FINAL

ZONE D GROUNDWATER FEASIBILITY STUDY

VOLUME I of III

F. E. Warren Air Force Base, Wyoming

April 2004

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F. E. Warren Air Force Base, Wyoming

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April 2004

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Appendices

Appendix A Technical Memorandum: Bioaugmentation Treatability Study – Preliminary Results

Appendix B Response to Agency Comments on the Draft Zone D Groundwater Feasibility Study

Volumes

Volume II Groundwater Modeling Report

Volume III Cost Estimates for Remedial Alternatives

List of Acronyms

µg/L	micrograms per liter
<	less than
≥	greater than or equal to
°C	degrees Centigrade
°F	degrees Fahrenheit
ADW	acid dry well
AFB	Air Force Base
AFCEE	Air Force Center for Environmental Excellence
AMR	annual monitoring report
AOC	area of concern
ARAR	applicable or relevant and appropriate requirement
ASTM	American Society for Testing and Materials
atm	atmosphere
AWR	air-to-water ratio
BATS	biological aqueous treatment system
bg	below grade
bgs	below ground surface
BRA	Baseline Risk Assessment
BTEX	benzene, toluene, ethylbenzene, xylene
C_2HCl_3	trichloroethene
CCl_4	carbon tetrachloride
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
cfm	cubic feet per minute
CFR	Code of Federal Regulations
cfs	cubic feet per second
$CHCl_3$	trichloromethane
cis-1,2-DCE	c*is*-1,2-dichloroethene
Cl	chlorine
Cl^-	chlorine ion
cm	centimeter
cm/sec	centimeters per second
CO_2	carbon dioxide
COC	contaminant of concern

List of Acronyms

Cr	chromium
CWA	Clean Water Act
DCA	dichloroethane
DCE	dichloroethene
DID	direct-injection delivery
DNAPL	dense non-aqueous phase liquid
DO	dissolved oxygen
DOC	dissolved organic carbon
DoD	United States Department of Defense
DQO	data quality objective
DSM	deep soil mixing
DVS	Design Verification Study
E-barrier	electrically induced redox barrier
EBCT	empty bed contact time
EBS	Environmental Baseline Survey
ECHOS	Environmental Cost Handling Options and Solutions
EE/CA	Engineering Evaluation/Cost Analysis
Eh	redox potential
EO	Executive Order Number
ERH	electrical resistance heating
ERPIMS	Environmental Restoration Program Information Management System
ESTCP	Environmental Security Technology Certification Program
FBR	fluidized bed reactor
Fe^{2+}	ferrous iron
Fe^{3+}	ferric iron
$Fe(OH)_3$	iron hydroxide
$FeSO_4$	iron catalyst
FEW	F.E. Warren Air Force Base
FFA	Federal Facility Agreement
FONPA	Findings of No Practical Alternative
FPTA	fire protection training area
FS	Feasibility Study
ft	feet
ft^2	square foot

List of Acronyms

GAC	granular activated carbon
GCW	groundwater circulation well
GIS	Geographic Information System
gm/day	grams per day
gpd	gallons per day
gpm	gallons per minute
H^+	hydrogen ion
H_2O	water
H_2O_2	hydrogen peroxide
HDPE	high-density polyethylene
Hg	mercury
HP	horsepower
HRC®	Hydrogen Release Compound
IDW	investigation-derived waste
iMOX™	*in situ* co-metabolic oxidation
IRA	interim remedial action
IRP	Installation Restoration Program
I-SF	*In situ* Fixation, Inc.
iSOC™	*in situ* submerged oxygen curtain
ISOTEC	*in situ*/Oxidative Technologies, Inc.
K^+	potassium ion
K_d	soil-water distribution coefficient
kg	kilogram
$KMnO_4$	potassium permanganate
kW	kilowatt
LAUST	Leaking Aboveground or Underground Storage Tank
lbs	pounds
lbs/day	pounds per day
LF	landfill
LNAPL	light non-aqueous phase liquid
LTM	long-term monitoring
LUC	land use control
m	meter
m^3	cubic meter

MCL	maximum contaminant level
MCLG	maximum containment level goal
mg	milligram
mg/kg	milligrams per kilogram
mgd	million gallons per day
mg/L	milligrams per liter
MgO_2	magnesium peroxide
$Mg(OH)_2$	magnesium hydroxide
min.	minimum
mL	milliliter
mm	millimeter
MNA	monitored natural attenuation
MnO_2	manganese dioxide
MSG	monosodium glutamate
msl	mean sea level
MW	monitoring well
N_2	nitrogen
NA	not applicable
NAAQC	National Ambient Air Quality Standards
NAD	North American Datum
NAPL	non-aqueous phase liquid
NASA	National Aeronautic and Space Administration
NAVD	North American Vertical Datum
NCP	National Oil and Hazardous Substances Pollution Contingency Plan
NGVD	National Geodetic Vertical Datum
NPDES	National Pollutant Discharge Elimination System
NPL	National Priorities List
NPV	net preset value
NTU	nephelometric turbidity unit
O_2	oxygen
O_3	ozone
O&M	operation and maintenance
OH•	hydroxyl free radical
OH^-	hydroxide ion

List of Acronyms

ORC®	Oxygen Release Compound
OU	operable unit
ppb	parts per billion
PCA	tetrachloroethane
PCE	tetrachloroethene
PCP	pentachlorophenol
PES	Parsons Engineering Science
PLC	programmable logic control
PMW	performance monitoring well
POTW	publicly owned treatment works
PPE	personal protective equipment
ppm	parts per million
PRB	permeable reactive barrier
psi	pounds per square inch
PVC	polyvinyl chloride
QA/QC	quality assurance/quality control
RACER™	Remedial Action Cost Engineering and Requirements
RAO	remedial action objective
RCRA	Resource Conservation and Recovery Act
RI	Remedial Investigation
ROD	Record of Decision
RPM	Remedial Project Manager
SAC	Strategic Air Command
SAPP	sodium acid pyrophosphate
SDWA	Safe Drinking Water Act
Sec.	Section
SHMP	sodium hexametaphosphate
SITE	Superfund Innovative Technology Evaluation
SIU	Standard International Units
SPH	six-phase heating
SS	spill site
STP	sodium tripolyphosphate
SVE	soil vapor extraction
SVOC	semivolatile organic compounds

SWRA	Surface Water Risk Assessment
TBC	to be considered
TCA	trichloroethane
TCE	trichloroethene
TDS	total dissolved solids
TMV	toxicity, mobility, or volume through treatment
TOC	total organic carbon
TPH	total petroleum hydrocarbons
trans-1,2-DCE	*trans*-1,2-dichloroethene
TSD	treatment, storage, and disposal
TSPP	tetrasodium pyrophosphate
TSS	total suspended solids
UCL	upper confidence limit
UIC	underground injection control
URS	URS Group, Inc.
US	United States
USAF	United States Air Force
USC	United States Code
USCS	Unified Soil Classification System
USEPA	United States Environmental Protection Agency
USFWS	United States Fish and Wildlife Service
USGS	United States Geological Survey
UV	ultraviolet
VC	vinyl chloride
V	volt(s)
VOC	volatile organic compound
WCA	waste co-location area
WDEQ	Wyoming Department of Environmental Quality
WS	Wyoming Statute
WSA	weapons storage area
WWQRR	Wyoming Water Quality Rules and Regulations
ZVI	zero valent iron

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800 to 1,000 feet. Vertical extent of contamination in groundwater generally does not extend deeper than 40 to 50 feet below the water table surface.

Section 2 identifies Remedial Action Objectives (RAOs), applicable or relevant and appropriate requirements (ARARs), general response action, and identifies technology types and process options. RAOs are site-specific initial cleanup objectives that provide the basis for selecting appropriate response actions, remedial technologies, and for developing alternatives. Zone D RAOs include:

- Prevent concentrations of TCE and its degradation products in surface water from exceeding the class-specific surface water standards listed in the Wyoming Water Quality Rules and Regulations;
- Restore groundwater to beneficial use, where TCE and its degradation products meet their respective maximum contaminant levels (MCLs); and
- Prevent volatile organic compound vapors that originate from groundwater plumes from accumulating to unacceptable risk levels in the indoor air of future buildings.

General response actions are medium-specific response categories that will satisfy the RAOs, and those applicable to the Zone D groundwater RAOs include:

- No action
- Institutional controls
- Monitored natural attenuation (MNA)
- Groundwater containment
- Groundwater extraction/*ex situ* treatment/discharge
- *In situ* groundwater treatment

Corresponding to these general response actions, a number of technologies and process options were identified as feasible for the *in situ* and *ex situ* physical/chemical treatment of TCE-contaminated groundwater in Zone D. These include MNA, biostimulation-bioaugmentation, chemical oxidation, PRB, electrical resistance heating, phytoremediation, mobilization, groundwater extraction, *ex situ* treatment, and discharge.

The *in situ* and *ex situ* treatment technologies and process options may be applicable only to specific portions of the Zone D groundwater plumes. To account for differences in the applicability of the groundwater technologies, the Zone D groundwater plumes were subdivided into areas of concern (AOCs). For most of the Zone D plumes, the AOCs include the plume head, shallow plume, intermediate-depth plume, hot spots within the shallow plume, and the creek intercept. For SS7, the AOCs included the area upgradient of the IRA PRB, downgradient of the PRB, and the intermediate-depth plume.

Section 3 contains descriptions of screening technologies in evaluating each for its effectiveness, technical and administrative implementability, and capital and operating, maintenance, and monitoring costs. This screening resulted in a wide range of acceptable *in situ* bioaugmentation, *in situ* chemical oxidation using both Fenton's Reagent and $KMnO_4$, iron-filled PRBs, electrical resistance heating, two-phase groundwater extraction, biological *ex situ* treatment, and surface

water discharge technologies. In order to select the best combinations of these technologies for developing alternatives and to define their optimum implementation locations, three-dimensional groundwater models were run for scores of technology combinations and permutations. The results of this modeling are presented in Volume II of this FS.

Each plume is self-contained, with alternatives for each plume developed, analyzed, and compared in Volume I of this FS. Institutional controls were incorporated into all of the alternatives, except the No Action Alternative, although the alternative names do not implicitly state that it is included. Each section presents the individual analysis and assessment of each groundwater remedial alternative with respect to nine evaluation criteria.

The first two (Overall Protection of Human Health-Environment and Compliance with ARARs) are threshold criteria that must be met by the alternative. The next five are balancing criteria, where the relative tradeoffs among the criteria are evaluated. These include Long-Term Effectiveness and Permanence; Reduction of Toxicity, Mobility, or Volume through Treatment; Short-Term Effectiveness; Implementability; and Cost. The final two (State Acceptance and Community Acceptance) are modifying criteria, in which the state and the community express whether they support or oppose the alternatives. These two criteria are not evaluated in this FS, but will be evaluated following the public comment period.

Following the individual analysis of each alternative is a comparative analysis among the groundwater alternatives. The comparative analysis assesses the relative performance of each groundwater alternative to all of the other alternatives with respect to each criterion. One method to qualitatively compare each alternative within a single plume is to directly rank each criterion for each alternative against one another. This ranking is not a quantitative number, but a number relative to the other alternatives in that plume. Therefore, the highest number is the same as the number of alternatives for that plume. Tables that rank the alternatives for each plume are included at the end of Sections 4 through 8.

Section 4 contains the following alternatives developed for the Plume A shallow zone, exclusive of SS7, whereas the "A" denotes "Plume A":

- Alternative 1A – No Action
- Alternative 2A – Institutional Controls
- Alternative 3A – MNA
- Alternative 4A – Groundwater Extraction and *Ex situ* Treatment
- Alternative 5A – Localized Bioaugmentation and MNA

Section 4 also contains the following options developed for the Plume A intermediate-depth zone, exclusive of SS7:

- Option 1A-INT – No Action
- Option 2A-INT – Institutional Controls
- Option 3A-INT – MNA
- Option 4A-INT – Localized Chemical Oxidation and MNA

These options for Plume A are identical in name and technologies to those for the other four plumes; therefore, they are not repeated below for each plume.

Section 5 discusses the following alternatives developed for the SS7 shallow zone:

- Alternative 1S – No Action
- Alternative 2S – Institutional Controls
- Alternative 3S – Existing PRB and MNA
- Alternative 4S – Expansion of PRB, West PRB, and MNA
- Alternative 5S – Existing PRB, Localized Bioaugmentation, and MNA
- Alternative 6S – Electrical Resistance Heating with Soil Vapor Extraction and Chemical Oxidation (disregard existing PRB)

Section 6 discusses the following alternatives developed for the Plume B shallow zone:

- Alternative 1B – No Action
- Alternative 2B – Institutional Controls
- Alternative 3B – MNA
- Alternative 4B – Groundwater Extraction, *Ex situ* Treatment, and MNA
- Alternative 5B – Localized Chemical Oxidation and MNA

Section 7 discusses the following alternatives developed for the Plume C shallow zone:

- Alternative 1C – No Action
- Alternative 2C – Institutional Controls
- Alternative 3C – Groundwater Extraction, *Ex situ* Treatment, and MNA
- Alternative 4C – Chemical Oxidation at Plume Head, Localized Chemical Oxidation, PRB, and MNA
- Alternative 5C – Electrical Resistance Heating, Localized Chemical Oxidation, PRB, and MNA
- Alternative 6C – Groundwater Extraction and *Ex situ* Treatment, Localized Chemical Oxidation, and MNA

Section 8 discusses the following alternatives developed for the Plume E shallow zone:

- Alternative 1E – No Action
- Alternative 2E – Institutional Controls
- Alternative 3E – MNA and Existing PRB
- Alternative 4E – Groundwater Extraction, *Ex situ* Treatment, Existing PRB, and MNA
- Alternative 5E – Existing PRB, Localized Bioaugmentation, and MNA
- Alternative 6E – Localized Chemical Oxidation, and MNA (without the existing PRB)

This Zone D Groundwater Feasibility Study (FS) was prepared to evaluate alternatives to address the contaminants of concern (COCs) in Zone D groundwater at F.E. Warren Air Force Base (FEW). The Groundwater FS was prepared in accordance with the United States Environmental Protection Agency's (USEPA's) *Guidance for Conducting Remedial Investigations and Feasibility Studies Under CERCLA* (USEPA 1988a). The FS was produced by URS Group, Inc. (URS) in accordance with Air Force Center for Environmental Excellence (AFCEE) Contract F41624-00-D-8028, Delivery Order 013.

