acceptance to implement *in situ* flushing. An illustration of *in situ* flushing is shown in **Figure 4-8**.

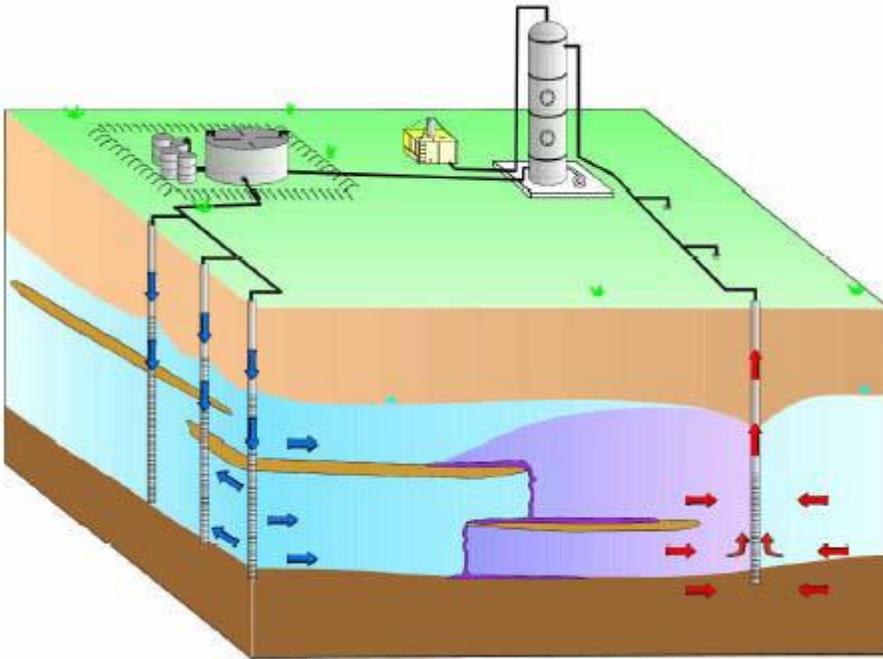


Figure 4-8. Illustration of *In Situ* Flushing (courtesy of NAVFAC 2002)

4.6.2.5 Dual-Phase Extraction/Multi-Phase Extraction

Dual-phase extraction/multi-phase extraction (DPE/MPE) is a remedial technology that utilizes a high-vacuum system to remove contaminants in both soil vapor and groundwater. The extracted liquids and vapors are treated *ex situ* and subsequently reinjected or disposed of offsite; this is similar to what is described above for both SVE and P&T. These systems are typically designed to maximize extraction rates and to intentionally rapidly dewater the target treatment zone. At some sites, biodegradation may also be stimulated during DPE/MPE implementation due to the increased oxygen flux into the subsurface, in a manner similar to air sparging.

4.6.3 *In Situ* Thermal Treatment

The following ISTR technologies may be applicable to some areas of interest within Area IV.

4.6.3.1 Electrical Resistive Heating

Developed by the DOE, electrical resistance heating (ERH) was first used in the oil and gas industry but has since been applied to enhance contaminant removal in soil, sediment, and/or bedrock in the field of environmental remediation. The technology involves heating the target subsurface volume by passing electrical current through saturated and unsaturated zones using an array of electrodes. The resistance to electrical current causes the water and subsurface material in the formation to heat up until its boiling point is reached, resulting in increased subsurface temperature. Because water is required for ERH to operate (it is the conductive material that the electrical current passes through), ERH is not generally able to increase the subsurface temperature above the boiling point of water. Once the water boils, the conductive material (water) is no longer present. Therefore, contaminants with boiling points lower than the boiling point of water such as TCE would be vaporized once their boiling point is reached. Contaminants with boiling points higher than water (e.g., chlorobenzene) would not be vaporized

and may not be completely removed from the subsurface through ERH. Although the resistivity in subsurface materials can vary greatly, heating of soil or rock will occur as the subsurface temperature approaches the boiling point of water (US Army Corps of Engineers [USACE] 2014). ERH has been applied extensively at sites worldwide for treating a wide variety of contaminants including VOCs, chlorinated VOCs (CVOCs), pesticides, polyaromatic hydrocarbons, and creosote.

The conceptual design schematic for a typical ERH application is illustrated in **Figure 4-9**. The three main elements of an ERH system are the heating system, extraction system (vapor and/or multi-phase) and treatment system for extracted vapor, liquid, and/or non-aqueous phase liquid (NAPL). Other elements of an ERH system include temperature and pressure monitoring equipment, a power control unit (PCU), and a computer control system. The electrodes are typically constructed of steel pipe or copper plates, although sheet piling has been used in some applications. Multiple electrodes may be installed within the same electrode boring to allow for targeted treatment of multiple discrete depth intervals. Steel pipe electrodes can be installed in a manner similar to installing a typical monitoring well. A conductive material such as graphite and/or steel shot may be used to pack the annulus of the borehole in depth intervals of interest to increase the effective conductive radius of each electrode. On the other hand, at depth intervals where heating is not desired, the electrode construction materials are insulated and the surrounding borehole annulus is filled with relatively non-electrically conductive materials such as sand or cement.

The vapor and/or multi-phase recovery system collects, condenses, and/or cools the generated steam and liquid to ambient temperatures and separates the NAPL, then conventional techniques are used to adsorb or destroy the vapor and liquid phase contaminants. The PCU, which includes isolation transformers, is used to provide three or six separate electrical phases and force the electrical current to flow between the electrodes. Three-phase heating provides a simple method to deliver uniform voltage potential among electrodes emplaced in an irregularly shaped treatment area. A six-phase electrode layout, on the other hand, is often applied to a circular treatment area. In ERH, heating can be applied to separate subsurface zones either independently or in unison. In many ERH applications, especially those with significant vadose zones, a potable water drip source is applied to soil immediately surrounding the electrodes to keep the soil adjacent to the electrodes from drying out and thus becoming less conductive.

ERH technology relies on heating the subsurface, volatilizing the groundwater, steam stripping the contaminants, and recovering and treating the aboveground vapor to remove contaminant mass. ERH typically requires between 2 and 8 weeks to reach the boiling point of water, which is the maximum achievable temperature for ERH. ERH has mostly been used to remediate sites contaminated with NAPL (chlorinated solvents, and to a smaller extent, fuels). Sites with a high groundwater flow may result in significant heat loss, although engineered hydraulic controls can help mitigate this issue. Contaminants with high boiling points (e.g., PAHs with boiling points exceeding 300°C) tend to be sorbed to soil matrices and generally immobilize in groundwater even at temperatures achievable by ERH, thus limiting the applicability of ERH for these contaminant types. However, increasing the temperature to the boiling point of water will result in increased NAPL mobilization as the NAPL's viscosity and density decrease and solubility and vapor pressure increase due to the rising temperature. The mobilized NAPL, although not vaporized, can be extracted from the subsurface via a multi-phase extraction (MPE) system.

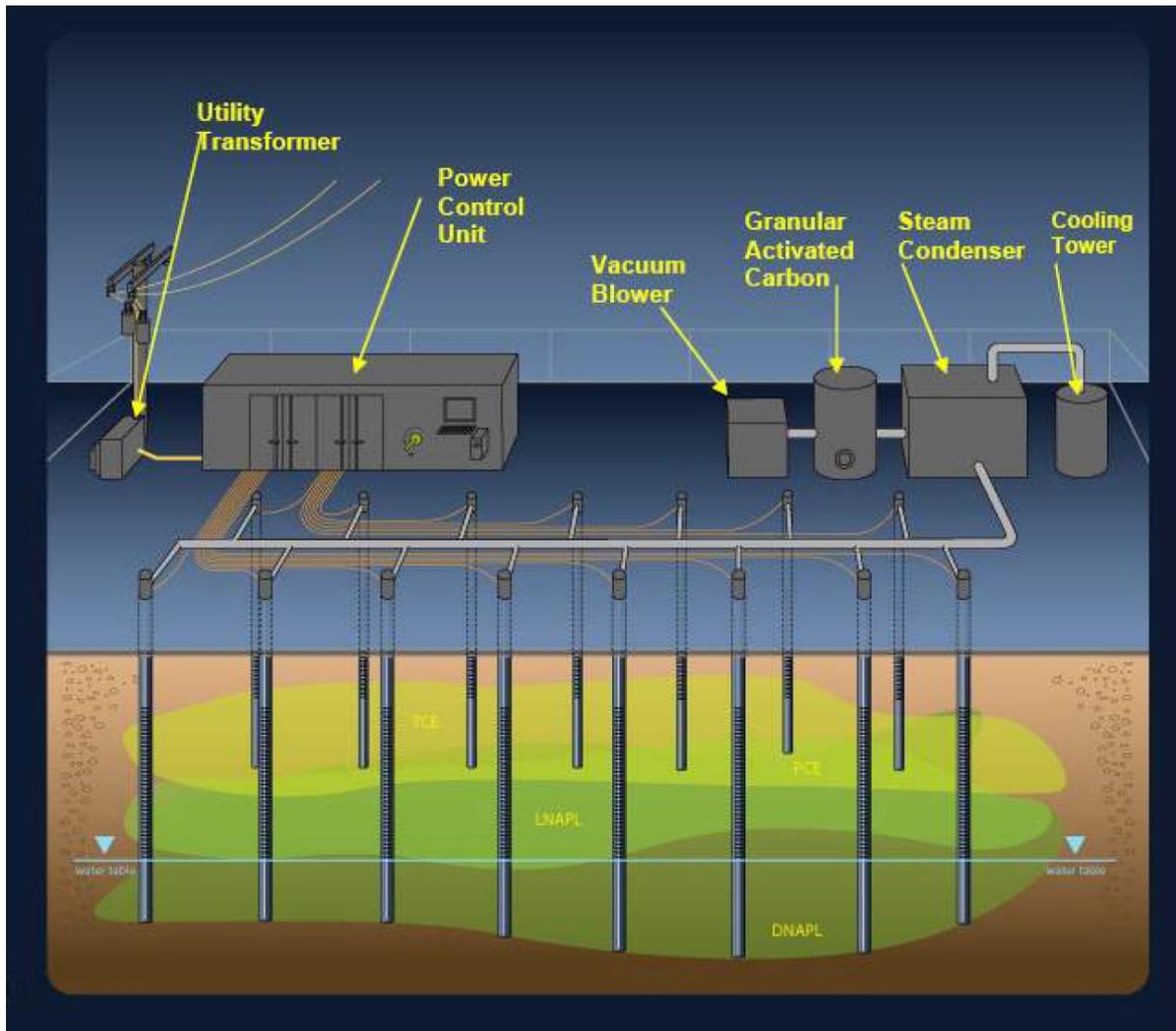


Figure 4-9. Conceptual Design of an ERH System (courtesy of ER-0314, 2010)

4.6.3.2 Thermal Conductive Heating

Thermal conductive heating (TCH), also often referred to as *in situ* thermal desorption, involves the use of conduction heater wells and vapor and/or multi-phase extraction to remove contaminants. The technology relies on heater wells that are operated at high temperature (up to 800°C) and rely on conduction to propagate heat into the subsurface formation. During the TCH process, electrical current is run inside heater wells and the subsurface surrounding the heater wells is heated via thermal conduction to temperatures up to 800°C. This heating creates significant temperature gradients in the formation between heater wells resulting in a heat front moving towards the lower temperature areas of the subsurface. The thermal conductivities of a wide range of subsurface materials including gravel, silt, and clay vary only by a factor of 3. Therefore, the application of heat using TCH is generally uniform across different lithologic or bedrock types and can potentially impact the entire treatment area more effectively than other *in situ* thermal remediation techniques that rely on distributing energy based on hydraulic,

pneumatic, and/or electrical conductivities. This allows for more predictable treatment duration and performance. However, groundwater flow through the treatment zone can impact the ability of the subsurface to heat up because nearly all of the energy is transferred to the water entering the zone.

TCH has been employed for full-scale remediation of a variety of contaminants ranging from low boiling temperature VOCs and chlorinated VOCs, to high boiling temperature PAHs and recalcitrant compounds such as PCBs and dioxins. TCH can treat a wider range of contaminants than ERH or steam injection because temperatures significantly greater than 100°C can be reached, thereby decreasing viscosity and density and increasing vapor pressures (allowing for volatilization) and solubility greatly. This technology has been successfully implemented for treatment in both the vadose and saturated zones and in varying lithologies including low-permeability silt and clay, and fractured bedrock. A conceptual design of a TCH system is graphically depicted in **Figure 4-10**.

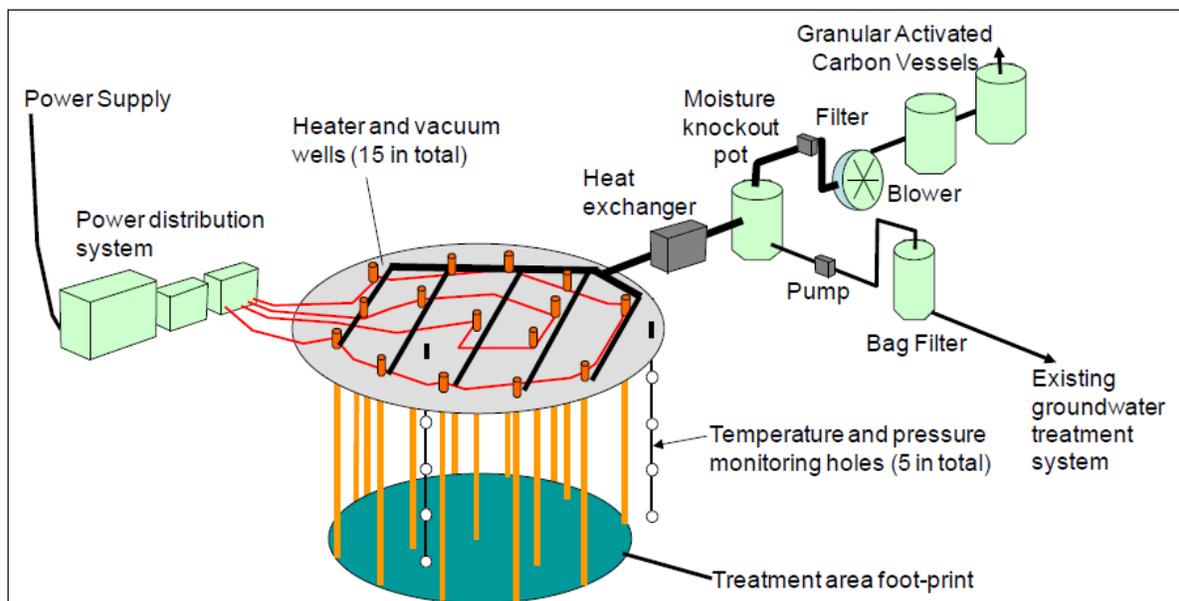


Figure 4-10. Conceptual Design of a TCH System (courtesy of ER-0314, 2010)

Typical operational phases of TCH, using the boiling point of water as an example and VOCs as the contaminants of concern, are illustrated in **Figure 4-11**. The extraction phase is typically used to document the efficacy of the pneumatic and hydraulic (if needed) control units as wells as the off-gas treatment system. During the heat-up phase, power is delivered into the heater wells to facilitate gradual heating of the subsurface to target temperature, resulting in contaminant extraction and convection of heated fluids such as steam, air, and water. The polishing phase is primarily where *in situ* steam-enhanced extraction and subsequent removal of contaminant mass occurs. Interim and final confirmation soil sampling typically occurs in latter stages of the polishing phase. Once the target remedial goals have been satisfactorily met (determined either by sampling or monitoring and modeling of contaminant mass removed), the cool-down phase commences, where steam is removed from the subsurface and the site is cooled to an acceptable

temperature. Following the cool-down phase, *in situ* thermal desorption equipment and other infrastructure are decommissioned and demobilized from the site.

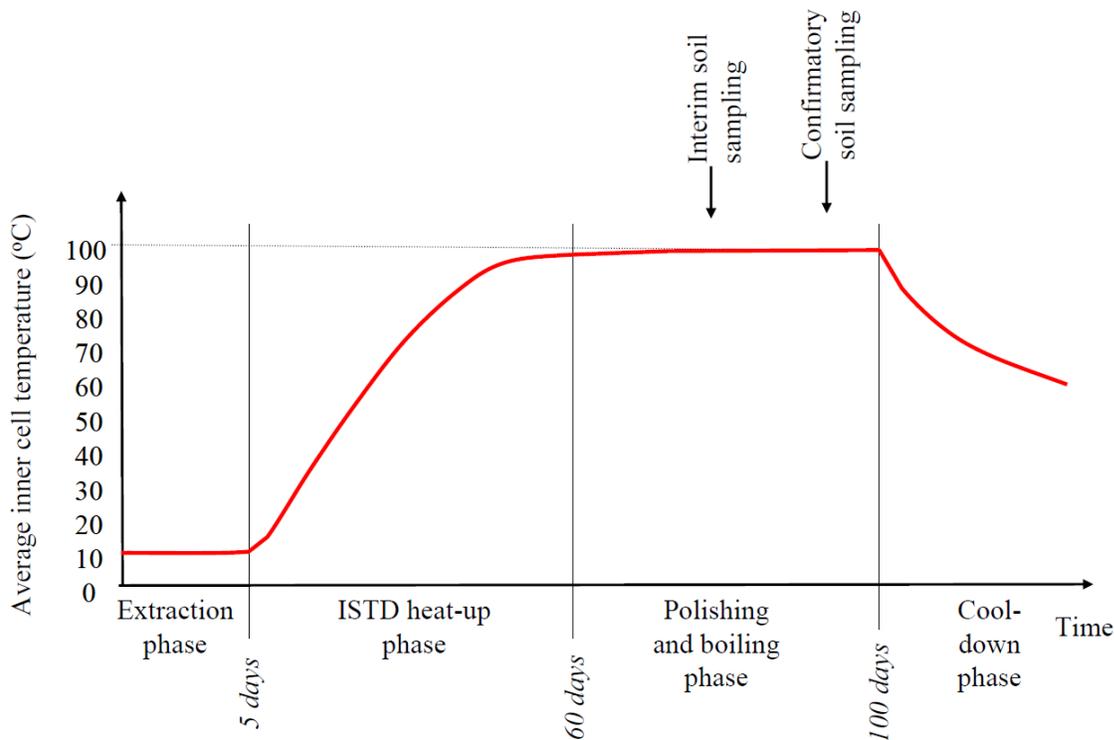


Figure 4-11. Typical Operational Phases of a TCH System (courtesy of ER-0314, 2010)

Steam stripping and vaporization are effective contaminant-removing mechanisms for compounds with a boiling point less than 150°C, and therefore the boiling point of water (i.e., 100°C) is often used as the target subsurface temperature. A higher target temperature ranging between 200°C and 350°C is often desired for SVOCs such as PCBs, coal tar, creosote, and PAHs. At these elevated temperatures, accelerated kinetics of oxidation and pyrolysis often result in higher *in situ* destruction efficiency and thus sites are rarely heated beyond 350°C.

4.6.3.3 Steam-Enhanced Extraction

The steam-enhanced extraction (SEE) technique involves the use of a network of injection and extraction wells to introduce steam into a formation to raise subsurface temperatures to the boiling point of water. Steam injection methods were started in the oil industry to enhance crude oil recovery and similar techniques have been adapted for recovery of contaminants in the environmental industry. Because this technology has been used extensively in the oil industry, the mechanisms have been studied extensively and are well understood (ESTCP 2009). The addition of steam creates a pressure gradient allowing for recovery, reduced viscosity to mobilize more NAPL, and increased vapor pressure. This heating results in mobilization and evaporation of contaminants towards the center of a treatment system for extraction. A conceptual design of a SEE system is presented in **Figure 4-12**.

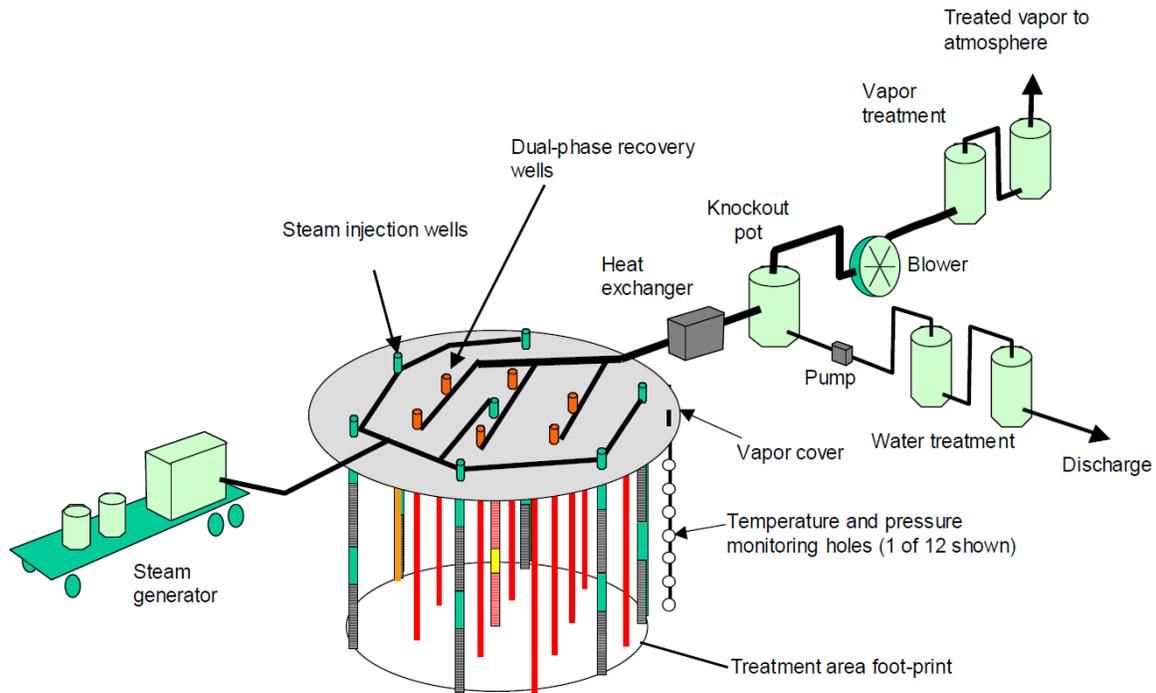


Figure 4-12. Conceptual Design of an SEE System (courtesy of ER-0314, 2010)

A typical SEE operational period, using the boiling point of water as an example, is illustrated in **Figure 4-13**. It includes four primary phases: extraction, SEE heat-up, pressure cycling, and cool-down. The initial extraction phase does not include steam injection; it is intended to demonstrate the efficacy of the pneumatic and hydraulic control system and the off-gas and water treatment system. During the heat-up phase, steam is injected into the subsurface at a pre-determined rate to heat the target treatment area and achieve steam breakthrough at the extraction wells. This “steam sweep” phase allows the subsurface temperature to approach steam temperature. Once target temperatures are approached, a pressure-cycling phase is implemented. During the pressure-cycling phase, pressures are varied, creating a thermodynamically unstable condition generating steam in the subsurface and allowing for steam-stripping of site contaminants. This phase maximizes the contaminant removal. The cool-down phase commences upon confirming remedial goals are satisfied. Interim and final soil confirmation sampling are often conducted to determine treatment effectiveness.

SEE may represent an attractive remedial option at sites with a large contaminant mass, high contaminant concentrations, and the presence of light non-aqueous phase liquid (LNAPL) above the water table and in shallow aquifers. The technology is suitable for a variety of contaminants including CVOCs, DNAPL, and creosote. Although literature suggests that SEE may be applicable at fractured bedrock sites, SEE is generally not effective at sites predominated by low-permeability materials such as clay, fine silt, and competent bedrock because SEE relies on transporting steam in conductive pathways (i.e., fractures) as opposed to thermal or electrical conductivity within the soil, groundwater, and/or bedrock matrix. Only three pilot demonstrations in fractured bedrock have been reported to date; these had varying success. In

addition, since it is very difficult to predict and control the flow path of the injected steam, it is often more challenging to predict contaminant removal efficiency in SEE than in ERH or TCH applications. However, SEE may be used in combination with ERH and TCH to facilitate enhanced contaminant mobility and recovery.

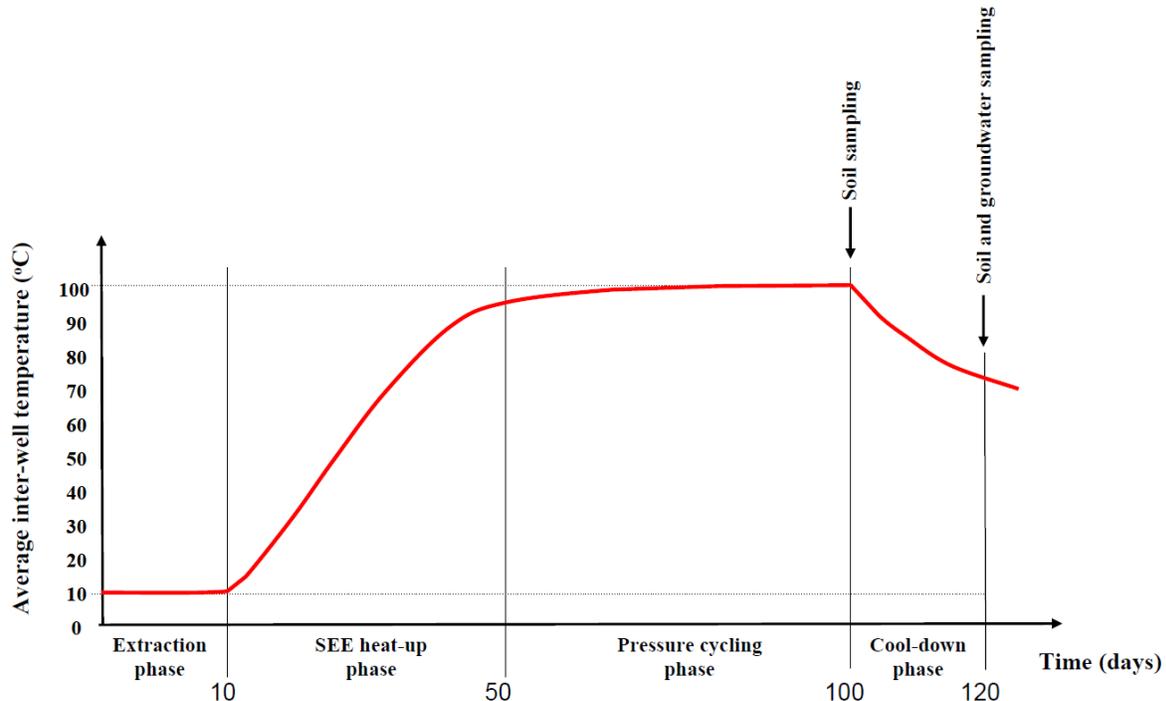


Figure 4-13. Typical SEE Operational Period (courtesy of ER-0314, 2010)

4.6.3.4 Vitrification

Vitrification uses large quantities of electric current to convert contaminated soil and sediment into a vitreous and crystalline material. During this process, materials are often heated above 1,500°C, which degrades organic contaminants via pyrolysis and dechlorination reactions, or locks them into a matrix with no leachability. The process can be performed *in situ* or *ex situ*, although it is likely limited to very shallow depths in *in situ* applications. The technology is suitable for nearly all contaminants including CVOCs, PAHs, heavy metals, and radionuclides. Because of its extremely high treatment unit cost, vitrification has not been widely implemented in full-scale settings. When it is, it is primarily intended for *ex situ* solidification and stabilization of radionuclides and heavy metals. For example, vitrification with nanometallic Ca/CaO amendments was used to immobilize simulated radionuclide Cesium-133 in soil at the Fukushima I Nuclear Power Plant in Japan (Denton 2012). The vitrification technique was also used to immobilize soil contaminated with chromium and other heavy metals and asbestos. It should be noted that extraction and *ex situ* treatment are generally not required with vitrification because the contaminants are either destroyed *in situ* or immobilized by turning the treatment area into a glass/crystalline material that is not leachable. Vitrification is less appropriate for treatment of chlorinated solvents due to the depth of contamination, the subsurface materials, the high cost to vitrify bedrock, and the unreliability of the technology.

4.6.3.5 Radio Frequency Heating

Radio frequency heating (RFH) involves the use of electromagnetic radiation to deliver controlled heating to the subsurface to stimulate contaminant removal. During RFH, the electromagnetic field is directed toward a non-conducting material (i.e., bedrock) and interacts with the electrically-charged particles within the subsurface, resulting in heating of the materials in a manner like a microwave oven (but at a lower frequency). A portion of the applied electromagnetic energy is transmitted through the material, a portion is reflected, and the remainder is absorbed. This absorbed energy heats the groundwater and/or DNAPL. RFH can be applied in both saturated and unsaturated soils and thus can increase temperatures in all media (including liquids and bedrock) anywhere from a few degrees above ambient temperature to more than 300°C depending on the application. Because it heats the subsurface similar to other thermal techniques, RFH supports the removal of contaminants by enhancing their mobility and water solubility, increasing vapor pressures, and decreasing viscosity, surface tension, and/or interfacial tension. In addition, directional application of RFH makes targeted treatment more feasible compared to ERH, TCH, and SEE.

Theoretically, RFH can be deployed at depths ranging from 10 feet to greater than 300 feet bgs with well spacing between 10 and 50 feet. Because it can be targeted, it can be performed more efficiently than other methods that require heating larger areas to achieve treatment. The first RFH application for environmental remediation was performed in the early 1990s at an east coast naval shipyard. Many RFH applications have been reported in literature over the years, including a successful RFH implementation to remove greater than 97% of 1,1,1-trichloroethane DNAPL in fractured bedrock (Kabir 2010). Based on a literature and internet research performed in July 2018, the only vendor offering radio-frequency heating services for environmental remediation applications is JR Technologies, LLC located in Great Barrington, Massachusetts. This research has shown that JR Technologies, LLC has only completed one pilot-scale study investigating the effectiveness of radio-frequency heating, and such study was conducted in 2003. No other application of the technology has been performed by JR Technologies, LLC in the last 15 years. Radio Frequency Co. (RFC) located in Millis, Massachusetts is the only other prominent Internet search result for radio-frequency heating. However, RFC primarily focuses on industrial food/material processing and disinfection applications. Recent internet research and phone conversation with RFC indicated that the company does not offer any remediation services. Overall, the commercial availability and demonstrated field success of the radio-frequency heating technology is extremely limited.

4.6.3.6 Hot Air Injection

Hot air injection is essentially a variation of steam injection developed by the petroleum industry to lower the viscosity of heavy oils, increase the volatility of light oils, and collectively enhance recovery of petroleum products. The technology involves injection of hot air/steam below the contaminated zone to promote heat-enhanced desorption and volatilization of VOCs.

While it has been shown that hot air injection can conceptually facilitate recovery of a large percentage of volatile contaminants, residual mass often remains following implementing this technique and other degradation mechanisms such as MNA or bioremediation must be relied upon to further reduce contaminant mass. Laboratory studies have proven that hot air injection can successfully strip contaminants from the subsurface (Lingineni 1992, Shah 1995). However,

application in the field is difficult, primarily due to the low heat capacity of air (1 kilojoule/kilogram °C, approximately four times lower than steam). It is therefore difficult to maintain the subsurface temperature with air injection.

4.6.3.7 Hot Water Injection

Hot water injection is another variation of the steam injection process that has been studied and, to a more limited extent, field-tested to aid in removing NAPL from the subsurface. The primary difference between hot water injection and the other ISTR methods is that this is a liquid-only remediation technique, intended to mobilize NAPLs by decreasing their viscosity and interfacial tension. Because this method does not vaporize contaminants or heat up the subsurface to impact bedrock pore water, it will likely have limited effectiveness outside of transmissive zones (i.e., bedrock fractures). Additionally, since this method does not aim to generate vapors, vapor recovery systems are generally not used and only liquid recovery systems are used. Because of this, a cold water “cover” is generally required to stop any vapors from releasing to the subsurface. However, the cold water cover will likely result in accumulation of vaporized contaminants with higher vapor pressures (i.e., benzene, TCE). While several hot water flooding studies have been conducted in the petroleum industry (Johnson 1997, Johnson 1990), limited work has been performed remediating contaminated subsurface using the hot water injection technique with varying degrees of success. It is generally recommended for NAPLs with relatively low viscosities and lower densities, as hot water will rise through the water table after injected, and certain NAPLs will rise with the water if their density is decreased sufficiently with the increased temperatures. However, the elevated subsurface temperature could also lead to an increase in specific gravity of certain contaminants (i.e., density relative to water increases as water density decreases), which could result in contaminants migrating deeper into the aquifer.