1.1 PURPOSE AND ORGANIZATION

The major elements of this Zone D Groundwater FS include:

- Site background and history
- Contaminant extent and transport
- Remedial action objectives (RAOs)
- Identification and screening of remedial technologies
- Development and screening of alternatives
- Detailed analysis of alternatives
- Comparative analysis of alternatives

This report is organized into three volumes. Volume I consists of the following:

- Executive Summary
- Section 1, Introduction
- Section 2, Identification of Technologies
- Section 3, Screening of Technologies
- Section 4, Development and Analysis of Alternatives for Plume A
- Section 5, Development and Analysis of Alternatives for Spill Site 7
- Section 6, Development and Analysis of Alternatives for Plume B
- Section 7, Development and Analysis of Alternatives for Plume C
- Section 8, Development and Analysis of Alternatives for Plume E
- Section 9, References

Volume II contains the Groundwater Modeling Report, and Volume III contains Cost Estimates for Remedial Alternatives.

1.2 BACKGROUND INFORMATION

The following subsections summarize background information including a general site description and history, previous investigations, quality and use of historic data, and an overview of background data.

1.2.1 Site Description and History

FEW is located west of the city of Cheyenne, in south-central Laramie County in southeastern Wyoming (Figure 1-1). The contiguous portion of FEW consists of approximately 5,900 acres. Ranch and farmland to the north and northwest and suburban areas to the south and southwest border FEW.

Zone D is generally defined as that portion of FEW east of Roundtop Road along the western boundary of the base, south and west of Crow Creek, south of Diamond Creek, and excluding Zones B and C (Figure 1-1 and Plate 1). The FEW General Plan identifies several land uses in Zone D including residential housing, industrial, administrative, aircraft operations and maintenance, community, and open space (USAF 2000b). Zone D also contains old landfills (LFs), former fire protection training areas (FPTA), and historic spill sites (SS).

1.2.1.1 Site History

The following subsections provide histories for FEW, the FEW Installation Restoration Program (IRP), and Zone D.

F.E. Warren Air Force Base

FEW has served a number of functions since its activation as a military base in the mid-1800s. United States Army outpost Fort D. A. Russell was established at this location in 1867 to protect railroad workers from Native American attacks. In 1930, the base was renamed for Francis E. Warren, the Wyoming Senator who played an important role in the development of the post. During World War II, the size of the installation more than doubled to support new missions, including training of Army personnel.

In 1947, the base was transferred to the newly formed United States Air Force (USAF), under control of the Air Training Command. The Strategic Air Command (SAC) assumed jurisdiction over the installation in 1958. FEW was the first base selected for deployment of the Atlas D missiles and became the operations center for the Atlas intercontinental ballistic missile in 1960. In 1965, the Atlas missiles were replaced by 200 Minuteman I missiles, and in 1975, Minuteman III missiles replaced Minuteman I missiles. FEW was assigned to Air Combat Command in June 1992 and then to USAF Space Command in July 1993.

On February 21, 1990, USEPA Region 8 placed FEW on the National Priority List (NPL). This brought FEW under the federal facilities provisions of Section 120 of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA). On September 26, 1991, USAF, USEPA, and the Wyoming Department of Environmental Quality (WDEQ) signed a Federal Facility Agreement (FFA) to perform installation-wide environmental investigations and restoration. The FFA is required by Section 120 of CERCLA and provides the framework for USEPA and WDEQ oversight of remedial investigations at FEW and identifies the USAF investigation activities and schedules. The FFA was finalized on December 18, 1991. Current deadlines and target dates for milestones reference Modification 11 of the FFA (USAF 1998).

Installation Restoration Program

The IRP is a comprehensive U.S. Department of Defense (DoD) program to identify, assess, and remediate hazardous waste sites at DoD installations. The IRP focuses on current environmental problems that have been caused by waste handling conducted during past operations. Environmental restoration activities are conducted in compliance with CERCLA and Resource Conservation and Recovery Act (RCRA) regulations.

Phase I

In 1984 and 1985, USAF (as part of the IRP Phase I) conducted a records search to identify past waste management practices at FEW. This search included contacting community members and past FEW employees to gather historic information. The findings of the IRP Phase I activity were presented in the *Phase I Records Search for F.E. Warren AFB* (USAF 1985). The report identified 14 areas at FEW where hazardous materials might have been used, stored, treated, or disposed of. That report also identified potential groundwater contamination as a major concern.

Phase II

Beginning in 1987, USAF conducted Phase II of the IRP, which was called Confirmation/ Quantification and included an initial assessment of contamination at the site and a more comprehensive assessment designed to quantify the extent, direction, and rate of contaminant migration. Phase II addressed 18 areas at FEW and evaluated surface water quality at the site. The report entitled *Phase II Installation Restoration Program for F E. Warren Air Force Base* (USAF 1987) recommended further investigative work to better define site contamination.

Basewide IRP Remedial Investigation

An IRP Remedial Investigation (RI) report was issued in 1991, entitled *Remedial Investigation for F E. Warren Air Force Base, Wyoming Administrative Report for the Installation Restoration Program* (USAF 1991). The report describes a soil- and water-sampling program to identify areas of potential contamination. Sites identified for further evaluation following the installation-wide RI effort included seven reported SS locations, two FPTAs, six inactive LFs, a battery acid dry (disposal) well (ADW), inactive firing ranges, an open burning and open detonation area, and plumes of contamination in groundwater.

Based on results from the installation-wide RI (USAF 1991), the FEW IRP sites were grouped into operable units (OUs) to facilitate and streamline cleanup. OU groupings were based on site type, location, and projected response actions. The currently defined OUs include:

- OU1 SS1 through SS7 (soils; groundwater addressed as part of OU2)
- OU2 SS1 through SS7, FPTA2, and Plumes A, B, C, and E* (groundwater)
- OU3 LF6 (all media)
- OU4 ADWs (all media)

*As discussed in Section 1.2.3, what historically has been referred to as Plume D in OU2 groundwater (USAF 1991) was determined not to exist during the Zone D RIs.

- OU5 FPTA2 (soils; groundwater addressed as part of OU2)
- OU6 Open Burning/Open Detonation Area (all media)
- OU7 Firing Ranges (all media)
- OU8 LF5 (all media)
- OU9 LF2 (all media)
- OU10 FPTA1 and LF7 (all media)
- OU11 LF3 (all media)
- OU12 LF4 (all media)
- OU13 Plumes A, B, C, and E (sources)

Following a comprehensive review of the IRP in 1997, the FEW IRP Project Team adopted a zone-specific strategy for further environmental investigation. Five zones were established based on similarities and relationships with respect to site or contaminant types, cleanup requirements, site locations, impacted environmental media, time frames for action, and priorities. Zones were given letter designations from A through E. The Firing Range site was originally placed in Zone E, but was subsequently removed and placed in a separate OU. Grouping sites in this manner streamlines project programming, funding, investigation, remedy selection, and cleanup. Whenever possible, environmental investigations proceed according to zones, and restoration and closure are organized and implemented by OU. Zones A, B, and C Final RI and FS reports are complete, and the remedial design for each zone is ongoing.

As stated in Section 1.2.1, Zone D is generally defined as that portion of FEW east of Roundtop Road along the western boundary of the installation, south and west of Crow Creek, south of Diamond Creek, and excluding Zones B and C (Figure 1-1 and Plate 1). Eight IRP sites are recognized within Zone D. These IRP sites include three spill sites (SS2, SS4, and SS7); two landfills (LF2 and LF7); one ADW area; and two FPTAs (FPTA1 and FPTA2) (Figure 1-1 and Plate 1).

Surface water and sediment risks at FEW are evaluated in the installation-wide *Surface Water Risk Assessment* (SWRA) (USAF 2002b). The SWRA was performed to assess human health and ecological risk within the stream system at FEW and to contribute to the risk assessment of individual zone and OU investigations, with the intent of minimizing duplication of effort in risk assessment for exposures to surface water and sediments. In addition, a risk evaluation was performed on surface water sampling results from the Zone D Groundwater RI and long-term monitoring (LTM) on SS7. The results of the SWRA and risk evaluation are summarized in Sections 6 and 7 of the RI Report (USAF 2003a).

Zone D Groundwater

Under USAF direction, and with concurrence from USEPA and WDEQ, Zone D was further subdivided into two components – one that addressed contaminant sources (OU13) and one that addressed groundwater (OU2). Some of the potential source areas under investigation are at the heads of Plumes A, B, C, and E. These plume head areas do not have formal designations under the IRP, other than to have been collectively grouped as OU13. Zone D groundwater also takes

into account groundwater associated with OU4 and OU9. Potential groundwater impacts associated with LF7 and FPTA1 (i.e., OU10) were evaluated during the LF7/FPTA1 RI (USAF 2002f). This includes the nature and extent of contamination and the fate and transport of contaminants in the groundwater. Impacted groundwater associated with Plume B and its fate and transport through the area of LF7/FPTA1 were evaluated in the context of the Zone D Groundwater RI (USAF 2003a).

Previous Investigations

A summary of documents associated with previous investigations conducted in Zone D is presented in Table 1-1 of the Zone D Groundwater RI (USAF 2003a). This table provides brief descriptions of work performed, monitoring wells sampled, types of analyses, level of data validation, and organic compounds detected. A synopsis of the primary reports is provided below.

The 1991 RI (USAF 1991) represents the first comprehensive RI at FEW. Preliminary investigations were conducted at all of the OUs. The quality of data validation for that RI is unknown, placing limitations on data usability.

RIs were conducted at OU1, OU4, OU5, OU9, and OU10 between 1992 and 1995. During these RIs, groundwater was sampled from several Zone D monitoring wells for a variety of analytical parameters. Investigations of Zone D sites have been performed with respect to the following OUs:

- OU1: SS2, SS4, and SS7 (USAF 1994a)
- OU4: ADWs (USAF 1992)
- OU5: FPTA2 (USAF 1993)
- OU9: LF2 (USAF 1995a)
- OU10: LF7 and FPTA1 (USAF 1996a, 1996b)

Quality and Use of Historic Data

Data review and validation are not described in the 1991 RI Report (USAF 1991). Therefore, quality of the analytical data collected between 1986 and 1989 is unknown. Data of unknown quality are not suitable for definitive uses, such as risk assessment and defining the nature and extent of contamination. As such, analytical data collected at FEW between 1986 and 1989 are not of sufficient quality to meet the data quality objectives (DQOs) of the Zone D Groundwater RI. However, this data has been used as screening level data to support decisions regarding well placement, sampling locations, and temporal trends for the Zone D Groundwater RI. Most other groundwater data were collected before 1996 (SS7 is the exception), and a few of the historic laboratory reporting limits are higher than the federal maximum contaminant levels (MCLs) (USEPA 2002a) or Wyoming groundwater standards (Wyoming 1993).

Limited numbers of groundwater samples have been collected from contaminant source areas since 1989. However, the quality of this analytical data is suitable for definitive uses and meets DQOs of the Zone D Groundwater RI. Data review and validation for analytical data collected

from 1992 to the present in Zone D are described in reports that accompanied these efforts (Table 1-1 of the Zone D Groundwater RI; USAF 2003a).

Zone D Removal Actions

Removal actions have been implemented at several sites within Zone D to mitigate imminent risks to human health and the environment. Interim efforts undertaken in Zone D to date include excavation of waste material at LF2, excavation of impacted soil at SS4 and the ADW, bioventing at FPTA1, removal of a grease trap and impacted soil at SS7, and groundwater extraction and air stripping at SS7. An iron filings permeable reactive barrier (PRB) was installed as an interim remedial action (IRA) for groundwater beneath SS7 in 1999.

An Engineering Evaluation/Cost Analysis (EE/CA) has been generated for an ongoing removal action at SS7 (USAF 2002c). This action is being conducted in association with the Zone D Source Areas RI. FPTA1 and LF7 are also being investigated as part of the Source Areas RI, and a final action for these sites is planned in 2004.

Zone D Records of Decision

There have been four previously completed Records of Decisions (RODs) for IRP sites within Zone D; three final and one interim. The OU4 ROD (USEPA 1992a) addressed soil and groundwater contamination associated with the ADW at an old transportation complex. Based on previously completed contaminated soil removal, the Baseline Risk Assessment (BRA) indicated no significant risk to human health and the environment. Therefore, no further action for soil or groundwater was required at this site.

The ROD for OU5 addressing the FPTA2 soils (USEPA 1996a) indicated no further action required based on the risk assessment findings of no significant risk to human health and the environment. As part of this decision, groundwater beneath FPTA2 was made part of OU2 installation-wide groundwater.

The OU1 ROD (USEPA 1996b) addressed contaminated soils at SS1 through SS7. Closure decisions were based on low contaminant concentrations, findings of insignificant risk to human health and the environment, and/or adequacy of implemented IRAs in addressing excessive soil contamination. As indicated in the closure documents, the No Further Action decisions do not consider potential impacts to groundwater related to leaching and migration of residual contaminants in soil. In the case of SS7, the closure was based on surface contact risks. Subsequent data from SS7 indicate that additional subsurface action is required. Groundwater beneath these sites was not included in the RODs, and therefore it was made part of OU2.

An interim ROD for an IRA of shallow groundwater at SS7 (part of OU2) was signed in 1997. The purpose of the IRA was to reduce contaminant concentrations in shallow groundwater and minimize contaminant loading to Diamond Creek. The IRA is in place in the form of an iron filings PRB. IRA monitoring is being performed under the installation-wide LTM program (USAF 2003e).

Ongoing Related Investigations

The Zone D Source Areas RI (USAF 2002a) is closely linked to this Zone D Groundwater RI, and as stated previously, that RI report is considered a companion to this document. The Source Areas RI focuses on contaminant sources within the vadose zone, although some groundwater investigation was necessary to help delineate the vadose zone sources. The Groundwater RI addresses contamination within the saturated zone. As such, the Groundwater RI has incorporated some of the groundwater data collected during the Source Areas RI for an improved understanding of the nature and extent of contamination in groundwater. For details regarding vadose sources responsible for the Zone D groundwater plumes (Plumes A through E and SS7), refer to the Zone D Source Areas RI (USAF 2002a).

Six treatability studies are being conducted in association with Zone D groundwater. These treatability studies serve two primary purposes: (1) to aid in the selection of a final remedy for Zone D groundwater, and (2) to aid in implementation of the selected remedy by providing site-specific details. The studies are being performed in accordance with USEPA's *Guidance for Conducting Treatability Studies Under CERCLA* (USEPA 1992b). These treatability studies are discussed in Section 1.3.

The installation-wide LTM program has been active since 2000, and three annual reports have been produced (USAF 2001c, 2002d, 2003e). The LTM program includes performance monitoring of the SS7 PRB. Data collected for the SS7 PRB includes groundwater and surface water elevation data, surface water flow discharge measurements, and contaminant concentrations in groundwater and surface water. These data have been evaluated as part of the Zone D Groundwater RI and provide additional insight into groundwater and surface water interaction and contaminant distribution.

1.2.2 Hydrogeologic Setting

The hydrogeologic setting includes descriptions of the surface water hydrology, geology, soils, and the groundwater hydrology of Zone D.

1.2.2.1 Surface Water Hydrology

This surface water hydrology section includes discussions of regional hydrology and site hydrologic conditions. Crow Creek, Diamond Creek, and the surface water locations on these creeks (referenced in the following subsections) are identified on Plate 1.

Regional Hydrology

Crow Creek, the only major stream draining FEW, originates in the Laramie Mountains west of Cheyenne and flows southeastward to the South Platte River near the Colorado-Nebraska border. Small tributaries to Crow Creek that also drain parts of the installation are Dry Creek, North Fork Dry Creek, Diamond Creek, and three unnamed creeks (USAF 1991).

The Crow Creek drainage area encompasses approximately 218 square miles west of the installation, not inclusive of the Dry Creek drainage as measured at Station C1 (USGS 2001). Within this area, three reservoirs provide water for irrigation, recreation, and municipal supplies.

Dry Creek and its tributary, North Fork Dry Creek, originate in the northern part of the installation and do not influence the Zone D investigation area. The main channel of Dry Creek passes north of FEW and joins Crow Creek east of the installation, in the city of Cheyenne. Two unnamed creeks, also in the northern part of the installation, have intermittent flows that seldom reach Crow Creek (USAF 1991).

Site Hydrologic Conditions

Crow Creek is the major perennial stream that drains southern areas of the installation and defines the northern boundary of Zone D. Crow Creek defines the northern and eastern boundaries of Zone D below the Diamond Creek confluence and is the primary surface water body within the site. According to the Wyoming Water Quality Rules and Regulations (WWQRR), Crow Creek is classified as a 2AB stream that supports game fish and drinking water. Reservoirs upstream from FEW provide storage that affects the flow characteristics of Crow Creek (USAF 1994a). Pumping of municipal wells and stream flow diversions upstream of FEW can cause Crow Creek to cease flowing west of FEW during the summer months (USAF 1991). Although sections of Crow Creek west of the installation may be classified as ephemeral, records indicate that Crow Creek flow is perennial within the installation itself (USGS 2001). The total drainage area of Crow Creek within the installation is approximately 18 square miles, as measured at Station C7 (USGS 2001).

Diamond Creek, the second largest stream entering FEW (USAF 1991) defines the northern boundary of Zone D where it enters the installation and joins Crow Creek within the Zone D study area. According to WWQRR, Diamond Creek is classified as a 3B stream that supports aquatic organisms other than fish. The total drainage area of Diamond Creek encompasses approximately 10.8 square miles, with approximately 0.15 square miles occurring on the installation (USGS 2001). Upstream reservoirs on Diamond Creek probably affect stream flow characteristics by reducing base flow and dissipating storm flows.

The Unnamed Tributary of Crow Creek has alternating reaches that are perennial, intermittent, and ephemeral (USAF 1995b). The Unnamed Tributary emanates from the southwest corner of FEW, flows northeast, and enters Crow Creek downstream of Missile Drive.

Groundwater seeps occur where the groundwater surface intersects the ground surface. These seeps are evident along terraces of the floodplain and are identified by growths of aquatic vegetation or seasonal pooling of water.

Historical Data

Vegetative interference and ponded water due to beaver dams influenced accuracy of the stream flow measurements in Crow Creek and Diamond Creek. In some instances, movement upstream or downstream from sampling locations was required to optimize measurement conditions. Measurement error may preclude accurate measurement of gains or losses to the groundwater system. Measurement errors would be exacerbated during high flow, and the discharge related to error would probably be much greater than any potential loss or gain from the groundwater system in any given segment of stream. Therefore, high flows preclude accurate estimates of stream flow gains or losses. Estimates of stream flow gains or losses should be restricted to the low flow regime.

Gain/Loss Analysis

This gain-loss analysis includes data for Crow Creek and for Diamond Creek, as discussed below.

Crow Creek. Historic stream flow data collected from continuous recorders indicate that Crow Creek is predominantly a gaining stream. Stream flow generally increases with distance downstream as the total drainage area increases. Stream flow increases are dominated by groundwater inflow during low flow periods. The percentage increase in flow through the installation during the low flow period is greater than that which occurs during high flow periods. During high flow periods, dominated by storm events and snowmelt runoff, surface inflows from tributaries and stormwater outfalls contribute to Crow Creek flows.

Determination of gains and losses between individual stations is limited because of insufficient data. However, historic instantaneous measurements indicate that the segment between Stations C1 and C2 is a losing reach and that Crow Creek is a gaining stream throughout the remainder of the site. Gain/loss hydrographs for Crow Creek are provided in Appendix F of the Zone D Groundwater RI Report (USAF 2003a).

Diamond Creek. Historic stream flow data collected from the continuous recorders indicate that Diamond Creek reacts differently to low flow and high flow regimes. During low flow periods, the stream segment between Stations D1 and D3 is a gaining reach with only groundwater adding to the baseflow. The lower reach between Stations D3 and D4 exhibits the same characteristics during low flow.

During storm-dominated high flow periods, stormwater outfalls contribute a significant volume of water to Diamond Creek, adding to the gains within the upper D1 to D3 reach and to a lesser degree, within the D3 to D4 lower reach. It is not uncommon, however, for all of the increase in flow to be the result of upstream contributions, depending on the spatial distribution of specific rainfall events. The D1 to D3 segment of the stream is a gaining reach, regardless of precipitation amount or distribution.

The D3 to D4 reach is occasionally a losing segment, showing losses almost proportional to the gains shown upstream, or smaller gains than would be anticipated. The occasional losses in the D3 to D4 reach may be due to a series of small gains and losses along the segment that ultimately result in a net loss for the reach. During high flows, this segment becomes a gaining reach, primarily after sustained rainfall events. Gain/loss hydrographs for Diamond Creek are provided in Appendix F of the Zone D Groundwater RI Report (USAF 2003a).

1.2.2.2 Geology

The uppermost geologic unit in the FEW area consists of Quaternary-age terrace and alluvial deposits composed of clay, silt, sand, gravel, and occasional boulders (USGS 1967). These Quaternary deposits are thickest along present day creeks and generally are less than 25 feet in depth (USAF 1991).

The Tertiary-age Ogallala Formation, with an estimated thickness of approximately 300 feet, lies beneath the Quaternary deposits (USGS 1967). The sedimentary unit composing the Ogallala Formation are understood to have been deposited under fluvial (stream and river) and localized eolian (windblown) conditions in a humid, alluvial fan environment (Gutentag *et al.* 1984). Lithologies consist of a heterogeneous mixture of clay, silt, poorly sorted sand, and gravel layers.

Boreholes for 37 monitoring wells were drilled and logged for the Zone D Groundwater RI. Lithologic logs for these boreholes are provided in Volume III of the Zone D Groundwater RI Report (USAF 2003a). The boreholes generally penetrated the Quaternary deposits and upper units of the Ogallala Formation. As shown in these logs, the boreholes encountered thin, alternating units of sand, silt, clay, and gravel. Some of these sand and silt layers are weakly to moderately cemented with calcium carbonate, forming discontinuous sandstone and siltstone layers.

The location of geologic cross sections parallel and perpendicular to groundwater flow for Plumes A, B, C, and E are shown on Plate 4 of the Zone D Groundwater RI Report (USAF 2003a). These cross sections of Plumes A, B, C, and E are illustrated on Plates 5 through 8 of the Zone D Groundwater RI Report (USAF 2003a). Specific borings were selected for the cross sections based on boring depths, with deeper borings selected to better illustrate the vertical geologic profile. As a visual aid, each lithology has been color-coded according to its Unified Soil Classification System (USCS) symbol.

As illustrated in the cross sections, the lithology in the Plume A, B, C, and E areas is primarily fine-grained materials including silty sand, silt, and clay. The cross sections demonstrate the vertical and lateral lithologic heterogeneity in Zone D. Boreholes throughout Zone D (as well as other FEW sites) display this pattern of lithologic heterogeneity, making lateral correlation of lithologic units difficult and uncertain between boreholes.

1.2.2.3 Soils

Several soil types are present at FEW. However, where average topsoil depths range from 4 to 6 inches, the predominant soil series is classified texturally as loamy. The subsoil extends from a depth of approximately 6 to 36 inches and is primarily alluvial clay (USAF 1995a).

No surface or subsurface soil samples were collected during the Zone D Groundwater RI for the purpose of characterizing the nature and extent of contamination. However, subsurface samples were collected for total organic carbon (TOC) analysis, as discussed in Section 2.1.6 of the Zone D Groundwater RI Report (USAF 2003a). TOC was not detected above the detection limit of 600 milligrams per kilogram (mg/kg) in any sample except MW-311, which indicated 630 mg/kg. TOC is likely present at all of the locations, but at concentrations less than 600 mg/kg.

1.2.2.4 Hydrogeology

The interpretation of groundwater occurrence and movement in Zone D is based on data derived from the Zone D Groundwater RI (USAF 2003a), supplemented with existing hydrologic and hydrogeologic data in Environmental Restoration Program Information Management System (ERPIMS), and previously published FEW investigative reports (USAF 1991, 1993).

The Quaternary-age alluvial and terrace deposits and the Tertiary-age Ogallala Formation are the uppermost geologic units at FEW. Where saturated with groundwater, the alluvial and terrace deposits are hydraulically connected to the Ogallala Formation, and together these units form the High Plains Aquifer, the principal source of water for most of the water supply wells in and around FEW.

Water level measurements within Zone D were taken at 482 monitoring wells, and 177 monitoring wells were sampled. Of the 177 wells sampled, 37 were installed during the Zone D

Groundwater RI and are referred to as "newly installed wells." The remaining wells were installed prior to this RI and are referred to as "existing monitoring wells." Well construction details for both newly installed wells and existing wells are provided in the Zone D Groundwater RI report Tables 3-2 and 3-3, respectively (USAF 2003a).

Well depths range from 10.5 to 134 feet below ground surface (bgs). Of these wells, approximately 121 are considered shallow wells (i.e., the well screens typically straddle the water table). In general, these shallow wells are completed within 30 feet of the ground surface. Depth to the water table in Zone D is typically 10 to 30 feet bgs, with progressively shallower groundwater depths occurring near Crow and Diamond creeks. However, there are some topographically higher areas where the depth to the water table is greater than 40 feet.

Groundwater elevations from water level measurements taken at Zone D wells during the RI have been used to interpret groundwater flow conditions and develop a potentiometric surface map of the site (Plate 1). The map is representative of the water table, and only the groundwater elevations in shallow wells were used for contouring. In general, shallow groundwater flow mimics the surface water flow patterns defined by Crow Creek and Diamond Creek. This can be observed in Plate 1, where inflections of the potentiometric contours coincide with alignment of the creeks. Groundwater flow directions are generally toward the creeks with regional groundwater flow to the southeast in the downstream direction of Crow Creek.

Groundwater elevations in shallow wells along Diamond and Crow creeks are consistent with surface water elevations measured at adjacent gauging stations. This correlation in water elevation provides further evidence of the hydraulic connectivity between surface water and groundwater. For example, the March 2001 surface water elevation at gauging station C4 was 6,102.47 feet above mean sea level (msl). C4 is located between wells MW-176B and MW-288, where the March 2001 groundwater elevations were 6,104.02 and 6,102.17 feet above msl, respectively.

The horizontal hydraulic gradients in shallow groundwater range from approximately 0.006 to 0.03 foot/foot and tend to be steepest near the creeks. The typical hydraulic gradient is approximately 0.01 foot/foot.