4.7 *Ex Situ* Treatment (Assuming Excavation)

The following discussion is intended to briefly describe *ex situ* treatment technologies to be used in conjunction with excavation at Area IV. Specifically, the contaminated soil/bedrock excavated from the subsurface may be treated by several biological, physical, or chemical processes, or a combination thereof, including *in situ* reduction, ISCO, ISS, ISTR, soil washing, landfilling or offsite disposal. Details pertinent to ISS, ISCO, and ISTR technologies are provided in Sections 4.4.2, 4.5.2, and 4.6.3, respectively. Soil washing refers to the use of water, with or without treatment agents, to remove contaminants from the excavated materials, treating the generated wastewater, storing the treated soil onsite, then disposing of treated soils offsite. Complex soil washing formulations and treatment processes may be required for sites with multiple contaminants, organic-rich soil, or varying soil particle sizes. The treatment processes in soil washing are generally very water- and energy intensive. Alternatively, the excavated (treated) materials may be stored onsite in engineered landfills, or hauled offsite and stored or disposed.

4.8 *Ex Situ* Treatment (Assuming P&T)

A variety of technologies can be employed to aid in removing VOCs in groundwater extracted via P&T. Specifically, VOCs can be removed via physical processes such as volatilization (air sparging), adsorption (granular activated carbon), and oxidation (permanganate-impregnated granular activated carbon or advanced oxidation processes using ultraviolet light). In addition, the VOCs can be degraded via biologically-mediated processes using a fluidized-bed reactor or

other bioreactor. It should be noted that, in general, other contaminants of concern in groundwater at Area IV including perchlorate and metals can also be addressed using the same *in situ* treatment processes used for VOC remediation. For example, biologically-mediated processes used for remediating VOCs can be used to treat perchlorate (specifically, nitrate-reducing bacteria), whereas some heavy metals may be removed using granular activated carbon. However, in some instances, separate treatment processes may be required to address the multiple groundwater contaminants. For example, select heavy metals can be removed more effectively and efficiently using ion exchange than using activated carbon. However, VOCs are not amenable to treatment using ion exchange. Ultimately, for any extraction-based technologies that are selected for implementation for Area IV groundwater, the selection of ex situ treatment technologies will be made during the design phase.

4.9 Preliminary Screening

Based on CDM Smith's understanding of Area IV groundwater issues including hydrogeological characteristics, coupled with technology implementability, technology maturity, and regulatory considerations, the following remedial alternatives are considered inappropriate for application within Area IV and have been dismissed from further evaluation in this CMS:

- Physical containment: remedial technologies that would involve the use of passive, vertical barrier to intercept and treat the contaminated groundwater are only applicable at sites with sufficient groundwater flow. Therefore, the relatively low groundwater flow in fractured bedrock and alluvial soils renders this group of remedial technologies inadequate to effectively contain groundwater contaminants.
- In situ Stabilization/Solidification: The primary remaining contaminant sources occur within bedrock fractures that are not amenable to mixing and solidification. Therefore, ISS is not applicable and was removed from further consideration.
- Microbially-Induced Calcite Precipitation: given its lack of demonstrated success on a commercial scale and the technology's susceptibility to leaching because of geochemical changes in the aquifer, MICP was removed from further consideration.
- Cometabolism: given the difficulty in attaining the appropriate geochemical and microbiological conditions to promote the target reactions in the subsurface, engineered cometabolism was removed from further consideration.
- Large Diameter Augering: because consolidated materials are not amenable to LDA applications, this technology was removed from further consideration.
- Surfactant/co-solvent washing: this remedial technology was eliminated due to its ineffectiveness in low-permeability materials.
- Dual Phase Extraction/Multiple Phase Extraction: often designed to maximize the extraction rate, this technology is not applicable in Area IV given its low groundwater flow and intrinsic low permeability.

- Steam Enhanced Extraction: this remedial technology was eliminated from further discussion in this CMS because of its ineffectiveness in low-permeability materials in the bedrock at Area IV.
- Vitrification, radio frequency heating, hot air injection, and hot water injection were all eliminated from further consideration because of their energy intensiveness, and lack of full-scale demonstration and commercial application for fractured bedrock.

It should be noted that the specific *ex situ* treatment technologies accompanying P&T or excavation will be further evaluated if P&T or excavation is the selected remedy at any of the remedial areas of interest within Area IV. The rationale for retaining or removing a remedial alternative is presented in **Table 4-2**. The list of remedial technologies that will be further evaluated are associated with the groundwater remediation areas in **Table 4-3**.

Table 4-1. Potentially Applicable Remedial Technologies Under Consideration, Area IV Corrective Measures Study

Category/sub-category		Example remedial technology	Description	General benefits	Design/implementation limitations
No action		-	<ul style="list-style-type: none"> * No remedial action will be implemented at the Site * Used as a baseline for comparing other remedial alternatives 	<ul style="list-style-type: none"> * No cost to be incurred 	<ul style="list-style-type: none"> * Unacceptable in most regulatory environment
Administrative and legal controls		Land use control	<ul style="list-style-type: none"> * Use of non-engineered measures including legal and administrative tools to limit land use and thus potential for human exposures to contaminated materials at the Site 	<ul style="list-style-type: none"> * Minimal cost to be incurred 	<ul style="list-style-type: none"> * Land use controls in place at Area IV; groundwater plumes not migrating offsite
Monitored Natural Attenuation (MNA)			<ul style="list-style-type: none"> * Reliance on a combination of naturally-occurring destructive or non-destructive attenuation mechanisms for reducing contaminant concentrations 	<ul style="list-style-type: none"> * Low cost * MNA may be a more economical remedial alternative than other active remedial approaches at sites with a large dilute plume 	<ul style="list-style-type: none"> * MNA may not be applicable at all sites as appropriate geochemical and microbiological conditions must be present * Extended remedial timeframe with periodic monitoring required * Active remediation will be required if MNA does not perform as expected
Containment	Physical Containment	Permeable reactive barrier with a chemical reagent such as zero-valent iron, persulfate or permanganate	<ul style="list-style-type: none"> * Vertical barrier wall to stop groundwater migration of contaminants 	<ul style="list-style-type: none"> * Relatively passive remedial approach * May represent a more economical remedial alternative than other active remedial approaches 	<ul style="list-style-type: none"> * Usually only applicable at sites with sufficient groundwater flow; not applicable to fractured bedrock * More appropriate for treatment of downgradient plumes rather than source treatment * At sites where the permeable reactive barriers cannot be constructed via trenching, performance may be predicated on uniform delivery and distribution of the treatment amendment * Site-specific lithologic conditions may result in spacing issues & fingering effects * Site-specific geochemical conditions may result in fouling/deactivation of the treatment reagents * Periodic amendment replenishment required * Intermediate degradation products may accumulate * Potential long remedial timeframe
		Permeable reactive barrier with a biological amendment such as lactate or emulsified vegetable oil			
		Use of injectable, liquid carbon substrate such as PlumeStop			
	In Situ Solidification (ISS)	ISS with LDA			
Hydraulic control	Hydraulic control with groundwater pumping	<ul style="list-style-type: none"> * Hydraulic control of groundwater table to prevent contact between groundwater and aquifer materials 	<ul style="list-style-type: none"> * Mature technology * Relatively easy to implement 	<ul style="list-style-type: none"> * Contaminant removal is limited in some situations 	

Table 4-1. Potentially Applicable Remedial Technologies Under Consideration, Area IV Corrective Measures Study

Category/sub-category	Example remedial technology	Description	General benefits	Design/implementation limitations	
Containment	Capping	Engineered cap	* Placement of a cover over contaminated materials	* Mature technology * Minimize contaminant migration	* Very limited, if any, contaminant removal * Requires long-term monitoring/controls
	Grouting	Cement/bentonite grouting	* Injection of a cement/bentonite slurry to seal fracture pathways	* If properly implemented, <i>in situ</i> grouting of the bedrock fractures could represent a very economical remedial alternative	* Used primarily in the geotechnical engineering world for remediation of concrete cracks, dams, foundations; not fractured bedrock * Success has not been demonstrated on a commercial scale for remediation purposes * Good understanding of the site-specific fracture network is needed * May require very close spacing of injection points to achieve aqueduct delivery * Grout materials may be susceptible to erosion/degradation in high-flow system * Long-term performance has not been verified
	Precipitation	Microbially-induced calcite precipitation	* Induction of a biogeochemical process that promotes calcium carbonate precipitation within the soil matrix and in the same process locks up contaminants.	* If properly implemented, microbially-induced calcite precipitation could be used to address a variety of contaminants observed at Area IV	* Not a mature technology * Success has not been demonstrated on a commercial scale for remediation purposes * Susceptible to leaching as a result of changes in aquifer geochemistry * May require very close spacing to achieve adequate delivery
<i>In situ</i> treatment	In situ reduction (biotic and abiotic)	<i>In situ</i> reductive dechlorination	* Delivery of a reducing agent or carbon source into the subsurface to promote reductive degradation of Site contaminants * The treatment amendment can be introduced into the subsurface via conventional injections through permanent well or direct-push rigs, high pressure distribution via environmental fracturing, or soil mixing via large diameter augers * Delivery can further be aided by a shear-thinning fluid in heterogeneous or low permeability aquifers	* Most reagents used are generally of food-grade quality * Biomass accumulated during implementation may serve as a carbon source for additional treatment after the initial amendment has been depleted (i.e., contaminant rebounds are minimized) * Can be used for treatment of source areas as well as downgradient plumes * Enhanced mass dissolution may be realized as a result of implementing these technologies	* Uniform amendment delivery is key to achieving performance objectives, which will be challenging in bedrock systems * Recirculation may be implemented for enhanced performance * Bioaugmentation may be required to achieve complete degradation of the parent compounds of interest if the microbial population required for such degradation is not adequately present * Transient changes in geochemical conditions including pH depression and metal mobilization may occur within the target treatment zone. In most cases, such geochemical changes are not observed outside of the treatment zone and often revert back to baseline conditions within several months.
		<i>In situ</i> chemical reduction	* Inoculation with a VOC-degrading culture is often performed to enhance degradation * Groundwater recirculation may also be implemented to facilitate enhanced mixing and distribution for more effective delivery and treatment		
		Low-temp, thermally-enhanced bio	* May be combined with low temperature ERH or TCH to further enhance degradation rates		

Table 4-1. Potentially Applicable Remedial Technologies Under Consideration, Area IV Corrective Measures Study

Category/sub-category	Example remedial technology	Description	General benefits	Design/implementation limitations
In situ treatment	In Situ Chemical Oxidation (ISCO)	ISCO with persulfate, permanganate, hydrogen peroxide * Introduction of an oxidizing reagent to the subsurface through injections for complete mineralization of Site contaminants * The most commonly used oxidizing agents include hydrogen peroxide, potassium permanganate, sodium permanganate, and sodium persulfate. * Delivery mechanisms are similar to <i>in situ</i> reduction	* May be used to rapidly reduce contaminant concentrations * Very fast reaction kinetics, resulting in a short remedial timeframe	* Uniform amendment delivery is key to achieving performance objectives, which will be challenging in bedrock systems * Transient changes in geochemical conditions including pH depression and metal mobilization may occur within the target treatment zone. In most cases, such geochemical changes are not observed outside of the treatment zone and often revert back to baseline conditions within several months * Potential clogging of the aquifer may occur as a result of using select <i>in situ</i> chemical oxidation reagents such as permanganate * The use of harsh chemical reagents may result in long-term adverse geochemical and microbiological effects in the subsurface, which impacts potential MNA
	Cometabolism	Nitrate reduction/methane cometabolism * Manipulation of microbially-mediated processes to promote fortuitous degradation of the contaminants of interest	* May be effective in some applications	* Not a mature technology * Success has not been demonstrated on a commercial scale for remediation purposes
	<i>In situ</i> soil mixing	- <i>In situ</i> mixing of chemical reagents to promote contaminant degradation	* Thorough mixing of the aquifer materials requiring treatment and the target treatment amendment can be achieved, resulting in effective remediation * Short remedial timeframe	* High capital cost * Very energy- and water-intensive * May only be implemented in unconsolidated and lightly-cemented materials (i.e., cannot be implemented in bedrock systems unless the bedrock materials is pre-excavated to facilitate <i>in situ</i> stabilization/solidifications <i>ex situ</i>) * May require multiple pass-throughs to achieve sufficient mixing at sites with a high degree of heterogeneity
Removal via excavation	Conventional excavation LDA	* Physical removal of contaminated materials via excavation and offsite disposal or onsite treatment.	* Effective source removal * Short remedial timeframe	* High capital cost * Water- and energy-intensive
	Pump and treat (P&T)	* Extraction of contaminated groundwater followed by Site contaminant recovery, treatment, and disposal * Pump-and-treat technologies require a long period of operation and maintenance * Most effective as a hydraulic containment and not removal alternative. * Can be combined with <i>in situ</i> reduction for enhanced delivery * <i>Ex-situ</i> treatment options include granular activated carbon, air stripping, chemical oxidation, thermal oxidation	* Mature technology	* Long remedial timeframe with periodic monitoring * May not be appropriate for low-permeability sites * Contaminant rebounds may occur as a result of matrix back-diffusion effects * An aboveground treatment system is required
	SVE	* Treatment of vadose zone by mobilizing VOCs in the subsurface followed by aboveground capture and treatment	* Mature technology * Promising results from previous NASA study in fractured bedrock	* Long remedial timeframe with periodic monitoring * Vadose zone treatment only * Limited application in low-permeability materials * Above ground treatment is required

Table 4-1. Potentially Applicable Remedial Technologies Under Consideration, Area IV Corrective Measures Study

Category/sub-category	Example remedial technology	Description	General benefits	Design/implementation limitations	
Source removal	Extraction	Air sparging/biosparging	* Injection of air to promote enhanced contaminant volatilization and degradation	* Mature technology	* Possible long remedial timeframe with periodic monitoring * Some VOCs are not susceptible to air sparging * Limited application in low-permeability materials
		Surfactant/Co-solvent	* Use of a surfactant/co-solvent to promote enhanced dissolution/diffusion of site contaminants. * Generally used in conjunction with another remedial alternative	* Potential for enhanced contaminant dissolution from matrix	* Limited application in low-permeability materials * Optimal formulation must be verified prior to field implementation * Chemical- and water-intensive
		DPE/MPE	* <i>In situ</i> removal of site contaminants followed by capture and aboveground treatment	* Applicable for treatment of both soil and groundwater	* Limited application in low-permeability materials * Aboveground treatment required * Potential for contaminant rebound
	<i>In situ</i> thermal remediation	Electric Resistivity Heating	* Heating of the subsurface via resistance or conductive heating to aid contaminant volatilization, recovery, and/or destruction. * Above-ground treatment of vapor and water streams containing contaminants of concern. Treatment options are similar to those shown in P&T.	* Mature technology	* High capital cost for installation of under- and above-ground infrastructure
		Thermal Conductive Heating		* Effective source removal	
		Steam-enhanced extraction		* Mature technology	* High capital cost for installation of under- and above-ground infrastructure
		Vitrification		* Effective source removal in some cases	* Not applicable in low-permeability materials
Radio frequency heating		* Shorter remedial timeframe			
Hot air injection	* May be effective in some applications	* Immature and unproven technology			
Hot water injection					
<i>Ex-situ</i> treatment (assuming excavation)	Biological treatment	Biopiles	* <i>Ex-situ</i> biological treatment of contaminated materials	* Used in conjunction with excavation for onsite/offsite soil treatment	* Potentially space-, energy-, and water-intensive * Applicable for treatment of excavated materials only
		Composting			
		Land farming			
		Slurry phase biological treatment			
	Physical/chemical treatment	Chemical extraction	* <i>Ex-situ</i> physical treatment of contaminated materials		
		Chemical reduction/oxidation			
		Soil washing			
Thermal treatment	Solidification/stabilization	* <i>Ex-situ</i> thermal destruction of contaminated materials			
	Incineration				
	Thermal desorption				
Pyrolysis					
<i>Ex-situ</i> treatment (assuming P&T)	Physical/chemical treatment	Air sparging	* Aboveground treatment of extracted groundwater via adsorption, oxidation or removal processes	* Used in conjunction with pump and treat for onsite groundwater treatment	* Spent materials used for treatment of contaminated groundwater must be disposed of properly
		GAC			
	Advanced oxidation				
Biological treatment	Fluidized bed reactor	* Removal of VOCs in extracted groundwater via biologically-mediated processes			

* **Notes :**
 - DPE: dual-phase extraction
 - ERH: electrical resistive heating
 - ISCO: chemical oxidation

Table 4-1. Potentially Applicable Remedial Technologies Under Consideration, Area IV Corrective Measures Study

Category/sub-category	Example remedial technology	Description	General benefits	Design/implementation limitations
<ul style="list-style-type: none"> - ISS: in situ solidification/stabilization - LDA: large diameter augering - MNA: monitored natural attenuation - MPE: multi-phase extraction - PRB: permeable reactive barrier - SVE: soil vapor extraction - TCH: thermal conductive heating - VOC: volatile organic compound - ZVI: zero-valent iron 				

Table 4-2. Preliminary Screening of Potentially Applicable Remedial Alternatives

Category/sub-category		Example remedial technology	Retained?	Rationale for retaining/removal
No action		-	Yes	* Used as a baseline for comparing other remedial alternatives
Administrative and legal controls		Land use control	Yes	* Boeing Covenant precluding use of groundwater in effect for Area IV
Monitored Natural Attenuation (MNA)			Yes	* Contaminant degradation attributable to MNA is evident at some areas within Area IV
Containment	Physical Containment	Permeable reactive barrier with a chemical reagent such as zero-valent iron, persulfate or permanganate	No	* Not applicable due to Area IV-specific groundwater flow regime
		Permeable reactive barrier with a biological amendment such as lactate or emulsified vegetable oil		
		Use of injectable, liquid carbon substrate such as PlumeStop		
	In Situ Solidification (ISS)	ISS with Large Diameter Augering	No	* The primary remaining contaminant sources observed at Area IV occur within bedrock fractures that are not amenable to ISS mixing and subsequent treatment
	Hydraulic control	Hydraulic control with groundwater pumping	Yes	* Mature technology that may be used to prevent contact between groundwater and impacted aquifer materials
Capping	Engineered cap	Yes	* May be used to prevent surface water percolation	

Table 4-2. Preliminary Screening of Potentially Applicable Remedial Alternatives

Category/sub-category		Example remedial technology	Retained?	Rationale for retaining/removal
	Grouting	Cement/bentonite grouting	Yes	* May be potentially used to minimize groundwater migration
	Precipitation	Microbially-induced calcite precipitation	No	* Lack of demonstrated success at a commercial scale * Very difficult to implement * Treated materials may be subject to leaching when significant changes in geochemical conditions are encountered in the aquifer
<i>In situ</i> treatment	In situ reduction (biotic and abiotic)	<i>In situ</i> reductive dechlorination	Yes	* Mature technology with well-understood treatment mechanisms * Novel delivery techniques can be used to overcome challenges often associated with remediation in low-permeability materials
		<i>In situ</i> chemical reduction		
		Low-temp, thermally-enhanced bio		
	In Situ Chemical Oxidation (ISCO)	ISCO with persulfate, permanganate, hydrogen peroxide	Yes	* Mature technology with well-understood treatment mechanisms * Novel delivery techniques can be used to overcome challenges often associated with remediation in low-permeability materials
	Cometabolism	Nitrate reduction/methane cometabolism	No	* High degree of difficulty in attaining appropriate geochemical and microbiological conditions to promote the target reactions in the subsurface
<i>In situ</i> soil mixing	-	No	* The primary remaining contaminant sources at Area IV occur within bedrock fractures that are not amenable to ISS mixing and subsequent stabilization/solidification	

Table 4-2. Preliminary Screening of Potentially Applicable Remedial Alternatives

Category/sub-category		Example remedial technology	Retained?	Rationale for retaining/removal
Source removal	Removal via excavation	Conventional excavation	Yes	* Direct removal of contamination sources
		Large Diameter Augering	No	* Consolidated materials are not amenable to LDA applications
	Extraction	Pump and treat	Yes	* Mature technology that can be used to address available mass
		SVE	Yes	* Mature technology that can be used to address available mass
		Air sparging/biosparging	Yes	* Mature technology that can be used to address available mass
		Surfactant/Co-solvent	No	* Lack of demonstrated success at a commercial scale * Ineffectiveness in low-permeability materials
		Dual Phase Extraction/Multi-Phase Extraction	No	* Not applicable due to Area IV-specific groundwater flow regime
	<i>In situ</i> thermal remediation	Electric Resistivity Heating	Yes	* Mature technology with demonstrated applicability in bedrock formations
		Thermal Conductive Heating		
		Steam-enhanced extraction	No	* Not applicable in low-permeability materials
		Vitrification	No	* Immature and unproven technology
		Radio frequency heating		
		Hot air injection		
Hot water injection				
<i>Ex-situ</i> treatment (assuming excavation)	Physical/chemical treatment	Vapor extraction, thermal desorption, etc...	Yes	* To accommodate <i>ex situ</i> treatment of excavated materials
<i>Ex-situ</i> treatment (assuming P&T)	Physical/chemical treatment	Air sparging	Yes	* To accommodate <i>ex situ</i> treatment of extracted groundwater contaminants
		GAC		
		Ion exchange		
		Advanced oxidation		
	Biological treatment	Fluidized bed reactor		

Table 4-2. Preliminary Screening of Potentially Applicable Remedial Alternatives

Category/sub-category	Example remedial technology	Retained?	Rationale for retaining/removal
-----------------------	-----------------------------	-----------	---------------------------------

* **Notes :**

- DPE: dual-phase extraction
- ERH: electrical resistive heating
- ISCO: chemical oxidation
- ISS: in situ solidification/stabilization
- LDA: large diameter augering
- MNA: monitored natural attenuation
- MPE: multi-phase extraction
- PRB: permeable reactive barrier
- SVE: soil vapor extraction
- TCH: thermal conductive heating
- VOC: volatile organic compound
- ZVI: zero-valent iron

Table 4-3. Association of Retained Remedial Technologies with Area IV Groundwater Impact Areas

Category/sub-category		Example remedial technology	Former Sodium Disposal Facility	Building 4100 Trench	Building 4100/B56 Landfill	Building 4057/4059/4626 PCE Plume	Hazardous Materials Storage Area - Weathered Bedrock Zone	Hazardous Materials Storage Area - Bedrock Zone	Tritium plume	Radioactive Materials Handling Facility Sr-90 Source	Old Conservation Yard	Metals Clarifier Laboratory Building 4065/DOE Leach Fields 3 RFI Site	Building 4064 Leach Field	Building 4030 and Building 4093 Leach Fields (#1) RFI Site	Building 4020 Rockwell International Hot Lab
None		-	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Administrative and legal controls		Land use control	✓		✓	✓	✓	✓	✓	✓					
MNA			✓		✓	✓		✓	✓	✓		✓			
Containment	Hydraulic control	Hydraulic control with groundwater pumping			✓	✓		✓		✓					
	Capping	Engineered cap								✓					
	Grouting	Cement/bentonite grouting								✓					
In situ treatment	In situ reduction (biotic and abiotic)	In situ reductive dechlorination	✓				✓	✓							
		In situ chemical reduction													
		Low-temp, thermally-enhanced bio													
	ISCO	ISCO with persulfate, permanganate, hydrogen peroxide	✓					✓							
Source removal	Removal via excavation	Conventional excavation	✓				✓			✓					
	Extraction	Pump and treat (P&T)	✓				✓	✓		✓					
		SVE	✓				✓	✓							
		Air sparging/biosparging	✓				✓	✓							
	In situ thermal remediation	ERH	✓												
TCH															
Ex situ treatment (assuming excavation)			✓				✓								
Ex situ treatment (assuming P&T)			✓				✓	✓							

* Notes :

- ERH: electrical resistive heating
- ISCO: chemical oxidation
- MNA: monitored natural attenuation
- SVE: soil vapor extraction
- TCH: thermal conductive heating

- VOC: volatile organic compound
- ZVI: zero-valent iron

Section 5

Remedial Technology Evaluation Criteria

This section describes the evaluation criteria that will be employed for detailed comparative analysis and subsequent screening and selection of the remedial technologies under consideration for each sub-area at Area IV, which is presented in **Section 6**. Threshold criteria that each remedial technology under consideration must meet are described in **Section 5.1**. The five criteria for the comparative analysis of remedial technologies potentially applicable for each sub-area of interest within Area IV are presented in **Section 5.2**. Note that modifying criteria including regulatory acceptance and community acceptance are not addressed at this point but will be evaluated following regulatory and public review and comment of the CMS. Costs are provided as a separate comparative value and are not scored in the same manner as the threshold and balancing criteria.

5.1 Threshold Criteria

Each remedial technology under consideration must meet the following three threshold criteria: (1) attain the relevant groundwater cleanup standard; (2) control the sources of releases; and (3) protect human health and the environment. Note that these threshold criteria are not applicable to the No Action, which is intended to serve as a baseline for the comparative analysis. Similarly, these threshold criteria are not applicable to Administrative and Legal Controls because they are already in place and will likely accompany every remedial technology selected for corrective action at Area IV. Details pertinent to these threshold evaluation criteria are provided below.

5.1.1 Attain Relevant Groundwater Cleanup Standard

Every remedial technology listed in **Table 4-3**, except for No Action and Administrative and Legal Controls, is capable of achieving the relevant groundwater cleanup standard specified in **Section 3**, irrespective of remedial timeframe, cost, and other considerations. For example, MNA, *in situ* reduction via reductive dechlorination, chemical reduction or thermally-enhanced bioremediation, ISCO, excavation, P&T, bedrock fracture SVE, and ISTR may be capable of treating VOCs in bedrock groundwater within the FSDF area at Area IV. However, the remedial timeframes may vary widely for the different remedial technologies. For example, excavation and ISTR may have the shortest remedial timeframes because of the aggressive source-removing nature of the technology, whereas MNA, which relies on natural degradation process, may have the longest remedial timeframes while still being able to achieve the cleanup goal. Some of the more aggressive remedial technologies such as excavation and ISTR (which has not been proven to be effective at SSFL) are more expensive than passive remedial approaches such as MNA. Therefore, while the ability to attain media cleanup standard is very similar among the retained remedial technologies, the prioritization in remedial timeframe, capital, operations and maintenance (O&M), and overall project cost, as well as other considerations that are reflected in the five balancing evaluation criteria can serve as the differentiator among the various technologies.

5.1.2 Control the Sources of Releases

The ability to control the contaminant sources and minimize further releases via treatment, containment, destruction or a combination therefore must be satisfactorily met by every remedial technology under consideration shown in **Table 4-3**. Similar to the first threshold criterion, this evaluation criterion can be met by all remedial technologies retained for this evaluation, except for the No Action and Administrative and Legal Controls, irrespective of remedial timeframe, cost, and other considerations.

5.1.3 Protect Human Health and the Environment

This evaluation criterion assesses whether each remedial technology provides adequate protection of human health and the environment. Note that the overall assessment of protection relies on other evaluation criteria, most notably, short- and long-term effectiveness, as well as the ability to attain groundwater cleanup standard. Like the threshold criteria described in **Sections 5.1.1** and **5.1.2**, this evaluation criterion can be met by all of the retained remedial technologies including No Action and Administrative and Legal Controls.

5.2 Balancing Criteria

The following balancing criteria will be used to further aid the comparative analysis of remedial technologies under consideration for each sub-area within Area IV: long-term reliability and effectiveness; reduction of toxicity, mobility or volume through treatment; short-term effectiveness; implementability; and cost. Based on the RCRA CMS guidance, each of these balancing criteria can be further divided into sub-criteria. Note that while the overarching evaluation criteria can differentiate the aforementioned remedial technologies retained for evaluation herein, some of the sub-criteria are not applicable at Area IV. Therefore, the specific sub-criteria provided in the RCRA CMS guidance will not be evaluated on an individual basis in this technology evaluation. Instead, sub-criteria providing the most significant differentiation among the technologies under consideration at Area IV are used as described in the following sections.

5.2.1 Long-Term Reliability and Effectiveness

Factors influencing the evaluation of long-term reliability and effectiveness of a particular remedial technology include magnitude of residual risk (residual risk remaining from untreated waste or treatment residuals at the conclusion of remedial activities) and adequacy and reliability of controls (the adequacy and suitability of engineering and/or institutional controls, if any, that are required to manage treatment residuals or untreated wastes that remain at the site). This criterion refers to the probability of a remedial technology to meet the remedial objectives and protect human health and the environment over the long term, and the degree of permanence provided by the remedy. Sub-criteria that will be used to evaluate the overarching long-term reliability and effectiveness include (1) the likelihood of a remedial technology to reach the objectives and (2) the permanence (i.e., irreversibility) of the remedial technology following completion.

5.2.2 Reduction of Toxicity, Mobility or Volumes of Wastes

Factors that influence the reduction of toxicity, mobility or volume of wastes include treatment and process used and material treated (degree to which the implemented technology treats the

contaminants of interest as well as the amount of materials treated), amount of hazardous materials destroyed or treated (the degree to which the contaminants of interest are destroyed or treated versus simply contained *in situ*), degree of expected reduction in toxicity, mobility or volume (the degree to which toxicity, mobility or volume of the contaminants of interest is reduced via removal, treatment, containment or a combination thereof), degree to which the treatment is irreversible (the permanent nature of the implemented treatment), and type and quantity of residuals remaining after treatment (the type and amount of residual waste remaining onsite following treatment).

5.2.3 Short-Term Effectiveness

This criterion addresses the effectiveness of a remedy during its initial implementation stages. It includes effectiveness at controlling contamination during the period of time needed to implement the remedy and the timeframe required to meet the remedial objectives, as well as adverse impacts that may be posed to workers, nearby community, and the environment during construction and operation of the remedy until remedial goals are achieved. Sub-criteria that will be used to evaluate the overarching short-term effectiveness of each remedial technology include (1) short-term impacts and potential for exposure to workers and the community, and (2) the time required to reach remedial action objectives.

5.2.4 Implementability

This criterion addresses the technical and administrative feasibility of implementing a remedy from design to construction and O&M phases. Factors such as availability of services and materials, administrative feasibility, and coordination with other governmental entities are also considered.

5.2.5 Cost

This criterion addresses the cost-effectiveness of a remedy based on design, construction, startup, and O&M costs. Note that capital and O&M costs are scored separately because while the overall project cost may be similar for some remedial technologies, the capital investment and O&M efforts may vary significantly. Based on funding availability, remedial technologies with a higher overall cost but lower initial capital investment requirements may be preferred. Note that the cost associated with each technology was not given a numerical score.

5.3 Comparative Analysis of Remedial Technologies

A comparative analysis was completed to identify the degree to which each remedial strategy performs with regard to evaluation criteria described above. A numerical scoring system was used to evaluate the criteria. Each technology was assigned a numerical score between 0 and 5 to represent its expected ability to meet the evaluation criteria, as defined below. Costs are presented as the estimated capital and O&M expenditures and are not given a numerical score.

- 0: worst (criterion not satisfied)
- 1: poor
- 2: below average

- 3: average (criterion partially satisfied)
- 4: above average
- 5: best (criterion completely satisfied)

These scores have no independent value and are only meaningful when compared amongst the different remedial technologies under consideration. All of the criteria except for cost were evaluated on a qualitative basis. Scoring was determined as follows:

- For short-term effectiveness, separate scores were given for the time required to reach RAOs, and for short-term impacts and potential for exposure to workers and the community. The overall score for short-term effectiveness was calculated by weighting the remedial timeframe score greater than the exposure potential score by a factor of two, as the time required to meet remedial objectives is considered to be more important for decision-making, and the potential for exposure during implementation is able to be mitigated for all technologies.
- For long-term effectiveness, separate scores were given for the likelihood of a remedial technology to reach the objectives, and for the permanence of the remedial technology following completion. These criteria were weighted equally in the final score.
- For cost, separate estimates are provided for the capital cost and the O&M cost. This allows for a direct comparison between technologies with similar effectiveness and implementability scores.

Detailed comparative analysis of the remedial technologies under consideration for each sub-area within Area IV is provided in **Section 6**.

Section 6

Remedial Technology Evaluation

A conceptual description of how each technology could be implemented at each sub-area of interest at Area IV is provided in this section. The descriptions are followed by a comparative analysis of the different remedial technologies under consideration for each sub-area. Separate descriptions are provided by sub-areas including the FSDF, Buildings 4057/4059/426 PCE plume, HMSA (near-surface bedrock zone and deeper bedrock), tritium plume, RMHF, and the Metals Clarifier Laboratory Building 4065/DOE Leach Fields 3 combined RFI Site. Note that no remedial action is anticipated for Building 4100 Trench, the Old Conservation Yard, Building 4064 Leach Field, Building 4030 and Building 4093 Leach Field (#1) RFI Site, and Building 4020 Rockwell International Hot Lab; therefore, these sub-areas are excluded from the following discussion. In addition, further discussion with Boeing is required for the Building 4100/B56 Landfill sub-area; the remedial technology evaluation specific to this area will be added following a determination of the source of groundwater contamination. In addition, any data gaps that must be filled to aid remedial design and subsequent corrective action implementation are described for each sub-area. Note that any remedy selected for corrective action implementation would be subject to a five-year review process. Such review would allow for an opportunity for remedial performance evaluation, optimization, and modification if needed.