Many of the monitoring wells in Zone D are grouped in pairs or clusters. Water level measurements from the paired and clustered wells were used to evaluate the magnitude and direction of vertical hydraulic gradients (Plates 4 through 7 of the Zone D Groundwater RI) (USAF 2003a). In areas away from Crow Creek and Diamond Creek (e.g., well cluster DRMO-003 and well cluster MW-121), downward hydraulic gradients have been observed. Upward hydraulic gradients are generally evident in well clusters located near the creeks, providing evidence that groundwater discharges to the creeks. Some of the well clusters exhibit a mixture of gradients. At well clusters WSA-5 and MW-105, downward gradients are evident between the shallow wells and mid-depth wells, while an upward gradient exists between the deepest wells and the mid-depth wells. Artesian conditions have been observed in wells MW-175, MW-214D, MW-334M, MW-334D, MW-335M, MW-335D, and MW-1005M.

Recharge to the shallow aquifer occurs by areal infiltration of local precipitation and upgradient sources. As described above, downward hydraulic gradients have been observed in areas located away from the creeks indicating the potential for groundwater recharge. In addition, there may be areas within the creek floodplains where upward vertical gradients do not exist, and surface water may recharge shallow groundwater.

Water levels in wells have been shown to have seasonal fluctuations; rising as much as 5 feet following periods of high precipitation and falling during drier periods. The greatest fluctuation in groundwater elevation at any of the Zone D wells during the period of record (up to 12 years) is approximately 8 feet (well MW-122) (USAF 2002g). Typically, spring is the wettest time of year, and water levels increase in late spring and early summer.

A plot of groundwater elevation versus monthly precipitation shows an increase in elevation following two months of high precipitation in spring of 1995 (Figure 3-1 of the Zone D Groundwater RI [USAF 2003a]). The fall and winter months tend to be the driest, and as a result, groundwater elevations drop during these months. In late 1995, groundwater elevations dropped to the levels that occurred prior to the Spring 1995 recharge period.

The site-wise horizontal hydraulic conductivity was estimated using slug test results from 184 wells with measured hydraulic conductivity values ranging from 0.003 to 179 feet/day with a geometric mean of 2.97 feet/day (USAF 2003a, Vol. 4). Slug tests within the Zone D alluvium range from 6 to 64 feet/day, as shown in Figure 2-2 of Volume II of the FS. The hydraulic conductivity of the alluvium along the floodplain of Crow Creek is generally higher than that of the Tertiary deposits. The generalization that hydraulic conductivities of the alluvium are higher is based on the observed flatter hydraulic gradient of approximately 0.006 foot/foot along the floodplain compared to a gradient of 0.03 foot/foot south of Crow Creek. Using the geometric mean of horizontal hydraulic conductivity, the typical value for the hydraulic gradient (0.01 foot/foot), and an assumed effective porosity of 20 percent (USAF 1991), the horizontal groundwater velocity is approximately 0.15 feet/day (54 feet/year). However, due to the highly variable nature of site geologic conditions, site groundwater velocities are expected to vary considerably. Volume II of the FS provides a detailed analysis of these hydraulic conductivity data and the methodology for incorporation of these data into the groundwater flow and transport model.

1.2.3 Nature and Extent of Contamination

Trichloroethene (TCE) is identified as the most widespread contaminant in Zone D groundwater and was reported at a maximum concentration of 13,170 micrograms per liter (μg/L) at SS7. This contaminant is distributed in five groundwater plumes identified as Plumes A, B, C, E, and SS7. Plume D, initially described in the OU1 RI, was determined during the Zone D Groundwater and Source Areas RIs not to be a plume, but an artifact of earlier reports (USAF 2003a, 2002a). Other less widespread and lower concentration contaminants include dichloroethene (DCE) and vinyl chloride. Rarely do these other contaminants exceed regulatory standards.

The plumes vary in lateral extent with lengths ranging from 600 feet (SS7) to 5,000 feet (Plume E), and plume widths range from approximately 800 to 1,000 feet. Vertical extent of contamination in groundwater generally does not extend deeper than 40 to 50 feet below the water table surface. The total estimated mass of TCE within Zone D groundwater is 477 kilograms (kg). This mass is distributed between the plumes as follows:

- Plume A (excluding SS7) – 44 kg
- SS7 – 216 kg
- Plume B – 30 kg

- Plume C – 130 kg
- Plume E – 57 kg

These quantities differ from those reported in the RI (USAF 2003a) and represent a more refined estimate of contaminant mass based on groundwater modeling described in Volume II.

Plume A

In Plume A, TCE distribution is indicative of three overlapping smaller plumes (Plate 1). Two of these plumes appear to originate from attenuating sources – one near the Weapons Storage Area (WSA) and one in the vicinity of SS4. The third plume originates from a continuing source at SS7. Because of the independent source and comparatively high concentrations within the SS7 plume, it is addressed as a separate plume for the FS (see below). Maximum reported TCE concentrations in the two former plumes are 102.2 and 43.62 µg/L, respectively. Reported TCE concentration data and the interpreted hydrogeology indicate portions of Plume A both flowing underneath and discharging to Diamond Creek.

In general, current TCE concentrations are similar to historic concentrations; however, a few significant decreases in concentrations were noted at SS4. For a more detailed discussion of the nature and extent of Plume A, see Section 4.1.3.1 of the Zone D Groundwater RI (USAF 2003a).

Spill Site 7

TCE concentrations in shallow groundwater at SS7 range as high as 13,170 µg/L. A consistent trend in the distribution of TCE concentrations at SS7 is not apparent. Analytical data from the LTM Program at SS7 indicate that all three sections of the PRB are working as designed. Performance monitoring wells (PMW-103B, PMW-203B, and PMW-303B) immediately downgradient of the PRB have generally had nondetectable concentrations of the COCs (TCE, *cis*-dichloroethene [*cis*-DCE], *trans*-DCE, total DCE, and vinyl chloride) since the LTM began in May 2000. This indicates that the PRB is meeting the primary objective of reducing COC concentrations to or below treatment goals in the upper 15 feet of the aquifer.

LTM data indicate that monitoring wells located within approximately 30 feet downgradient of the PRB have generally shown decreasing concentration trends for the COCs. TCE concentrations 30 to 50 feet downgradient of the PRB are comparable to TCE concentrations upgradient of the PRB likely due to desorption of TCE from saturated soil. Once sufficient pore volumes of groundwater flush through the system, desorption effects will likely diminish, causing a decrease in TCE concentrations over time. For a more detailed discussion of the nature and extent of SS7, see Section 4.1.3.1 of the Zone D Groundwater RI (USAF 2003a).

The presence of TCE at wells MW-174C and MW-172C located north of Diamond Creek indicate that the SS7 plume is migrating under Diamond Creek. Surface water samples are collected from Diamond Creek as part of the LTM Program (USAF 2003e). TCE was detected in samples collected from surface water Stations D3, D3.5, and D3.6 at concentrations of 10.1, 13, and 18.3 µg/L, respectively (USAF 2001c); Station D3 is located upgradient and upstream of SS7, and Stations D3.5 and D3.6 are located downgradient and downstream of SS7. The TCE detections in surface water indicate that groundwater from SS7 is discharging into Diamond Creek (Figure 1-2). However, TCE concentrations have generally been decreasing in Diamond Creek directly downgradient of the PRB.

1,1-DCE was detected in one well at a concentration exceeding the MCL of 7 µg/L. *Cis*-1,2-DCE was detected in wells ranging from 1.8 to 282 µg/L, with two wells exceeding the MCL of 70 µg/L. The presence and distribution of 1,1-DCE and *cis*-1,2-DCE suggests that biodegradation may be occurring.

Plume B

In Plume B, only concentrations of TCE and *cis*-1,2-DCE were reported at levels above the MCLs and Wyoming groundwater standards. Maximum concentrations of these contaminants were 102.7 and 123 µg/L, respectively. TCE concentrations decrease to below the reporting limit between LF7 and Crow Creek in wells MW-048, MW-286, and MW-289; therefore, the downgradient edge of the plume (as defined by the 5-µg/L isoconcentration) does not appear to extend to Crow Creek; however, the potential exists. For a more detailed discussion of the nature and extent of Plume B, see Section 4.1.3.2 of the Zone D Groundwater RI (USAF 2003a).

Plume C

In Plume C, TCE was the only organic compound that exceeded an MCL or Wyoming groundwater standard. The maximum reported concentration from Zone D Groundwater RI data was 2,273 µg/L (the Zone D Source Areas RI reported 6,870 µg/L from a temporary well and 6,400 µg/L from a permanent well). The downgradient edge of Plume C extends to Crow Creek, and trace TCE concentrations in MW-1018S north of the creek indicate a portion of the plume migrating underneath the creek. For a more detailed discussion of the nature and extent of Plume C, see Section 4.1.3.3 of the Zone D Groundwater RI (USAF 2003a).

Current TCE concentrations have decreased relative to historic maximum concentrations in some wells and increased relative to historic maximum concentrations in other wells. The primary source is at the head of Plume C. Based on the contaminant distribution and trend analyses, there were suspected localized sources of TCE in the vicinity of FPTA2 and the ADW. In February 2003, additional investigations were conducted to determine whether these were localized sources or whether the concentration trends were a function of plume dynamics. Based on results of the investigation, it was concluded that the concentrations and trends were representative of localized plume dynamics (Attachment 4 of the RI, USAF 2003a).

Plume E

In Plume E, MCL exceedances were reported for TCE, bis(2-ethylhexyl)phthalate, and benzene. Bis(2-ethylhexyl)phthalate was reported in one sample above its respective MCL, but is not considered to be site-related because of the distribution and recognition as a common field or laboratory contaminant. Benzene was reported only slightly above the MCL in one well. Additional investigation was conducted to delineate the extent and potential source of the benzene, but no other occurrences were identified. For a more detailed discussion of the nature and extent of Plume B, see Section 4.1.3.4 of the Zone D Groundwater RI (USAF 2003a).

The maximum TCE concentration reported in Plume E was 449.7 µg/L from MW-075S located at the approximate midpoint of the plume. This distribution suggests an attenuating plume originating from the vicinity of Building 945.

Surface Water

Surface water sampling was conducted to assess the impact on surface water from groundwater discharge at Plume A, SS7, and Plume C. Data from the LTM Program were also evaluated to develop a comprehensive understanding of the groundwater-surface water interaction. In general, contaminant levels in surface water appear to vary according to stream flow and base flow. Higher concentrations of contaminants in surface water appear to occur during lower stage levels when baseflow is proportionally the greatest. For a more detailed discussion of the nature and extent of Zone D surface water contamination, see Section 4.1.4 of the Zone D Groundwater RI (USAF 2003a).

Based on data collected during the RI, Wyoming surface water standards for TCE (2.7 µg/L) were exceeded only for TCE in Crow Creek at location C5.2 (12.1 µg/L). LTM data indicate that TCE has been detected in Diamond Creek at locations D2.9, D3, D3.5, D3.6, and D4 (USAF 2003e), but there are no TCE standards for a Class 3B stream. However, during subsequent reviews of the ERPIMS database, historical data for D4 and C3.5 (the first Crow Creek surface water station downstream of the confluence) were compared. A correlation in fluctuating TCE concentrations between these locations was observed (Figure 1-2). Although C3.5 was not sampled as part of the RI, it is assumed that TCE concentrations in Crow Creek occasionally exceed the Class 2AB standards due to the influx of TCE-contaminated water from Diamond Creek.

1.2.4 Contaminant Fate and Transport

The TCE groundwater plumes migrate in a northeastern direction as evidenced by groundwater potentiometric surface contours, corresponding flow directions, and corresponding plume geometries. For a more detailed discussion of the groundwater contaminant fate and transport trends in each plume of Zone D, see Section 5.4 of the Zone D Groundwater RI (USAF 2003a). Leading edges of the TCE plumes either intercept surface water, locally flow under the surface water bodies (where in some instances they continue to migrate and eventually intercept surface water further downstream as observed with the leading edge of Plume A), and/or become attenuated.

In Zone D, advection is the dominant contaminant transport process in groundwater. Groundwater flow is generally from southwest to northeast toward Crow Creek, with some flow toward Diamond Creek in the northwestern portion of the zone. Plume A is primarily migrating toward Diamond Creek and Plumes B, C, and E are migrating toward Crow Creek. Advective transport also can occur in surface water and is likely occurring in Diamond Creek and Crow Creek within Zone D. Contaminants dissolved in shallow groundwater may discharge to Diamond Creek and Crow Creek where they are transported downstream with surface water flow. For a more detailed discussion of the surface water contaminant fate and transport trends at Zone D, see Section 5.5 of the Zone D Groundwater RI (USAF 2003a).

The potential for dispersion of contaminants in groundwater is enhanced by the heterogeneity of the shallow aquifer system in Zone D, as indicated by its discontinuous geologic units and wide range of hydraulic conductivity values.

Volatilization of TCE from shallow groundwater may occur in the floodplains and wetlands of Diamond Creek and Crow Creek, where the depth to groundwater is generally less than 5 feet

bgs. Dissolved TCE in Plume A may volatilize to the atmosphere along the northern portion of the plume where shallow groundwater intercepts Diamond Creek. Similarly, dissolved TCE in Plumes B, C, and E may volatilize to the atmosphere in the floodplain of Crow Creek where the plumes approach the creek.

Volatilization of TCE also may occur in surface water at Zone D. Results from surface water sampling conducted during the Zone D Groundwater RI indicate that TCE-contaminated groundwater is discharging to Diamond Creek and Crow Creek. The lack of TCE in the surface water samples is likely attributable to volatilization or dilution from upgradient surface water in the creek.

In Zone D groundwater, dilution is most apparent where Plume B encounters the Crow Creek floodplain downgradient of LF7. In this region, groundwater flow is generally parallel to the creek and groundwater from north of Crow Creek (Zone E) appears to converge with Plume B groundwater. The groundwater from Zone E appears to effectively dilute the TCE concentrations from greater than the MCL upgradient of LF7 to generally less than 1 µg/L downgradient of LF7. The reduced concentrations of TCE in this area may also be related to biodegradation associated with anthropogenic carbon.

In surface water, dilution of TCE concentrations is apparent in Crow Creek where Plume C appears to discharge to the creek. The TCE concentration in shallow well MW-038S, located approximately 250 feet upgradient of Crow Creek, was 220 µg/L. It is reasonable to assume that the TCE concentration entering Crow Creek, while possibly less than 220 µg/L, is still significantly elevated. However, surface water samples collected from location C5.2 in the approximate discharge zone of Plume C to Crow Creek have contained TCE concentrations typically less than or equal to 1 µg/L (the maximum reported TCE concentration was 12 µg/L). This indicates that significant dilution of TCE concentrations is taking place within Crow Creek.

An evaluation of the monitored natural attenuation (MNA) field and laboratory data for Plume B and a temporal trend analysis were conducted to assess the potential for biodegradation of TCE. For a more detailed discussion of this analysis of Plume B, see Sections 5.2.3 and 5.4.2 of the Zone D Groundwater RI (USAF 2003a). The evaluation involved a comparison of the MNA sampling results to criteria specified in *Technical Protocol for Evaluating Natural Attenuation of Chlorinated Solvents in Groundwater* (AFCEE 1996). The temporal trend analysis indicates that the TCE concentrations in the center and periphery of the plume have been decreasing. The decrease is primarily attributed to biodegradation as evidenced by the presence of *cis*-1,2-DCE and vinyl chloride, both breakdown products of TCE. Analytical data suggest that a portion of TCE in Plume B has degraded to DCE via reductive dechlorination. Analytical data also suggest that oxidation of DCE and possibly vinyl chloride to carbon dioxide, water, and chloride ions may be occurring.

Temporal trend analyses were also conducted for Plumes A, C, and E (see Sections 5.4.1, 5.4.3, and 5.4.4 of the Zone D Groundwater RI [USAF 2003a]). The results suggest that:

- TCE in Plumes A, B, E, and part of C are stable, and the edges of the plumes are shrinking.
- Concentrations within Plumes A, B, and E have decreased over the last 10 to 15 years. Concentrations measured within Plumes A and B in 2001 are two to five times lower than

those measured between 1989 and 1992. Concentrations within Plume E are five to ten times lower.

- Concentrations of TCE in SS7 and part of Plume C are increasing; indicating sources in those areas are active.
- Decreasing TCE concentrations are attributed to source decay, advection, dispersion, sorption, dilution, and biodegradation. It appears that the most important contributions in the upgradient and middle part of the plumes are from source decay and biodegradation.
- Biodegradation appears to have occurred through out all plumes, including areas where sources are still active. This is evidenced by the presence of *cis*-1,2-DCE.
- Approximate attenuation half-life was estimated for the average conditions of Plumes A, B, E, and part of C. The half-lives range from five to 12 years.

The TCE mass loading to surface water from Zone D groundwater was estimated at 12.4 grams per day (gm/day). The section of Diamond Creek upstream of SS7 is estimated to be receiving 1.1 gm/day of TCE from groundwater. The section of Diamond Creek in contact with the SS7 plume is receiving an estimated 6.7 gm/day. Plumes B, C, and E are discharging into Crow Creek at a rate of 0.6, 3.7, and 0.3 gm/day, respectively.

1.3 ZONE D INTERIM REMEDIAL ACTIONS AND TREATABILITY STUDIES

Zone D contains eight IRP sites: SS2, SS4, SS7, LF2, LF7, ADW, FPTA1, and FPTA2 (Plate 1). Removal actions have been implemented at several of these sites to mitigate risks to human health and the environment, as discussed below. Bench-scale and pilot-scale treatability studies within Zone D that have been completed or are in progress are also discussed in the following sections.

1.3.1 Interim Remedial Actions

Interim efforts undertaken in Zone D to date include:

- Excavating waste material at LF2 (1999);
- Excavating impacted soil at SS4 and the ADW (1984 and 1986, respectively);
- Bioventing at FPTA1 (1995-1996);
- Shallow groundwater extraction and air stripping pilot test at SS7 (1995-1996);
- Two-phase extraction and gas-phase bioreactor pilot-testing for treatment of soil and groundwater at the head of Plume C (1995);
- Installing an iron filings PRB at SS7 to treat shallow groundwater and reduce contaminant loading to Diamond Creek (1999); and
- Removing a grease trap and impacted soil at the SS7 source area (1989 and 2003, respectively).

An EE/CA has been prepared in association with the Zone D Source Areas RI for an ongoing removal action at SS7. FPTA1 and LF7 (OU10) are also being investigated as part of the Source Areas RI, and a final action for these sites is planned in 2004.

1.3.2 Bench-Scale Treatability Studies

A bench-scale treatability study for *in situ* reductive dechlorination using Hydrogen Release Compound (HRC®) (USAF 2003g) has been conducted from samples collected at the head of Plume C. Results from this study indicated that the HRC® can degrade TCE to DCE, but cannot completely mineralize the DCE to ethene and water. The test was rerun to determine whether this incomplete degradation was a function of the site conditions or the test procedures and it appears that there are limitations with this technology at FEW due to site conditions. Although biostimulation using HRC® is not recommended for Zone D groundwater remediation by itself, it may be successful as a stimulant when used in conjunction with microbes grown specifically for use in anaerobic, chlorinated volatile organic compound (VOC) plumes.

1.3.3 Pilot-Scale Treatability Studies

Pilot-scale treatability studies for Zone D groundwater served two primary purposes: (1) to aid in selecting effective technologies for remediating Zone D groundwater, and (2) to aid in implementing a final remedy by providing site-specific construction and operation and maintenance (O&M) data. All of the treatability studies were performed in accordance with USEPA's *Guidance for Conducting Treatability Studies Under CERCLA* (USEPA 1992b), with the most recent ones documented in the *Treatability Study Report for Zone D Groundwater* (USAF 2002f). The pilot-scale treatability studies completed for Zone D are discussed in the following sections.

1.3.3.1 Pump-and-Treat

In 1995, a one-year *ex situ* shallow groundwater extraction and air stripping pilot test was conducted at SS7. O&M problems with the collection trenches and packed tower air stripper limited the effectiveness of this system.

1.3.3.2 Permeable Reactive Barrier

In 1996, the pump-and-treat system was shut down and, in 1999, replaced with a continuous, iron-filings PRB. This PRB has been very successful at reducing downgradient TCE concentrations in shallow groundwater at SS7.

1.3.3.3 Pump-and-Treat, Dual-Phase, and Two-Phase Extraction

Also in 1995, a two-phase extraction and gas-phase bioreactor treatment treatability study was successfully completed for remediating TCE in soil and groundwater at the head of Plume C (USAF 1996d). This treatability study was designed to compare the effectiveness, implementability, and cost of three groundwater extraction and *ex situ* treatment technologies – conventional pump-and-treat, vacuum-assisted (dual-phase) pumping, and two-phase extraction – at a single site. The study also included aquifer (pump) testing and slug testing to determine aquifer properties at the site. The aquifer testing results indicated a recovery rate of 0.011 pounds per day (lbs/day) of TCE for pump-and-treat, 0.011 lbs/day for dual-phase, and 0.023 lbs/day for two-phase extraction. Thus, the two-phase extraction system was approximately twice as effective as conventional pump-and-treat and dual-phase extraction results for the same

well. Based on these results, two-phase extraction is recommended over conventional pump-and-treat and dual-phase extraction for remediation of Zone D groundwater.

1.3.3.4 Electrical Barrier

A pilot study of an electrically induced redox barrier (E-barrier) is currently being conducted in Plume C by Colorado State University (Sale *et al.* 2001). The E-barrier has been constructed at the leading edge of Plume C, adjacent to Crow Creek and well cluster MW-038. Its purpose is to use a low-voltage electrical current in a buried, vertical-panel, three-node electrical grid as the electron donor to mineralize the chlorinated VOCs in the groundwater flowing through the grid. This study is an innovative technology being funded by the Environmental Security Technology Certification Program (ESTCP). To date, no data regarding the performance of the E-barrier are available.

1.3.3.5 Feasibility Study-Specific Treatability Studies

Four *in situ* treatability studies were completed in Zone D in 2003 (USAF 2003f) specifically to support the selection of technologies in this FS. The four technologies include:

(1) Installation and operation of an *in situ* Submerged Oxygen Curtain (iSOC™)/*in situ* co-Metabolic Oxidation (iMOX™) biostimulation technology designed to co-metabolize chlorinated VOCs by infusion of contaminated groundwater at SS7 with oxygen and methane gas;

(2) Direct injection of liquid $KMnO_4$ solution to chemically oxidize chlorinated VOCs in groundwater in Plume C;

(3) Mechanical C-Sparger™system that combines *in situ* air stripping with injection of encapsulated ozone to chemically oxidize chlorinated VOCs in Plume C groundwater; and

(4) Direct injection of a zero-valent iron (ZVI) PRB designed to reductively dehalogenate chlorinated VOCs in Plume E groundwater.

The results of these four recent pilot treatability studies are discussed in the following paragraphs.

iSOC/iMOX™. TCE concentrations in the portion of SS7 near MW-027 prior to the initiation of the iSOC/iMOX™ system ranged from approximately 70 to 110 µg/L. These concentrations increased in three of the four wells sampled in the first post-startup monitoring round and decreased by the last round to near or below the initial concentrations. The most significant decrease was observed in the iSOC/iMOX™ well (MW-027), where concentrations decreased from 108 to 16 µg/L, or by 85 percent (USAF 2003f). Similar to these TCE concentration decreases, the decrease in *cis-1,2*-DCE concentrations indicated that aerobic biostimulation appeared to be occurring in the well where the iSOC/iMOX™ is installed. However, decreases in TCE concentrations observed in the other three iSOC/iMOX™ monitoring wells ranged from only 1 to 22 percent. This variability in concentration decreases could be the result of poor diffusive processes within the area selected for the test.

Although biostimulation appears to be occurring within the well where the iSOC/iMOX™ is installed, a significant amount of oxygen and methane may not be transported downgradient with groundwater. Further evidence of this lack of gas diffusion is indicated by the low dissolved oxygen (DO) concentrations measured in the downgradient wells. Due to the lack of downgradient diffusion and reducing TCE to its MCL of 5 µg/L, even in well MW-027, this technology is not recommended for long-term use in Zone D.

Chemical Oxidant Injection. TCE concentrations prior to initiating the $KMnO_4$ injection ranged from approximately 220 to 350 µg/L. As expected, these concentrations decreased to non-detectable levels in the first post-startup monitoring round, except for TW-K2, located crossgradient of the $KMnO_4$ injection zone. Although the concentration at MW-070, located upgradient of the $KMnO_4$ injection zone, initially dropped to non-detectable levels, its TCE concentration recovered more rapidly than any other well, probably due to the influx of upgradient contaminated groundwater. For the 10 remaining monitoring wells located within the $KMnO_4$ treatment zone, the concentrations were reduced to non-detectable levels in post-injection monitoring rounds until the May 2003 sampling event (USAF 2003f).

Results from the May 2003 event—when increased concentrations were detected in TW-K4, TW-K5, and TW-K7—suggested that partial recontamination of the test area was most likely occurring because of the influx of contaminated, upgradient groundwater. This pilot test demonstrated that $KMnO_4$ is far more persistent and has a wider radius of influence in groundwater at Plume C than was expected. Therefore, $KMnO_4$ is highly recommended for future consideration in remediating Zone D TCE-contaminated groundwater.

C-Sparger™ Chemical Oxidation. TCE concentrations prior to the initiation of the C-Sparger™ air/ozone sparging system ranged from approximately 175 to 400 µg/L in the six existing wells located in the test area of Plume C. These concentrations decreased immediately after system startup to between 50 and 100 µg/L, but leveled off at these concentrations and were not reduced further in subsequent sampling rounds. Nonetheless, reductions in the TCE concentrations in monitoring wells located 10, 15, and 20 feet downgradient of the sparge points ranged from a low of 50 percent to a high of 75 percent during the nine-month test period. During the same period, the crossgradient and upgradient wells have remained nearly constant or decreased as much as 25 percent (USAF 2003f).

This pilot test proved that ozone is effective in reducing TCE concentrations, destroying contaminant mass, and that the radius of effective influence of the sparge points may be 50 feet or more in Plume C, but it did not reach its target MCLs. A factor that may have prevented further reduction in TCE concentration was a series of equipment breakdowns requiring parts replacement that caused an operating efficiency of only slightly more than 50 percent. Although pilot-scale equipment efficiency may be improved with larger-sized, commercial-grade components, the high O&M costs and lack of reaching RAOs prevent recommendation of the C-Sparger™ technology for further use in Zone D groundwater.

Injected Iron PRB. Granular iron was injected into the Plume E aquifer using jet-grouting technology commonly used in the geotechnical industry for emplacement of bentonite-cement grout or slurry walls. TCE concentrations prior to initiation of iron injection ranged from approximately 450 µg/L in the shallow aquifer to only 32 µg/L in the intermediate aquifer at monitoring well cluster MW-075.

Executive Summary

This Zone D Groundwater Feasibility Study (FS) was prepared by URS Group, Inc. to evaluate alternatives to address the contaminants of concern at F.E. Warren Air Force Base (FEW) in accordance with the United States Environmental Protection Agency *Guidance for Conducting Remedial Investigations and Feasibility Studies Under CERCLA* (USEPA 1988a), Air Force Center for Environmental Excellence Contract F41624-00-D-8028, Delivery Order 013.