6.1 FSDF

Features of the FSDF are illustrated in **Figure 2-1**. Contamination at the FSDF is characterized by VOC and metals in groundwater contained in the near-surface bedrock fractures (20 to 40 feet bgs) and VOC contamination in the deeper bedrock fractures (40 to 100 ft bgs). It should be noted that the FSDF has been documented to have the tightest and least fractured bedrock at Area IV (CDM Smith 2018a).

As presented in **Table 6-1**, remedial technologies retained for further evaluation at the FSDF sub-area within Area IV include (1) Groundwater Extraction via Fracture Dewatering, (2) Bedrock Fracture Soil Vapor Extraction, (3) *In Situ* Reduction (ISR), (4) ISR with Permeability Enhancement, (5) *In Situ* Chemical Oxidation (ISCO), (6) ISCO with Permeability Enhancement, (7) Source Excavation, (8) Enhanced Groundwater Extraction via Permeability Enhancement, and (9) *In Situ* Thermal Reduction (ISTR). Data gaps pertinent to future remedial design and technology implementation at the FSDF, a brief description on how each remedial technology would be implemented with regard to the initial construction phase and the subsequent operation and maintenance (O&M) phase, and a preliminary analysis of each remedial technology under consideration for the FSDF with regard to the long-term reliability and effectiveness; reduction of toxicity, mobility or volume of wastes; short-term effectiveness; implementability, and cost are presented in this section. Subsequently, a comparative analysis of all technologies under consideration for the FSDF, and recommendations with regard to data gap investigation and remedial technology to be considered for corrective action implementation are provided.

6.1.1 Data Gaps

A study was completed in the spring of 2018 to further delineate the extent of VOC contamination in the near-surface bedrock zone at the FSDF (CDM Smith 2018b). Results of the recent near-surface

bedrock coring coupled with the data collected during the GWIM have increased the understanding of the presence of VOCs within near-surface bedrock fractures. Fractures contributing to VOC contamination in the shallower and deeper bedrock have been identified. The lateral extent of the VOC-impacted shallow fracture network is partially understood; additional coring of the shallow bedrock may be necessary as part of remedy design. Hydrogeological information pertinent to the design of a groundwater extraction and treatment system involving dewatering of fractures can be obtained through additional packer isolation of water bearing fractures in boreholes.

6.1.2 Conceptual Design and Implementation and Preliminary Analysis

A high-level conceptual description of the design and implementation of each remedial technology under consideration for the FSDF and its preliminary analysis are presented in the following subsections. No Action and Administrative and Legal Controls are excluded from the following discussion as they are intended for baseline analysis. Elements of the existing administrative and legal controls that are in place for Boeing-owned property at SSFL would be incorporated into and/or modified as appropriate in the remedy selected for the FSDF. Note that MNA would be performed at the completion of any active treatment performed at the FSDF to allow for long-term remedial performance monitoring and evaluation. Implementation of MNA would involve using existing monitoring wells screened within target depth intervals to obtain data on the reduction in concentrations for contaminants of interest over time. Data on associated geochemical and microbiological characteristics of the groundwater would also be collected. Monitoring would continue until the groundwater cleanup standard was met. Note that ***no*** major construction activities are anticipated for implementation of MNA at the FSDF.

6.1.2.1 Groundwater Extraction via Fracture Dewatering

Conceptual Design and Implementation

An interim action involving extraction, collection, and offsite disposal of contaminated groundwater utilizing existing infrastructure has already been performed at FSDF. For the near-surface bedrock fractures, the extraction rate was observed to be less than 100 gallons per month. Experience with sampling of deeper fractures using isolation packer produced similar low groundwater productivity results. Once pumped dry, groundwater recharge rate into the boreholes was low, typically less than 1 foot per day. Given that the readily accessible groundwater contamination is present within the fractures, addressing this contamination would result in some mass removal. The near-surface fractures require rainfall to recharge once they have dried out. If annual rainfall is relied upon as a means for recharging the fractures, an extended remedial timeframe may be required, unless treated water or potable water is injected into the subsurface fractures and recaptured from the extraction wells (i.e., groundwater flushing).

Groundwater that accumulates in extraction wells would be periodically pumped to remove the contaminants. The existing near-surface wells would be pumped on a periodic basis when water accumulates. The deeper fractures within wells exhibiting TCE above 50 µg/L (e.g., C-08, RD-23, RD-64, RD-65) would be first isolated using inflatable packers installed below the fractures. Groundwater that accumulates above the packers would be periodically extracted. Pumping would be repeated until the groundwater cleanup standard is met. The low volumes of groundwater extracted from the fractures would not warrant the construction and operation of an onsite treatment system; instead, the water would be temporarily stored in a holding tank at the FSDF and then transferred to an offsite treatment facility.

Construction

The construction activities for implementing groundwater extraction via fracture dewatering at the FSDF are anticipated to be minimal as the existing well network to support fracture dewatering is likely sufficient. Given the limited amount of groundwater that can be extracted from core holes at the FSDF and the very slow recovery rate, full-scale remedy utilizing groundwater extraction would likely require additional core holes. It was assumed that up to 20 additional core holes would be drilled to facilitate groundwater extraction from fractures. The number and lateral spacing of these wells would depend on results of additional hydrogeological characterizations to be performed at the FSDF as part of the pre-design investigation. Other construction activities would likely involve installation of downhole extraction wells and aboveground conveyance piping (if needed) to facilitate groundwater collection at a centralized location. Because it is not expected that large volumes of groundwater would be extracted, there would likely be no need for constructing an onsite groundwater treatment system.

O&M

Upon completion of all construction activities, it is assumed that groundwater extraction would be performed periodically for approximately 25 years. Specifically, it is anticipated that the full-scale groundwater extraction system would be operated once per month and that up to 3 monitoring events would be performed on an annual basis to facilitate performance evaluation and potential system optimization. All O&M activities and associated performance results would be reported in an annual groundwater monitoring report.

Preliminary Analysis – Long-Term Reliability and Effectiveness

Given an extended remedial timeframe (25 years), the likelihood to achieve remedial action objectives (RAOs) using this technology is relatively high. Previous pumping of groundwater at the FSDF indicated that contaminant rebound would be unlikely; therefore, the irreversibility of the technology is likely high. Collectively, this technology would likely be reliable long-term as well as effective in achieving RAOs.

Preliminary Analysis – Reduction of Toxicity, Mobility or Volume of Wastes

This technology would be effective in reducing the toxicity, mobility or volume of wastes, and would probably meet the established groundwater RAOs given an extended remedial timeframe (25 years).

Preliminary Analysis – Short-Term Effectiveness

Because of the minimal construction efforts required to implement this technology, there is very little short-term impacts and potential for exposure to workers and the community. However, the remedial timeframe required to achieve the RAOs, which is important to DOE, is anticipated to be very long. Collectively, the short-term effectiveness associated with this technology is likely moderate.

Preliminary Analysis – Implementability

This technology has already been implemented at the FSDF, albeit at a small-scale. There is no proprietary service or equipment required. Therefore, this technology is highly implementable.

Preliminary Analysis – Cost

While there is only minimal capital cost associated with implementing this technology, the long-term O&M cost is high given the extended remedial timeframe likely required to achieve RAOs.

6.1.2.2 Bedrock Vapor Extraction

Conceptual Design and Implementation

Bedrock vapor extraction (BVE) would involve the use of existing near-surface bedrock wells to extract VOCs in air contained within the fractures. Removal of VOCs from the bedrock matrix would be dependent on the rate of back-diffusion of VOCs from the matrix. BVE probably would be implemented jointly with groundwater extraction and would follow the dewatering of the fractures as described above. A vacuum would be placed on one of the wells, with the other wells left open to the atmosphere to allow for air entry into the fractures. VOCs brought to the surface at the extraction well would be treated using activated carbon. The spent activated carbon would then be transported offsite for treatment and disposal.

Construction

Minimal construction activities would be anticipated under this remedial technology as existing near surface bedrock wells would be utilized.

O&M

Periodic system check, monitoring, and optimization as well as data analysis and reporting would be performed.

Preliminary Analysis – Long-Term Reliability and Effectiveness

While contamination within the vadose zone in the near-surface bedrock may have been attributable to groundwater contamination observed in the deep bedrock, treating the vadose zone contamination alone would not likely facilitate achieving groundwater RAOs within a reasonable remedial timeframe (25 years) as the treatment effectiveness is controlled by back-diffusion from the matrix. Therefore, the long-term reliability and effectiveness of this remedial technology is considered to be low.

Preliminary Analysis – Reduction of Toxicity, Mobility or Volume of Wastes

Although it is expected that BVE could remove VOCs from open fractures, pilot testing would be required to assess the effectiveness of this technology in removing VOCs from the bedrock matrix. As aforementioned, implementation of BVE alone at the FSDF would require an extended time period to achieve groundwater RAOs.

Preliminary Analysis – Short-Term Effectiveness

Because of the minimal construction efforts required to implement this technology, there is very little short-term impacts and potential for exposure to workers and the community. However, the remedial timeframe required to achieve the RAOs, which is considered to be of significant importance to DOE, is anticipated to be very long (25 years). Collectively, the short-term effectiveness associated with this technology is likely moderate.

Preliminary Analysis – Implementability

There is no proprietary service or equipment required for implementing BVE at the FSDF. In addition, existing surface bedrock wells may be utilized to facilitate the BVE. Therefore, this technology is highly implementable.

Preliminary Analysis – Cost

While there is only minimal capital cost associated with implementing this technology, the long-term O&M cost is high given the extended remedial timeframe likely required to achieve RAOs.

6.1.2.3 In Situ Reduction

Conceptual Design and Implementation

Implementation of the ISR technology at the FSDF would involve installation of injection wells in a gridded configuration and screened within the fractures harboring VOCs. Given the highly competent nature of the bedrock observed at the FSDF, it is anticipated that a relatively close injection well spacing would be required. Following proper well installation and development, an aqueous amendment would be introduced to the subsurface via the injection wells to promote microbially-mediated degradation of the VOCs. It is anticipated that bioaugmentation would be required to overcome the relatively low VOC concentrations observed in groundwater. Note that ISR is a highly-specific remedial technology that has not been demonstrated at the FSDF. Therefore, pilot testing of the technology is recommended to obtain pertinent full-scale design parameters.

Construction

Construction activities supporting implementation of the ISR technology at the FSDF would involve installation of numerous injection wells at a relatively close spacing. A tracer test would be performed following completion of several injection and monitoring wells to aid in assessing achievable injection volume/rate/pressure and the anticipated injection radius of influence (ROI). Such ROI assessment would provide insights into the well spacing required to adequately address the target treatment zone. Given the extended vertical treatment zone, multiple injection wells screened within different depth-discrete vertical intervals would be required. In addition, a network of monitoring wells screened appropriately within the target depth intervals would be required to facilitate performance monitoring and optimization. Up to 50 injection wells may be required to implement ISR to address the high contaminant concentration areas at the FSDF. Depending on results of the data gap investigations, which would be performed to aid in delineating the source of groundwater contamination, ISR may be implemented at the FSDF in a gridded injection approach or as a biobarrier. For cost estimating purposes, it was estimated that up to 50 injection wells would be installed as part of the ISR implementation at the FSDF and that up to eight monitoring wells would be installed to facilitate performance monitoring and evaluation. Upon completion of all well installation and development activities, an injection system consisting of several manifolds allowing for simultaneous inline injections into multiple wells using a pneumatically-operated chemical dosing pump would be constructed. A commercially-available, oil-based, emulsified vegetable oil (EVO) designed to promote reductive dechlorination of TCE and associated daughter products would be used during the ISR implementation at the FSDF. A fermentable carbon concentration of approximately 3 percent (by weight) in the amendment solution would be targeted. Following amendment injections and establishment of geochemical conditions conducive to bioaugmentation, a commercially-available culture containing high concentrations of *Dehalococcoides* would be injected into the injection wells to

further enhance the contaminant degradation kinetics. Because of the inability to extract large volume of groundwater at the FSDF, groundwater recirculation, which could greatly enhance amendment/contaminant contact and therefore treatment effectiveness, would not be implemented. The lack of available water is another technical limitation associated with implementing ISR at the FSDF.

O&M

Depending on site-specific hydrogeological conditions, a typical EVO product may last between 2 and 5 years. Therefore, periodic EVO replenishments would be required. It is anticipated that up to 5 amendment reinjection events would be performed at the FSDF over the 15-year O&M duration. In addition, periodic groundwater monitoring would be conducted at relevant nearby monitoring wells to facilitate assessment of remedial progress and allow for performance optimization. All O&M activities and associated performance results would be reported in an annual groundwater monitoring report.

Preliminary Analysis – Long-Term Reliability and Effectiveness

Given that an extended remedial timeframe (25 years) is permissible, the likelihood to achieve RAOs using this technology is relatively high. Based on CDM Smith's experience with groundwater extraction in the FSDF area and also based on contemporary literature that shows ISR can minimize rebound, contaminant rebound is thought to be unlikely after ISR implementation; therefore, the irreversibility of the technology is likely high. Assuming it is implementable and effective, this technology would likely be reliable long-term as well as effective in achieving RAOs.

Preliminary Analysis – Reduction of Toxicity, Mobility or Volume of Wastes

This technology would be effective in reducing the toxicity, mobility or volume of wastes, and would probably meet the established groundwater RAOs given an extended remedial timeframe.

Preliminary Analysis – Short-Term Effectiveness

Construction activities primarily consisting of well installation and development would be anticipated as part of the ISR implementation at the FSDF. Engineered controls previously employed can be implemented to mitigate short-term impacts and potential for exposure to workers and the community. However, the remedial timeframe required to achieve the RAOs, which is important to DOE, is anticipated to be relatively long (25 years). Collectively, the short-term effectiveness associated with this technology is likely moderate.

Preliminary Analysis – Implementability

The effectiveness of ISR is highly site-specific. Because this technology has never been implemented at the FSDF, a pilot-scale test would be required. However, there is no proprietary service or equipment required for constructing and implementing the ISR technology. Therefore, this technology is highly implementable.

Preliminary Analysis – Cost

The primary capital cost for implementing ISR at the FSDF is associated with the well drilling and installation activities. The primary components of the O&M cost are the periodic amendment reinjection, groundwater monitoring, and data analysis and reporting.

6.1.2.4 *In Situ* Reduction with Permeability Enhancement

Conceptual Design and Implementation

A pilot study of ISCO performed by Boeing demonstrated the difficulty in injecting an oxidizing reagent into narrow fractures containing groundwater with VOCs. Therefore, implementation of the ISR technology at the FSDF may benefit from hydraulic permeability enhancement (i.e., hydraulic fracturing) of the near-surface bedrock. Emplacement of silica sand in target vertical treatment intervals via hydraulic permeability enhancement can result in orders-of-magnitude increases in bulk hydraulic conductivity of the bedrock. While ISR and hydraulic permeability enhancement have been implemented in similar geologic settings, these highly site-specific technologies have not been demonstrated at the FSDF; therefore, pilot testing of these technologies would be required to quantify the benefits of incorporating permeability enhancement technology and to, as applicable, obtain design parameters pertinent to full-scale implementation.

Construction

Construction activities supporting implementation of the ISR with permeability enhancement technology at the FSDF would be relatively similar to that associated with the ISR technology alone. A number of bedrock borings would be drilled, assumed to be a grid of 50-foot spacing. Once the borings are advanced to the target depth, then the permeability enhancement would be performed at select vertical intervals to emplace the silica sand. In addition to the silica sand, zero-valent iron and/or a solid phase electron donor could be incorporated into the injection fluid to facilitate direct chemical and/or biological reduction of the chlorinated solvents. As needed, select emplacement boreholes used for hydraulic permeability enhancement would be converted into permanent injection wells to allow for delivery of an aqueous amendment into the target treatment zone during future reinjection events. In addition to *in situ* reduction, the injection of aqueous amendment into the target treatment zone could facilitate microbially-facilitated reductive dechlorination. Bioaugmentation with a commercially available culture containing high concentrations of *Dehalococcoides* could also be performed, if necessary, following the initial permeability enhancement and subsequent amendment injection. Bioaugmentation is intended to overcome possible incomplete reductive dechlorination and to improve reactive kinetics at sites with relatively low contaminant concentrations (less than 200 µg/L). In contrast to ISR without permeability enhancement, groundwater recirculation could be performed for enhanced contaminant/amendment contact. Performance monitoring wells would be installed at appropriate depth-discrete treatment intervals to collect data on the performance of the injections and to optimize the injection process. Because of the enhanced injection ROI as a result of permeability enhancement, a significantly fewer number of injection wells would be required to address the target treatment zone at the FSDF. For cost estimating purposes, it was assumed that approximately 15 injection wells would be installed as part of the ISR with permeability enhancement implementation.

O&M

Similar to the implementation of ISR, amendment replenishment requirements depend largely on site-specific hydrogeological conditions. Note that inclusion of the ZVI would significantly increase the longevity of the treatment zone and therefore limit the frequency for amendment reinjections. Note that if amendment replenishment is desired, an EVO product would be used (ZVI can only be emplaced during the initial permeability enhancement and cannot be replenished via injections through the injection wells). It is anticipated that up to 3 EVO injection events would be performed

over a 15-year O&M duration. MNA would be performed upon completion of the O&M phase. In addition to amendment replenishment, similar to implementation of other technologies, periodic groundwater monitoring would be conducted at relevant nearby monitoring wells to facilitate assessment of remedial progress and allow for performance optimization. All O&M activities and associated performance results would be reported in an annual groundwater monitoring report.

Preliminary Analysis – Long-Term Reliability and Effectiveness

Assuming that it can be implemented, the likelihood to achieve RAOs using this technology is relatively high due to the emplacement of a highly reactive reagent (ZVI) and enhanced contaminant/amendment contact via permeability enhancement and groundwater recirculation. The irreversibility of the technology is likely high. Collectively, this technology would likely be reliable long-term as well as effective in achieving RAOs.

Preliminary Analysis – Reduction of Toxicity, Mobility or Volume of Wastes

Assuming that this technology can be implemented, it could be effective in reducing the toxicity, mobility or volume of wastes, and would probably meet the established groundwater RAOs in a reasonable timeframe (less than 25 years).

Preliminary Analysis – Short-Term Effectiveness

Construction activities primarily consisting of permeability enhancement and subsequent well installation and development would be anticipated as part of the ISR implementation at the FSDF. Engineered controls previously employed can be implemented to mitigate short-term impacts and potential for exposure to workers and the community. However, the remedial timeframe required to achieve the RAOs, which is important to DOE, is anticipated to be shorter than actions without permeability enhancement as, if proven to be effective, would allow for greater exposure of VOCs in the bedrock matrix to the increased fracture density. Collectively, the short-term effectiveness associated with this technology, assuming it can be implemented, is likely high.

Preliminary Analysis – Implementability

The effectiveness of ISR with permeability enhancement is highly site-specific. Because neither component of this remedial technology has been implemented at the FSDF, a pilot-scale test would be required. Problems experienced by Boeing in its tests would need to be overcome via permeability enhancement implementation. While there are several vendors offering permeability enhancement services, it is CDM Smith's experience that only few have the right equipment and amendment delivery system necessary to achieve the desired results. On the other hand, there is no proprietary service or equipment required for the subsequent well installation. Collectively, the implementability of this technology is moderate.

Preliminary Analysis – Cost

The primary capital cost for implementing ISR with permeability enhancement at the FSDF is associated with the initial permeability enhancement and the subsequent well drilling and installation activities. The primary components of the O&M cost are the periodic amendment reinjection, groundwater monitoring, and data analysis and reporting. Note that the remedial timeframe associated with implementing ISR with permeability enhancement would be significantly reduced, compared to ISR alone. Therefore, the O&M cost and overall project cost would be lower.

6.1.2.5 *In Situ* Chemical Oxidation

Conceptual Design and Implementation

Similar to ISR, implementation of the ISCO technology at the FSDF would involve installation of injection wells in a gridded configuration, at a relatively close injection well spacing, and screened within the fractures harboring VOCs. Unlike ISR, following well installation and development, an aqueous chemical oxidant such as persulfate or permanganate instead of a biological amendment would be introduced to the subsurface via the injection wells to promote oxidation of the VOCs. Similar to ISR, ISCO is a highly-specific remedial technology that has not been demonstrated at the FSDF and thus pilot testing is required to obtain pertinent design parameters for full-scale implementation at the FSDF. Problems encountered by Boeing testing the technology would need to be overcome.

Construction

Construction activities supporting implementation of the ISCO technology at the FSDF would essentially resemble those associated with ISR (described in **Section 6.1.2.3**). The only difference is that, instead of an ISR amendment, a chemical oxidant such as permanganate or persulfate would be utilized.

O&M

Similar to the implementation of ISR, ISCO reinjections would be required periodically. Unlike ISR, ISCO reinjections would be needed very frequently. It is anticipated that up to 20 reinjection events may be required over a 20-year O&M duration. In addition, periodic groundwater monitoring would be conducted at relevant nearby monitoring wells to facilitate assessment of remedial progress and allow for performance optimization. All O&M activities and associated performance results would be reported in an annual groundwater monitoring report. Upon completion of the O&M phase, MNA would be performed.

Preliminary Analysis – Long-Term Reliability and Effectiveness

The likelihood of achieving RAOs using this technology is uncertain based on the lack of demonstrated success associated with the previous Boeing ISCO injection. Contaminant rebounds are often observed following the initial ISCO injection and contaminant degradation; therefore, the irreversibility of the technology is likely high. This technology may not be effective in achieving RAOs within a reasonable timeframe.

Preliminary Analysis – Reduction of Toxicity, Mobility or Volume of Wastes

This technology may not be effective in reducing the toxicity, mobility or volume of wastes, and would probably require an extended time frame to meet the established groundwater RAOs.

Preliminary Analysis – Short-Term Effectiveness

Construction activities primarily consisting of well installation and development would be anticipated as part of the ISCO implementation at the FSDF. Engineered controls previously employed can be implemented to mitigate short-term impacts and potential for exposure to workers and the community. However, the remedial timeframe required to achieve the RAOs, which is important to

DOE, is anticipated to be very long. Collectively, the short-term effectiveness associated with this technology is likely moderate.

Preliminary Analysis – Implementability

Given the difficulty in distributing ISCO reagents into the target treatment zone observed during previous Boeing work, the implementability of the technology at the FSDF is questionable and would require pilot testing. However, there is no proprietary service or equipment required for constructing and implementing the ISCO technology. Collectively, the implementability of this remedial technology is considered to be relatively low.

Preliminary Analysis – Cost

The primary capital cost for implementing ISR at the FSDF is associated with the well drilling and installation activities. The primary components of the O&M cost are the periodic amendment reinjection, groundwater monitoring, and data analysis and reporting.

6.1.2.6 *In Situ* Chemical Oxidation with Permeability Enhancement

Conceptual Design and Implementation

Similar to ISR, implementation of the ISCO technology with permeability enhancement would first involve emplacement of silica sand at discrete depth intervals to create permanent high-permeability pathways within the bedrock matrix followed by installation of injection wells screened within these depth intervals. Following proper well installation and development, an aqueous chemical oxidant would be injected into the subsurface via the permeability-enhanced injection wells.

Construction

Construction activities supporting implementation of the ISCO technology with permeability enhancement at the FSDF would essentially resemble those associated with ISR with permeability enhancement (described in **Section 6.1.2.4**). The only difference is that, instead of an ISR amendment, a chemical oxidant such as permanganate or persulfate would be utilized.

O&M

Similar to the implementation of ISR with permeability enhancement, oxidant reinjections would be required periodically as part of implementing the ISCO with permeability enhancement technology. Compared to ISCO alone, addition of the permeability enhancement component in the remedial technology would allow for enhanced contaminant/amendment contact and therefore better treatment. While enhanced amendment distribution would be achieved with permeability enhancement, such technique does not improve the ISCO oxidant longevity. Therefore, a reinjection frequency of approximately twice a year over the course of approximately 20 years would be required. Note that the presence of the permanent sand-propped fracture network would allow for an opportunity to perform groundwater recirculation for even better amendment distribution and contaminant/amendment contact. Similar to other remedial technologies, periodic groundwater monitoring would be conducted at relevant nearby monitoring wells to facilitate assessment of remedial progress and allow for performance optimization. All O&M activities and associated performance results would be reported in an annual groundwater monitoring report.

Preliminary Analysis – Long-Term Reliability and Effectiveness

The likelihood to achieve RAOs using this technology would likely be improved with permeability enhancement. Pilot testing would be required to demonstrate its site-specific effectiveness. It is anticipated that the use of permeability enhancement would enhance treatment effectiveness. In addition, the potential for performing groundwater recirculation, as needed, allows for better contaminant/amendment contact and thus reduces the extent and likelihood of contaminant rebounds.

Preliminary Analysis – Reduction of Toxicity, Mobility or Volume of Wastes

It is unknown whether this technology could be effective in reducing the toxicity, mobility or volume of wastes.

Preliminary Analysis – Short-Term Effectiveness

Construction activities primarily consisting of the initial permeability enhancement and subsequent well installation and development would be anticipated as part of implementing the ISCO technology with permeability enhancement at the FSDF. Engineered controls previously employed can be implemented to mitigate short-term impacts and potential for exposure to workers and the community. The remedial timeframe required to achieve the RAOs, which is important to DOE, is anticipated to be moderate. Collectively, the short-term effectiveness associated with this technology is likely moderate.

Preliminary Analysis – Implementability

Given the difficulty in distributing ISCO reagents into the target treatment zone observed during previous Boeing work and the fact that permeability enhancement has never been tested at the FSDF, the remedial technology proposed herein should be subject to pilot testing. As previously mentioned, there are only few permeability enhancement vendors with the right equipment and amendment delivery system needed to achieve the desired results. On the other hand, there is no proprietary service or equipment required for the subsequent well installation. Without completion of successful pilot tests, the implementability of this technology is uncertain.

Preliminary Analysis – Cost

Similar to ISR with permeability enhancement, the primary capital cost for implementing ISCO with permeability enhancement at the FSDF is associated with the initial permeability enhancement and the subsequent well drilling and installation activities. The primary components of the O&M cost are the periodic amendment reinjection, groundwater monitoring, and data analysis and reporting. Note that the remedial timeframe associated with implementing ISCO with permeability enhancement would be significantly reduced, compared to ISCO alone. Therefore, the O&M cost and overall project cost would be lower.

6.1.2.7 Excavation**Conceptual Design and Implementation**

Excavation of contaminated near-surface bedrock materials at the FSDF would involve removal of overburden materials followed by blasting of the underlying competent bedrock. The excavated bedrock would be placed into haul trucks for offsite disposal. Bedrock confirmation sampling would

be performed on the bottom and the side wall of the excavation to determine if additional bedrock removal is necessary. The excavated site would be then backfilled to grade with clean fill. In parallel, groundwater encountered during excavation would be captured, containerized, and treated on- or off-site.

Construction

Construction activities required for implementing excavation at the FSDF would include removal of the overburden materials, blasting of the underlying bedrock, sheet piling/shoring/benching of the excavation area, segregation and stockpiling of the excavated materials, construction of a dewatering and groundwater treatment system, and backfilling the excavation with clean fill.

O&M

Following confirmation that all contaminated materials have been excavated, no further remedial action besides periodic groundwater monitoring for a relatively short period of time (5 years) would be performed.

Preliminary Analysis – Long-Term Reliability and Effectiveness

Because all contaminated materials would have been removed via excavation, the likelihood to achieve RAOs using this technology is very high. In addition, the proposed remedy is irreversible as nearly all contaminated would have been removed upon completion of the remedial action. Collectively, this technology would likely be reliable long-term as well as effective in achieving RAOs.

Preliminary Analysis – Reduction of Toxicity, Mobility or Volume of Wastes

This technology would be effective in reducing the toxicity, mobility or volume of wastes, and would likely meet the established groundwater RAOs within a relatively short remedial timeframe. Note that excavated materials would have to be treated and disposed of appropriately offsite.

Preliminary Analysis – Short-Term Effectiveness

Given the extensive construction efforts required to implement this technology, there are potentially significant short-term impacts and potential for exposure to workers and the community. However, engineer controls could be employed to minimize such impacts and potential for exposure. In addition, the remedial timeframe required to achieve the RAOs under this technology, which is important to DOE, is anticipated to be very short. Collectively, the short-term effectiveness associated with this technology is high.

Preliminary Analysis – Implementability

While extensive construction activities would be required to implement excavation at the FSDF, such proposed remedy can be implemented without the need for proprietary equipment and services. Therefore, the implementability of this technology is considered to be moderate.

Preliminary Analysis – Cost

Significant capital expenditure would be required for implementing excavation of all contaminated overburden and bedrock materials at the FSDF. However, only minimal O&M efforts would be needed following excavation.

6.1.2.8 Enhanced Groundwater Extraction/SVE with Permeability Enhancement

Conceptual Design and Implementation

The groundwater extraction/SVE technologies could both be augmented using enhancement of bedrock permeability. This would involve using permeability enhancement technology to emplace silica sand to significantly increase the bulk hydraulic conductivity of the shallow and deep bedrock. Such increases in hydraulic conductivity would result in enhanced vapor and/or groundwater flushing/extraction and therefore improved contaminant mass removal. Similar to applications of ISR or ISCO, the permeability enhancement boreholes would be converted into SVE or extraction wells. If applicable from both a technical and economic sense, a conveyance piping and an aboveground treatment system would be constructed to allow for capture and treatment of the extracted VOC-impacted vapor. To mitigate issues associated with the observed slow groundwater recovery rate, flushing with potable water could be performed for enhanced contaminant contact and extraction rate. Note that a variety of treatment techniques such as granular activated carbon could be used to treat/contain the extracted vapor.

Construction

Construction activities required for implementing enhanced groundwater extraction/SVE with permeability enhancement at the FSDF would likely include the initial permeability enhancement followed by conversion of the permeability-enhanced boreholes into either injection/extraction wells or SVE wells to facilitate groundwater extraction and vapor extraction, respectively. A vapor/groundwater recovery piping conveyance would be constructed to allow for aboveground collection of the extracted vapor/groundwater, respectively. The need for an onsite groundwater treatment system would be evaluated during the remedial design. Similarly, treatment media required for treatment of the contaminated vapor would be disposed of offsite.

O&M

Periodic system check, maintenance, and optimization as well as performance monitoring would be performed. All O&M activities and associated performance results would be reported in an annual groundwater monitoring report. It is anticipated that permeability enhancement would allow for more efficient groundwater extraction and thus enhanced contaminant mass removal rate. Therefore, a shorter overall remedial timeframe of approximately 15 years is anticipated.

Preliminary Analysis – Long-Term Reliability and Effectiveness

Given an allowable extended remedial timeframe, the likelihood to achieve RAOs using this technology is relatively high. Previous pumping test results at the FSDF indicated that contaminant rebound would be unlikely; therefore, the irreversibility of the technology is likely high. Collectively, this technology would likely be reliable long-term as well as effective in achieving RAOs.

Preliminary Analysis – Reduction of Toxicity, Mobility or Volume of Wastes

This technology would be effective in reducing the toxicity, mobility or volume of wastes, and would probably meet the established groundwater RAOs given an extended remedial timeframe. Note that while contaminants would be removed from the extracted groundwater using treatment media such as GAC, the spent GAC product would have to be disposed properly.

Preliminary Analysis – Short-Term Effectiveness

Because of the minimal construction efforts required to implement this technology, there is very little short-term impacts and potential for exposure to workers and the community. However, the remedial timeframe required to achieve the RAOs, which is important to DOE, is anticipated to be very long. Collectively, the short-term effectiveness associated with this technology is likely moderate.

Preliminary Analysis – Implementability

Because permeability enhancement has not been implemented at the FSDF, a pilot-scale test of such technology would be highly recommended. While there are several vendors offering permeability enhancement services, it is CDM Smith's experience that only few have the right equipment and can deliver the desired results. On the other hand, there is no proprietary service or equipment required for the subsequent well installation. Collectively, the implementability of this technology is high.

Preliminary Analysis – Cost

The primary capital cost for implementing this remedial technology at the FSDF is associated with the initial permeability enhancement and the subsequent well drilling and system installation activities. The primary components of the O&M cost are the periodic system O&M, soil vapor and groundwater monitoring, and data analysis and reporting. Note that the remedial timeframe associated with implementing enhanced groundwater/SVE with permeability enhancement would be significantly reduced, compared to groundwater extraction alone. Therefore, the O&M cost and overall project cost would be lower.