FEW is located west of Cheyenne, Wyoming, in south-central Laramie County. Based on results from the installation-wide Remedial Investigation (RI), the FEW Installation Restoration Program (IRP) sites include former landfills (LFs), former fire protection training areas (FPTAs), and historic spill sites (SSs). These sites were first grouped into operable units (OUs) based on site type, location, and projected response action to facilitate and streamline cleanup. OU2 included SS1 through SS7, FPTA2, and groundwater Plumes A, B, C, and E. These groundwater plumes and the groundwater at SS7 were later combined into Zone D. Zone D is located east of Roundtop Road, south and west of Crow Creek, south of Diamond Creek, and excluding Zones B and C. The following is contained in Volume I of this FS:

Section 1 contains the introduction with purpose and organization, background information, and Zone D treatability studies and interim remedial actions (IRAs). The 1991 RI (USAF 1991) represents the first comprehensive RI at FEW and, in 2003, a Zone D-specific groundwater RI was completed (USAF 2003a). Interim removal actions in Zone D to date include excavating waste material at LF2, excavating impacted soil at SS4 and the acid dry well, bioventing at FPTA1, removing a grease trap and impacted soil at SS7, and groundwater extraction and air stripping at SS7. An iron filings permeable reactive barrier (PRB) was installed as an IRA for groundwater beneath SS7 in 1999.

An Engineering Evaluation/Cost Analysis has been generated for an ongoing removal action at SS7. FPTA1 and LF7 are also being investigated as part of the source areas RI, and a final action for these sites is planned in 2004. Several treatability studies and pilot tests have also been completed for Zone D in order to test various remedial technologies, including:

- Bioventing at FPTA1;
- Groundwater extraction and air stripping at SS7;
- Two-phase extraction and gas-phase bioreactor for treatment of soil and groundwater at the head of Plume C;
- Co-metabolic biodegradation using *in situ* submerged oxygen curtain – *in situ* co-metabolic oxidation (iSOC/iMOX™) oxygen and methane infusion at SS7;
- Chemical oxidation using potassium permanganate ($KMnO_4$) and C-Sparger™ ozone/air sparging in Plume C; and
- Direct injection of an iron PRB near the center of Plume E.

The Zone D RI identified trichloroethene (TCE) as the principal contaminant in the five Zone D groundwater plumes. TCE was reported at a maximum concentration of 13,170 micrograms per liter (µg/L) at SS7. The total estimated mass of TCE within Zone D groundwater is 553 kilograms (kg) distributed between Plumes A, B, C, E, and SS7. The plumes vary in lateral extent with lengths ranging from 600 to 5,000 feet, and plume width ranges from approximately

After injection, the northwestern segment (Segment 1) of the PRB showed a 91 percent reduction in shallow groundwater TCE concentrations during the nine-months of monitoring (USAF 2003f). Upgradient c*is*-1,2-DCE concentrations in this shallow segment increased slightly, but remained less than 1 µg/L, while the downgradient DCE concentrations decreased from 7 µg/L in the first sampling round to less than 2 µg/L in the last monitoring round. Virtually no change was detected between upgradient and downgradient TCE concentrations in Segment 1 in intermediate depth groundwater during the test. No vinyl chloride was detected in any of the monitoring wells at this site during the pilot test.

The central segment (Segment 2) showed nearly a 100 percent reduction in shallow TCE concentrations during the same nine-month period (USAF 2003f). Upgradient *cis*-1,2-DCE concentrations in this segment have ranged from nondetect to less than 1 µg/L, while downgradient DCE concentrations increased from nearly 1 µg/L in the first monitoring round to 3 µg/L in the second, then dropped to less than 1 µg/L in the later rounds. The intermediate-zone groundwater at Segment 2 showed a maximum reduction in TCE concentration of 89 percent, while both upgradient and downgradient *cis*-1,2-DCE remained virtually nondetect throughout the test.

In the southeastern segment (Segment 3), the shallow aquifer showed an 83 percent reduction in shallow TCE concentrations immediately after construction, but this was reduced to 60 percent during the ninth month (USAF 2003f). However, this reduction in effectiveness corresponded to a 57 percent reduction in upgradient TCE concentration during the same time period, while the downgradient concentration remained virtually the same. Upgradient and downgradient *cis*-1,2-DCE concentrations in this shallow segment were near nondetect in the first round, but increased both upgradient and downgradient in the later monitoring rounds to a final concentration near 4 µg/L. A 50 percent reduction in intermediate-depth TCE concentrations occurred during the first two months after injection of the PRB, but dropped to 36 percent after nine-months. Again, part of this reduction in effectiveness can be attributed to a drop in upgradient TCE concentrations while the downgradient concentrations remained constant. The upgradient and downgradient *cis*-1,2-DCE concentrations in this segment remained less than 0.25 µg/L throughout the test.

Although jet-grouted iron injection is an innovative installation method for constructing a PRB, it has been proven to successfully treat TCE-contaminated groundwater to nearly 100 percent of its initial concentration in the shallow zone of Plume E. However, the shallow zone may be more easily treated by more conventional PRB trenching techniques such as those used at SS7. In addition, the mobilization cost, equipment size, surface area requirements, damage during construction, and significant investigation-derived waste (IDW) storage and handling requirements are limitations to the implementability of the technology in parts of Zone D. Therefore, this technology is not recommended for future use for Zone D groundwater remediation.

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This section describes the RAOs and general response actions for Zone D, and identifies the focused technology types and process options for groundwater treatment of TCE.

2.1 REMEDIAL ACTION OBJECTIVES

RAOs are site-specific initial cleanup objectives that have been established based on the nature and extent of contamination, potential for human and environmental exposure, and applicable or relevant and appropriate requirements (ARARs). The RAOs provide the basis for selecting appropriate response actions, remedial technologies, and for developing alternatives.

The following RAOs have been identified:

- Restore groundwater to beneficial use, where restoration means TCE and its degradation products meet their respective MCLs.
- Prevent concentrations of TCE and its degradation products in surface water from exceeding the class-specific surface water standards listed in Chapter 1 of the WWQRR (Diamond Creek is Class 3B and Crow Creek is Class 2AB).
- Prevent VOC vapors that originate from groundwater plumes from accumulating to unacceptable risk levels in the indoor air of future buildings.

The surface water RAO applies directly to Crow Creek, which is designated as a Class 2AB stream under the WWQRR, Chapter 1. Class 2AB streams have a TCE standard of 2.7 µg/L. Based on RI results (USAF 2003a), the only TCE plume that has led to an exceedance of this standard is Plume C (12 µg/L at C5.2). Plumes B and E have no documented exceedances of the TCE standard in Crow Creek (USAF 2003a). In addition, decreasing concentration trends in these plumes are presumed to preclude any future exceedances at corresponding surface water locations.

Diamond Creek, a Class 3B stream, is not subject to these standards; however, the contribution of TCE to Diamond Creek from SS7 presents a potential impact to Crow Creek. This is observed in the correlation of TCE concentrations in surface water in Diamond Creek (D4) and downstream of the confluence of Diamond Creek and Crow Creek (C3.5) as shown in Figure 1-2. Therefore, contribution of TCE to the surface waters of Diamond Creek will be addressed within the appropriate remedial alternatives.

Unacceptable risk levels in indoor air do not have corresponding numerical endpoints at this time due to uncertainties associated with the modeling of VOCs from groundwater to indoor air. These uncertainties are discussed in Section 7.2.1 of the Zone D Groundwater RI Report (USAF 2003a). Based on these uncertainties, actions related to future construction should be addressed on a case-by-case basis. In compliance with the FEW General Plan, it is anticipated that all new construction over, or adjacent to, groundwater plumes would require sub-slab vapor venting systems.

2.2 APPLICABLE, RELEVANT AND APPROPRIATE REQUIREMENTS

ARARs are cleanup standards, control standards, and other substantive environmental protection requirements, criteria, or limitations promulgated under federal or state law that may not be applicable to a specific hazardous substance, pollutant, contaminant, remedial action, location, or

other circumstance at Zone D, but address problems or situations sufficiently similar to those encountered at Zone D to render them suitable for use at that particular site.

Section 121(d) of CERCLA requires that on-site remedial actions be evaluated to determine if they meet laws, standards, requirements, regulations, criteria, or limitations under federal environmental laws that are determined to be ARARs. However, ARARs determined by state law must be met if they are promulgated, consistently applied, and more stringent than federal requirements. The National Oil and Hazardous Substances Pollution Contingency Plan (NCP) requires compliance with ARARs during and at completion of remedial actions. Under limited circumstances, ARARs for on-site remedial actions may be waived.

ARARs are identified on a site-specific basis using a two-part analysis: (1) determining whether or not a given requirement is applicable, and (2) determining whether a requirement is relevant and appropriate if it is not applicable (USEPA 1988a). To determine whether a requirement is relevant and appropriate, characteristics of the remedial action, the hazardous substances present, and the physical characteristics of the site must be compared to those addressed in the statutory or regulatory requirement. In some cases, a requirement may be relevant but not appropriate. In other cases, only part of a requirement will be considered relevant and appropriate. When it has been determined that a requirement is both relevant and appropriate, the requirement must be complied with to the same degree as if it were applicable (USEPA 1988a).

Remedial actions may have to comply with the following requirements (USEPA 1988a):

- Chemical-Specific ARARs. Health- or risk-based numerical values or methodologies that, when applied to site-specific conditions, result in the establishment of numerical values. These numerical values establish the acceptable amount or concentration of a chemical that may be found in, or discharged to, the ambient environment.

  In general, chemical-specific requirements are set for a single chemical or closely related group of chemicals. These requirements typically do not consider mixtures of chemicals that might be found at CERCLA sites. For this reason, cleanup goals set at levels of single chemical-specific requirements may not adequately protect human health or the environment at a site. When this occurs, cleanup goals are set below the chemical-specific requirements (i.e., at more stringent levels).

- Location-Specific ARARs. Restrictions placed on the concentrations of hazardous substances or the conduct of activities only because they occur in specific or sensitive locations (e.g., wetlands or areas of historical significance).

- Action-Specific ARARs. Technology- or activity-based requirements of, or limitations on, actions taken with respect to the COC. These requirements are triggered by the specific remedial activities selected to accomplish a remedy. Action-specific requirements do not in themselves determine the remedial alternative; rather, they indicate how a selected alternative must be achieved (e.g., emission standards for air strippers and incinerators, underground storage tank regulations, or land disposal restrictions).

"To be considered" (TBC) items are nonpromulgated advisories, proposed rules, criteria, or guidance documents issued by federal or state government that are not legally binding and do not have the status of potential ARARs. However, these items are to be considered when

determining protective cleanup levels where no ARAR exists, or where ARARs are not sufficiently protective of human health and the environment.

The decision whether to consider an item as a potential ARAR or TBC was based on the assumption that the alternatives under consideration are limited to those discussed in Sections 4, 5, 6, 7, and 8 of this report. This means that none of the potential alternatives would involve (1) discharge to a publicly owned treatment works (POTW); (2) release of any radioactive materials, ammonia, or bacterial contamination; (3) treatment, disposal, or storage more than 90 days on site of any hazardous waste; or (4) release of hazardous air pollutants from pump-and-treat operations.

All of the federal and state requirements were considered as potential ARARs for groundwater. Many of these were determined not to be ARARs, based on site characteristics, site location, and the alternatives considered. Those requirements that were identified as ARARs are listed on Table 2-1 (Chemical-Specific ARARs), Table 2-2 (Action-Specific ARARs), and Table 2-3 (Location-Specific ARARs [and TBCs]), and are briefly described below.

2.2.1 Chemical-Specific ARARs

Chemical-specific federal ARARs include:

- Safe Drinking Water Act (SDWA), 40 Code of Federal Regulations (CFR), Subparts B, F, and G. Provides MCLs and MCL goals for select chemicals in drinking water. Primary drinking water regulations include health-based allowable concentrations of carcinogens and noncarcinogens in drinking water sources.

Chemical-specific state of Wyoming ARARs include:

- Wyoming Environmental Quality Act/Wyoming Air Quality Standards and Regulations. Provides air emission standards for various chemicals and compounds, including fugitive emissions.
- Wyoming Environmental Quality Act/WWQRR. Provides standards for protection of surface water and groundwater. Crow Creek is a Class 2AB stream (cold water fishery), while Diamond Creek and the Unnamed Tributary to Crow Creek are Class 3B streams (aquatic life other than fish).
- Wyoming Hazardous Waste Rules and Regulations. Identifies and lists hazardous wastes.

Chemical-specific ARARs are listed in Table 2-1.

2.2.2 Action-Specific ARARs

Action-specific federal ARARs include:

- Clean Water Act (CWA), 33 United States Code (USC) 1251 et seq. Provides criteria and chemical standards for discharge of pollutants into waters of the United States. Sets requirements for the control of stormwater discharges under the National Pollutant Discharge Elimination System (NPDES) Program.

- Clean Air Act, 40 CFR Part 50. Establishes standards for ambient air quality to protect public health and welfare.

The principal action-specific state of Wyoming ARARs include:

- Wyoming Environmental Quality Act. Provides requirements for discharge into waters of the state or emission of air contaminants.
- WWQRR. Provides regulations for discharges to waters of the state, including surface water and groundwater.
- Wyoming Air Quality Standards and Regulations. Provides standards for control of emissions, including particulates and odors. Also includes requirements for construction, modification, and operation.
- Wyoming Hazardous Waste Rules and Regulations. Provides standards for hazardous waste generators, transporters, and interim status standards for owners or operators of hazardous waste treatment, storage, and disposal (TSD) facilities that also apply to short-term storage of hazardous waste.
- Wyoming Solid Waste Management Rules and Regulations. Prohibits dumping of nonhazardous solid waste (i.e., trash) on the site.

The specific parts of the action-specific ARARs are identified in Table 2-2.