6.1.2.9 In Situ Thermal Remediation

Conceptual Design and Implementation

DOE performed a literature review of the state-of-the-art of thermal technologies that are potentially applicable at the SSFL. Based on results of such review [which was documented in the Thermal White Paper (CDM Smith 2018c)], thermal conductive heating (TCH) would likely be the appropriate ISTR application at the FSDF given the area-specific low permeability, near-surface bedrock zone contamination, and general lack of water present in the bedrock fractures. Implementation of TCH at the FSDF would involve installation of electrically-powered heaters to facilitate mobility of VOCs along with vapor extraction wells to capture the mobilized VOCs in a high contaminant concentration area with a relatively small footprint of approximately 100 feet by 100 feet. The heaters would be used for *in situ* heating of the contaminated bedrock to the target treatment temperature. The heating would facilitate contaminant degradation via a variety of mechanisms including evaporation, oxidation, and pyrolysis. Vapor extraction wells would be used to capture the mobilized VOCs in the same manner as previously described for BVE.

Construction

Construction activities required for implementing the TCH technology at the FSDF would require installation of heater wells, vapor extraction and recovery wells, temperature monitoring probes, monitoring wells, and an aboveground vapor and liquid separation and treatment system. In addition, a power drop and appropriate transformer units would be procured.

O&M

Periodic system check, maintenance, and optimization as well as performance monitoring would be performed upon completion of all construction/startup activities. O&M duration is estimated to be 1 year. All O&M activities and associated performance results would be reported in an annual groundwater monitoring report. Upon completion of the O&M phase, MNA would commence to aid in evaluating the long-term effectiveness of the treatment.

Preliminary Analysis – Long-Term Reliability and Effectiveness

The likelihood to achieve RAOs using this technology is relatively high. Because contaminants within the bedrock matrix would be thermally desorbed and subsequently destroyed via a number of mechanisms, the treatment proposed is irreversible. Collectively, this technology would likely be reliable long-term as well as effective in achieving RAOs.

Preliminary Analysis – Reduction of Toxicity, Mobility or Volume of Wastes

This technology would be effective in reducing the toxicity, mobility or volume of wastes, and would meet the established groundwater RAOs in a relatively short remedial timeframe. Note that while contaminants would be removed from groundwater and the bedrock matrix, treatment media used as part of the aboveground treatment system including GAC would have to be disposed offsite properly.

Preliminary Analysis – Short-Term Effectiveness

While there would be significant construction activities performed at the start of the TCH implementation at the FSDF, engineered controls could be used to mitigate short-term impacts and potential for exposure to workers and the community. However, the remedial timeframe required to achieve the RAOs, which is important to DOE, is anticipated to be very relatively short (10 years). Collectively, the short-term effectiveness associated with this technology is likely very high.

Preliminary Analysis – Implementability

Because TCH has not been implemented at the FSDF, a pilot-scale test evaluating the potential for and effectiveness of the proposed remedy would need to be performed. While there is no proprietary equipment required for the well drilling and installation, only few vendors can offer the TCH services. Collectively, the implementability of this technology is moderate.

Preliminary Analysis – Cost

The primary capital cost for implementing this remedial technology at the FSDF is associated with the initial well drilling and TCH system installation. Significant capital expenditure would be required to install and operate the TCH system. However, note that because the remedial timeframe is anticipated to be relatively short, only minimal O&M costs would be incurred.

6.1.3 Comparative Analysis

Remedial technologies under consideration for the FSDF are compared against each other with regard to long-term reliability and effectiveness, reduction of toxicity, mobility or volume of wastes, short-term effectiveness, and implementability. The following discussion presents the relative score and justification for each technology against each of the aforementioned criteria. Note that the high-level

cost estimates associated with implementation of the technologies under consideration are presented independent of the technical evaluation.

6.1.3.1 Long-Term Reliability and Effectiveness

The long-term reliability and effectiveness of each remedial technology under consideration at the FSDF was evaluated based on its likelihood to achieve the remedial objective and the permanence of the remedy. Note that these factors were evaluated on an equal weight. Overall, excavation received the highest long-term reliability and effectiveness score of 5 because its ability to nearly completely remove the near-surface contaminant source mass. Enhanced groundwater extraction with permeability enhancement received the second highest score for long-term reliability and effectiveness of 4.5. Note that groundwater extraction is the only technology with demonstrated success in removing contaminant mass, albeit at a very low rate, at the FSDF. Therefore, it is reasonable to project that, when performed in conjunction with permeability enhancement, the enhanced groundwater extraction technology represents a potentially applicable full-scale remedy at the FSDF. ISR with permeability enhancement, groundwater extraction, and ISTR received the score of 4 under this evaluation criterion. ISR and ISCO as standalone technologies received the similar and lowest score of 3 for long-term reliability and effectiveness, similar to non-active technologies under consideration.

6.1.3.2 Reduction of Toxicity, Mobility or Volume of Wastes

Excavation received the highest score of 5 under this evaluation criterion due to its ability to nearly completely remove near-surface contaminant mass in bedrock at the FSDF followed by ISR with permeability enhancement, enhanced groundwater extraction with permeability enhancement, and ISTR. Note that among the aforementioned remedial technologies that received a score of 4 for reduction of toxicity, mobility or volume of waste, the groundwater extraction component of the enhanced groundwater extraction with permeability enhancement is the only technology with demonstrated success at the FSDF despite the low contaminant removal rate. While receiving the same score, ISR with permeability enhancement, ISCO with permeability enhancement, and ISTR have not been demonstrated at the FSDF and would need to be pilot-tested prior to being further evaluated for full-scale implementation. Groundwater extraction, as currently implemented at the FSDF, received a score of 3 under this evaluation criterion due to its relatively low contaminant mass removal rate whereas the non-active remedial technologies including No Action and Administrative and Legal Controls received the lowest score for reduction of toxicity, mobility or volume of wastes of 2.

6.1.3.3 Short-Term Effectiveness

The short-term effectiveness of each remedial technology under consideration at the FSDF was evaluated based on its short-term impacts and potential for exposure to workers and the nearby community as well as remedial timeframe. The overall score for short-term effectiveness was calculated by weighting the remedial timeframe score greater than the exposure potential score by a factor of two, as the time required to meet remedial objectives is an important factor for DOE, and the potential for exposure during implementation can be mitigated via administrative or engineered means for all remedial technologies under consideration.

Despite its intrusive nature, ISTR received the highest overall score for short-term effectiveness of 3.5 because of the short remedial timeframe (relative to other *in situ* technologies) which has a higher

weight than the short-term impacts and potential for exposure to workers and the community. While both ISTR and Excavation received the highest score of 5 for remedial timeframe, Excavation would likely have more significant short-term impacts and potential for exposure to workers and the community and thus received the lowest score of 1 for such evaluation criterion. Similar to Excavation, the remaining active remedial technologies under consideration received an overall short-term effectiveness score of 3.5. Note that, in general, *in situ* technologies implemented in conjunction with permeability enhancement would likely result in a shorter remedial timeframe because of the enhanced ability to access contaminant mass in the bedrock. However, implementation of permeability enhancement would require specialized heavy equipment to facilitate such intrusive activity in the subsurface, resulting in a higher short-term impacts and potential for exposure to workers and the nearby community. Non-active remedial technologies including No Action and Administrative and Legal Controls received the lowest overall score for short-term effectiveness, despite the highest score for short-term impacts and potential for exposure to workers and the community, due to the prolonged remedial timeframe when no active remediation is implemented at the FSDF.

6.1.3.4 Implementability

Groundwater extraction via fracture dewatering has already been conducted at the FSDF and requires minimal effort and infrastructure; therefore, this technology received the second highest implementability score of 5. ISR is relatively implementable and thus received an overall score for implementability of 3. Incorporation of the permeability enhancement technology would complicate the implementation of an *in situ* technology and therefore ISR with permeability enhancement, and enhanced groundwater extraction with permeability enhancement received slightly lower scores than their counterparts without permeability enhancement. Given its complex underground and aboveground requirements, ISTR received the lowest score for implementability of 1, similar to Excavation which requires blasting to aid in segregation of bedrock materials as well as significant heavy equipment and labor requirements for excavation, dewatering, and onsite and offsite waste disposal. Given the difficulty in implementing ISCO observed at the Boeing site, ISCO also received the lowest implementability score of 1.

6.1.3.5 Overall Score

The individual and overall scores for each remedial technology under consideration at the FSDF are provided in **Table 6-1**. The overall scores are a sum of the long-term reliability and effectiveness, reduction of toxicity, mobility or volume of wastes, short-term effectiveness, implementability, and cost scores. Groundwater extraction received the highest overall score of 15.5 followed by and enhanced groundwater extraction with permeability enhancement (15). Except for ISCO and ISCO with permeability enhancement which received the lowest overall scores among the active remedial technologies under consideration of 9.5 and 11, respectively, the remaining technologies received very similar overall scores ranging between 11 and 14.5.

6.1.3.6 Cost

The cost associated with each remedial technology under consideration at the FSDF is presented in **Table 6-1** in terms of the capital expenditure, the O&M costs, and the overall project costs. Note that these are high-level estimated costs that would be subject to further refinement prior to remedial design and implementation. The overall O&M cost was calculated with respect to the estimated remedial timeframe presented in the same table with a 7% discount factor. As expected, the capital

and overall project costs were the highest for Excavation followed by ISTR. Note that given the relatively fast remedial timeframe, the O&M costs associated with these technologies were the lowest among the technologies under consideration.

6.1.4 Retained Remedial Technologies

Groundwater extraction (fracture dewatering) and enhanced groundwater extraction with permeability enhancement received some of the highest overall technical evaluation scores and had some of the lowest overall project costs among the remedial technologies under consideration and should be retained for further evaluation. Therefore, it is recommended that these technologies (with the exception of groundwater extraction via dewatering which has already been implemented at FSDF) be pilot tested in the field prior to full-scale implementation at the FSDF. Regardless of the selected remedy, it is anticipated that MNA would be considered following the active treatment period to address residual low-level contamination.

6.2 PCE Plume

Groundwater in the northwestern portion of Area IV is impacted by the chlorinated solvent tetrachloroethene (PCE). This is the only location of Area IV with this chlorinated solvent in groundwater. Bedrock groundwater results for wells in the vicinity of the plume show the plume to be primarily found within near-surface groundwater. PCE data for well PZ-109 show a decline in PCE concentrations from 300 µg/L in 2002 to 72 µg/L in 2018, indicating that the PCE present in groundwater within this portion of Area IV has been subject to natural attenuation. The recommendation for the near-surface groundwater is to extract groundwater using well PZ-109 until concentrations remain below 50 µg/L. At that time, the PCE plume would be reevaluated for shifting to MNA as the remedy.

6.2.1 Pump and Treat

Conceptual Design and Implementation

Implementation of the P&T technology for the PCE plume would involve dewatering of contaminated groundwater found in the near-surface weathered bedrock using PZ-109. It is expected that less than 100 gallons per day can be pumped from this well before dewatering the near-surface groundwater. Treatment could be combined with an action at the adjacent HMSA. It is not anticipated that an onsite treatment system would be required as part of this technology implementation.

Construction

No construction activities would be required as only PZ-109 would be pumped under this action.

O&M

Periodic system check, maintenance, and optimization as well as performance monitoring would be performed. All O&M activities and associated performance results would be reported in an annual groundwater monitoring report.

Preliminary Analysis – Long-Term Reliability and Effectiveness

Significant contaminant mass removal would likely be achieved initially. However, diminishing returns often associated with long-term P&T operation as the system reaches asymptotic conditions would likely be encountered. The likelihood to achieve the established groundwater RAOs under this

remedial technology, given an extended remedial timeframe, is relatively high. However, since contaminant rebounds would likely occur, the degree of treatment irreversibility is moderate. Collectively, the long-term reliability and effectiveness of the proposed technology are considered to be moderate.

Preliminary Analysis – Reduction of Toxicity, Mobility or Volume of Wastes

This technology would be effective in reducing the toxicity, mobility or volume of wastes, and would meet the established groundwater RAOs in a relatively short remedial timeframe. Note that while contaminants would be removed from groundwater and the bedrock matrix, treatment media used as part of the aboveground treatment system including GAC would have to be disposed offsite properly.

Preliminary Analysis – Short-Term Effectiveness

No construction activities would be performed as part of this technology implementation; therefore, short-term impacts and potential for exposure to workers and the community are considered to be minimal. Although pumping is expected to reduce PCE concentrations to less than 10 µg/L in a relatively short time frame (less than 5 years based on pumping results in other locations of Area IV), achievement of the RAO may need to rely on further natural degradation processes to meet the overall RAO. Collectively, the short-term effectiveness associated with this technology is moderate.

Preliminary Analysis – Implementability

There have been several P&T actions across Area IV. All have shown to be effective in reducing contaminant concentrations in groundwater. Therefore, the implementability of this technology is high.

Preliminary Analysis – Cost

Minimal capital expenditure would be required as part of this technology implementation. Because of the extended remedial timeframe, significant O&M efforts including system operation, maintenance, and performance evaluation would be required.

6.2.2. Monitored Natural Attenuation

Conceptual Design and Implementation

Following an active groundwater treatment remedy, implementation of MNA would involve use of existing monitoring wells to obtain data on the further reduction in PCE concentrations over time. Data on associated geochemical and microbiological characteristics of the groundwater would also be collected. Monitoring would continue until the groundwater cleanup standard was met.

Construction

No major construction activities are anticipated for implementation of MNA for the PCE Plume.

O&M

Periodic groundwater monitoring would be conducted at relevant nearby monitoring wells to facilitate assessment of remedial progress. All O&M activities and associated performance results would be reported in an annual groundwater monitoring report.

Preliminary Analysis – Long-Term Reliability and Effectiveness

Based on previous assessment, MNA is likely occurring at the SSFL and thus represents a potentially applicable remedial technology. The likelihood to achieve RAOs using this technology is moderate given extended (greater than 10 year) remedial timeframe.

Preliminary Analysis – Reduction of Toxicity, Mobility or Volume of Wastes

This technology may reduce the toxicity, mobility or volume of wastes, and would probably meet the established groundwater RAOs in an extended timeframe.

Preliminary Analysis – Short-Term Effectiveness

Because there is no construction, there would be limited short-term impacts and potential for exposure to workers and the community. However, the remedial timeframe required to achieve the RAOs, which is important to DOE, is anticipated to be long (greater than 10 years). Collectively, the short-term effectiveness associated with this technology is likely moderate.

Preliminary Analysis – Implementability

The implementability of the MNA for the PCE Plume is considered to be very high.

Preliminary Analysis – Cost

No significant capital expenditure would be required for implementing MNA for the PCE Plume. Therefore, the overall cost is primarily associated with the periodic groundwater monitoring, and data analysis and reporting. Because an extended remedial timeframe would be anticipated, the overall cost for implementing MNA is considered to be moderate.

6.3 Hazardous Materials Storage Area

TCE is the primary contaminant of concern in groundwater within the near-surface (i.e., water-bearing zone within the weathered bedrock which is underlain by competent bedrock) and the underlying bedrock within the HMSA. Prior to installation of monitoring well DD-144 in 2016, and wells PZ-162, PZ-163, DD-146 and DD-147 in 2018, the impacted area was defined by piezometers PZ-108, PZ-120, and PZ-122. The impacted groundwater straddles the groundwater divide that runs through the central portion of Area IV. PZ-108 exhibits TCE at 160 µg/L in near-surface groundwater. DD-144 exhibits the TCE at 98 µg/L in bedrock groundwater (2017 data). The horizontal extent of TCE contamination is defined by piezometer and bedrock well data, and the vertical extent by DD-146. Although attempts to locate a VOC source have been inconclusive, it is anticipated that contamination in the near-surface zone contributed to the groundwater impacts observed in underlying bedrock groundwater. Given the contaminant concentrations and concentration trends observed in near-surface groundwater, it is anticipated that active treatment would be required within both groundwater zones.

6.3.1 Data Gaps

A data gap investigation of the vertical and horizontal extent of TCE contamination at the HMSA was conducted spring/early summer 2018 (CDM Smith 2018d). This investigation allowed for better understanding of the vertical extent of TCE in the bedrock groundwater and determination of the properties of the near-surface groundwater.

6.3.2 Conceptual Design and Implementation

A high-level conceptual description of the design and implementation of each remedial technology under consideration for the near-surface and bedrock groundwater within the HMSA is presented in the following paragraphs. No Action and Administrative and Legal Controls are excluded from the following discussion as they are intended for baseline analysis. The elements of the existing administrative and legal controls that are in place for Boeing-owned property at SSFL would be incorporated into and/or modified as appropriate in the remedy selected for the HMSA. Note that groundwater contamination in the deeper bedrock appears to be localized around DD-146. Therefore, proposed remediation of this portion of the HMSA would simply involve extracting groundwater from DD-146 for subsequent on- or off-site treatment and disposal. Remediation of the deep bedrock using Pump and Treat would accompany any active treatment selected for the near-surface bedrock. If a technology other than Pump and Treat is selected for the near-surface groundwater, then that technology may be “extended” into parts of the bedrock groundwater, as this could accelerate the remedial timeframe for the bedrock groundwater compared to Pump and Treat. The following discussion, therefore, pertains only to remediation of the near-surface bedrock groundwater.

As presented in **Table 6-2**, remedial technologies retained for detailed analysis of the near-surface bedrock remediation include Pump and Treat, ISR, ISCO, Low-Temperature Thermally-Enhanced Bioremediation (Low-Temp Thermal), Excavation, Air sparging, and MNA.

6.3.2.1 Pump and Treat

Conceptual Design and Implementation

Implementation of the P&T technology for near-surface groundwater remediation at the HMSA would involve using existing piezometers PZ-108, PZ-120, PZ-163, and the possibility of a fourth piezometer installed west of PZ-120 to pump and dewater the near surface groundwater. Groundwater pump tests performed in the spring of 2018 (CDM Smith 2018d) demonstrated that the near-surface groundwater could initially sustain a pumping rate of 200 gallons per day (decreasing as the water level is lowered) rendering on-site treatment of groundwater a viable possibility. The treatment facility would utilize granular activated carbon for removing TCE, followed by on-site discharge of the treated water. Given the porous nature of the weathered bedrock at the HMSA, soil vapor extraction could be used following dewatering to remove residual mass of TCE, assuming recharge was sufficiently slow.

Construction

Construction activities required for implementing the Pump and Treat technology at the HMSA would require installation of up to 8 additional wells to facilitate groundwater extraction (and soil vapor extraction, if needed), installation of downhole extraction pumps, installation of groundwater/vapor recovery conveyance system, and installation of an onsite treatment system.

O&M

Periodic system check, maintenance, and optimization as well as performance monitoring would be performed. All O&M activities and associated performance results would be reported in an annual groundwater monitoring report.

Preliminary Analysis – Long-Term Reliability and Effectiveness

Significant contaminant mass removal would likely be achieved initially. However, diminishing returns often associated with long-term Pump and Treat operation as the system reaches asymptotic conditions would likely be encountered. The likelihood to achieve the established groundwater RAOs under this remedial technology, given an extended remedial timeframe, is relatively high. However, since contaminant rebounds would likely occur, the degree of treatment irreversibility is moderate. Collectively, the long-term reliability and effectiveness of the proposed technology are considered to be moderate.

Preliminary Analysis – Reduction of Toxicity, Mobility or Volume of Wastes

This technology would be effective in reducing the toxicity, mobility or volume of wastes, and is expected to reduce TCE concentrations to less than 50 µg/L in less than 10 years. Note that while contaminants would be removed from groundwater and the bedrock matrix, treatment media used as part of the aboveground treatment system including GAC would have to be disposed offsite properly.

Preliminary Analysis – Short-Term Effectiveness

Engineering controls would be used to minimize construction of the treatment system to mitigate short-term impacts and potential for exposure to workers and the community. The remedial timeframe required to achieve the reduce TCE concentrations to where MNA could be considered, which is considered to be of significant importance to DOE, is anticipated to be very relatively short. MNA as discussed below would take an extended period to achieve RAOs. Collectively, the short-term effectiveness associated with this technology is moderate.

Preliminary Analysis – Implementability

Results of recent hydrogeological testing at the HMSA indicate that Pump and Treat could be a viable remedial technology. In addition, no proprietary equipment or services would be required for implementing the proposed technology. Therefore, the implementability of this technology is high.

Preliminary Analysis – Cost

The capital cost for implementing this remedial technology at the HMSA is primarily associated with the initial well drilling and treatment system installation. Because of the extended remedial timeframe of approximately 10 years, significant O&M efforts including system operation, maintenance, and performance evaluation would be required.

6.3.2.2 In Situ Reduction**Conceptual Design and Implementation**

Implementation of the ISR technology at the HMSA near-surface would involve installation of injection wells in a gridded configuration and screened within the target treatment depth. Pilot testing would be warranted to aid in determining the effective radius of influence and injection well spacing. Following well installation and development, an aqueous amendment would be introduced into the subsurface via the injection wells to promote microbially-mediated degradation of the VOCs. If needed, recirculation of groundwater would be performed to further enhance amendment distribution within the subsurface, which would ultimately increase contaminant degradation kinetics. It is anticipated that bioaugmentation would be required to overcome the relatively low VOC

concentrations observed in groundwater. Note that ISR is a highly-specific remedial technology that has not been demonstrated at the HMSA. Therefore, the aforementioned pilot testing would be required to assess its applicability as well as to obtain design parameters pertinent to full-scale implementation.

Construction

Construction activities required for implementing the ISR technology within the near-surface bedrock of the HMSA would require installation of up to 25 injection wells and additional monitoring wells (if needed) to facilitate amendment injection and performance monitoring, respectively. In addition, an injection manifold equipped with the appropriate instrumentation would be constructed to facilitate amendment injections into multiple wells simultaneously.

O&M

Periodic amendment reinjections would be required to sustain the desired treatment. It is anticipated that such reinjections would be performed every 3 years during the 20-year O&M phase. In addition to amendment reinjections, periodic performance monitoring and evaluation would be performed as part of the O&M efforts. Performance monitoring results would be summarized in an annual groundwater monitoring report.

Preliminary Analysis – Long-Term Reliability and Effectiveness

The likelihood to achieve RAOs using this ISR at the HMSA near-surface bedrock is high given the demonstrated success achieved at numerous sites. Note that pilot testing is required to assess how it could be implemented most cost-effectively. If effective, the irreversibility of the technology is likely high. Collectively, this technology would likely be reliable long-term as well as effective in achieving RAOs.

Preliminary Analysis – Reduction of Toxicity, Mobility or Volume of Wastes

If proven effective, this technology could result in reduction of toxicity, mobility or volume of wastes, and would probably meet the established groundwater RAOs in a reasonable timeframe.

Preliminary Analysis – Short-Term Effectiveness

Construction activities primarily consisting of well installation and development would be anticipated as part of the ISR implementation at the HMSA. Engineered controls previously employed can be implemented to mitigate short-term impacts and potential for exposure to workers and the community. However, the remedial timeframe required to achieve the RAOs, which is important to DOE, is anticipated to be relatively short. Collectively, the short-term effectiveness associated with this technology is likely high.

Preliminary Analysis – Implementability

While the effectiveness of the ISR technology is highly site-specific and such technology has not been tested at the HMSA, the area-specific lithology is potentially amenable to ISR implementation. A pilot injection test would need to be performed to evaluate full-scale design parameters as well as to assess the effectiveness of the technology at the HMSA. All equipment and services required for implementing the proposed technology at the HMSA are readily available. Collectively, the implementability of this remedial technology is considered to be high.

Preliminary Analysis – Cost

The capital cost for implementing ISR at the HMSA is primarily associated with the initial well installation and amendment injection activities. Because periodic amendment reinjections would be warranted to sustain the desired treatment, such activity primarily comprises the O&M costs. Note that if properly implemented, the remedial timeframe associated with ISR could be relatively short. Therefore, the overall project cost is considered to be moderate.

6.3.2.3 In Situ Chemical Oxidation

Conceptual Design and Implementation

Similar to ISR, implementation of the ISCO technology at the HMSA would involve installation of injection wells in a gridded configuration and screened appropriately within the vertical treatment interval. Unlike ISR, following well installation and development, an aqueous chemical oxidant such as persulfate or permanganate instead of a biological amendment would be introduced to the subsurface via the injection wells to promote oxidation of the VOCs. Similar to ISR, ISCO is a highly-specific remedial technology that has not been demonstrated at the HMSA and thus pilot testing would be required to assess its applicability and to obtain design parameters pertinent to full-scale implementation of the technology.

Construction

Construction activities supporting implementation of the ISCO technology at the HMSA would essentially resemble those associated with ISR (described in **Section 6.3.2.2**). The only difference is that, instead of an ISR amendment, a chemical oxidant such as permanganate or persulfate would be utilized.

O&M

Similar to the implementation of ISR, ISCO reinjections would be required periodically. Unlike ISR, ISCO reinjections would be needed much more frequently (in the order of every few months). It is anticipated that such reinjections would be performed twice a year over a 20-year O&M period. In addition, periodic groundwater monitoring would be conducted at relevant nearby monitoring wells to facilitate assessment of remedial progress and allow for performance optimization. All O&M activities and associated performance results would be reported in an annual groundwater monitoring report.

Preliminary Analysis – Long-Term Reliability and Effectiveness

Assuming that the technology is demonstrated to be implementable in Area IV bedrock, pilot tests would be needed to demonstrate that difficulties experienced by Boeing's ISCO injection study could be overcome. Because ISCO technology is often subject to matrix diffusion-influenced contaminant rebounds; therefore, the irreversibility of the technology is likely high. Collectively, this technology may not be effective in achieving RAOs within a reasonable timeframe.

Preliminary Analysis – Reduction of Toxicity, Mobility or Volume of Wastes

This technology may not be effective in reducing the toxicity, mobility or volume of wastes, and would probably only meet the established groundwater RAOs in an extended timeframe.

Preliminary Analysis – Short-Term Effectiveness

Construction activities primarily consisting of well installation and development would be anticipated as part of the ISCO implementation at the HMSA. Engineered controls previously employed can be implemented to mitigate short-term impacts and potential for exposure to workers and the community. However, the remedial timeframe required to achieve the RAOs, which is important to DOE, is anticipated to be longer than other active technologies. Collectively, the short-term effectiveness associated with this technology is likely moderate.

Preliminary Analysis – Implementability

Given the difficulty in distributing ISCO reagents into the target treatment zone observed during previous Boeing work, the implementability of the technology at the HMSA is questionable and thus would require pilot testing. However, there is no proprietary service or equipment required for constructing and implementing the ISCO technology. Collectively, the implementability of this remedial technology is considered to be relatively high.

Preliminary Analysis – Cost

The primary capital cost for implementing ISR at the HMSA is associated with the well drilling and installation activities. The primary components of the O&M cost are the periodic ISCO amendment reinjection, groundwater monitoring, and data analysis and reporting.

6.3.2.4 Low-Temperature Thermal Biological Treatment

Conceptual Design and Implementation

Implementation of the Low-Temperature Thermal technology at the HMSA would be performed in the highest contaminant concentration area in a phased approach. First, injection wells would be installed within the target treatment area and screened appropriately within the target vertical treatment interval. Following proper well installation and well development, an aqueous amendment solution intended to promote microbially-mediated degradation of VOCs would be introduced into the subsurface via the injection wells. Upon completion of the first phase of work, small-diameter electrodes would be placed into the target vertical treatment interval. Electrical resistance heating would be applied to increase the subsurface temperature to approximately 50°C. The elevated temperature would increase the dissolution of contaminant into the groundwater and accelerate the rate and extent of dechlorination within the target treatment area.

Construction

Initial construction activities supporting implementation of the low-temperature thermal technology at the HMSA would resemble those associated with ISR (described in **Section 6.3.2.2**). Following the initial amendment injection, heater wells would be installed to increase the subsurface temperature within the target treatment zone. Besides the power supply, it is anticipated that no other aboveground equipment would be required for thermal heating portion of the proposed remedy.

O&M

Because the electrical resistance heating is anticipated to result in enhanced contaminant degradation kinetics, less frequent amendment injections are anticipated. Therefore, the primary O&M efforts associated with the proposed remedy would likely include periodic performance monitoring,

evaluation, and optimization. All O&M activities and associated performance results would be reported in an annual groundwater monitoring report. It is anticipated that an active heating duration of 1 year followed by 5 years of ISR amendment injections would be performed as part of this technology implementation.

Preliminary Analysis – Long-Term Reliability and Effectiveness

The likelihood to achieve RAOs using this technology is high given the area-specific lithology and demonstrated success implementing this technology at other sites. A pilot test would be required to demonstrate its effectiveness. Experience with other sites has demonstrated that ISR can result in enhanced matrix back-diffusion due to the thermal heating and enhanced contaminant degradation kinetics, the irreversibility of the technology is considered to be high. Collectively, this technology would likely be effective in achieving RAOs within a reasonable timeframe.

Preliminary Analysis – Reduction of Toxicity, Mobility or Volume of Wastes

If proven to be effective based on Area IV bedrock conditions, this technology could be effective in reducing the toxicity, mobility or volume of wastes, and could probably meet the established groundwater RAOs in a relatively short timeframe.

Preliminary Analysis – Short-Term Effectiveness

Construction activities primarily consisting of injection well and heating installation and subsequent amendment injection are anticipated as part of the implementation of the low-temperature, thermal technology at the HMSA. Engineered controls previously employed can be implemented to mitigate short-term impacts and potential for exposure to workers and the community. The remedial timeframe required to achieve the RAOs, which is important to DOE, is anticipated to be relatively short. Collectively, the short-term effectiveness associated with this technology is likely high.

Preliminary Analysis – Implementability

Because low-temperature, thermal technology has not been tested at the HMSA, it must be pilot tested and assessed for full-scale applicability. While drilling equipment and services are readily available, only few vendors can offer the proprietary equipment and services required for implementing thermal heating. Collectively, the implementability of this remedial technology is considered to be moderate.

Preliminary Analysis – Cost

The primary capital cost for implementing the proposed remedial technology at the HMSA is associated with the well drilling and thermal system installation activities. The primary components of the O&M cost are the periodic performance monitoring and evaluation.

6.3.2.5 Excavation

Conceptual Design and Implementation

Implementation of the excavation technology at the HMSA near-surface groundwater would first involve the dewatering of the near-surface groundwater zone to reduce the volume of liquids for off-site disposal. Once dewatering is complete, TCE-impacted bedrock materials would be excavated and transported for subsequent offsite disposal, followed by backfilling of the excavated area with clean

fill materials. Confirmation sampling on the side walls and the bottom of the excavated area would be performed to ensure that, to the extent practicable, all of the contaminated materials are excavated. Similar to excavation at other sub-areas of Area IV, existing monitoring wells would likely be removed prior to commencement of the excavation. Therefore, upon completion of all excavation work, new monitoring wells would be installed for long-term monitoring and evaluation of the remedy.

Construction

Construction activities supporting implementation of the excavation technology at the HMSA would essentially resemble those described in **Section 6.1.2.7**. Note that reinstallation of monitoring wells may be required to facilitate post-excavation monitoring and assessment.

O&M

Following confirmation that all contaminated materials have been excavated, no further remedial action besides periodic groundwater monitoring for a relatively short period of time (5 years) would be performed.

Preliminary Analysis – Long-Term Reliability and Effectiveness

Because all contaminated materials would have been removed via excavation, the likelihood to achieve RAOs using this technology is high. In addition, the proposed remedy is irreversible. Collectively, this technology would likely be reliable long-term as well as effective in achieving RAOs.

Preliminary Analysis – Reduction of Toxicity, Mobility or Volume of Wastes

This technology would be effective in reducing the toxicity, mobility or volume of wastes, and would likely meet the established groundwater RAOs within a relatively short remedial timeframe. Note that excavated materials would have to be treated and disposed of appropriately offsite.

Preliminary Analysis – Short-Term Effectiveness

Given the extensive construction efforts required to implement this technology, there are potentially significant short-term impacts and potential for exposure to workers and the community. However, engineer controls could be employed to minimize such impacts and potential for exposure. In addition, the remedial timeframe required to achieve the RAOs under this technology, which is considered to be of significant importance to DOE, is anticipated to be very short. Collectively, the short-term effectiveness associated with this technology is high.

Preliminary Analysis – Implementability

While extensive construction activities would be required to implement excavation at the HMSA, such proposed remedy can be implemented without the need for proprietary equipment and services. Therefore, the implementability of this technology is considered to be moderate.

Preliminary Analysis – Cost

Significant capital expenditure would be required for implementing excavation of all contaminated near-surface bedrock materials at the HMSA. However, only minimal O&M efforts would be needed following excavation.

6.3.2.6 Air Sparging – Near-Surface Groundwater Zone

Conceptual Design and Implementation

Implementation of air sparging (also referred to as *in situ* air stripping) within the near-surface groundwater zone at the HMSA would involve installation of air sparging wells into the top of the competent bedrock to create a target vertical treatment interval for delivery of air into the weathered bedrock. Using an air compressor, the resulting bubbles would promote stripping and aerobic degradation of the contaminants of interest. If needed, soil vapor extraction wells screened within the overlying vadose zone would be used to collect the extracted VOCs from the groundwater. The collected vapor would then be treated aboveground using GAC.

Construction

Construction activities that would be performed to support implementation of the air sparging in the near-surface groundwater at the HMSA would include installation of air sparging wells and construction of an air sparging manifold with appropriate monitoring instrumentation. In addition, vapor recovery wells and associated conveyance piping system would be constructed to facilitate aboveground collection and treatment of the VOC-impacted vapor.

O&M

It is anticipated that active sparging would be performed for approximately 5 years. Periodic groundwater monitoring would be conducted at relevant nearby monitoring wells to facilitate assessment of remedial progress. All O&M activities and associated performance results would be reported in an annual groundwater monitoring report.

Preliminary Analysis – Long-Term Reliability and Effectiveness

Based on the area-specific lithology, air sparging may represent a potentially applicable remedial technology for treating VOC-impacted groundwater within the near-surface groundwater zone. Air sparging has been performed at many sites with relatively good success. Therefore, the likelihood to achieve RAOs using this technology is high.

Preliminary Analysis – Reduction of Toxicity, Mobility or Volume of Wastes

This technology may be effective in reducing the toxicity, mobility or volume of wastes, and would probably meet the established groundwater RAOs given an extended remedial timeframe.

Preliminary Analysis – Short-Term Effectiveness

Short-term impacts and potential for exposure to workers and the community associated with the construction of the air sparging system could be mitigated via engineered controls. However, the remedial timeframe required to achieve the RAOs, which is important to DOE, is anticipated to be relatively long. Collectively, the short-term effectiveness associated with this technology is likely moderate.

Preliminary Analysis – Implementability

Near-surface bedrock lithology observed at the HMSA appears to be amenable to air sparging. In addition, no proprietary equipment or services are required to implement the proposed technology. Collectively, the implementability of air sparging at the HMSA is considered to be high. Note that

because air sparging has not been performed at a full-scale setting at the HMSA, a pilot study would be required to provide important design parameters pertinent to the full-scale system design including sparging radius of influence.

Preliminary Analysis – Cost

Well installation and air sparging system construction would represent the primary capital expenditure required for implementing air sparging in the near-surface bedrock at the HMSA. O&M cost is primarily associated with the periodic groundwater monitoring, and data analysis and reporting. Because an extended remedial timeframe would be anticipated, the overall cost for implementing air sparging is considered to be moderate.

6.3.2.7 Monitored Natural Attenuation

Conceptual Design and Implementation

Following an active groundwater treatment remedy, implementation of MNA at the HMSA would involve use of existing monitoring wells to obtain data on the reduction in TCE concentrations over time. Data on associated geochemical and microbiological characteristics of the groundwater would also be collected. Monitoring would continue until the groundwater cleanup standard was met.

Construction

No major construction activities are anticipated for implementation of MNA at the HMSA.

O&M

Periodic groundwater monitoring would be conducted at relevant nearby monitoring wells to facilitate assessment of remedial progress. All O&M activities and associated performance results would be reported in an annual groundwater monitoring report.

Preliminary Analysis – Long-Term Reliability and Effectiveness

Based on previous assessment, MNA is likely occurring at the SSFL and thus represents a potentially applicable remedial technology. The likelihood to achieve RAOs using this technology is moderate given extended remedial timeframe.

Preliminary Analysis – Reduction of Toxicity, Mobility or Volume of Wastes

This technology may not be effective in reducing the toxicity, mobility or volume of wastes, and would probably only meet the established groundwater RAOs in an extended timeframe.

Preliminary Analysis – Short-Term Effectiveness

Because no construction activities would be anticipated in the implementation of MNA as a remedial technology for the HMSA, there would be no short-term impacts and potential for exposure to workers and the community. However, the remedial timeframe required to achieve the RAOs, which is important to DOE, is anticipated to be very long. Collectively, the short-term effectiveness associated with this technology is likely moderate.

Preliminary Analysis – Implementability

The implementability of the MNA at the HMSA is considered to be very high.

Preliminary Analysis – Cost

No significant capital expenditure would be required for implementing MNA at the HMSA. Therefore, the overall cost is primarily associated with the periodic groundwater monitoring, and data analysis and reporting. Because an extended remedial timeframe would be anticipated, the overall cost for implementing MNA is considered to be moderate.

6.3.3 Comparative Analysis

Remedial technologies under consideration for the HMSA are compared against each other using the criteria of long-term reliability and effectiveness, reduction of toxicity, mobility or volume of wastes, short-term effectiveness, implementability, and cost. The following discussion presents the relative score and justification for each technology against each of the aforementioned criteria.

6.3.3.1 Long-Term Reliability and Effectiveness

The long-term reliability and effectiveness of each remedial technology under consideration within the near-surface groundwater zone of the HMSA was evaluated based on its likelihood to achieve the remedial objective and the permanence of the remedy. Note that these factors were evaluated on an equal weight. Overall, excavation received the highest long-term reliability and effectiveness score of 5 because its ability to remove the near-surface contaminant source mass completely. Low-temperature thermal received the second highest score for long-term reliability and effectiveness of 4.5 due to the enhanced contaminant extraction at elevated temperature and the ability to sustain contaminant degradation via ISR. As a standalone technology, ISR received the third highest score of 4 for long-term reliability and effectiveness. Given the area-specific lithology and hydrogeology (perched zone) as well as results of the Spring 2018 pumping test (CDM Smith 2018d) (which indicate that sufficient volume of groundwater can be extracted), the near-surface bedrock of the HMSA may be very amenable to the Pump and Treat technology. Therefore, Pump and Treat was given the second highest score for long-term reliability and effectiveness of 4, similar to ISR. The remaining active remedial technologies under consideration at the HMSA near-surface groundwater zone including ISCO, and Air Sparging followed by MNA received the same score for long-term reliability and effectiveness of 3.5. Note that successful implementation of the active remedial technologies under consideration at the HMSA is site-specific and would have to be demonstrated in the field in a pilot-study setting prior to full-scale implementation.

6.3.3.2 Reduction of Toxicity, Mobility or Volume of Wastes

Excavation received the highest score of 5 under this evaluation criterion due to its ability to nearly completely remove contaminants within the weathered bedrock at the HMSA followed by Low-Temperature Thermal technology (4.5), Pump and Treat (4), and ISR (4). ISCO and Air Sparging received the lowest score (3) under this evaluation criterion among the active remedial technologies under consideration whereas the non-active remedial technologies including No Action, Administrative and Legal Controls, and MNA received the lowest score for reduction of toxicity, mobility or volume of wastes of 2.

6.3.3.3 Short-Term Effectiveness

The short-term effectiveness of each remedial technology under consideration within the near-surface groundwater zone of the HMSA was evaluated based on its short-term impacts and potential for exposure to workers and the nearby community as well as remedial timeframe. The overall score for short-term effectiveness was calculated by weighting the remedial timeframe score greater than the exposure potential score by a factor of two, as the time required to meet remedial objectives is considered to be more important for decision-making to DOE, and the potential for exposure during implementation can be mitigated via administrative or engineered means for all remedial technologies under consideration.

Despite its intrusive nature, Excavation received the highest overall score for short-term effectiveness of 4 because of the short remedial timeframe (relatively to other *in situ* technologies) which has a higher weight than the short-term impacts and potential for exposure to workers and the community. Similar to Excavation, Low-Temperature Thermal technology received the highest score for short-term effectiveness of 4; while the remedial timeframe would likely be longer than excavation, the short-term impacts and potential for exposure to workers and nearby community during implementation of the Low-Temperature Thermal technology would likely be much less significant than Excavation. ISR and Pump and Treat received the third highest short-term effectiveness score of 3.5 whereas ISCO and Air Sparging received the lowest score (3) among the active remedial technologies under consideration. Non-active remedial technologies including No Action, Administrative and Legal Controls, and MNA also received the lowest overall score for short-term effectiveness of 3, despite the highest score for short-term impacts and potential for exposure to workers and the community, due to the prolonged remedial timeframe when no active remediation is implemented at the HMSA.

6.3.3.4 Implementability

MNA is the most implementable technology under consideration within the near-surface groundwater zone of the HMSA as it only requires additional well installation and periodic groundwater sampling and data evaluation. The existing well network may be sufficient to support implementation of Pump and Treat for remediation of the near-surface bedrock at the HMSA. In addition, Pump and Treat has been performed successfully at the HMSA to aid remediation of the near-surface bedrock, albeit for a short duration. Therefore, Pump and Treat received the second highest implementability score of 4.5. ISR, ISCO, Air Sparging, and Low-Temperature Thermal Technology received the third highest score for implementability of 4 because very minimal aboveground infrastructure would be required. Injection wells would represent the primary component of these remedial systems. Extensive construction activities would be required as part of the implementation of Excavation technology at the HMSA; as a result, Excavation received the lowest implementability score amongst remedial technologies under consideration.

6.3.3.5 Cost

The cost associated with each remedial technology under consideration at the HMSA is presented in **Table 6-2** in terms of the capital expenditure, the O&M costs, and the overall project costs. Note that these are high-level estimated costs that would be subject to further refinement prior to remedial design and implementation. The overall O&M cost was calculated with respect to the estimated remedial timeframe presented in the same table with a 7% discount factor. As expected, the capital and overall project costs were the highest for Excavation. Note that given the relatively fast remedial

timeframe, the O&M costs associated with these technologies were the lowest among the technologies under consideration. MNA was projected to result in the lowest overall project cost followed by ISR.

6.3.3.6 Overall Score

The individual and overall scores for each remedial technology under consideration for the HMSA near-surface groundwater zone are provided in **Table 6-2**. The overall scores are a sum of the long-term reliability and effectiveness, reduction of toxicity, mobility or volume of wastes, short-term effectiveness, implementability, and cost scores. Pump and Treat received the highest overall score of 16 followed by ISR (15.5), Low-Temperature Thermal (15.5), and Excavation (15). Air Sparging and ISCO received the lowest overall scores amongst active treatment technologies under consideration of 13.5 and 14, respectively, whereas MNA received the lowest overall score (13) among all technologies under consideration.

6.3.3.7 Cost

The cost associated with each remedial technology under consideration at the HMSA is presented in **Table 6-2** in terms of the capital expenditure, the O&M costs, and the overall project costs. Note that these are high-level estimated costs that would be subject to further refinement prior to remedial design and implementation. The overall O&M cost was calculated with respect to the estimated remedial timeframe presented in the same table with a 7% discount factor. As expected, the capital and overall project costs were the highest for Excavation followed by P&T, Air Sparging, ISCO, and ISR. MNA and Low-Temperature Thermal had the lowest overall project costs.

6.3.4 Retained Remedial Technologies

Recent aquifer testing at the HMSA show it to be amenable to P&T. Low-Temperature Thermal technology, ISR, and MNA received the highest overall scores among the remedial technologies under consideration and should be retained for further evaluation. Note that the Low-Temperature Thermal and ISR technologies are site-specific and have not been demonstrated at Area IV. Therefore, pilot testing is required for further development of these technologies. Similar to other sub-areas within Area IV, it is anticipated that MNA would be performed as a supplementary technology to aid long-term performance monitoring and evaluation following the active treatment period as well as to address low-level contamination residual.

6.4 Tritium Plume

Located in the north central part of Area IV where former test reactor buildings existed, this groundwater impact area is characterized by tritium contamination exceeding its 20,000 pCi/L MCL. In 2004 and 2005, bedrock cores were sampled for the presence of tritium. The results showed the highest levels immediately above and just below the water table in bedrock. Although the original source of tritium contamination has not been identified, the groundwater data for the last 12 years show a steady decline in tritium concentration consistent with tritium's 12.5-year half-life, indicating that a significant source of contamination no longer exists. In addition, impacted groundwater remains within the boundaries of SSFL and is not expected to migrate any further; the downgradient edge of the plume is defined by seep well points at cluster SP-T02. Based on historical tritium concentration, it is anticipated that tritium concentrations will be reduced via natural attenuation processes to below its MCL of 20,000 pCi/L within the next 10 years.

Due to the demonstrated effectiveness of MNA to reduce tritium concentrations within this groundwater plume, no active treatment technologies are being considered in this portion of Area IV and MNA is the retained remedy for this groundwater plume. Implementation of MNA at the Tritium plume would involve periodic sampling of the existing monitoring wells and downgradient seep well points with continued data analysis of contaminant trends over time. Monitoring would continue until the groundwater cleanup standard was met at all relevant monitoring wells.

6.5 Radioactive Materials Handling Facility

The RMHF was used for processing, packaging, and shipping of radioactive wastes and materials – solids and liquids. In 1959, a leach field was constructed in the drainage north of the RMHF into the top of weathered bedrock. Although it was intended for discharge of domestic wastes, the leach field was also connected to a radioactive liquid waste hold up tank. Contents of the tank was discharged to the leach field after it was taken out of service for domestic wastes. The radioactive liquids contaminated the bedrock with Sr-90. In addition to Sr-90, TCE was apparently present in the mixed wastes, resulting in TCE contamination in the bedrock.

Sr-90 contamination at the leach field site was discovered in 1975 when routine monitoring found radioactivity in plants growing over the leach field. In 1978, soils above bedrock and some bedrock were excavated to remove accessible Sr-90 contamination. Bedrock fractures were sealed with tar and the site backfilled. In 2008, well RD-98 was installed through the footprint of the site of the leach field. The concentration of Sr-90 in RD-98 is dependent on groundwater elevation, meaning that the source of Sr-90 in bedrock remains relatively shallow; Sr-90 was detectable at the bedrock surface during the 1978 removal action. During relatively low rainfall years prior to 2010, Sr-90 concentration was at about 2.8 pCi/L, when the depth to groundwater was 40 feet bgs or more. During wet rainfall years, when depth to groundwater was less than 40 feet bgs, Sr-90 concentrations greatly increased in RD-98 to 126 pCi/L (wet period 2010-2011). The Sr-90 concentrations then decreased again as a result of the dry years (2013 to 2016); but increased again during the normal rainfall of 2016-2017. This places the Sr-90 impacted bedrock from near surface to about 45 feet bgs. Sr-90 has been occasionally observed in RD-30 and not detected in new well DD-143. The vertical and lateral extent of Sr-90 contamination is defined.

TCE in groundwater was discovered in 1989 when RD-30 was installed (50 µg/L). RD-34A installed in 1991 showed 91 µg/L TCE in 1993. RD-63 was installed in 1994 for the specific purpose of pumping groundwater in RMHF drainage. It showed 9.4 µg/L following installation. Pumping of RD-63 occurred during the years 1995 to 2005. The highest TCE concentration observed in RD-63 was 20 µg/L in 1998 (possibly indicating the drawing of contamination to the well during pumping). Since cessation of pumping, concentrations of TCE in RD-63 have remained around the 5 µg/L MCL. In 2017, concentrations of TCE in RD-30 and RD-34A are at or below the MCL. The vertical and horizontal extent of TCE contamination is defined for the RMHF drainage. Because TCE concentrations are below the 50 µg/L active treatment criterion, the only contaminant of concern and focus of the remedial technology evaluation for the RMHF is Sr-90. Monitoring of the RMHF area wells for VOCs would continue, however, until attainment of the MCL is observed in all wells.

6.5.1 Data Gaps

The vertical and lateral extent of Sr-90 contaminant within the RMHF is sufficiently delineated for remedial design and remedial action implementation. Additional data gap investigations are not expected to be necessary.

6.5.2 Conceptual Design and Implementation

A high-level conceptual description of the design and implementation of each remedial technology under consideration for the RMHF is presented in the following paragraphs. No Action and Administrative and Legal Controls are excluded from the following discussion as they are intended for baseline analysis. Elements of the existing administrative and legal controls that are in place for Boeing-owned property at SSFL would be incorporated into and/or modified as appropriate in the remedy selected for the RMHF. Technologies retained for further analysis at the RMHF include Bedrock Fracture Grouting, Excavation, Groundwater Hydraulic Control via Pumping, and MNA.

6.5.2.1 Bedrock Fracture Grouting

Conceptual Design and Implementation

Implementation of the bedrock fracture grouting technology at the RMHF would involve high-pressure delivery of a cement/bentonite slurry to facilitate in-place grouting of high-permeability fractures and subsequently minimizing contaminant migration. Depending on the nature of the bedrock fracture network, relatively close spacing may be required to adequately contain the groundwater migration. Note that the use of pressure grouting in the environmental remediation applications has been very limited and that a field-scale pilot study would be warranted given the lack of demonstrated success. In addition, a detailed delineation of specific fractures to be grouted would need to be developed.

Construction

Construction activities required for implementing the bedrock fracture grouting technology at the RMHF would include drilling of closely-spaced boreholes to facilitate grouting at depth-discrete vertical intervals containing fractures and harboring significant groundwater flow.

O&M

Upon completion of the proposed treatment, O&M efforts would include periodic performance monitoring at nearby groundwater monitoring wells, data evaluation, and reporting.

Preliminary Analysis – Long-Term Reliability and Effectiveness

Contaminant migration pathways would likely be diminished following completion of the fracture grouting. However, the likelihood to achieve the established groundwater RAOs under this remedial technology, is probably low given the lack of demonstrated success. In addition, the treatment may be subject to weathering and other geochemical reactions in the subsurface, rendering the remedy potentially somewhat reversible. Collectively, the long-term reliability and effectiveness of the proposed technology are considered to be low.

Preliminary Analysis – Reduction of Toxicity, Mobility or Volume of Wastes

If successfully implemented, contaminant migration pathways would be completely cut off. Therefore, this technology may be effective in reducing the toxicity, mobility or volume of wastes, and would meet the established groundwater RAOs in a relatively short remedial timeframe.

Preliminary Analysis – Short-Term Effectiveness

Significant drilling and injection activities would be performed as part of the bedrock fracture grouting work at the RMHF. However, engineered controls previously employed during prior remedial action could be used to mitigate short-term impacts and potential for exposure to workers and the community. The remedial timeframe required to achieve the RAOs, which is considered to be of significant importance to DOE, is anticipated to be very relatively short. Collectively, the short-term effectiveness associated with this technology is moderate.

Preliminary Analysis – Implementability

Given the lack of demonstrated success and vendor-provided bedrock fracture grouting services, the implementability of this technology is considered to be low.

Preliminary Analysis – Cost

The capital cost for implementing this remedial technology at the RMHF is primarily associated with the initial well drilling and subsequent fracture grouting. While only minimal O&M efforts would be required, the significant capital expenditure needed renders the overall project cost high.

6.5.2.2 Excavation

Conceptual Design and Implementation

Implementation of the Excavation technology at the RMHF would involve blasting and mechanical removal and subsequent offsite disposal of the contaminated bedrock materials, containment and subsequent disposal of groundwater collected during the remedial action, and backfilling of the excavated area with clean fill materials. Confirmation sampling on the side walls and the bottom of the excavated area would be performed to ensure that, to the extent practicable, all of the bedrock materials are excavated. The surface casing of RD-98, which was installed through the leach field proper, would be removed prior to commencement of the excavation. Therefore, upon completion of all excavation work, new monitoring wells would be installed to facilitate long-term monitoring and evaluation of the remedy.

Construction

Construction activities required for implementing excavation at the RMHF would include removal of the contaminated materials, sheet piling/shoring/benching of the excavation area, segregation and stockpiling of the excavated materials, construction of a dewatering and groundwater treatment system, and backfilling the excavation with clean fill.

O&M

Following confirmation that all contaminated materials have been excavated, no further remedial action besides periodic groundwater monitoring for a relatively short period of time (5 years) would be performed.

Preliminary Analysis – Long-Term Reliability and Effectiveness

Because all contaminated materials would have been removed via excavation, the likelihood to achieve RAOs using this technology is very high. In addition, the proposed remedy is irreversible. Collectively, this technology would likely be reliable long-term as well as effective in achieving RAOs.

Preliminary Analysis – Reduction of Toxicity, Mobility or Volume of Wastes

This technology would be effective in reducing the toxicity, mobility or volume of wastes, and would likely meet the established groundwater RAOs within a relatively short remedial timeframe. Note that excavated materials would have to be treated and disposed of appropriately offsite.

Preliminary Analysis – Short-Term Effectiveness

Given the extensive construction efforts required to implement this technology, there are potentially significant short-term impacts and potential for exposure to workers and the community. However, engineer controls could be employed to minimize such impacts and potential for exposure. In addition, the remedial timeframe required to achieve the RAOs under this technology, which is important to DOE, is anticipated to be very short. Collectively, the short-term effectiveness associated with this technology is high.

Preliminary Analysis – Implementability

While extensive construction activities would be required to implement excavation at the RMHF, such proposed remedy can be implemented without the need for proprietary equipment and services. Therefore, the implementability of this technology is considered to be moderate.

Preliminary Analysis – Cost

Significant capital expenditure would be required for implementing excavation of all contaminated overburden and bedrock materials at the RMHF. However, only minimal O&M efforts would be needed following excavation.

6.5.2.3 Groundwater Elevation Control**Conceptual Design and Implementation**

Implementation of groundwater elevation control would involve installation a pumping well upgradient of the leach field site to lower the water table (i.e., dewatering) below the zone of impacted bedrock to minimize groundwater contact with the Sr-90 contamination. An extraction pump would be installed in a newly installed well to remove groundwater below the S-90. Groundwater elevation control pumping would continue for at least 150 years until when the Sr-90 source decayed and no longer threatened groundwater quality. Because the pumping would occur upgradient of the leach field, it is anticipated that no treatment of the extracted groundwater would be necessary, and the extracted water would be released down gradient of the site. An impermeable barrier would be installed above the Sr-90 to prevent surface water from coming in contact with the material.

Construction

Construction activities that would be performed as part of this remedial technology at the RMHF would include installation of the pumping well and downhole extraction pump.

O&M

Periodic groundwater monitoring would be conducted at relevant nearby monitoring wells to facilitate assessment of remedial progress. All O&M activities and associated performance results would be reported in an annual groundwater monitoring report.

Preliminary Analysis – Long-Term Reliability and Effectiveness

Because of the nature of the radioactive decay, the likelihood to achieve remedial action objectives (RAOs) using this technology is high given a very long remedial timeframe. However, the 150-year remedial timeframe may make this technology untenable.

Preliminary Analysis – Reduction of Toxicity, Mobility or Volume of Wastes

This technology would be effective in reducing the toxicity, mobility or volume of wastes, and would probably meet the established groundwater RAOs in a very long timeframe.

Preliminary Analysis – Short-Term Effectiveness

Short-term impacts and potential for exposure to workers and the community associated with the initial drilling and well installation activities could be readily mitigated via engineered controls. However, the remedial timeframe required to achieve the RAOs, which is important to DOE, is anticipated to be very long. Collectively, the short-term effectiveness associated with this technology is likely moderate.

Preliminary Analysis – Implementability

The effectiveness of pumping to facilitate control of the groundwater elevation the RMHF would need to be verified in a small-scale prior to full-scale implementation. Note that no proprietary equipment or services would be needed. Collectively, the implementability of this remedial technology is considered to be moderate.

Preliminary Analysis – Cost

The only significant capital expenditure required for implementing the proposed technology at the RMHF would be the well installation as well as the extraction pump and associated piping and instrumentation. Minimal O&M efforts consisting of periodic groundwater monitoring, assessment, and reporting would be warranted. Overall, given the extended remedial timeframe to meet the established groundwater RAOs, the overall cost for implementing this remedial technology is considered to be moderate.

6.5.2.4 Monitored Natural Attenuation**Conceptual Design and Implementation**

Because Sr-90 concentrations would decay over time, MNA as a standalone remedy is being retained as a comparison with the active remedies. Implementation of MNA would involve use of existing monitoring wells to obtain data on the reduction in concentrations of Sr-90 over time. Monitoring would continue until the groundwater cleanup standard was met. Monitoring would also be performed after source removal, during the grouting period, and as part of groundwater elevation control.

Construction

No major construction activities are anticipated for implementation of MNA at the RMHF.

O&M

Periodic groundwater monitoring would be conducted at relevant nearby monitoring wells to facilitate assessment of remedial progress. All O&M activities and associated performance results would be reported in an annual groundwater monitoring report.

Preliminary Analysis – Long-Term Reliability and Effectiveness

Because of the nature of the radioactive decay, the likelihood to achieve remedial action objectives (RAOs) using this technology is high given a very long (150 years) remedial timeframe.

Preliminary Analysis – Reduction of Toxicity, Mobility or Volume of Wastes

This technology would be effective in reducing the toxicity, mobility or volume of wastes, and would probably meet the established groundwater RAOs in an extended timeframe.

Preliminary Analysis – Short-Term Effectiveness

Because no construction activities would be anticipated in the implementation of MNA as a remedial technology for the RMHF, there would be no short-term impacts and potential for exposure to workers and the community. However, the remedial timeframe required to achieve the RAOs, which is considered to be of significant importance to DOE, is anticipated to be very long. Collectively, the short-term effectiveness associated with this technology is likely moderate.

Preliminary Analysis – Implementability

The implementability of the MNA at the RMHF is considered to be very high.

Preliminary Analysis – Cost

No significant capital expenditure would be required for implementing MNA at the RMHF. Therefore, the overall cost is primarily associated with the periodic groundwater monitoring, and data analysis and reporting. Because an extended remedial timeframe would be anticipated, the overall cost for implementing MNA is considered to be moderate.

6.5.3 Comparative Analysis

Remedial technologies under consideration for the RMHF are compared based on their respective abilities to address the criteria of long-term reliability and effectiveness, reduction of toxicity, mobility or volume of wastes, short-term effectiveness, implementability, and cost. The following text presents the relative score and justification for each technology based on the criteria evaluations.

6.5.3.1 Long-Term Reliability and Effectiveness

The long-term reliability and effectiveness of each remedial technology under consideration at the RMHF was evaluated based on its likelihood to achieve the remedial objective and the permanence of the remedy. The decay of radioactive materials such as Sr-90 is an intrinsic property that is largely independent of environmental factors. Therefore, regardless of the remedial timeframe, the likelihood for Sr-90 concentrations to gradually and naturally decrease to below the cleanup level is the same for all remedial technologies under consideration as shown in **Table 6-3**. Similarly, the natural radioactive decay is the primary attenuation mechanism for Sr-90. Therefore, all five technologies

under consideration for the Sr-90 source received the same score for long-term reliability and effectiveness.

6.5.3.2 Reduction of Toxicity, Mobility or Volume of Wastes

Excavation received the highest score of 5 under this evaluation criterion due to its ability to nearly completely remove the contaminated bedrock materials at the RMHF. Bedrock fracture grouting received the second highest score of 4 for reduction of toxicity, mobility or volume of wastes due the isolation and control of contaminant transport to groundwater via fracture sealing. Groundwater level control received a lower score. Although isolation of the Sr-90 from the groundwater, toxicity and volume is only reduced through natural mechanisms. Non-active remedial technologies including No Action, Administrative and Legal Controls, and MNA received the lowest score of 3 under this evaluation criterion. The concentration of Sr-90 will decay over time, but remedial goals would not be met for 150 years.

6.5.3.3 Short-Term Effectiveness

The short-term effectiveness of each remedial technology under consideration at the RMHF was evaluated based on its short-term impacts and potential for exposure to workers and the nearby community during the action, as well as remedial timeframe. The overall score for short-term effectiveness was calculated by weighting the remedial timeframe score greater than the exposure potential score by a factor of two, as the time required to meet remedial objectives, which is important for DOE decision-making, and the potential for exposure during implementation can be mitigated via administrative or engineered means for all remedial technologies under consideration.

Excavation received the highest overall score for short-term effectiveness of 4 because of the short remedial timeframe (relatively to other *in situ* technologies) which has a higher weight than the short-term impacts and potential for exposure to workers and the community. This technology does pose the greatest risk to workers and community as the bedrock needs to be handled and transported off site. Bedrock Fracture Grouting received an overall short-term effectiveness score of 3. While the remedial timeframe to implement the Bedrock Fracture Grouting is short, the technology does leave the Sr-90 impacted bedrock in place for 150 years. Groundwater elevation control would need to be operated for 150-year period. There is a potential for exposure to workers during implementation of the technologies, but limited potential for exposure to the community. whereas Sr-90 source removal received a score of 2. While there would be no short-term impacts and potential for exposure to worker and the community should non-active remedial technologies such as No Action, Administrative and Legal Controls, and MNA be implemented (thus the score of 5), a prolonged remedial timeframe (150 years) would likely be required to achieve the cleanup goal (thus the score of 0). Collectively, the non-active remedial technologies received an overall short-term effectiveness score of 1.5.

6.5.3.4 Implementability

MNA is the most implementable technology under consideration at the RMHF as it only requires additional well installation (if needed) and periodic groundwater sampling and data evaluation. Therefore, MNA received the highest implementability score of 5. Excavation at the RMHF would require specialized heavy equipment to aid in separation, segregation, and removal of bedrock materials as well as subsequent onsite and offsite waste disposal. Given the difficult nature of bedrock excavation work, source excavation received an implementability score of 3. The success and

effectiveness of the Bedrock Fracture Grouting technology in environmental remediation applications have not been demonstrated at a commercial scale. In addition, the technology has never been tested at the RMHF. The Bedrock Fracture Grouting technology received an implementability score of 2. Groundwater elevation control is readily implementable, but would require long-term operations and maintenance work, not needed for the other action technologies.

6.5.3.5 Overall Score

The individual and overall scores for each remedial technology under consideration at the RMHF are provided in **Table 6-3**. The overall scores are a sum of the long-term reliability and effectiveness, reduction of toxicity, mobility or volume of wastes, short-term effectiveness, implementability, and cost scores. Source removal of the Sr-90 bedrock received the highest overall score of 17 followed by MNA. Groundwater elevation control received a score of 16.5. Although source removal would cost significantly more than MNA, the timeframe to achieve remedial goals could be reduced by about 140 years.

6.5.3.6 Cost

The costs associated with each remedial technology under consideration at the RMHF are presented in **Table 6-3** in terms of the capital expenditure, the O&M costs, and the overall project costs. Note that these are high-level estimated costs that would be subject to further refinement as part of remedial design and implementation. The overall O&M cost was calculated with respect to the estimated remedial timeframe presented in the same table with a 7% discount factor. As expected, the capital and overall project costs were the highest for Excavation. The next highest overall project costs were associated with Bedrock Fracture Grouting and Groundwater Extraction. MNA had the lowest overall project cost as expected. Note that the NPV cost presented does not account for more than 100 years of cost that would be incurred for groundwater extraction; this is due to the nature of the NPV cost calculation, negligible costs are incurred beyond approximately 30 years.

6.5.4 Retained Remedial Technologies

MNA and excavation of the Sr-90 source received the highest overall scores among the remedial technologies under consideration and are retained for further evaluation. All technologies would be accompanied by monitoring to demonstrate effectiveness of contamination concentration reduction.

6.6 Metals Clarifier Laboratory Building 4065/DOE Leach Fields 3 RFI Site

TCE contamination in near-surface groundwater in this portion of Area IV is delineated through three piezometers PZ-005, PZ-104, and PZ-105 as well as bedrock well DD-145 (**Figure 2-9**). The TCE concentrations are below the active treatment criterion of 50 µg/L in all of the aforementioned wells and the only TCE exceedance of the 5 µg/L MCL, as of 2017, was observed at piezometer PZ-105 at 7.9 µg/L. Given the generally decreasing TCE trend observed at PZ-105 and other wells, indicating that natural attenuation of TCE is occurring, no active treatment technologies are being considered in this portion of Area IV and MNA is the retained remedy for this groundwater area. Implementation of MNA would involve periodic monitoring of existing wells and subsequent data analysis of contaminant trends and geochemical parameters pertinent to MNA over time. Monitoring would continue until the groundwater cleanup standard was met at all relevant monitoring wells.

Table 6-1. Remedial Technology Evaluation at the FSDF (VOCs in Near Surface Bedrock)

Remedial technology category	Remedial technology	Long-term reliability and effectiveness			Reduction of toxicity, mobility or volume of wastes	Short-term effectiveness			Implementability	Total score	Cost			
		Likelihood to achieve remedial objective	Permanence of remedy	Overall long-term reliability and effectiveness score		Short-term impacts and potential for exposure to workers and community	Remedial timeframe	Overall short-term effectiveness score			Remedial timeframe	Capital	O&M	Overall project cost
None		3	3	3	2	5	1	2.5	-	7.5	-	-	-	-
Administrative and legal controls		3	3	3	2	5	1	2.5	-	7.5	-	-	-	-
In situ treatment	In situ reduction (biotic and abiotic)	3	3	3	3	4	3	3.5	3	12.5	25	\$2,459,000	\$1,342,000	\$3,801,000
	In situ reduction (biotic and abiotic) with permeability enhancement	4	4	4	4	3	4	3.5	3	14.5	15	\$1,719,000	\$1,220,000	\$2,939,000
	ISCO	3	3	3	2	4	3	3.5	1	9.5	25	\$2,459,000	\$1,718,000	\$4,177,000
	ISCO with permeability enhancement	4	3	3.5	3	3	4	3.5	1	11.0	15	\$1,719,000	\$1,562,000	\$3,281,000
Source removal	Removal via excavation	5	5	5	5	1	5	3.5	1	14.5	5	\$12,202,000	\$395,000	\$12,597,000
	Groundwater extraction via dewatering	4	4	4	3	4	3	3.5	5	15.5	25	\$846,000	\$2,596,000	\$3,442,000
	Enhanced groundwater extraction with permeability enhancement	4	5	4.5	4	3	4	3.5	3	15.0	20	\$2,328,000	\$2,097,000	\$4,425,000
	In situ thermal remediation	4	4	4	4	2	5	4	2	14.0	5	\$4,725,000	\$308,000	\$5,033,000

Monitored Natural Attenuation (MNA) would accompany any active treatment selected for full-scale implementation to allow for long-term monitoring and evaluation of treatment effectiveness.