2.2.3 Location-Specific ARARs and TBCs

Location-specific federal ARARs include the following:

- CWA – Dredge and Fill Regulations
- Endangered Species Act
- Fish and Wildlife Coordination Act
- Migratory Bird Treaty Act
- National Historic Preservation Act
- Archaeological and Historical Data Preservation Act
- Archaeological Resources Protection Act

There are also two federal TBC items listed in Table 2-3:

- Executive Order (EO) 11990 – Protection of Wetlands
- EO 11988 – Protection of Floodplains

The principal location-specific state of Wyoming ARARs include:

- WWQRR. Provides water quality standards for groundwater and surface waters based on the particular stream segment and provides for protection of wetlands.

Table 2-3 lists location-specific ARARs and TBCs.

2.3 GENERAL RESPONSE ACTIONS

General response actions are medium-specific response categories that will satisfy the RAOs. General response actions applicable to the RAOs for Zone D groundwater include (Table 2-4a):

- No action
- Institutional controls
- MNA
- Groundwater containment
- Groundwater extraction/*ex situ* treatment/discharge
- *In situ* groundwater treatment—biological, chemical, or physical

2.4 IDENTIFICATION OF TECHNOLOGY TYPES AND PROCESS OPTIONS

The purpose of this section is to identify remedial technologies and process options that will meet the RAOs identified in Section 2.1. Remedial technologies are the methods by which a general response action may be undertaken. Process options are the specific processes within a technology type by which the technology may be implemented.

Remedial technologies and process options corresponding to general response actions for contaminated groundwater in Zone D are presented in Table 2-4a. Within these general categories, a number of technologies and process options were identified as feasible for the *in situ* and *ex situ* physical/chemical treatment of TCE-contaminated groundwater in Zone D. These *in situ* and *ex situ* treatment technologies and process options can be categorized into natural attenuation, biostimulation/bioaugmentation, chemical oxidation, PRB, electrical resistance heating, phytoremediation, mobilization, groundwater extraction, *ex situ* treatment, and discharge. These options and technologies are described in more detail in the following sections and in Table 2-4b.

2.4.1 Institutional Controls

The use of institutional controls allows for both legal and managerial control of a specific area, including resources such as groundwater. Examples of such controls at FEW would be extended land use restrictions (including required review by 90 SW/EM for potential conflicts with implementation of groundwater cleanup activities, and/or control of groundwater access. Additionally, all new construction over or adjacent to groundwater plumes would require sub-slab vapor venting systems to limit risk from indoor air potentially caused by volatilization of VOCs in groundwater. This approach does not address treatment of contamination, however, it restricts exposure to the contamination and development of the affected area until contaminant concentrations are within acceptable levels.

In the case of MNA, longer time frames may be required to achieve RAOs in comparison to active remediation. Because the site may not be available for reuse in comparison to other strategies, extended monitoring and land use restrictions must be used whenever unlimited use and unrestricted exposure do not result from any alternative.

2.4.2 Monitored Natural Attenuation

MNA makes use of natural processes to contain the spread of contamination from chemical spills and reduce the concentration and amount of pollutants at contaminated sites. MNA is also referred to as "intrinsic remediation," "bioattenuation," or "intrinsic bioremediation" and is an *in situ* process. This means that environmental contaminants are left in place while physical, biological, and chemical processes such as dilution, volatilization, biodegradation, dispersion, adsorption, and chemical reactions with subsurface materials are allowed to reduce contaminant concentrations to acceptable levels.

Compared with other remediation technologies, MNA has the following advantages over active remediation:

- Less generation or transfer of remediation wastes;
- Less intrusive, as few surface facilities are required;
- Can be applied to all or part of a given site, depending on site conditions and cleanup objectives;
- Can be used in conjunction with, or as a follow-up to, other (active) remedial measures; and
- Overall cost will likely be lower than active remediation.

A point of consideration is that some degradation products are more harmful than the original contaminants. For example, in some chlorinated solvent plumes, vinyl chloride is more persistent, more mobile, and more toxic than its parent products (e.g., TCE). It must demonstrate that human or environmental receptors will not be exposed to greater risks during the attenuation process.

At sites where groundwater flows to surface water, fate of the contaminants in surface water must also be considered and addressed as appropriate.

2.4.3 Bioremediation

Bioremediation is a general term used to describe the destruction of contaminants by biological processes in which indigenous or inoculated microorganisms (i.e., fungi, bacteria, and other microbes) degrade (metabolize) contaminants found in soil and/or groundwater. Two components of bioremediation are biostimulation and bioaugmentation.

Biostimulation attempts to accelerate the natural biodegradation process by providing nutrients and electron acceptors to indigenous microbes to stimulate a rapid conversion of contaminants to innocuous end products. Although this process is inexpensive when effective, there are performance limitations associated with the various biological parameters, soil interactions, and the requirement of intimate mixing between the microbes and the contaminated groundwater.

Bioaugmentation involves the addition of foreign microbes into an established microbial system and is used to accelerate biodegradation processes when the indigenous microbial population is stressed, non-existent, or not effective in degrading site contaminants. During bioaugmentation, laboratory-cultured microbes that have demonstrated the ability to degrade the site contaminants

are introduced into the contaminated subsurface. Under ideal conditions, the introduced species will thrive, creating a population of microbes able to degrade contaminants specific to the site.

Bioremediation can occur under aerobic or anaerobic conditions. Under aerobic conditions, microorganisms consume atmospheric oxygen in order to function. Under anaerobic conditions, limited oxygen is present, and the microorganisms metabolize other chemical compounds in the soil or groundwater to obtain the energy they need.

Aerobic bacteria degrade any contaminants present through a co-metabolic process where degradation of the contaminant occurs as another carbon source is metabolized. This process is fortuitous, and the microorganisms receive no benefit from metabolizing the contaminant. Aerobic bacteria also consume dissolved oxygen during metabolic oxidation-reduction reactions. These reactions allow the aerobic microorganisms to obtain energy needed for respiration and cell production.

Anaerobic bacteria degrade chlorinated hydrocarbons through reductive dechlorination, where the contaminant is used as an electron acceptor (i.e., is reduced). In this process, a chlorine atom is replaced by a hydrogen atom, sequentially reducing tetrachloroethene (PCE) to TCE to a dichloroethene (DCE) isomer to vinyl chloride and eventually to ethene. This process is not always complete and may only occur in segments based on site conditions. PCE is the most susceptible to reductive dechlorination, since it is a highly oxidized compound. Conversely, vinyl chloride is the least susceptible, since it is the least oxidized.

The following *in situ* groundwater technologies are discussed in this section:

- Anaerobic biostimulation using nutrient enhancement
- HRC®
- Anaerobic bioaugmentation (SiREM KB-1™) with nutrients (iMOX™; HRC®)
- Aerobic biostimulation using biosparging
- Aerobic biostimulation using iSOC/iMOX™
- Aerobic bioaugmentation (Cl-Out™) with oxygen (iSOC™; Oxygen Release Compound [ORC®])

2.4.3.1 Anaerobic Biostimulation using Nutrient Enhancement

To degrade chlorinated ethenes, anaerobic microorganisms require a growth substrate (food source) to facilitate cell development and reproduction, promoting the biodegradation process. Common anaerobic substrates that promote biodegradation are molasses, lactate, or glucose. Components of these food substrates are metabolized to hydrogen, which in turn drives reductive bioremediation processes that effectively degrade chlorinated contaminants.

As a food substrate is added to the subsurface, the microbial community grows and reproduces faster and more efficiently than under natural conditions. This increase in microbial growth stimulates the anaerobic biodegradation process, increasing the extent of the reductive dechlorination processes, and therefore, the rate of contaminant destruction.

Using nutrients to enhance biodegradation by native microorganisms can initiate the reduction of contaminants in place rather than transferring contamination to other locations (e.g., landfills or

water treatment facilities) or phases (atmospheric vapors). Anaerobic bioremediation is an established, relatively low-cost technology that is ideally suited to long-term passive treatment of contaminants.

Evidence suggests there is competition between microorganisms that efficiently degrade contaminants (reductive dehalogenators) and those that do not (methanogens), where the less efficient microbes compete for the use of hydrogen in metabolizing compounds other than the contaminants (i.e., methanogens use hydrogen to convert carbon dioxide [CO_2] to methane). This competition could produce a rapid consumption of hydrogen that does not result in a significant decrease in contaminant concentrations, therefore multiple applications of nutrients may be required.

Molasses injections were delivered during pilot test and full-scale installations at two USEPA sites to reduce concentrations of chlorinated solvents. Performance of the two systems varied significantly and may be attributed to the differences in the type of injection system installed, the soil type, and the groundwater velocity.

At a site located in Emeryville, California, molasses injection created favorable conditions for reducing TCE, DCE, and vinyl chloride in the subsurface. Molasses was delivered during two injection events where a mixture of water, molasses, and a supernatant, containing additional TCE degrading bacteria, was injected into temporary injection points. The soil type at the site was interbedded sand and clay units with a groundwater velocity of 0.16 foot/day. Over an 18-month period, reducing conditions were established and average concentrations of TCE decreased by 99 percent from more than 3,000 to 4 µg/L (USEPA 2000a).

At another site located in Williamsport, Pennsylvania, molasses was injected into semi-permanent injection wells through a programmable feed system where molasses was repeatedly injected at various concentrations and rates based on results from system monitoring. The soil type at the site was sandy silt with a groundwater velocity of 0.02 to 2.3 feet/day. After 18 months of monitoring, reducing conditions were established, however encouraging results were observed at only one out of 16 well location where TCE concentrations in groundwater decreased by 90 percent from 67 to 6.7 µg/L (USEPA 2000b).

2.4.3.2 Hydrogen-Release Compound®

HRC® is a patented product used to stimulate anaerobic biodegradation of contaminated hydrocarbons in groundwater and soil. HRC® is a polylactate ester formulated for slow release of lactic acid upon hydration (Table 2-4b). Indigenous anaerobic microbes (such as acetogens) metabolize the lactic acid, producing consistent low concentrations of dissolved hydrogen. Other subsurface microbes (reductive dehalogenators) in groundwater and saturated soils then use the resulting hydrogen to remove chlorine atoms from the chlorinated contaminant molecules, reducing them to lesser chlorinated compounds, as discussed in Section 2.4.2.

When in the subsurface, HRC® has a time-release feature that slowly releases lactic acid into contaminated environments for periods of up to three years (Regenesis 2002). Lactic acid is widely known as one of the most effective ways to provide hydrogen and electrons to microbial populations as it undergoes microbial breakdown (fermentation). The hydrogen is then exploited by the microbial population for the availability of its electrons and, by example, as a replacement for chlorine in chlorinated contaminants. It is in this manner that HRC® purposefully allows for

prolonged periods of enhanced biodegradation of anaerobically degradable contaminants to occur.

HRC® is a passive, *in situ* approach avoiding substantial design, capital, and O&M costs. It is currently utilized in more than 7,500 soil and groundwater restoration projects in the United States to treat chlorinated solvents. It is widely accepted by regulatory agencies, and it can be applied almost anywhere very quickly, unobtrusively, and cost-effectively. Injection applications are relatively non-invasive, allowing undisturbed operation of commercial facilities during treatment installation and offering lack of visibility during the working phase.

HRC® can be expensive for multiple applications, making it infeasible for long-term and large plume applications. Moreover, it may not be added to existing monitoring wells, due to residual depleted chemical that cannot easily be removed. Therefore, newly installed injection wells are necessary for application.

HRC® is best utilized for the remediation of dissolved-phase plumes and the associated hydrophobically sorbed contaminant. Evidence suggests there is competition between reductive dehalogenators and methanogens in which the methanogens compete for the use of hydrogen in the conversion of CO_2 to methane. Some researchers believe that a low concentration of hydrogen favors the reductive dehalogenators and starves out the methanogens. The objective, therefore, is to keep hydrogen concentrations low. The time-release feature of HRC®, which is based on the hydrolysis rate of lactic acid from the ester and the subsequent lag time to hydrogen conversion, facilitates this objective.

HRC® can be manufactured as a moderately flowable, injectable material or as a thicker, implantable hard gel to facilitate localized treatment and passive barrier designs.

2.4.3.3 Anaerobic Bioaugmentation (SiREM KB-1™) with Nutrients

Bioaugmentation can be an effective treatment method when indigenous microbes are present in small numbers or are not able to biodegrade a specific contaminant (Table 2-4b). Through bioaugmentation, pregrown microbial cultures are added to the subsurface to perform a specific remediation task in a given environment.

In many cases, indigenous microorganisms do not have the ability to completely degrade a specific contaminant, and degradation could "stall" at the *cis*-1,2-DCE stage of TCE conversion even after months of electron donor (HRC®, glucose, etc.) addition. Bioaugmentation can establish anaerobic dechlorinating bacteria at sites to stimulate reduction of contaminants by increasing dechlorinator population densities or to accelerate biodegradation rates to meet treatment goals. An example of a specific bacteria isolated to enhance biodegradation is the SiREM KB-1™ Dechlorinator. This patented *Dehalococcoides* species is a safe, natural microbial consortia that has demonstrated the ability to remediate chlorinated contaminants at USAF installations under diverse field sites and conditions such as those in Texas, Nevada, and Delaware.

As microorganisms are added to the subsurface, nutrients to help establish the population are added simultaneously. These nutrients consist of a food source (carbon source/electron donor) specific to the type of bacteria added to most efficiently assist the growth process. Two technologies that could be used to supply a nutrient food source are iMOX™ and HRC®, as discussed in Sections 2.4.3.5 and 2.4.3.2, respectively.