Table 6-2. Remedial Technology Evaluation at the HMSA (VOCs in

Remedial technology category	Remedial technology	Long-term reliability and effectiveness			Reduction of toxicity, mobility or volume of wastes	Short-term effectiveness			Implementability	Total score	Cost			
		Likelihood to achieve remedial objective	Permanence of remedy	Overall long-term reliability and effectiveness score		Short-term impacts and potential for exposure to workers and community	Remedial timeframe	Overall short-term effectiveness score			Remedial timeframe	Capital	O&M	Overall project cost
None		3	3	3	2	5	2	3	-	8.0	-	-	-	-
Administrative and legal controls		3	3	3	2	5	2	3	-	8.0	-	-	-	-
MNA		3	3	3	2	5	2	3	5	13.0	30	\$218,000	\$1,194,000	\$1,412,000
In situ treatment	In situ reduction (biotic and abiotic)	4	4	4	4	4	3	3.5	4	15.5	15	\$1,376,000	\$1,049,000	\$2,425,000
	ISCO	4	4	4	3	3	3	3	4	14.0	25	\$1,376,000	\$1,718,000	\$3,094,000
	Low-temperature, thermally-enhanced bioremediation	4	5	4.5	4.5	3	4	3.5	3	15.5	10	\$1,225,000	\$308,000	\$1,533,000
Source removal	Removal via excavation	5	5	5	5	2	5	4	1	15.0	5	\$12,202,000	\$395,000	\$12,597,000
	Pump and treat	4	4	4	4	4	3	3.5	4.5	16.0	25	\$846,000	\$2,596,000	\$3,442,000
	Air sparging	3	4	3.5	3	3	3	3	4	13.5	20	\$846,000	\$2,360,000	\$3,206,000

Table 6-3. Remedial Technology Evaluation at the RMHF (Sr-90 in Bedrock)

Remedial technology category	Remedial technology	Long-term reliability and effectiveness			Reduction of toxicity, mobility or volume of wastes	Short-term effectiveness			Implementability	Total score	Cost			
		Likelihood to achieve remedial objective	Permanence of remedy	Overall long-term reliability and effectiveness score		Short-term impacts and potential for exposure to workers and community	Remedial timeframe	Overall short-term effectiveness score			Remedial timeframe	Capital	NPV	Overall cost score
None		5	5	5	3	5	0	1.5	-	9.5	-	-	-	-
Administrative and legal controls		5	5	5	3	5	0	1.5	-	9.5	-	-	-	-
MNA		5	5	5	3	5	0	1.5	5	14.5	10.0	\$218,000	\$676,000	\$894,000
Containment	Bedrock fracture grouting	5	5	5	4	3	3	3	2	14.0	10.0	\$2,975,000	\$528,000	\$3,503,000
Source removal	Removal via excavation	5	5	5	5	2	5	4	3	17.0	5.0	\$12,202,000	\$395,000	\$12,597,000
	Groundwater hydraulic control via pumping	5	5	5	4	4	3	3.5	4	16.5	5.0	\$846,000	\$914,000	\$1,760,000

Section 7

Recommended Remedial Technologies

Based on the groundwater remedial technology assessments provided in the prior sections, the groundwater issues presented in the Area IV Groundwater RI Report (CDM Smith 2018a), and the relative threat that the contamination poses to human health and the environment, this section presents DOE's recommended groundwater remedial technologies for Area IV. The presentation of the recommendations follows the order of groundwater investigation areas discussed in **Section 6**.

7.1 Former Sodium Disposal Facility

The recommended technology for the FSDF groundwater is the dewatering of fractures harboring VOCs. This would include the near-surface fractures and deeper bedrock fractures. For the shallow fractures, existing coreholes drilled to approximately 50 feet bgs would be used to collect groundwater released from the fractures (these include RS-54 and coreholes 20 through 27 drilled spring of 2018). Groundwater emanating from fractures that collects at the bottoms of the coreholes would be pumped to the surface and placed in a storage tank.

For the deeper bedrock fractures, packers would be set in the open core wells below fractures exhibiting VOCs. Water released from the fractures into the borehole would accumulate on the top of the packer. When sufficient water is accumulated, it would be pumped to the surface. Existing wells RD-23, RD-64, RD-65, and RD54A would be initially used as groundwater capture wells. As part of the design of this remedy, the need for additional bedrock coreholes, drilled to the depth of fractures with VOCs, would be assessed as a measure of enhancing capture of VOCs.

Based on the experience of packer testing of the FSDF wells in 2016 and the recent extraction of groundwater from shallow well RS-54, a weekly production rate of between 10 and 20 gallons is expected. DOE would most likely contain the water in multiple 2,500-gallon storage tanks, and then transport the water to an offsite treatment/disposal facility. If extracted groundwater production is greater, or a decision is made to inject water to facilitate VOC migration through fractures, DOE may consider construction of an on-site treatment system to remove VOCs and metals for reuse of the water.

Dewatering of fractures would occur over a 5-year period. After 5 years of pumping, the effectiveness of the remedy in reducing VOC threat to the Chatsworth Formation groundwater would be assessed. If the assessment indicates that VOC concentrations have been effectively reduced, then a decision may be made to stop dewatering and continue groundwater monitoring to demonstrate that effectiveness. If the 5-year review indicates that dewatering has not been effective, or the groundwater monitoring indicates that there is a rebound in VOC concentrations, then additional actions may be considered. This could be recirculation of water through the fractures to further mobilize VOCs, drilling of additional coreholes to provide greater access to groundwater, implementation of permeability enhancement to allow for enhanced groundwater extraction and subsequent treatment, or a combination thereof.

This technology has been selected because it addresses the primary threat to the Chatsworth Formation groundwater. The technology addresses the readily extractable VOC mass in bedrock. It is recognized that back-diffusion of VOCs in the bedrock matrix will continue to release VOCs into the fractures, but at much lower concentrations observed in the bedrock fractures today. The groundwater contaminants at the FSDF have been demonstrated to not be moving away from Area IV and will not be threatening human health or the environment.

7.2 Building 4100/B56 Landfill TCE Plume

The source for the TCE in the groundwater associated with Building 4100 and the B56 Landfill has not been identified. Investigations of the B56 landfill as a source have failed to identify the area of the landfill as a groundwater VOC source. DOE investigated the Building 4009 former leach field site as a potential source using passive soil gas analysis technique and determined the leach field not to be a source (CDM Smith 2018d). This indicates that the source is probably in the vicinity of monitoring well RD-91 near Building 4100. Boeing is investigating this area.

The B56 Landfill RFI Site is the responsibility of DOE. Although the impacted groundwater beneath the landfill site may be the leading edge of groundwater from the Building 4100 area, DOE will continue to sample wells monitoring the landfill location per the revised WQSAP (wells RD-07, DD-141). The recommended changes for the WQSAP are described in **Section 9**.

7.3 Buildings 4059/4057/4626 PCE Plume

Monitoring well data for this RFI site have demonstrated continued decline in PCE concentrations over time. This indicates that the original source for the PCE has dissipated and what remains is within near-surface groundwater. The most impacted well, PZ-109, exhibits PCE concentrations near 80 µg/L. The recommended technology for this location is to perform a short-term pump test to dewater the groundwater zone lying atop bedrock at the PZ-109 location. The pumped water would be stored in a temporary tank for subsequent off-site transport for disposal. The dewatering would be followed by a period of monitoring to ascertain any rebound. If no rebound is observed, then the remedy for the location will be MNA. If there is a rebound in PCE concentration, then the dewatering step would be repeated, followed by monitoring until a trend of decreasing PCE concentrations is established. Monitoring would be in accordance with the revised WQSAP. Wells PZ-109, RD-24, DD-142, and RD-96 would be included in this effort.

7.4 HMSA TCE Plume

Near-surface and bedrock groundwater in this RFI site area is impacted by TCE greater than 100 µg/L. The recommended technology is pumping of the near-surface and bedrock groundwater zones to remove contaminated groundwater. Initially, pumping would occur using wells PZ-163 and DD-144 which would draw impacted groundwater towards the center of the HMSA. Based on pump tests conducted in 2018 on groundwater at the HMSA (CDM Smith 2018e), it is anticipated that these wells could sustain, at least initially, a 200 gallon per day pumping rate. Additional wells may be utilized/installed to facilitate enhanced groundwater extraction. As part of the design effort for the remedy, an evaluation will be made related to placement of a portable treatment system on site, or to contain and transport the extracted water for off-site treatment. Pumping of the near-surface groundwater would occur until its level reached the top of competent bedrock. Pumping of the bedrock well would continue until purge sample results

demonstrate a steady decline of TCE concentrations below 50 µg/L. When these conditions are met, pumping would stop and monitoring of the response of groundwater to the pumping would commence. If a rebound in concentrations is observed, then pumping would be re-initiated. If no rebound is observed, then monitoring for MNA demonstration would start. All monitoring would be in accordance with the WQSAP in effect at the time MNA was initiated.

Depending on volume, extracted groundwater would be either trucked off-site for treatment/disposal, or a portable water treatment system be brought to the site. It may be possible that concurrent pumping at the FSDF, PCE plume, and/or HMSA could warrant use of a portable on-site treatment system. The decision to treat on-site would be made as part of the remedy design evaluation of total extracted volumes. During and after pumping, existing wells RD-29, DD-147, PZ-120, and PZ-108 would be monitored for water elevation and contaminant concentrations changes.

7.5 Tritium Plume

The location of the remaining tritium source in bedrock has been defined by bedrock coring (CDM Smith 2018a). The lateral extent of the tritium plume has been defined by the existing well network. Water quality trend data collected since 2005 illustrate a steady decline in tritium concentrations at a rate consistent with the 12.5-year half-life of tritium. The decline curve indicates that tritium concentrations will be below the 20,000 pCi/L MCL within the next 10 years. Therefore, monitored natural attenuation is the recommended remedial action for the tritium plume. This recommendation will be reviewed after 5 years of monitoring to document the continued decline in tritium concentrations. Existing monitoring wells RD-87, RD-88, RD-90, RD-94, and RD-95 will be monitored for tritium annually in accordance with the revised WQSAP.

7.6 Radioactive Materials Handling Facility

There are two different groundwater impact issues at the RMHF: TCE in near-surface bedrock groundwater and Sr-90 in near-surface bedrock. Recommended remedies for these issues are described separately below.

7.6.1 RMHF TCE Impacted Groundwater

Since groundwater pumping ceased in 2005, TCE concentrations in all wells at the RMHF area have steadily declined to be at, or below, the 5 µg/L MCL. It is believed that what is observed in groundwater today represents residual TCE that is back-diffusing from the bedrock matrix. This back-diffusion process will be slow, but residual TCE concentrations will continue to decline. The recommended action at the RMHF for TCE impacted groundwater would be to continue annual monitoring to document further decline in concentrations. Monitoring would continue for 5 years, at which time the need for continued TCE monitoring would be assessed.

Existing monitoring wells RD-30, RD-34A, and RD-63 will be monitored annually as part of this effort. Well RD-98 would be included until the time of abandonment during removal of the Sr-90 source. It is expected that a replacement well would be drilled immediately downgradient of the leach field site to assess effectiveness of the Sr-90 source removal.

7.6.2 RMHF Leach Field Sr-90 Source

Bedrock below the former RMHF leach field site is impacted by Sr-90 released as radioactive waste water into the leach field. The depth of impacted bedrock is based on the rise and fall of Sr-90 concentrations in groundwater samples relative to bedrock groundwater elevation differences. These observations place the bottom of impacted bedrock at about 45 feet bgs. Sr-90 has a 28.8-year half-life.

There are two viable options to addressing the Sr-90. The first would be to place an impermeable cap over the site and then through pumping, maintain a groundwater elevation below 45 feet bgs. This would keep groundwater from intermingling with the Sr-90 in bedrock. Existing bedrock well RD-98 and two new wells installed east of RD-98 could be used to lower the groundwater elevation. This option would require groundwater pumping and monitoring to occur for an approximately 150 years until the presence of Sr-90 was reduced by natural radioactivity decay.

The second option would be to excavate and remove the Sr-90 impacted bedrock. Conventional excavation equipment with hydraulic chisel hammers could be used to break up bedrock for placement in haul trucks. The impacted bedrock would be transported to a licensed radioactive materials disposal facility. Removal of the impacted bedrock would take less than 6 months to accomplish. The excavation would be backfilled to existing ground surface. Groundwater monitoring would continue for 5 years to verify that the source was removed. Given the short-term nature of this option, it is the recommended action for the Sr-90 impacted bedrock.

The only information as to where bedrock with Sr-90 is present at the leach field site is anecdotal descriptions of three “deep” vertical fractures with observed Sr-90 contamination. The extent and locations where Sr-90 can only be determined through bedrock coring and excavation. If Sr-90 exists to a depth of 45 feet below ground surface, then there is a potential for up to 3,000 cubic yards of impacted bedrock to be excavated. It is assumed that the bedrock may also be impacted by TCE observed in well RD-98 and that the excavated bedrock would need to be disposed of as mixed waste. The excavation could be backfilled using soil material comprising the man-made ridge that separates the RMHF from the former Sodium Reactor Experiment (SRE) facility to the east, or by soil imported from an off-site borrow.

Existing well RD-98 would be removed as part of the bedrock excavation. The well would be replaced with a new well downgradient of the leach field site. The new well and RD-30 would be sampled for presence of Sr-90 following completion of bedrock excavation as part of a 5-year post removal monitoring period.

7.7 Metals Clarifier/DOE Leach Field 3 TCE Plume

Groundwater in this area is impacted by TCE near or below the 5 µg/L MCL (7.9 µg/L in PZ-105 in 2017). The recommended action for this location is continued monitoring for 5 years, with a review of remaining contamination at that time. Existing wells PZ-005, PZ-104, PZ-105, and DD-145 would be monitored over this period.

Section 8

Area IV Groundwater Remediation Schedule

A high-level schedule for implementing groundwater remediation in Area IV of SSFL is provided in **Table 8-1**. This table only presents timeframes to initiate remediation. Completion dates will be determined only after remedy effectiveness review, which can only be determined after a remedy is implemented and data from the action assessed.

Table 8-1 High-Level Area IV Groundwater Remediation Schedule	
Activity	Timeframe
Submittal of Draft Groundwater RI Report to DTSC	September 2018
Submittal of Draft Corrective Measures Study to DTSC	September 2018
Final Area IV EIS	TBD
Acceptance of Final Groundwater RI Report by DTSC	January 2019
Acceptance of Corrective Measures Study by DTSC	March 2019
NEPA Groundwater Record of Decision	TBD
Submittal of Draft Ground Remediation Corrective Measures Implementation Plan to DTSC	June 2019
DTSC CEQA Findings on Area IV Groundwater	July 2019
DTSC Acceptance of Groundwater Corrective Measures Implementation Plan	October 2019
DOE Procures Groundwater Remediation Contractor	TBD
Finalization of Design of Groundwater Remedies	March 2021
Implementation of Groundwater Remedies	June 2021

TBD – To be determined

NEPA – National Environmental Policy Act

CEQA – California Environmental Policy Act

Section 9

Evaluation of Area IV Monitoring Well Network for Water Quality SAP Revision and Adequacy

This section includes a review of the existing monitoring well network. In Section 9.1 the purpose of each existing well is reviewed and compared to the requirements of the current groundwater sampling and analysis program. Recommendations for revisions to the current sampling program are identified. Section 9.2 presents an evaluation the current monitoring well network to adequately monitor the known groundwater contamination and to transition into the corrective measures phase. Data gaps in the current monitoring well network are identified.

9.1 Evaluation of Monitoring Well Network for Water Quality SAP Revision

The current groundwater sampling and analysis program for Area IV is governed by Site-wide WQSAP (Haley & Aldrich 2010) that was developed based on the perceived groundwater monitoring data needs prior to 2010. Since the time the WQSAP was issued, 27 additional wells have been installed in Area IV. Based on the analysis of the data, several of the older wells have met their groundwater characterization purpose stated in the WQSAP. This section of the Area CMS provides a summary of evaluation of information for each well and concludes with the recommended WQSAP changes. Table 9-1 summarizes the purpose of each well for groundwater monitoring, and the trends in sample results.

Table 9-2 provides the recommended changes for future sampling of Area IV wells that are the responsibility of DOE. With the exception of wells being actively used for groundwater remediation (e.g., pump and treat), the recommended sampling frequency for remedy demonstration wells is once per year during the late spring, and for non-remedy demonstration wells once every 5 years. The frequency of sampling of remedy demonstration wells may also be adjusted per data needs determinations to be described the Corrective Measures Study Implementation Plan.

Water levels in all wells should be measured on a quarterly basis, particularly to continue the observation of water level fluctuations resulting from changes in rainfall. Due to the maturity of the Area IV groundwater program, some wells with adequate characterization data are recommended for sampling once every 5 years. As part of a 5-year assessment of groundwater trends (which will include effectiveness of groundwater remedies), recommendations can be made to change the sampling program including wells to be sampled, specific analytes, and frequency of sampling.

Table 9-1 – Summary of Purpose of each Area IV Well under DOE Responsibility

Well	Design	Current Purpose	Data Trends	WQSAP Recommendations
Former Sodium Disposal Facility (FSDF)				
FSDF Issues: highest concentrations of VOCs observed in Area IV. Metals exceeding screening levels. Source appears to be in near-surface bedrock fractures. Transport of VOCs in bedrock fractures highly likely, wells drilled through VOC source area appear to conduits for facilitated VOC mobility downward. Metals are also Contaminants of Concern (COCs) for the FSDF pond area.				
PZ-97	Conv., screen 33-43 ft, 44.5 ft deep	Beyond area of FSDF GW Impact	Normally dry; never sampled?	If the well never produces water, abandon it
PZ-98	Conv., screen 24-34 ft, 37.5 ft deep	Downgradient in surface drainage from FSDF	Normally dry, 29 ppb TCE in 2003, 1.2 in 2017, perchlorate 0.69 ppb in 2017, metals (Co, Ni, Ag, V) above screening values	Well located in bedrock drainage. Shallow vertical fractures may direct overflow from FSDF to well location. Keep in program.
PZ-100	Conv., screen 5.7-15.7 ft, 16.5 ft deep	Upgradient of FSDF, downgradient of ESADA	VOCs non-detect in 2002, 2003 and 2017	Well is normally dry; too shallow to provide useful data for FSDF, Boeing should assess need relative to ESADA.
PZ-101	Conv., screen 10-20 ft, 27 ft deep	Upgradient of FSDF, downgradient of ESADA	Sampled once in 2005; TCE 140 ppb	Well is normally dry; too shallow to provide useful data for FSDF, Boeing should assess need relative to ESADA.
RS-18	Conv., screen 7.5-13 ft, 13 ft deep	Downgradient in surface drainage from FSDF	Exhibits elevated TCE levels during and immediately following above average rainfall; most likely from spillage along bedrock surface interface from FSDF. Metals (Sb, As, Ba, Co, Mo, Ni, Se, Ag) above screening level; perchlorate below screening level.	Key well for monitoring the near-surface groundwater down gradient from FSDF; keep monitoring.
RS-54	Conv., screen 7-44 ft, 44 ft deep	Situated in lower FSDF pond source area	Well is dry during low rainfall years; Exhibits elevated VOCs; metals (As, Ba, Be, B, Cd, Cr, Co, Cu, Mn, Hg, Mo, Ni, Se, Ag, Tl) above	Monitors near-surface VOC bedrock fracture source and will be key remedy evaluation well; keep monitoring.

Table 9-1 – Summary of Purpose of each Area IV Well under DOE Responsibility

Well	Design	Current Purpose	Data Trends	WQSAP Recommendations
			screening levels; perchlorate now below screening level. Low TPH	
C-08	Core hole 8 is a 400 ft open boring, cased 0-65 ft	Original purpose was to collect bedrock core for TCE analysis; currently serves as a duplicate deep well beneath FSDF pond source	Sampling starting in 2016; TCE <1 ppb.	Consider abandonment as it is drilled through main source area and could become a conduit. (RD-54A serves as the bedrock FSDF site well.)
RD-21	Open corehole 30-175 ft deep, cased 0-30 ft.	Upgradient of FSDF and adjacent to ESADA	Impacted by VOCs, only bedrock well in Area IV with elevated carbon tetrachloride; metals (As, Cr, Cu, Hg, Mo, Se, Tl) above screening level; perchlorate now below screening levels; hydraulically separate from FSDF wells.	Upgradient of FSDF, adjacent to ESADA, continue monitoring for upgradient data
RD-22	Open corehole 30-440 ft deep, cased 0-30 ft	Downgradient of FSDF per numeric modeling	TCE never detected in well. Sampled for metals 26 times; no consistent metals exceedances except for strontium; strontium not a soil contaminant.	Consider grouting well up to depth of contaminated fractures below FSDF ponds; use as sentinel well per groundwater modeling results.
RD-23	Open corehole 30-440 ft deep, cased 0-30 ft	Immediately north of lower FSDF pond	Elevated TCE comparable to RS-54; wide fluctuations corresponding to rainfall; no consistent reporting of metals above screening levels; only one detection of perchlorate below screening level	Based on surficial geologic evidence, near surface fractures may direct groundwater flow northward from RS-54. RD-23 is key monitoring point. Consider grouting well up to depth of contaminated fractures and sample above.

Table 9-1 – Summary of Purpose of each Area IV Well under DOE Responsibility

Well	Design	Current Purpose	Data Trends	WQSAP Recommendations
RD-33A	Open corehole 100-320 ft deep; cased 0-100 ft	In NBZ northwest of FSDf, in numeric model pathway	TCE mostly <1 ppb; cis-1,2-DCE present; consistent with modeling results. No consistent detection of metals, or perchlorate above screening levels.	Key sentinel well for remedy demonstration.
RD-33B	Open corehole 300-415 ft deep; cased 0-300 ft	In NBZ northwest of FSDf, in numeric model pathway	One report of TCE at 0.76 (1991) out of 71 samples; no consistent detection of metals, perchlorate above screening levels.	Use as sentinel well for remedy demonstration.
RD-33C	Open corehole 480-450 ft deep; cased 0-480 ft	In NBZ northwest of FSDf, in numeric model pathway	No VOCs reported in 75 samples; no consistent detection of metals above screening levels	Abandon the well. Model flow paths and VOCs are not this deep.
RD-54A	Open corehole 119-278 ft deep; cased 0-119 ft	Well drilled through former pond source area; may be a conduit	TCE up to 580 ppb present in the 1990s; TCE < 5 ppb since 2011 may result from less average rainfall; no consistent report of TPH, metals above screening levels except for manganese	Identify deepest fracture exhibiting TCE above MCL; grout well to just below that fracture.
RD-54B	Open corehole 379-473 ft deep; cased 0-379 ft	Well drilled through former pond source area; potential future conduit	One report of TCE in 2002 appears to be a sampling artifact; no consistent report of metals above screening levels	Abandon well. No evidence of deep vertical migration
RD-54C	Open corehole 557-638 ft deep; cased 0-638 ft	Well drilled through former pond source area; potential future conduit	No detections of VOCs; metals below screening levels	Abandon well. No evidence of deep vertical migration
RD-57	Open corehole 19.5-419 ft; cased 0-19.5; currently blocked by torn FLUTE liner	Located northwest of FSDf in NBZ; replaced by well DD-139	No detections of VOCs; metals below screening levels	Abandon well; location area monitored by DD-139

Table 9-1 – Summary of Purpose of each Area IV Well under DOE Responsibility

Well	Design	Current Purpose	Data Trends	WQSAP Recommendations
DD-139	Open corehole 19-206 ft; cased 0-19.5 ft	Located northwest of FSDf in NBZ; replacement well for RD-57	Installed in 2016; no detections of VOCs; metals, perchlorate below screening levels	Continue monitoring as FSDf sentinel well
DS-46	Open corehole 37-52 ft., cased 0-37 ft	Adjacent to piezometer PZ-098 for monitoring near surface bedrock groundwater down drainage from FSDf	Installed in 2016; sampled twice, TCE 1.1 ppb in 2017	Monitors historic surface bedrock pathway down drainage from the FSDf, continue monitoring.
DD-140	Open corehole 60-167 ft., cased 0-60	Monitors bedrock groundwater in downgradient direction from FSDf.	Installed in 2016; TCE 0.29 ppb in 2017	Monitors historic surface bedrock pathway down drainage from the FSDf, continue monitoring.
RD-64	Open corehole 19-398 ft; cased 0-19 ft	Located immediately west of ponds; shows strong evidence of being a conduit	TCE in well went from non-detect to 680 ppb over first 10 years; connected to FSDf source fractures; no consistent metals, perchlorate above screening levels	Consider grouting up to depth of fractures contributing VOCs; continued monitoring; possible remedy well
RD-65	Open corehole 19-397 ft; cased 0-19 ft	Located north of FSDf in bedrock fracture-controlled direction;	Significant increase in TCE following installation, a conduit. Demonstrates northward fracture flow from FSDf	Consider grouting up to depth of fractures contributing VOCs; continued monitoring; possible remedy well
Building 4100/B56 Landfill				
Building 4100/B56 Landfill issues: Source of TCE in well RD-07 is probably not the landfill based on soil-gas data; nearest groundwater TCE source likely near Building 4100				
PZ-124	Conv., screen 11.3-31 ft, 31 ft deep	Located in the drainage at the toe of B56 landfill, assumed purpose to monitor near-surface groundwater	Well is typically dry, even in wet years, last sampled in 2011 and TCE was non-detect	Abandon. It has been replaced by DD-141.
RS-16	Conv., screen 16.5-20.5 ft, 20.5 ft deep	Located on top of landfill, original purpose unknown as well too shallow	Well is typically dry, even in wet years, last sampled 2008, TCE was non-detect	The well serves no purpose, much to shallow to encounter groundwater, abandon the well.

Table 9-1 – Summary of Purpose of each Area IV Well under DOE Responsibility

Well	Design	Current Purpose	Data Trends	WQSAP Recommendations
		to monitor groundwater		
RD-07	Open corehole 25-300 ft, cased 0-25 ft.	Located on top of landfill; monitors leading edge of Building 4100 plume?	TCE 16 to 45 ppb 1986-1995, 38-76 ppb 1996-2001, 29-57 ppb 2013-2017.	TCE source investigations of landfill proper show it not to be a VOC source. Nearest groundwater impact is RD-91 at Building 4100. RD-07 will remain in program until source is identified and remediated.
RD-74	Open corehole, 30-101 ft, cased 0-30 ft.	Installed on top of landfill near RD-07	Typically dry. Has metal pump lodged at bottom.	Abandon as it is too shallow to provide useful data.
DD-141	Open corehole 19.5-133 ft, cased 0-19.5 ft	Located in drainage at the toe of B56 landfill, serves as a landfill monitoring point	Sampled three times since 2016 installation; all VOCs non-detect. Low concentration of TPH, perchlorate.	Continue sampling as a landfill groundwater compliance point.
RD-91	Open corehole 20-140 ft., cased 0-20 ft	Located adjacent to B4100	Sampled 5 times, 270 ppb TCE in 2009, last sampled in 2014 TCE 200 ppb; cis-1,2-DCE at 34 ppb. Sampled twice for metals, Be, Cu, and Mo slightly above screening levels	Well needs to be retained and included within Boeing’s sampling requirements in the revised WQSAP.
Building 100 Trench				
RD-20	Open corehole 30-127 ft., cased 0-30 ft.	Installed at former building debris trench site; all debris has been removed	Sampled 28 times since 1989. One-time report of TCE at 0.21 ppb in 1990. Se slightly above screening level.	Use well for water level measurements; sample as part of 5-year review.
Buildings 4057/4059/4626 PCE Plume				
PCE Plume issues: Near-surface groundwater exhibiting PCE as the VOC contaminant; trends are for decreasing PCE concentration				
PZ-109	Conv. screen 25-35 ft, 36.5 ft deep.	Monitors PCE plume at Building 4057	PCE 42-76 ppb 2013 to 2017, 300 ppb in 2002; TCE 2.8 to 8.9 ppb; metals Cd and Mo observed above screening level	Well monitors PCE perched groundwater; continue monitoring

Table 9-1 – Summary of Purpose of each Area IV Well under DOE Responsibility

Well	Design	Current Purpose	Data Trends	WQSAP Recommendations
DS-43	Open corehole 28-84 ft, cased 0-28 ft.	Monitors near surface bedrock groundwater, adjacent to PZ-109	In 3 sampling events PCE has been <1 ppb; TCE non-detect	Continue to monitor to confirm minimal bedrock impact at location
DD-142	Open corehole 34-91 ft, cased 0-34	Replacement well for RD-28, monitors bedrock groundwater at former Building 4059 location	In 3 sampling events, PCE has been <1 ppb to 12 ppb; TCE <1 and non-detect. RD-28 non-detect in 28 events, 1989-2004	Continue to monitor minimal bedrock groundwater impact
RD-24	Open corehole 30-150 ft, cased 0-30	Monitors east lateral area from former Building 4059; also downgradient edge of HMSA plume	In 45 sampling events from 1989, TCE reported once at 0.45 ppb and PCE 22 times at a maximum 2.0 ppb (1998); last detection in 2007. Metals below screening levels.	Continue to monitor as a plume edge defining well.
RD-96	Open corehole 20-90 ft, cased 0-20 ft	Downgradient of DD-142, plume edge defining well	Sampled 9 times since 2006, PCE and TCE non-detect. Se slightly above screening levels. Low TPH.	Continue to monitor as a plume edge defining well.
RD-97	Open corehole 20-74.5 ft, cased 0-20 ft.	Downgradient of PCE plume in NBZ. May also monitor tritium plume	PCE and TCE non-detect in 4 sample events.	Continue to monitor as plume edge defining well.
Hazardous Material Storage Area TCE Plume				
TCE in near-surface groundwater above competent bedrock, and in bedrock groundwater 150 to 200 ppb.				
PZ-041	Conv. screen 19-20 ft, 0-29.6 ft deep.	Located at the PDU, well may monitor eastern edge of HMSA plume	TCE at 2 ppb in 2003; non-detect in 2014, 2015, 2016, 2017. Cd slightly above screening level	Retain to confirm minimal TCE plume migration; Boeing PDU responsible well.
PZ-108	Conv. screen 26-30 ft., 30 ft deep	In central portion of TCE near-surface plume	TCE 160 ppb in 2002, 160 ppb in 2017 and 2018. Cd and V slightly above screening levels	Key well for perched zone remediation, keep monitoring.
PZ-120	Conv. screen 15-25 ft, 25 ft deep	In central portion of TCE perched plume	TCE 90 ppb in 2014, 13 ppb in 2017. V slightly above screening level.	Key well for perched zone remediation, keep monitoring.

Table 9-1 – Summary of Purpose of each Area IV Well under DOE Responsibility

Well	Design	Current Purpose	Data Trends	WQSAP Recommendations
PZ-121	Conv. screen 15-25 ft, 25 ft deep.	North lateral portion of TCE perched plume	Only sampled once; TCE ND in 2003; dry/insufficient water 2014-2017.	A deeper, near-surface well has been installed in vicinity, abandon PZ-121.
PZ-122	Conv. screen 15.5-25.5, 27.5 ft deep	South lateral portion of TCE perched plume, also near PDU leach field	TCE 1.6 in 2017; no discernable metals impacts. Low TPH.	Key well for near-surface remediation monitoring; keep monitoring
PZ-162	Conv. screen	New well northeast of plume center	TCE 11 ppb in 2018	Potential near surface remedy monitoring well; keep monitoring
PZ-163	Conv. screen	New well in center of HMSA	TCE 190 in 2018	Key well for near-surface remediation; keep monitoring
RD-24	Open corehole 30-150 ft, cased 0-30	Monitors east lateral area from former Building 4059; also downgradient edge of HMSA plume	In 45 sampling events from 1989, TCE reported once at 0.45 ppb and PCE 22 times at a maximum 2.0 ppb (1998); last detection in 2007. Metals below screening levels.	Continue to monitor as a plume edge defining well.
RD-29	Open corehole 30-100 ft., cased 0-30 ft.	Located near PDU leach field (Boeing); may monitor southern boundary of HMSA plume	TCE typically between 1 and 3 ppb since 1989, increasing trend since 2010 with 4.4 ppb in 2017; one report of copper above screening level	Monitor as a remedy demonstration well for bedrock.
DD-144	Open corehole 38-71 ft., cased 0-38 ft.	Serves as a near-surface bedrock monitoring point beneath central plume area	Installed in 2016, sampled 3 times. TCE 98-190 ppb.	Key near-surface bedrock monitoring well, keep monitoring.
DD-146	Open corehole 120-140 ft, cased 0-120	Deeper well collocated with DD-144	Installed in 2018	Keep monitoring for vertical definition
DD-147	Open corehole 30-257 ft, cased 0-30 ft.	Replaces RD-89 which was too shallow for monitoring	Installed in 2018	Use for monitoring lateral bedrock groundwater

Tritium Plume

Area of groundwater in north central Area IV impacted by tritium; declining concentrations consistent with tritium half-life

Table 9-1 – Summary of Purpose of each Area IV Well under DOE Responsibility

Well	Design	Current Purpose	Data Trends	WQSAP Recommendations
RD-87	Open corehole 20-60 ft., cased 0-20 ft.	Immediately downgradient of RD-90	Well exhibited 14,800 pCi/L in 2005, 3,240 pCi/L in 2017	Retain as MNA demonstration well.
RD-88	Open corehole 20-30 ft., cased 0-20 ft.	Immediate downgradient source area well RD-95	When it contains water, well exhibited 86,800 pCi/L in 2005, 44,800 pCi/L in 2010, and 1,050 pCi/L in 2017	Well is too shallow to monitor core of Tritium plume; as part of MNA demonstration, recommend abandonment of RD-88 and replacement with deeper well.
RD-89	Open corehole 30-50 ft., cased 0-30 ft.	Located at Building 4028 lateral to tritium plume	Well too shallow, typically dry.	Well replaced by DD-147 in 2018
RD-90	Open corehole 20-125 ft., cased 0-20 ft.	Located downgradient of source location	Well exhibited 83,000 pCi/L in 2005, 38,300 pCi/L in 2017, 33,000 pCi/L in 2018	Retain as a MNA demonstration well
RD-93	Open corehole 20-60 ft., cased 0-20 ft.	Located as an upgradient source area well	Well exhibited 28,400 pCi/L in 2005, 5,460 pCi/L in 2017	Retain as a MNA demonstration well
RD-94	Open corehole 20.5-35 ft., cased 0-20.5 ft.	Downgradient well in pathway to SP-T02C seep cluster	Well exhibited 12,300 pCi/L in 2005, 1,740 pCi/L in 2017	Continue monitoring
RD-95	Open corehole 50-80 ft., cased 0-50 ft.	Tritium source area well	Well exhibited 119,000 pCi/L in 2005, 19,600 pCi/L in 2017, 31,500 pCi/L in 2018	Retain as MNA demonstration well
RD-97	Open corehole 20-74.5 ft., cased 0-20 ft.	Downgradient lateral well west side of plume	Outside of tritium plume	Use for water level measurements
RD-34A	Open corehole 16-60 ft., cased 0-16 ft.,	Downgradient of RMHF; possible pathway from tritium source	Well exhibited 1,050 pCi/L in 2005, 391 pCi/L in 2016	Continue monitoring for both tritium and RMHF issues
RD-34B	Open corehole 360-415 ft., cased 0-360	Downgradient of RMHF	Results have always reflected a background value for tritium	Consider abandonment as the well no longer serves a purpose. See also RMHF description
Radioactive Materials Handling Facility				
Source of TCE assumed to be former RMHF leach field, declining TCE concentrations to MCL; leach field site contaminated by Sr-90, presence of Sr-90 in groundwater controlled by groundwater elevation				

Table 9-1 – Summary of Purpose of each Area IV Well under DOE Responsibility

Well	Design	Current Purpose	Data Trends	WQSAP Recommendations
PZ-116	Conv. screen 22-32 ft., 35 ft. deep	Down drainage from RMHF, collocated with RD-34-A,B,C. Serves as shallow above bedrock monitoring point.	Only sampled for VOCs in 2005 and 2017. All VOCs non-detect both events	Well provides indication that VOCs are in the bedrock groundwater only. Continue to monitor to confirm.
RS-28	Conv. screen 14-19, 19 ft deep	Collocated with RD-30, serves as a near surface bedrock monitoring point down drainage from RMHF leach field.	Exhibited 11 to 16 ppb TCE 2005 to 2014, non-detect in 2017. Se slightly above screening level. High TPH	Well provides indication that shallow bedrock is contaminated. Continue to monitor.
RD-19	Open corehole 30-135 ft., cased 0-30 ft.	Installed near top of fill material upgradient of RMHF	Non-detect for VOCs; no metals impact	Use for water level measurements; sample per 5-year review
RD-27	Open corehole 30-150 ft., cased 0-30 ft	Located within fenced area of RMHF, northeast corner, upgradient to expected groundwater flow beneath the RMHF	VOCs non-detect in 52 sampling events; metals below screening levels; radionuclides?	Monitoring of this well should be in accordance with the RCRA closure permit. No need for additional sampling until RCRA closure is established.
RD-30	Open corehole 30-75 ft., cased 0-30 ft,	Down drainage from RMHF leach field, serves as upper bedrock monitoring point	TCE 8.4 ppb (2014) to 3.2 ppb (2017); Sr-90 non-detect in 2017; no metals impact.	Well is a midpoint between leach field (RD-98) and RD-34 cluster. Key monitoring well for continued TCE MNA demonstration.
RD-34A	Open corehole 16-60 ft., cased 0-16 ft.	In NBZ down drainage from RMHF leach field	TCE 0.98 ppb (2014) to 2.3 ppb (2017), last measurement above MCL 5.3 ppb in 2008; Sr-90 non-detect in 2017; low TPH; Se and TI slightly above screening levels.	Furthest down gradient monitoring point. Provides downgradient monitoring point.
RD-34B	Open corehole 360-415 ft., cased 0-360 ft.	In NBZ down drainage from RMHF leach field collocated with RD-34A	TCE 1.5 ppb (2010) to non-detect (2015, 2016, 2017); no metals impact	Has obstruction at 167 ft due to casing collapse. Abandon well.
RD-34C	Open corehole 480-520 ft., cased 0-480	Collocated with RD-34A	TCE non-detect; no metals impact.	Abandon well.

Table 9-1 – Summary of Purpose of each Area IV Well under DOE Responsibility

Well	Design	Current Purpose	Data Trends	WQSAP Recommendations
RD-63	Open corehole 20-230 ft., cased 0-20 ft.	In drainage between RD-30 and RD-34A down gradient of RMHF leach field. Used as pumping well 1994-2005.	TCE was 3.3 ppb to 20 ppb during pumping era. TCE 4.9 to 11 ppb in years 2006 to 2010; 4.3 to 6.4 in years 2011 to 2017. No metals impact.	Continue monitoring for TCE MNA demonstration.
RD-98	Open corehole 20-65 ft., cased 0-20 ft.	Drilled through former RMHF leach field site.	TCE was 8.8 ppb to 10 ppb 2008 and 2009, 2.1 ppb to 5.6 ppb 2014-2017. Impacted by Sr-90. No metals impact.	Continue monitoring for VOCs and Sr-90.
DD-143	Open corehole 19.7-100 ft, cased 0-19.7 ft	Lateral gradient from RMHF leach field monitoring well installed in 2016	Non-detect for COCs and Sr-90	Continue monitoring for VOCs and Sr-90
Building 4133 Hazardous Waste Management Facility				
B4133 is part of the HWMF RCRA Closure action. Future groundwater monitoring will be determined through the RCRA process				
RS-25	Conv., screen 8.5-13.5 ft.	Drilled into the fill excavated for the basement of SRE reactor building. Well is typically dry	In the few sampling events, no contaminants detected	Address monitoring needs for B4133 during the RCRA closure process.
Old Conservation Yard				
One well monitors this location, no significant contamination identified in groundwater				
RD-14	Open corehole 30-125 ft., cased 0-30 ft.	Located in the center of the OCY footprint, the only monitoring well in the footprint. PZ-151 is on a slope above the OCY and it monitors NASA contamination from Area II; WS-07 was not designed as a monitoring well, but is monitored by NASA	TCE last above MCL at 5.9 ppb in 2011; at trace concentrations since. Metal Se above screening level. Low TPH.	Continued monitoring for MNA demonstration
PZ-151		PZ-151 is on a slope above the OCY and		NASA monitoring well

Table 9-1 – Summary of Purpose of each Area IV Well under DOE Responsibility

Well	Design	Current Purpose	Data Trends	WQSAP Recommendations
		it monitors NASA contamination from Area II		
WS-07		WS-07 was not designed as a monitoring well, but is monitored by NASA		NASA monitoring well
DOE Leach Field No. 1 Building 4030/4093				
No groundwater impact issues identified for this area.				
DS-44	Open corehole 19-91 ft., cased 0-19 ft.	Installed in 2016 adjacent to B4030 leach field site	All VOCs non-detect in 3 sampling events; all metals below screening level	Sample for 5 years, then reconsider well's purpose.
RD-17	Open corehole 30-125 ft, cased 0-30 ft.	Installed adjacent to B4093 leach field; may also monitor eastern edge of HMSA TCE plume	Sampled 23 times since 1989; maximum TCE in 2011 of 1.9 ppb, 0.71 in 2017; metals below screening levels in two events	Sample as part of 5-year review
Building 4064 Leach Field				
No groundwater impact issues identified for this area.				
DS-45	Open corehole 18-75 ft., cased 0-18	Installed in 2016 adjacent to B4064 leach field site	Installed dry	If the well never produces water for 5 years, consider abandonment
DS-47	Open corehole 19-145 ft., cased 0-19	Installed in 2016 adjacent to B4064 leach field site	All VOCs non-detect in 3 sampling events; all metals below screening levels	Sample for 5 years, then reconsider well's purpose.
Building 4065 Metals Clarifier/DOE Leach Fields 3				
TCE concentrations have been demonstrated to be declining; near the MCL.				
PZ-005	Conv. screen 25-45 ft., 45 ft. deep	Closest perched well to Building 4065	TCE 7 ppb in 2001, 8 ppb in 2002, 3.4 in 2013, 1.5 in 2017; metals Al, Cd, Cu, Ag, V above screening levels.	Continue monitoring for MNA demonstration
PZ-104	Conv. screen 18-28 ft., 28.5? ft. deep	In vicinity of B4383 leach field; presumed downgradient of	TCE 8 ppb in 2002, 9 ppb in 2003, 6.4 ppb in 2013, 3.4 ppb in 2014, 1.8 ppb in 2017; metals reports show	Continue monitoring for MNA demonstration

Table 9-1 – Summary of Purpose of each Area IV Well under DOE Responsibility

Well	Design	Current Purpose	Data Trends	WQSAP Recommendations
		B4065; collocated with DD-145	inconsistent Al, Co, K, Ag above screening levels	
PZ-105	Conv. screen 17-27 ft., 27 ft. deep	Situated between B4353, B4363, and B4383 leach fields	TCE typically between 5.8 and 12 ppb 2002-2009, TCE 9.3 in 2013, 8.7 ppb in 2014, 5.9 ppb in 2015, 7.9 ppb in 2017; metals Cd, Cu, Se inconsistent detections, Mo and V above screening levels; elevated TPH.	Continue monitoring for MNA demonstration
DD-145	Open corehole 27-82 ft., cased 0-27 ft.	Collocated with PZ-104, installed in 2016	Sampled 3 times, TCE 0.31 ppb, 0.35 ppb, 0.92 ppb; TPH; metals Al above screening level	Continue monitoring for MNA demonstration
Offsite Wells				
RD-59A	Open corehole 21-58 ft bgs, cased 0-21 ft	Offsite on Brandeis property northwest of Area IV	No impact	Well used to demonstrate no groundwater impact from Area IV
RD-59B	Open corehole 178-214 ft bgs, cased 0-178 ft	Offsite on Brandeis property northwest of Area IV	No impact	The need for a well this deep off site has not been justified
RD-59C	Open corehole 345-397 ft bgs, cased 0-345 ft	Offsite on Brandeis property northwest of Area IV	No impact	The need for a well this deep off site has not been justified

Table 9-2 WQSAP Analytical Revision Recommendations

Well	Recommendation	Water Level Measurement	Analytes	Frequency
FSDF Wells				
PZ-97	None, abandon well			
PZ-98	FSDF remedy demonstration well	Yes	VOCs, metals	Annual
PZ-100	Well too shallow, abandon well	--		
PZ-101	Well too shallow, abandon well	--		

Table 9-2 WQSAP Analytical Revision Recommendations

Well	Recommendation	Water Level Measurement	Analytes	Frequency
RS-18	FSDF remedy demonstration	Yes	VOCs, metals	Annual
RS-54	FSDF remedy well	Yes	VOCs, metals, TPH, perchlorate	Annual
C-08	Abandon	--		
RD-21	Upgradient of FSDF	Yes	VOCs, metals	Annual
RD-22	Grout corehole up to depth of FSDF fractures with TCE, continue monitoring for remedy demonstration	Yes	VOCs, metals	Annual
RD-23	Grout corehole up to depth of FSDF fractures with TCE, continue monitoring for remedy demonstration	Yes	VOCs, metals	Annual
RD-33A	Grout corehole up to depth of FSDF fractures with TCE, continue monitoring for remedy demonstration	Yes	VOCs, metals	Annual
RD-33B	Abandon well	--		
RD-33C	Abandon well	--		
RD-54A	Grout corehole up to depth of FSDF fractures with TCE, continue monitoring for remedy demonstration	Yes	VOCs, metals, TPH	Annual
RD-54B	Abandon well	--		
RD-54C	Abandon well	--		
RD-57	Abandon Well	--		
DD-139	Plume definition well	Yes	VOCs, metals	Annual
DS-46	Remedy demonstration well	Yes	VOCs, metals	Annual
DD-140	Remedy demonstration well	Yes	VOCs, metals	Annual
RD-64	Grout corehole up to depth of FSDF fractures with TCE, continue monitoring for remedy demonstration	Yes	VOCs, metals	Annual
RD-65	Grout corehole up to depth of FSDF fractures	Yes	VOCs, metals	Annual

Table 9-2 WQSAP Analytical Revision Recommendations

Well	Recommendation	Water Level Measurement	Analytes	Frequency
	with TCE, continue monitoring for remedy demonstration			
B56 Landfill Wells				
PZ-124	Abandon; replaced by DD-141	--		
RS-16	Abandon	--		
RD-07	Monitors plume assumed to originate at B4100	Yes	VOCs, metals	Annual
RD-74	Abandon	--		
DD-141	Monitors toe of B56 landfill	Yes	VOCs, metals, TPH	Annual
B100 Trench Well				
RD-20	Central Area IV water level elevation data	Yes	Water levels only, VOCs, metals for 5-year sampling	Annual for water level; 5-year review sampling
Buildings 4057/4059/4626 PCE Plume				
PZ-109	Remedy demonstration well	Yes	VOCs, metals	Annual
DS-43	Remedy demonstration well	Yes	VOCs, metals	Annual
DD-142	Remedy demonstration well	Yes	VOCs, metals	Annual
RD-24	Monitors edge of plume	Yes	VOCs	5-year review
RD-94	Perimeter well	Yes	VOCs, metals	5- year review
RD-96	Perimeter well	Yes	VOCs, metals, TPH	5-year review
RD-97	Perimeter well	Yes	VOCs, metals	5-year review
Hazardous Materials Storage Area				
PZ-41	Perimeter well	Yes	VOCs, metals	5-year review
PZ-108	Remedy well	Yes	VOCs, metals	Annual
PZ-120	Remedy well	Yes	VOCs, metals	Annual
PZ-121	Perimeter well	Yes	VOCs, metals	5-year review
PZ-122	Perimeter well	Yes	VOCs, metals, TPH	5-year review
PZ-163	Remedy Well	Yes	VOCs, metals	Annual
PZ-164	Perimeter well	Yes	VOCs, metals	Annual
RD-24	Perimeter well	Yes	VOCs, metals	5-year review
RD-29	Perimeter well	Yes	VOCs, metals	5-year review
DD-144	Remedy well	Yes	VOCs, metals	Annual
DD-146	Remedy well	Yes	VOCs, metals	Annual
DD-147	Perimeter well	Yes	VOCs, metals	Annual

Table 9-2 WQSAP Analytical Revision Recommendations

Well	Recommendation	Water Level Measurement	Analytes	Frequency
Tritium Plume				
RD-87	Remedy demonstration well	Yes	Tritium	5-year review
RD-88	Remedy demonstration well	Yes	Tritium	Annual
RD-90	Remedy demonstration well	Yes	Tritium	Annual
RD-93	Remedy demonstration well	Yes	Tritium	5-year review
RD-94	Remedy demonstration well	Yes	Tritium	5-year review
RD-95	Remedy demonstration well	Yes	Tritium	Annual
RD-97	Perimeter well	Yes	Tritium`	5-year review
Radioactive Materials Handling Facility				
PZ-116	Confirmation well	Yes	VOCs, metals, Sr-90, TPH	Sample when it contains water
RS-28	Remedy demonstration well	Yes	VOCs, metals, Sr-90, TPH	Sample when it contains water
RD-19	Perimeter well	Yes	VOCs, metals	5-year review
RD-27	RCRA facility well	Yes	VOCs, metals, radionuclides	Sample per RCRA closure requirements
RD-30	Remedy demonstration well	Yes	VOCs, metals, Sr-90	Annual
RD-34A	Sentinel well	Yes	VOCs, Metals, Sr-90, TPH	Annual
RD-34B	Abandon	--		
RD-34C	Abandon	--		
RD-63	Remedy demonstration well	Yes	VOCs, metals, Sr-90	Annual
RD-98	Remedy demonstration well	Yes	VOCs, metals, Sr-90	Annual
DD-143	Perimeter well	Yes	VOCs, metals, Sr-90	Annual
Old Conservation Yard				
RD-14	Eastern Area IV water levels	Yes	VOCs, metals, TPH	5-year review
DOE Leach Field No. 1 – Buildings 4030/4093				
DS-44	Sample; verify no groundwater impact	Yes	VOCs, metals	Annual
RD-17	Sample; verify no groundwater impact	Yes	VOCs, metals	5-year review

Table 9-2 WQSAP Analytical Revision Recommendations

Well	Recommendation	Water Level Measurement	Analytes	Frequency
Building 4064 Leach Field				
DS-45	Sample; verify no groundwater impact	Yes	VOCs, metals	Sample if contains water
DS-47	Sample; verify no groundwater impact	Yes	VOCs, metals	Annual
Building 4065 Metals Clarifier/DOE Leach Fields 3				
PZ-005	Remedy demonstration well	Yes	VOCs, metals	Annual
PZ-104	Remedy demonstration well	Yes	VOCs, metals	Annual
PZ-105	Remedy demonstration well	Yes	VOCs, metals, TPH	Annual
DD-145	Remedy demonstration well	Yes	VOCs, metals, TPH	Annual
Off-site Wells				
RD-59A	Perimeter well	Yes	VOCs, metals, rads	Annual
RD-59B	Perimeter well	Yes	VOCs, metals, rads	5-year review
RD-59C	Perimeter well	Yes	VOCs, metals, rads	5-year review

9.2 Evaluation of the Adequacy of the Existing Monitoring Well Network

The existing monitoring well network was evaluated to determine its adequacy in three dimensions to provide groundwater quality data for the assessment of groundwater impact, migration, and for the evaluation of remedy effectiveness.

The evaluation was conducted at each known groundwater contaminant plume or locations where organic contamination was indicated in the past. The monitoring points (wells, piezometers and seeps) were compared to the conceptual site model (CSM) (as presented in the RI) to see if they were screened (or open to) the groundwater at locations and depths, within the current plume, at the downgradient edges and along the downgradient flow path. In addition, the migration pathways from the current source of the plumes were determined through particle track simulations modeled by the site-wide contaminant transport model that was developed as part of the RI. The pathways, “particle tracks” were examined to see if monitoring wells were present at the correct locations and depths to monitor contaminant migration as predicted by the model.

Appendix C and Chapter 6 of the Groundwater RI report provide the results of the numerical groundwater flow model and contaminant transport model. The modeling performed in the RI provided modeled contaminant transport results including timing and depth of the contaminants in the bedrock fractures as they flow through the fracture system. The model produces “particle tracks” that provide the path of the particles “placed” in to the fractures at a particular point

(monitoring well) in 2 dimensions. However, the source of most of the contaminant plumes is not a single identified point, but instead is a known larger area (e.g., the Former Ponds at the FSDF), generalized areas where releases from multiple sources are indicated (e.g. the PCE plume), or are unknown (e.g. the tritium plume). Therefore, professional judgement was used when comparing the locations of current wells, to particle tracks; the tracks were considered to be general indicators that were likely broader than depicted by a modeled line. This is also appropriate as the particle traces do not account for the contaminant diffusion or dispersion that is occurring in the unconsolidated, weathered, or bedrock matrix. The modeling results discussed below are shown in figures in Section 6 of the Groundwater RI report and those figures are referenced in the text.

Table 9-3 presents the results of the well adequacy evaluation by groundwater investigation area. As noted on the table and in the text below, the review of soil with elevated metals concentrations (i.e., hot spots) resulted in the identification of two areas where groundwater may not be adequately monitored for the presence of metals.

Adequacy Review Results and Recommendations

The groundwater monitoring well network is evaluated for each groundwater investigation area where contamination has been identified in groundwater.

FSDF

Conceptual Site Model

The information and data collected during the many investigations of the hydrogeologic conditions across the FSDF have been used to develop the CSM for the occurrence and migration of VOCs within both the Near-surface and Chatsworth Formation groundwater. The local VOC-impacted groundwater within the FSDF plume most likely originated from discharges to the ground surface (e.g., drum storage) and from the former FSDF treatment ponds. Of note, removal actions have eliminated contaminated soil and sediment to bedrock that comprised the original source of VOC to groundwater. Following historic removals, the area was backfilled with clean local fill soil. The current source of contaminants to groundwater are residual VOCs entrained in the weathered and unweathered bedrock occurring as either water in open fractures or along bedding planes, or as porewater in the bedrock sandstone matrix. VOCs in open and interconnected fractures/bedding planes correspond to solute transport while VOC transfer from impacted porewater to water/groundwater corresponds to diffusion. Both processes are believed to be currently active at the FSDF.

The historical studies performed at the FSDF show that the vertical migration of water from the Near-surface system to the bedrock system is hindered by the low bulk hydraulic conductivity of the Chatsworth Formation as well as a general lack of a bedrock fractures and/or tight or less transmissive fractures within the FSDF, which is different within Area IV compared to Areas I, II, III of SSFL. Local alluvial soil (fill) and/or weathered Chatsworth Formation act as a water storage reservoir following precipitation events. The lateral extent of the VOC-impacted groundwater entrained in the alluvial soil changes as water levels rise (the plume expands outward) and fall (the plume contracts) in this zone. The plume's horizontal extent is controlled by presence of alluvium (thin and occurs as fingers between bedrock outcrops), the contact with low K_b bedrock

members, and groundwater elevation. During wet periods, when water is found in the Near-surface monitoring wells, the groundwater elevations are higher to the southeast and lower to the northwest. The wells that monitor the Near-surface groundwater include PZ-98, PZ-100, PZ-101, RS-18. Although it is not a DOE well, RS-23 monitors the Near-surface groundwater upgradient of the former pond area. RS-18 and DS-46, located down gradient from the source area, was below the MCL for TCE in 2016 and 2017. In June 2018, eight coreholes were drilled to a depth of about 60 feet bgs to assess Near-surface groundwater at the FSDF. No further wells are needed to monitor the Near-surface groundwater.

The Near-surface groundwater is separated from the Chatsworth Formation groundwater by a vadose (unsaturated) zone. Contaminated groundwater migrates vertically and horizontally from the Near-surface system to the bedrock system, through fractures and bedding planes. Migration through the bedrock matrix is constricted by the low bulk conductivity of the bedrock matrix. Because the fractures and bedding planes are not continuous, and the hydraulic conductivity is very low, extent of groundwater movement and therefore contaminant plumes movement is limited. The other limiting factor is the small amount of precipitation and associated infiltration that moves into the fractures/bedding planes to facilitates the transport VOCs away from their sources.

Bedrock well RD-21 monitors upper bedrock groundwater upgradient of the Former Ponds. RD-23 is located about 40 feet from the former pond near surface fractures that may direct groundwater flow; TCE has been detected in the well. Wells RD-64 and RD-65 are screened in fractures connected to the source area; TCE has also been detected both wells. Further along strike, and downgradient along a surface drainage, DD-140 (installed in 2016) monitors groundwater in the upper 100 feet of competent bedrock. No TCE was detected in DD-140 in 2016 or 2017. DD-139 is located downgradient of RD-65 (where TCE has been found) and DD-140, and acts as a sentinel well for the FSDF plume. TCE has not been detected in DD-139.

Wells RD-33A, RD-33B, and RD-33C are a cluster of bedrock wells located downdip and downslope from the source area. They provide vertical and horizontal control on the extent of contamination. TCE has been detected consistently only in the shallowest well (RD-33A), and only once 0.76 µg/L in 1991) in RD-33B. RD-33B has been recommended for abandonment.

Numerical Flow Model Results

In the contaminant transport numerical modeling work done for the RI monitoring well RD-23 was used as the modeling points to assess movement of VOCs in the FSDF area. Subsequent to the RI, additional particle track simulation was also performed for RD-54A. The particle track possibilities for contamination associated with both RD-23 and RD-54, assuming there is no restriction on time, is an initial northwesterly flow prior to a sharply-defined southwesterly flow (see Groundwater RI report **Figure 6-1**). The contaminant transport modeling indicates that transport in the northwesterly direction is slow; particles moving from RD-23 do not reach the southwesterly flow path until somewhere between 50 and 100 years. The modeling results are consistent with groundwater sampling results for this location that show minimal movement of VOCs from its source since the release. There are no wells located in the modeled flow path between the former ponds and the point where the flow path turns to the southwest; this represents a gap in the monitoring well network. RD-22 is along the southwesterly segment of

the flow path. No TCE has been detected in this well; the absence of TCE in this well is also consistent with the modeling results as TCE would not be expected to have reached this segment of the flow path.

Conclusion

The monitoring well network is sufficient to monitor the contaminant plume in the Near-surface groundwater and downgradient of the ponds in the direction of groundwater flow predicted by the potentiometric surface of the Chatsworth Formation groundwater. However, there are no wells located in the modeled flow path between the former ponds and the point where the flow path turns to the southwest; this represents a gap in the monitoring well network.

Building 4100/B56 Landfill

Conceptual Site Model

TCE has been consistently detected in well RD-07, starting with 16 µg/L in January 1986, a maximum concentration of 130 µg/L in December 1987, and most recently in 2018 at 29 µg/L. No source for TCE has been identified at the Building 56 Landfill, including the Building 56 excavation and the Southern Debris Area. Perched Near-surface groundwater has been observed in RS-16, located about 60 feet west of the Building 56 Excavation and adjacent to bedrock well RD-07. The near-surface groundwater is hydraulically connected to the water in the excavation. Near-surface groundwater has been sporadically found in PZ-124 downgradient of the toe (downgradient) edge of the landfill in the Northern Buffer Zone (NBZ). Shallow Chatsworth formation well, RD-74, is frequently dry.

Within RD-07, the TCE is associated with bedding features and fractures deeper in the well indicating that the contaminant source is likely upgradient and along geologic strike from well RD-07. Based on the 2013 groundwater elevation data, groundwater flows from well RD-91 (1,740 feet MSL) located at Building 4100, toward RD-07 (1,728 feet MSL). Well RD-91 exhibited TCE at 200 µg/L in 2014 and is located approximately 450 feet to the southwest of well RD-07. Flow along bedding plane fractures from RD-91 to RD-07 may have been accelerated when wells RD-25 and RD-28 (now both abandoned) were pumped between 1996 and 2004, which temporarily lowered the water level in RD-07. TCE at concentrations above the MCL have not been detected in wells (RD-24, DD-142, and RD-96) in the area of former wells RD-25 and RD-28. The numerical flow model does not support flow from RD-91 toward RD-07 under unstressed (non-pumping) conditions. The TCE at RD-07, therefore, is presumed to be present only from being drawn from the Building 4100 area during the 8-year period when RD-28 and RD-25 were pumped. Packer testing indicates that the fractures containing TCE are at a depth of approximately 120 feet. Because there is no longer induced groundwater flow from the suspected primary source area, the current (secondary) source of TCE in the Chatsworth Formation groundwater in this investigation area is the groundwater in bedding plane fractures (intersected by RD-07) at depths of about 120 feet (in the Upper Burro Flats member below the Lot Bed).

Monitor well DD-141, downgradient of RD-07, is adjacent to PZ-124 at the toe of the landfill and is open in the Upper Burro Flats member below the Lot Bed. No Contaminants have been detected in DD-141; it serves as a sentinel well downgradient of the plume.

Numerical Flow Model

Monitoring well RD-07 was used as the modeling point to assess movement of TCE in the Building 56 Landfill area. Contaminant transport modeling indicates a westerly flow path from RD-07 with a turn to the northwest at about 100 feet west of RD-07 (see Groundwater RI report **Figure 6-6**). The model indicates a low simulated flow rate and bulk conductivity of the bedrock that controls contaminant transport, so that the contaminant remains within about 100 meters (330 feet) of the RD-07 after 100 years. The modeling results are consistent with groundwater sampling results for this location showing little movement of TCE from the Building 56 Landfill. As the current source is likely a linear feature (bedding plane) DD-141 is along the modeled flow path.

Conclusion

The current monitoring well network consisting of RD-07 in the source area and RD-141, downgradient of the source area are sufficient to monitor the leading edge of this TCE plume given the very slow rate of migration through the tight bedrock.

Building 100 Trench**Conceptual Site Model**

The Building 4100 trenches, located east of Building 4100, were the presumed source of contamination. All potential sources have been removed. RD-20, located adjacent to the trenches has been sampled 28 times since installation in 1989. TCE has only be detected one time at a concentration of 0.21 µg/L in 1990 and selenium was detected slightly above screening levels.

Numerical Flow Model

No numerical modeling was done for this location due to the infrequent and low levels of TCE detections.

Conclusion

RD-20 is sufficient to monitor the Building 100 trenches.

Buildings 4057/4059/4626 PCE Plume**Conceptual Site Model**

There are multiple sources of the PCE contamination in the Building 4057/4059/4626 area. PCE in the soil is carried by infiltrating precipitation to the Near-surface groundwater. Under a downward vertical hydraulic gradient, PCE-impacted groundwater moves within the fractures of the Chatsworth Formation.

Near-surface groundwater is present in the upper weathered Chatsworth Formation at the Building 4057/4059/4626 PCE Plume. Monitoring well PZ-109, installed into the weathered Chatsworth Formation bedrock in the presumed source area, monitors the Near-surface groundwater at this location. The Near-surface groundwater monitored at PZ-109 appears to be continuous with the groundwater “mound” observed in central Area IV to the immediate east-northeast. Near-surface groundwater is absent at well RS-16 so PZ-109 is likely the western edge of the localized groundwater mound and represents the extent of TCE-contaminated

groundwater in the Near-surface groundwater. Near-surface groundwater at PZ-109 has been reported to be continuous with the Chatsworth Formation groundwater (CH2M Hill 2008).

There is a downward vertical hydraulic gradient from the Near-surface groundwater at PZ-109 to the underlying Chatsworth Formation groundwater. Under static (non-pumping) conditions, groundwater flow in the Chatsworth Formation is toward the west-northwest. However, from about 1986 to 2004 pumping from the French drain sump and wells RD-24, RD-25, and RD-28 were used to lower the water table around Building 4059 and probably caused a localized cone of depression in the potentiometric surface around the building. In 2001, PCE was detected in each of these wells (although at concentrations below MCLs in RD-28 and RD-24). Monitoring well DS-43 is located in the shallow Chatsworth Formation near the historical highest concentrations of PCE in the Near-surface groundwater (PZ-109). Concentrations of PCE in 2016 were below the MCL. RD-24 located downgradient (north) of the source area, monitors the northern edge of the plume which had low concentrations of PCE in 2001. DD-142 monitors the center of the PCE plume (12 µg/L in 2016) in the upper Chatsworth Formation groundwater; the well is open from 34 to 91 feet bgs. Two monitoring wells, RD-96 (open from 20 to 90 feet bgs) and RD-97 (open from 20 to 74.5 feet bgs) act as sentinel wells to monitor Chatsworth Formation groundwater beyond the downgradient edge of the of the PCE plume.

Numerical Flow Model

Piezometer PZ-109 was used as the modeling point to assess movement of TCE from the Building 4057 area. The particle track simulation predicts that groundwater in Chatsworth Formation groundwater at PZ-109 would move to the northeast (see Groundwater RI report **Figure 6-11**). This figure shows a northeast pathway for groundwater flow. From 1996 through 2005 PCE (2.9 µg/L maximum concentration) was detected in well RD-24 (open from 30 to 150 feet bgs), located in the modeled pathway. This indicates movement of PCE from the source area towards RD-24. PCE has been non-detect in the well since 2008.

Conclusion

The existing monitoring well network provides sufficient coverage to monitor the Buildings 4057/4059/4626 PCE plume in the suspected source area, including the center, beyond the downgradient edges of the plume and along the modeled flow path.

Hazardous Material Storage Area

Conceptual Site Model

The source area for the TCE appears to be in the vicinity of PZ-108 and PZ-120, where the highest concentrations of TCE have historically been observed (Buildings 4006, 4355, 4426, 4026, and 4359); the exact location of the release(s) is not known. Releases to soil would be carried by infiltrating precipitation to the Near-surface groundwater. TCE present in soil from leaks or spills at these source areas would be carried downward by precipitation infiltrating the surface soil and migrating to the perched Near-surface groundwater. Once in the groundwater, dissolved TCE will migrate with groundwater flow. There is not a clear direction of groundwater flow in the Near-surface groundwater; however, between April 2004 and February 2014 groundwater levels typically were higher in PZ-108 than in PZ-120 indicating that groundwater flow within the relatively porous media of the perched water table was from northeast to southwest.

Concentrations of TCE increased in PZ-120 over that period (from 7 µg/L in April 2004 to 90 µg/L

in February 2014). This distribution of the contamination indicates a source area northeast of PZ-120.

Near-surface groundwater in the HMSA is discontinuous and perched above the Chatsworth Formation groundwater (MWH 2008b) in the weathered Chatsworth formation. The ELV fine-grained member may be providing a barrier to the downward infiltration of precipitation, causing the water to perch, particularly in the eastern portions of the HMSA. The center of the Near-surface groundwater TCE plume is monitored by PZ-163 (30 to 40 feet bgs), PZ-108 (16 to 26 feet bgs), and PZ-120 (15 to 25 feet bgs). The edges of the plume in the Near-surface groundwater are monitored by PZ-162 (screened from 31 to 41 feet) and PZ-121 (screened from 15 to 25 feet bgs) to the north, by PZ-109 (25 to 35 feet bgs) (7.9 µg/L) to the southwest, PZ-122 (15.5 to 25.5 feet bgs) (1.6 µg/L in 2017) to the south, and PZ-41 (screened from 19 to 29 feet bgs) to the east.

The HMSA is located on a groundwater divide within the Chatsworth Formation, with bedrock groundwater flowing radially outward, predominantly to the south, southwest, and northwest. There is a slight downward gradient from the Near-surface groundwater to the Chatsworth formation groundwater. Monitoring well DD-144 (open from 38 to 71 feet bgs) monitors the shallow consolidated Chatsworth Formation beneath the Near-surface groundwater plume and is contaminated (200 µg/L TCE in 2018). The deeper Chatsworth Formation groundwater (120 to 140 feet bgs) at the same location as DD-144 is monitored by DD-146 and is uncontaminated (non-detect for TCE in 2018). DD-146 acts as a sentinel well for deeper Chatsworth Formation groundwater. Chatsworth Formation groundwater at the edges of the plume are monitored by RD-24 (30 to 150 ft bgs; non-detect in 2017) to the west of the HMSA, DS-43 (28 to 84 feet bgs) to the southwest, RD-29 (30 to 100 feet bgs) and RS-27 (5 to 9 feet bgs) to the south, and RD-93 (20 to 60 feet bgs) to the northwest.

Numerical Flow Model

Well DD-144 was used as the modeling point to assess movement of TCE in groundwater at the HMSA. Groundwater RI report **Figure 6-26** illustrates the particle tracking possibilities for groundwater movement from well DD-144 assuming there is no restriction in time. This figure shows a north-northeast pathway for groundwater flow. Wells RD-89 (30 to 50 feet bgs) and RD-93 (20 to 60 feet bgs) are within the pathway of contaminant movement, however the plume at both locations is predicted by the model to be deeper (164 to 257 feet bgs) than these wells. In 2018, well DD-147 was drilled through the location of well RD-89 to extend the open interval. The new well is open from 50 to 257 feet bgs and monitors the HMSA TCE plume along the modeled flow path. TCE has not been detected in DD-147.

Conclusion

The existing monitoring well network provides sufficient coverage to monitor the Hazardous Materials Storage Area plume, in both the Near-surface groundwater and the Chatsworth Formation groundwater, in the suspected source area, including the center and downgradient edges of the plume and along the modeled flow path.

Tritium Plume

Conceptual Site Model

Tritium in Area IV groundwater was discovered by EPA in 1989 when EPA staff sampled groundwater collected from the Building 4059 French drain. The source of the tritium has not been determined but may have been the neutron captured in lithium in the concrete walls of Buildings 4059 or 4010. The extent of tritium-impacted groundwater was defined in 2004 and 2005 with the installation of wells RD-87, RD-88, RD-90, RD-93, RD-94, and RD-95. Near-surface groundwater is not found extensively in the tritium Plume Groundwater investigation area. The RI determined that the tritium is found in upper Chatsworth formation groundwater and porewater in the rock matrix. The potentiometric surface indicates that groundwater in the Chatsworth Formation flows to the northwest. The plume is located on the western edge of Burro Flats near the NBZ. Vertical groundwater gradients in this area transition from downward on Burro Flats, to upward on the slopes of the NBZ. Tritium has been found at concentrations well below the MCL at RD-34A located in an area of upward gradients in the RMHF area north of the Tritium plume.

Highest tritium activities, the center of the plume, have been found in RD-95 (open from 50 to 80 feet bgs). Well RD-88 also monitors the center of the plume (20 to 30 feet bgs), although it is shallower than the highest concentrations found at RD-90. The plume is monitored on the northeast by RD-87 (30 to 60 feet bgs), on the northeast by RD-89 /DD-147 (50 to 257 feet bgs), on the north by RD-90 (20 to 125 feet bgs) and RD-87 (20 to 60 feet bgs), and to the northwest by RD-94 (20.5 to 35 feet bgs) and the groundwater seep cluster well SP-T02.

Numerical Flow Model

The particle track simulations (see Groundwater RI report **Figure 6-16**) indicate that tritium contaminated groundwater would flow to the northeast and remain in approximately the upper 160 feet of bedrock for the first for about 250 feet from RD-95. RD-90 and RD-87 are along the simulated flow path and are open to the correct depth to monitor this plume. If a broader source area, extending to Building 4010 is considered, RD-93 (20 to 60 feet bgs), DD-147 (50 to 257 feet bgs), and RD-34A (16 to 60 feet bgs) where low levels of tritium have been found) are along the modeled flow path.

Conclusion

The existing monitoring well network provides sufficient coverage to monitor the tritium plume in the suspected source area, including the center and downgradient edges of the plume and along the modeled flow path.

Radioactive Materials Handling Facility

Conceptual Site Model

The source of the Sr-90 and TCE contamination is the RMFH leach field. Contaminated soil from the leach field was removed in 1978. Surface drainage from the leach field area flows westward down a prominent drainage feature. Groundwater within the drainage feature has been found to be contaminated with TCE. The RI demonstrated that the current source of Sr-90 to Chatsworth Formation groundwater is Sr-90 bound to the upper bedrock in the immediate leach field area.

This Sr-90 is released to groundwater when the water table is high enough to intersect this contaminated zone of rock.

Following the discovery of TCE in RD-30 and RD-34A, RD-63 was installed as an extraction well and was intermittently pumped for 10 years; 4.3 million gallons of groundwater were removed. During the pumping years, the maximum TCE concentration reported was 20 µg/L in 1998. Recently TCE concentrations in well RD-63 were reported at 6.1 µg/L (2014), 4.6 µg/L (2015), 4.9 µg/L (2016), and 6.2 µg/L (2017). Pumping of well RD-63 may have had a significant impact on hydraulic gradients and groundwater flow direction near the RMHF Leach Field and may have resulted in preferential migration of TCE contamination in the direction of RD-63 during pumping. The Concentration of TCE in RD-98 (the source area well) is below the MCL; it appears that the remaining mass of TCE in groundwater is located in Chatsworth formation groundwater within the drainage feature, although only the concentration at RD-63 in 2017 was above the MCL.

Near surface groundwater is not present in the source area (leach field); but is found at the base of the drainage (PZ-116 and RS-28).

Based on site water level measurements, under non-pumping conditions, Chatsworth Formation groundwater is predicted to flow to the northwest. Two wells (RD-19 and RS-25) are upgradient of the leach field and no TCE has been detected in these wells. At the base of the drainage feature, the RD-34A, B, C well cluster (with PZ-116) provides insight to the vertical gradients. Groundwater elevation differences in the RD-34 well cluster suggest a small downward vertical hydraulic gradient in the shallower part of the Upper Burro Flats member and a moderate upward hydraulic gradient between the lower and upper strata of the Upper Burro Flats member.

Monitoring well RD-98 (open from 20 to 65 feet bgs) provides data from the source area for Sr-90. RD-30, where concentrations of Sr-90 have been detected below MCLs in the past, provides monitoring of the edges of the Sr-90 plume. The TCE plume is monitored by the RD-30 (open from 30 to 75 feet bgs), RD-63 (open from 20 to 230 feet bgs), and the RD-34A (16 to 60 feet bgs,) and RD-34B (160 to 240 feet bgs) and RD-34C (360 to 450 feet bgs). Monitoring of this well cluster indicates that the plume is limited to the upper Chatsworth formation groundwater; TCE has not been found in RD-34B since 2010 (1.5 µg/L).

Numerical Flow Model

Well RD-98 was used as the modeling point to assess movement of Sr-90 in groundwater from the RMHF leach field. **Figure 6-21** of the Groundwater RI report illustrates the particle tracking possibilities for groundwater movement from well RD-98 assuming there is no restriction on time. This figure shows a north trending pathway for groundwater for more than 100 feet into the bedrock. Site data for groundwater less than 50 feet bgs indicate a more westerly flow at this location. The numerical model predicts a very slow migration rate for Sr-90; 100 years after the release the plume (greater than the MCL) is modeled to migrate only a few tens of meters due to strong sorption with the bedrock matrix.

Monitoring well DD-143 (open from 19.7 to 100 feet bgs) monitors Chatsworth Formation groundwater north of the drainage features, the direction of the simulated particle track. This

well defines the TCE plume to the north and monitors for Sr-90 that may be in groundwater in the drainage feature.

Conclusion

The existing monitoring well network provides sufficient coverage to monitor the TCE and Sr-90 plumes in the current source areas, including the center and downgradient edges of the plume and along the modeled flow path.

Building 4133 Hazardous Waste Management Facility

Groundwater monitoring requirements for this facility will be determined under the RCRA Closure process. The one existing monitoring well in this area, RS-25 monitors shallow (8.5 to 13.5 feet bgs) Near-surface groundwater and is frequently dry.

Old Conservation Yard

Conceptual Site Model

The OCY groundwater investigation area is approximately 10 acres located along a topographic ridge in the northeastern part of Area IV. Several former storage and debris disposal areas are included in the OCY. Soil and soil gas data indicate that TCE was likely release to the soil in the OCY; however, the low concentrations found in these media in 2014 are not indicative of an on-going source.

TCE has been detected in the one Chatsworth formation well, RD-14 (open from 30 to 125 feet bgs), since 1989. The highest concentration was detected in 1990 (13 µg/L); the anaerobic breakdown product of TCE, cis-1,2-DCE, was also detected at that time. TCE concentrations since 2014 have been below the MCL. TCE found in groundwater was likely the result of a spill or leak to the surface soil at the OCY. The TCE would have dissolved in, and migrated through, the soil and weathered bedrock, with infiltrating precipitation until it reached the water table.

Near-surface groundwater is discontinuous and perched above the Chatsworth Formation groundwater when present. Piezometer PZ-151, located outside of the OCY on the easternmost edge of Area IV about 450 feet from well RD-14 was installed to monitor a TCE plume in the NASA-administered Area II. Piezometer PZ-151 was drilled to 82 feet bgs and is typically dry. It is more representative of groundwater conditions beneath Areas II and III, than the OCY.

Groundwater is monitored by one Chatsworth Formation groundwater well RD-14. Another well, WS-07 is installed as a water supply well, is cased to 200 feet and has a total depth of 700 feet. The construction of W-07 is not suitable for monitoring Chatsworth Formation groundwater contamination found at RD-14. The potentiometric surface of Chatsworth Formation groundwater indicates that flow is to the north.

Numerical Flow Model

Numerical groundwater and contaminant transport modeling of the OCY groundwater was not performed due to the low concentrations (below the MCL).

Conclusion

The Chatsworth Formation groundwater is adequately monitored for TCE given the low historic and current levels and the evidence of natural degradation. A hotspot of metals contamination in soils was identified in the RI. There is no monitoring located near or downgradient of the hotspot. Therefore, whether or not groundwater at the metals hot spot has been impacted by metals is not known. Additional monitoring in this area may be necessary, should soil cleanup be delayed.

DOE Leach Field No. 1 Building 4030/4093**Conceptual Site Model**

The RFI identified potential chemical use in several buildings included in the Building 4030 and Building 4093 leach field groundwater investigation area (CH2M Hill 2008). TCE has been consistently detected in bedrock well RD-17, but always at concentrations below the MCL. VOC contamination was not observed in bedrock well DS-44, located downgradient of RD-17. TCE has not been detected in piezometer PZ-112 (to the southeast), although it is frequently dry.

Near-surface groundwater is not present at the leach field. Chatsworth formation groundwater is monitored by RD-17 (open from 30 to 125 feet bgs) and well DS-44 (open from 19 to 91 feet bgs). Water level readings indicate that groundwater flow in the Chatsworth Formation is to the east, i.e., from the leach field toward DS-44.

Numerical Flow Model

Numerical groundwater and contaminant transport modeling of the DOE Leach Field No. 1 Building 4030/4093 groundwater was not performed due to the low concentrations (below the MCL) detected in the source area well.

Conclusion

The existing monitoring well network provides sufficient coverage at the appropriate depths (upper Chatsworth formation) to monitor the groundwater near the suspected source area (the leach field) and downgradient of the source area.

Building 4064 Leach Field**Conceptual Site Model**

The Building 4064 Leach Field is located about 20 feet northeast of former Building 4064 in the northeastern part of Area IV. There have been documented releases of radiological materials at Building 4064 and soil impacted by Cs-137 was removed from the side yard of the building. The soil was found to also be contaminated with methylene chloride (40 µg/kg) and acetone (130 µg/kg). The leach field and septic tank were not used after 1961 and were removed in 1997.

The leach field was found to be above the subcropping ELV member of Sandstone 2 which dips beneath Building 4064. DS-45 (open from 18 to 75 feet bgs) was drilled into the ELV. No Near-surface groundwater was encountered (the well is dry). A deeper well, DS-47, was installed to 145 feet and is open from 18 to 145 feet bgs) and monitors the shallowest groundwater (Chatsworth Formation groundwater) at this potential source area. No VOCs or metals contamination was detected in DS-47.

Numerical Flow Model

Because there is no groundwater contamination at this former leach field. Therefore, no groundwater or contaminant transport modeling was performed for this area.

Conclusion

The existing monitoring well network provides sufficient coverage at the appropriate depths (uppermost groundwater at the potential source) to monitor the groundwater near the suspected source area (the leach field). There is no evidence of groundwater contamination in this area.

Building 4065 Metals Clarifier/DOE Leach Fields 3**Conceptual Site Model**

This groundwater investigation area is approximately 20 acres in the south-central part of Area IV. The DOE Leach Fields 3 RFI site includes four leach fields associated with Buildings 4353, 4363, 4373 and 4383. Building 4065 did not have a leach field but is included in this groundwater investigation area because of its proximity and overlap with the DOE Leach Fields 3 area, and because Building 4065 is a potential source of TCE to groundwater. The Metals Clarifier Laboratory Building 4065 and several former structures are where TCE may have been used and released to the environment.

The majority of the area is within the Lower Burro Flats member of the Chatsworth Formation, although the far southeast corner of the investigation area is underlain by the fine-grained SPA member of Sandstone 2 and Silvernale member of the Chatsworth Formation.

There are four piezometers in the groundwater investigation area: PZ-005, PZ-103, PZ-104, and PZ-105 screened in the weathered bedrock. Piezometer PZ-005, screened from 25 to 45 feet bgs, located immediately downgradient of Building 4065, is frequently dry. PZ-103 (screened from 36 to 39 feet bgs), PZ-104 (screened from 17 to 27 feet bgs) and PZ-105 (screened from 17 to 25 feet bgs) are near the former leach fields. All piezometers are screened in Near-surface groundwater within the weathered bedrock. The potentiometric surfaces indicate that the groundwater investigation straddles the southwestern portion of the groundwater mound present in Area IV.

Bedrock well DD-145 was installed into the consolidated Chatsworth Formation in 2016 to monitor bedrock groundwater water quality conditions; DD-145 is screened from 27 to 85 feet bgs.

Concentrations less than 10 µg/L of TCE have been detected in piezometers PZ-005, PZ-104, and PZ-105 since 2013. TCE has decreased in recent years. In 2013 concentrations at piezometers PZ-005, PZ-104, and PZ-105 were 3.4, 6.4 and 9.3 µg/L, respectively. Concentrations decreased to 1.5, 1.8 and 7.9 µg/L, respectively in 2017. Note that PZ-005, closest to the Metals Clarifier building is frequently dry or has insufficient water for sampling.

Bedrock well DD-145, located near PZ-104, contained TCE at a concentration of less than 1 µg/L indicating that depth of impacted groundwater is approximately 30 feet bgs.

Numerical Flow Model

Piezometer PZ-105, where TCE concentrations exceeded the MCL in 2017 (7.9 µg/L) was used as the modeling point to assess movement of groundwater from this groundwater area. The particle

tracking possibilities for groundwater movement from piezometer PZ-105 (see Groundwater RI report **Figure 6-31**) shows a westward trending groundwater pathway. The model predicts that concentrations of TCE above the MCL would migrate 400 to 500 feet west in 50 years. PZ-103 (0.53 $\mu\text{g/L}$ TCE in 2017) monitors Near-surface groundwater at the edge of the plume to the about 500 feet west of the center of the plume (PZ-104 and PZ-105). Because TCE in this area is already at the MCL, advective and dispersion properties are expected to continue to degrade this plume.

Conclusion

The existing monitoring well network provides sufficient coverage at the appropriate depths (Near-surface groundwater in weathered bedrock) to monitor the groundwater near the suspected source areas and edges of the plume. Groundwater quality on the modeled groundwater flow path is also monitored by the existing well network (PZ-103). The vertical extent is defined and monitored by Chatsworth Formation well DD-145. The analysis of the metals hotspots in soil concluded that there is insufficient groundwater monitoring downgradient of a soil metals hotspot close to the Metals Clarifier building. A Near-surface groundwater well, screened deeper than existing piezometer PZ-005 is recommended.

Table 9-3 Area IV Monitoring Well Network Evaluation

Existing Groundwater Monitoring Network Wells							
Groundwater Investigation Area	Near-surface Groundwater Plume			Fractured Bedrock Plume			Conclusions and Recommendations
	Source Area/Plume	Sentinel Wells	Along Model Simulated Flow Path	Source Area/Plume	Sentinel Wells	Along Model Simulated Flow Path	
Former Sodium Disposal Facility	RS-54	PZ-98, RS-18, DS-46	Not Applicable	RD-23, RD-54A, RD-64, RD-65	DD-139, RD-33A, RD-33B, DD-140, RD-22, RD-21	Data Gap	The particle tracks from RD-23 show an intercept with a predicted extension of the North Fault. There are no wells along the path. In addition, the path turns to the southwest at the presumed fault intersect. A well here could serve as a sentinel point and determination of the North Fault presence.
Building 4100/B56 Landfill	Not Applicable	Not Applicable	Not Applicable	RD-07	DD-141	DD-141	Existing monitoring well network is adequate.
Building 100 Trench	No Plume	RD-20	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Existing monitoring well network is adequate.
Buildings 4057/4059/4626 PCE Plume	PZ-109	Not Applicable ¹	Not Applicable	DD-142, DS-43	RD-24, RD-96, RD-97	RD-24	Existing monitoring well network is adequate.
Hazardous Material Storage Area	PZ-108, PZ-120, PZ-163	PZ-162, PZ-109, PZ-121, PZ-122	Not Applicable	DD-144, DD-146	RD-24, DS-43, RD-29, RS-27, RD-93, DD-147	DD-147	Existing monitoring well network is adequate.

Table 9-3 Area IV Monitoring Well Network Evaluation

Existing Groundwater Monitoring Network Wells							
Groundwater Investigation Area	Near-surface Groundwater Plume			Fractured Bedrock Plume			Conclusions and Recommendations
	Source Area/Plume	Sentinel Wells	Along Model Simulated Flow Path	Source Area/Plume	Sentinel Wells	Along Model Simulated Flow Path	
Tritium Plume	Not Applicable	Not Applicable	Not Applicable	RD-88 ² , RD-90 RD-95	RD-87, RD-89/DD-147, RD-93, RD-94, RD-33A, SP-T02	RD-93, DD-147, RD-34A	Existing monitoring well network is adequate.
Radioactive Materials Handling Facility	Not Applicable	PZ-116, RS-28	Not Applicable	Sr-90: RD-98; TCE: RD-30, RD-63	Sr-90: RD-30, DD-143; TCE: RD-34A, DD-143	DD-143	Existing monitoring well network is adequate.
Old Conservation Yard	Not Applicable	Not Applicable	Not Applicable	RD-14	RD-14	Not Applicable	Install a well, located downgradient of the metals hotspot in soil if soil cleanup is delayed.
DOE Leach Field No. 1 Building 4030/4093	Not Applicable	Not Applicable	Not Applicable	RD-17	DS-44	Not Applicable	Existing monitoring well network is adequate.
Building 4064 Leach Field	Not Applicable	Not Applicable	Not Applicable	Not Applicable	DS-47	Not Applicable	Existing monitoring well network is adequate.
Building 4065 Metals Clarifier ³ /DOE Leach Fields 3	PZ-104, PZ-105	PZ-005, PZ-103	PZ-103	DD-145	DD-145	Not Applicable	Installation of a well screened in the Near-surface groundwater (deeper than PZ-005), located adjacent or

Table 9-3 Area IV Monitoring Well Network Evaluation

Existing Groundwater Monitoring Network Wells							
Groundwater Investigation Area	Near-surface Groundwater Plume			Fractured Bedrock Plume			Conclusions and Recommendations
	Source Area/Plume	Sentinel Wells	Along Model Simulated Flow Path	Source Area/Plume	Sentinel Wells	Along Model Simulated Flow Path	
							downgradient of the metals hotspot in soils.

Notes:

1 - the extent of the Near-surface groundwater in the PZ-109 area is limited. RS-16, downgradient to the west is frequently dry.

2- As noted in Section 9.1, RD-88 is generally too shallow to effectively monitor the center of the Tritium Plume.

Section 10

References

- Achal V, Pan X, Zhang D. Remediation of copper-contaminated soil by *Kocuria flava* CR1 based on microbially induced calcite precipitation. *Ecol Eng.* 2011;37:1601–1605. doi: 10.1016/j.ecoleng.2011.06.008.
- Achal V, Pan X, Zhang D, Fu Q. Bioremediation of Pb-contaminated soil based on microbially induced calcite precipitation. *J Microbiol Biotechnol.* 2012;22:244–247. doi: 10.4014/jmb.1108.08033.
- Achal V, Pan X, Fu Q, Zhang D. Biomineralization based remediation of As(III) contaminated soil by *Sporosarcina ginsengisoli*. *J Hazard Mater.* 2012;201–202:178–184. doi: 10.1016/j.jhazmat.2011.11.067.
- Achal V, Pan X, Zhang D. Bioremediation of strontium (Sr) contaminated aquifer quartz sand based on carbonate precipitation induced by Sr resistant *Halomonas* sp. *Chemosphere.* 2012;89:764–768. doi: 10.1016/j.chemosphere.2012.06.064.
- Achal V, Pan X, Lee DJ, Kumari D, Zhang D. Remediation of Cr(VI) from chromium slag by biocementation. *Chemosphere.* 2013;93:1352–1358. doi: 10.1016/j.chemosphere.2013.08.008.
- Air Force Center for Engineering and the Environment. 2008. Technical Protocol for Enhanced Anaerobic Bioremediation Using Permeable Mulch Biowalls and Bioreactors.
- Atlas, R.M., and R. Bartha, 1987. *Microbial Ecology: Fundamentals and Applications*. The Benjamin/Cummings Publishing Company, Inc., Menlo Park, California.
- Battelle 2004. GUIDANCE FOR ENVIRONMENTAL BACKGROUND ANALYSIS VOLUME III: GROUNDWATER. NAVFAC N47408-01-D-8207, Task Order No. 0059
- California Regional Water Quality Control Board (RWQCB) 2018 Water Quality Control Plan, Los Angeles Region, Basin Plan for the Coastal Watershed of Los Angeles and Ventura County (Basin Plan).
- Carr, C. S.; Garg, S.; Hughes, J. B., 2000. Effect of dechlorinating bacteria on the longevity and composition of PCE-containing nonaqueous phase liquids under equilibrium dissolution conditions. *Environ. Sci. Technol.* 2000, 34 (6), 1088-1094.
- CDM Smith, 2015a. Area IV Groundwater Remedial Investigation Work Plan.
- CDM Smith 2017. Technical Memorandum, Results of Packer Testing of Wells at the Former Sodium Disposal Facility.
- CDM Smith 2018a. Draft RCRA Facility Groundwater Investigation Report (GW RFI) Area IV, Santa Susana Field Laboratory Ventura County, California. September.
- CDM Smith 2018b. Status Report, Former Sodium Disposal Facility Groundwater Interim Measure. July.

- CDM Smith 2018c. Technical Memorandum, Additional Soil Gas Investigation of Former Sodium Disposal Facility, Building 4009 Leach Field, and Hazardous Materials Storage Area. July
- CDM Smith 2018d. Technical Memorandum, Results of Near-Surface Groundwater Testing at the Hazardous Materials Storage Area.
- CDM Smith 2018e. Technical Memorandum, Bedrock Coring Results for Former Sodium Disposal Facility.
- CDM Smith 2018f. Thermal White Paper
- Chapuis, R. (2002). "The 2000 RM Hardy Lecture: Full-scale hydraulic performance of soil-bentonite and compacted clay liners." *Canadian Geotechnical Journal*, 39(2), 417-439.
- CH2M Hill 2008. Group 5 – Central Portion of Areas III and IV, RCRA Facility Investigation, Santa Susana Field Laboratory, Ventura County California. November.
- CH2M 2016. Final Report of Results for the In Situ Chemical Oxidation Field Experiment, Santa Susana Field Laboratory, Ventura County, California. June
- Clu-in 2008. A Citizen's Guide to Soil Vapor Extraction and Air Sparging. https://clu-in.org/download/Citizens/a_citizens_guide_to_soil_vapor_extraction_and_air_sparging.pdf
- DeJong JT, Mortensen BM, Martinez BC, Nelson DC. Bio-mediated soil improvement. *Ecol Eng.* 2010;36:197–210. doi: 10.1016/j.ecoleng.2008.12.029.
- De Muynck W, De Belie N, Verstraete W. Microbial carbonate precipitation in construction materials: a review. *Ecol Eng.* 2010;36:118–136. doi: 10.1016/j.ecoleng.2009.02.006.
- Denton, M. S., Mertz, J.L., & Bostick. W.D., 2012. Fukushima Nuclear Crisis Recovery: A Modular Water Treatment System Deployed in Seven Weeks – 12489. WM 2012 Conference, Phoenix, AZ. February 26 – March 1. Department of Defense, 2006. Design: In Situ Thermal Remediation. Department of Defense.
- Department of Toxic Substances Control (DTSC) 2007. Consent Order for Corrective Action. August.
- DOE. 2015. Performance Assessment for Pump-and-treat Closure or Transition. Prepared for DOE by the Pacific Northwest National Laboratory under contract DE-AC05-76RL01830.
- EPA 2001. Groundwater Pump and Treat Systems: Summary of Selected Cost and Performance Information at Superfund-Financed Sites. December.
- ESTCP, 2007. Applying Electrical Resistance Heating at Below Steaming Temperatures to Enhance Bioremediation Kinetics at the Well 12A Superfund Site. ESTCP project ER-200719.
- ESTCP, 2010. ER-0314 Final Report. Critical Evaluation of State-of-the-Art In Situ Thermal Treatment Technologies for DNAPL Source Zone Treatment. Environmental Security Technology Certification Program. January.
- ESTCP, 2009. Critical Evaluation of State-of-the-Art In Situ Thermal Treatment Technologies for DNAPL Source Zone Treatment. Environmental Security Technology Certification Program.

- Haley & Aldrich 2010. Site-wide Water Quality Sampling and Analysis Plan Santa Susana Field Laboratory Ventura County, California. Revision 1. December.
- Horvath, A. R., 1982. Halogenated Hydrocarbons: Solubility-miscibility with water; Marcel Dekker: New York. NY, 1982.
- Hua B, Deng B, Thornton EC, Yang J, Amonette JE. Incorporation of chromate into calcium carbonate structure during coprecipitation. *Water Air Soil Pollut.* 2007;179:381–390. doi: 10.1007/s11270-006-9242-7.
- Imhoff, P. T.; Frizzell, A.; Miller, C. T., 1997. An evaluation of thermal effects on the dissolution of a nonaqueous phase liquid in porous media. *Environ. Sci. Technol.* 1997, 31 (6), 1615–1622.
- Idaho National Engineering Laboratory. 1996. Pressure Grouting of Fractured Basalt Flows. INEL-96/0143.
- Kabir, A. R., 2010. Successful DNAPL Remediation Using Radio Frequency Heating and Return to Thermal Equilibrium. PowerPoint presentation presented at the Federal Remediation Technologies Roundtable meeting, Arlington, Virginia.
- Kang CH, Choi JH, Noh JG, Kwak DY, Han SH, So JS. Microbially induced calcite precipitation-based sequestration of strontium by *Sporosarcina pasteurii* WJ-2. *Appl Biochem Biotechnol.* 2014;174:2482–2491. doi: 10.1007/s12010-014-1196-4.
- Kohring, G W, Rogers, J. E.; Wiegel, J., 1989. Anaerobic biodegradation of 2,4-dichlorophenol in freshwater lake sediments at different temperatures. *Appl. Environ. Microbiol.* 1989, 55, 348-353.
- Li M, Cheng X, Guo H. Heavy metal removal by biomineralization of urease producing bacteria isolated from soil. *Int Biodeter Biodegr.* 2013;76:81–85. doi: 10.1016/j.ibiod.2012.06.016.
- Lingineni, S., & Dhir, V., 1992. Modeling of Soil Venting Processes to Remediate Unsaturated Soils. *Journal of Environmental Engineering*, 118:1, 135-152.
- NAVFAC. 2002. Surfactant-Enhanced Aquifer Remediation Design Manual. Naval Facilities Engineering Command. Technical Report TR-2206-ENV.
- North Wind 2018. Report on Quarterly Groundwater Monitoring, Area IV First Quarter 2018, Santa Susana Field Laboratory, Ventura County, California. June.
- Strategic Environmental Research and Development Program. 2000. Design Guidance for Application of Permeable Reactive Barriers for Groundwater Remediation. Contract No. F08637-95-D-6004. Delivery Order No. 5503.
- SERDP, 2014. Project ER-2129. Secondary Impacts of *In Situ* Remediation on Groundwater Quality and Post-Treatment Management Strategies.
- Shah, F. H., Hadim, H. A., & Korfiatis, G. P., 1995. Laboratory studies of air stripping of VOC-contaminated soils. *Journal of Soil Contamination*, 4:1, 93-109.
- Soon, NW, Lee LM, Khun TC, Ling HS (2014) Factors affecting improvement in engineering properties of residual soil through microbial-induced calcite precipitation. *J Geotech Geoenviron Eng* 140. doi:10.1061/(ASCE)GT.1943-5606.0001089

Suyama, Akiko, Masaki Yamashita, Sadazo Yoshino, and Kensuke Furukawa, 2002. "Molecular Characterization of the PceA Reductive Dehalogenase of *Desulfitobacterium* sp. Strain Y51," *Journal of Bacteriology*, July 2002, p. 3419-3425, Vol. 184, No. 13.

US Army Corps of Engineers. 2014. Design: In Situ Thermal Remediation Engineer Manual. EM-200-1-21.

US Army Corps of Engineers. EM-200-1-21, 2014. Design: In Situ Thermal Remediation Engineer Manual.

Ventura County 2017. *Grant Deed of Conservation Easement*. Entered by the Boeing Company and North American Land Trust for Boeing-owned property at the Santa Susana Field Laboratory, and Recorded by Ventura County Clerk, April 24, 2017.

Yang, Y.; McCarty, P. L., 2000. "Biologically Enhanced Dissolution of Tetrachloroethene DNAPL." *Environ. Sci. Technol*, 34 (14), 2979-2984.

Yaws, C. L.; Narasimhan P. K.; Gabbula C., 2009. *Yaws' Handbook of Antoine Coefficients for Vapor Pressure* (2nd Electronic Edition); Knovel: Electronic ISBN 978-1-59124-879-8.