2.4.3.4 Aerobic Biostimulation using Biosparging

Oxygen enhancement with biosparging is a widely used and accepted technology that consists of injecting air under pressure below the water table to increase groundwater oxygen concentrations and enhance the rate of biological degradation of organic contaminants by naturally occurring microbes (Table 2-4b). The addition of oxygen stimulates aerobic degradation, which for some chlorinated VOCs such as DCE, dichloroethane (DCA), and vinyl chloride is faster than anaerobic degradation. Biosparging alone is generally not effective in the dechlorination of trichloroethane (TCA) and TCE.

Bacteria require a carbon source for cell growth and an energy source to sustain metabolic functions required for growth. The biodegradability of a contaminant is a measure of its ability to be metabolized by chlorinated solvent-degrading bacteria or other microorganisms. Chlorinated solvents such as DCE, DCA, and vinyl chloride are generally biodegradable as long as indigenous microorganisms have an adequate supply of oxygen and/or nutrients. For heavier constituents (which are generally less volatile and less soluble than lighter constituents), biodegradation will exceed volatilization as the primary removal mechanism, even though biodegradation is generally slower for heavier constituents than for lighter constituents. The presence of very high concentrations can be toxic or inhibit the growth and reproduction of bacteria responsible for biodegradation. Conversely, very low concentrations of organic material will result in diminished levels of microbial activity.

To support bacterial growth, the pH should be within the 6 to 8 range, with a value of approximately 7 (neutral) being optimal. If the groundwater pH is outside of this range, it is possible to adjust the pH prior to and during biosparging operations. However, pH adjustment is often not cost-effective because natural buffering capacity of the groundwater system generally necessitates continuous adjustment and monitoring throughout the biosparging operation. In addition, efforts to adjust pH may lead to rapid changes in pH, which are also detrimental to bacterial activity.

2.4.3.5 Aerobic Biostimulation using iSOC/iMOX™

Co-metabolism is best documented in aerobic environments (ITRC 1998). During biodegradation through co-metabolism, an enzyme is produced by the microorganisms for other physiological purposes, such as metabolizing carbon sources (i.e., methane, propane, or butane) for cell growth, fortuitously metabolizes contaminants (Table 2-4b). The microorganisms receive no physiological benefit from degrading contaminants such as TCE, and this degradation can be harmful to the microbe over time. Delivering a supply of oxygen and a carbon source to the microbial environment will continually support the aerobic population so that high levels of cell growth will be maintained during biodegradation of contaminants. The addition of oxygen (100 percent, as opposed to 21 percent found in ambient air) is more efficient in maintaining aerobic conditions for aerobic co-metabolic degradation to occur.

The iSOC/iMOX™ technology is an innovative process capable of delivering high concentrations of gases directly into contaminated groundwater to enhance aerobic biodegradation. The stainless steel, in-well infuser contains closely packed tubes and is connected by a gas line to a surface cylinder of gas. The nearly microscopic infuser tubes are formed from a gas-permeable membrane that allows gases to pass through the tube walls into the surrounding groundwater without allowing

water into the tubes. Gas flow is regulated by super saturation, the process by which groundwater adjacent to the infuser becomes saturated with gas until natural groundwater flow moves the saturated water away from the well. The process is, therefore, self-controlled and operates at hydrostatic pressure, producing no bubbles or stripping (no potentially hazardous vapors), eliminating the need for soil vapor recovery or treatment. The iSOC™ system is designed to supply oxygen to the subsurface and the iMOX™ system is designed to supply the carbon source (i.e., electron donor).

Where the subsurface is heterogeneous, it is very difficult to circulate the oxygen-carbon solution throughout every portion of the contaminated zone. Higher permeability zones may be cleaned up more rapidly since groundwater flow rates are greater and oxygen delivery is more efficient.

This technology is under development and limited treatment data exist.

2.4.3.6 Aerobic Bioaugmentation with Nutrients and Oxygen

Bioaugmentation can be an effective treatment method when indigenous microbes are present in small numbers or are not able to biodegrade a specific contaminant. Through bioaugmentation, pregrown microbial cultures are added to the subsurface to perform a specific remediation task in a given environment. In many cases, indigenous microorganisms do not have the ability to completely degrade a specific contaminant. Bioaugmentation can establish a microbial community at a site to stimulate decreasing contaminant concentrations by increasing population densities or to accelerate biodegradation rates to meet treatment goals. An example of a specific aerobic bacteria isolated to enhance biodegradation of chlorinated compounds is Cl-Out™.

Cl-Out™ is comprised of patented *Pseudomonas* species, which were isolated from a contaminated site in the northern United States. These species have the ability to degrade chlorinated contaminants such as TCE under aerobic conditions without producing harmful byproducts. Cl-Out™ oxidizes chlorinated chemicals using a co-metabolic metabolism, where oxygenase enzymes oxidize TCE, forming an epoxide, which is further oxidized to 1,2-dihydroxy-TCE, then oxidized completely to CO_2, fatty acids, and water.

Cl-Out™ is produced in a freeze-dried form and packaged in 55-gallon bags. Once hydrated, Cl-Out™ can be applied under light pressure through injection wells within 24 hours of adding water to the culture. As the microorganisms are added to the subsurface, nutrients to help establish the population are added simultaneously. These nutrients consist of a food source such as dextrose to most efficiently assist the microbial growth process.

Cl-Out™ is relatively low cost and is designed for standalone application or for augmentation of existing treatments. Complex monitoring of nutrients such as biological growth, oxygen, phosphorous, and nitrogen are required to optimize the performance of Cl-Out™. Effectiveness is dependent upon groundwater conditions within the following ranges: pH equals 5 to 9, temperature = 55 to 95 degrees Fahrenheit (ºF), salinity equals 0 to 5 percent, and DO greater than or equal to (≥) 1.0 part per million (ppm).

In addition to microorganisms and a food source, oxygen must also be added to the subsurface to maintain the aerobic degrading environment. ORC™ or the iSOC™ device can be used to provide oxygen for microbial co-metabolism.

ORC™ is a patented formulation of magnesium peroxide (MgO_2) intercalated with food grade phosphate that produces a slow sustained release of molecular oxygen when in contact with soil moisture or groundwater (Table 2-4b). The term "intercalation" is used to describe the permeation of phosphates into the crystal structure of the magnesium peroxide. This placement of phosphates within the crystalline structure at the molecular level forms pores with the crystal which allows for a continued release of the oxygen for a period of up to one year. ORC™ is insoluble and releases its oxygen while being converted to ordinary magnesium hydroxide, which is also insoluble, in accordance with the following reaction where MgO_2 is magnesium peroxide, H_2O is water, O_2 is oxygen, and $Mg(OH)_2$ is magnesium hydroxide:

$$MgO_2 + H_2O \rightarrow \tfrac{1}{2}O_2 + Mg(OH)_2$$

Both MgO_2 and $Mg(OH)_2$ are environmentally benign and safe enough to ingest. In fact, they are both recognized as medicinal antacids - the more common one being magnesium hydroxide, also known as Milk of Magnesia®.

Controlling the rate of hydration of the crystal affects a timed oxygen release. The concentration of phosphate, and the manner in which it is reacted with and permeates the MgO_2 crystal, creates a product that is well matched to the needs of subsurface remediation. Finally, intercalation facilitates the release of all the oxygen by keeping a "hydroxide ring" from sealing up individual particles during the hydration reaction. Intercalation also increases shelf life stability; ORC™ can be stored for several years without risking significant product degradation.

ORC™ has been utilized in more than 7,500 soil and groundwater restoration projects worldwide to treat fuel hydrocarbons. Using direct-push or monitoring well injection, ORC™ can be applied quickly and unobtrusively in many different types of locations.

2.4.4 Chemical Oxidation and Reduction

In situ chemical oxidation is based on the delivery of a chemical oxidant to contaminated media to destroy the contaminants or to convert them to innocuous compounds commonly found under natural settings. Three oxidants typically applied in this process are Fenton's Reagent (which is hydrogen peroxide [H_2O_2] combined with soluble iron), $KMnO_4$, and ozone.

Different chemical oxidants can be more effective for treating different contaminants. For example, Fenton's Reagent has proven to be effective in treating chlorinated solvents such as PCE, TCE, TCA, DCE, DCA, and vinyl chloride, polyaromatic hydrocarbons, and petroleum products. In comparison, a less aggressive oxidant such as $KMnO_4$ can oxidize PCE, TCE, DCE, and vinyl chloride, but may have limited effectiveness to oxidize TCA, DCA, diesel fuel, gasoline, or benzene, toluene, ethylbenzene, and xylenes (BTEX).

Chemical oxidation can be an effective remedial option, but it is not a universal solution for soil or groundwater contamination. Projects exist where *in situ* chemical oxidation may be ineffective and/or uneconomical based on site-specific conditions. In particular, if the carbonate or bicarbonate content or the total oxidant demand of the site soil or groundwater is elevated, *in situ* treatment may not be cost-effective due to excessive chemical demand for the oxidant. The geochemistry of both the soil and groundwater must be considered for *in situ* application since the oxidant will react with both.

In situ chemical reduction follows a similar premise as chemical oxidation, in which the delivery of a chemical reductant is introduced to the contaminated media to destroy the contaminants or to convert them to innocuous compounds commonly found under natural settings. Common reductive chemicals used in remedial scenarios are dithionite (sodium hydrosulfite), sodium sulfite, calcium polysulfide, sodium borohydride, and gaseous hydrogen sulfide. Chemical reduction is a relatively new technology that is currently under evaluation.

The following *in situ* groundwater technologies are discussed in this section:

- $KMnO_4$
- Fenton's Reagent
- Air/ozone sparging with C-Sparger™ system
- Chemical reduction

2.4.4.1 Potassium Permanganate

$KMnO_4$ is a strong oxidant that has been used in drinking water and wastewater treatment for several decades to oxidize raw water contaminants (Table 2-4b). $KMnO_4$ effectively attacks and breaks the carbon-carbon bonds in chlorinated ethenes such as PCE, TCE, DCE, and vinyl chloride. The following represents the chemical reaction for the complete destruction of TCE by $KMnO_4$:

$$2KMnO_4 + C_2HCl_3 \rightarrow 2CO_2 + 2MnO_2 + 2K^+ + 3Cl^- + H^+$$

where C_2HCl_3 is TCE, CO_2 is carbon dioxide, MnO_2 is manganese dioxide, K^+ is the potassium ion, Cl^- is the chloride ion, and H^+ is the hydrogen ion.

$KMnO_4$ is received from a chemical distributor in the form of a dry crystalline purple powder. The powder is mixed with water at the treatment site to achieve the desired aqueous concentration. The purple color acts as a built-in indicator for unreacted oxidant since reacted chemical is black or brown. The brown color indicates the presence of a MnO_2 byproduct, which is also naturally present in soil.

Recent studies have demonstrated that $KMnO_4$ may be more effective at treating moderate to low levels of dissolved groundwater contamination rather than dense non-aqueous phase liquids (DNAPL) and significant sorbed-phase material located in source areas. As show in the reaction above, MnO_2 is produced during the reaction with TCE. MnO_2 is a brown solid occurring at neutral pH levels and under redox potential (Eh) conditions from +0.6 volts (V) to approximately +1 V. MnO_2 can precipitate out of solution and cause a reduction in aquifer permeability. Concern over permeability loss due to precipitation is thought to be greatest for sites with high concentrations of contaminants or DNAPL, to which a high concentration of $KMnO_4$ is delivered for treatment. MnO_2 solids can coat porous media or even DNAPL particle surfaces as interfacial deposits, causing a reduction in DNAPL solubility and aquifer permeability. In addition, permeability loss can be significant due to MnO_2 formation on well screens and filter packs (Siegrist *et al.* 2001). However, following more precise delivery methods, MnO_2 solids can be discrete and agglomerated micron-sized particles that remain mobile in groundwater. To address the potential problem of permeability loss from MnO_2 particles, small volumes of low-

concentration $KMnO_4$ (1 to 2 weight percent) can be delivered using multiple injection locations and depths.

Other $KMnO_4$ oxidation byproducts include CO_2, Cl^-, H_2O, and K^+. Soil with a high carbonate or bicarbonate content has no negative impact on its performance. However, multiple injections of the chemical will be required when $KMnO_4$ is most likely to be consumed during oxidation of other compounds, such as sulfide, metals, or TOC, to more stable forms, such as sulfate and iron oxide.

$KMnO_4$ application is generally found to result in significant degradation of TCE, PCE, and DCE under a wide range of conditions. It is inherently more stable than H_2O_2, which tends to decompose rapidly to water and oxygen when contacted with soil. $KMnO_4$ is very effective for application where oxidizing power must be maintained over longer time periods, such as when the oxidant must access large volumes of subsurface media.

The effectiveness of $KMnO_4$ is limited by the extent of subsurface distribution and the need to establish contact with contaminant. Multiple treatments are generally required to achieve treatment goals. Where the subsurface is heterogeneous, it is very difficult to circulate the oxidizing solution throughout the different zones of contamination. Higher permeability zones are cleaned up much faster due to preferential flow and better distribution of $KMnO_4$.

2.4.4.2 Fenton's Reagent

In situ chemical oxidation using Fenton's Reagent is based upon Fenton's chemistry, developed by H.J.H. Fenton in the mid-1890s, and involves the oxidation of malic acid using H_2O_2 and iron salts as catalysts (Table 2-4b). Fenton's Reagent is a chemical oxidant that can be injected into the subsurface to treat DNAPL, sorbed-phase, or dissolved-phase contamination in the saturated zone. Conventional Fenton's chemistry reactions are produced when H_2O_2 is applied with the iron catalyst, creating a hydroxyl free radical (OH•) capable of oxidizing complex organic compounds such as PCE, TCE, DCE, and vinyl chloride. The fundamental Fenton's reaction involving the addition of H_2O_2 to a solution of ferrous iron (Fe^{2+}) is shown as follows:

$$H_2O_2 + Fe^{2+} \rightarrow OH\bullet + OH^- + Fe^{3+}$$

where OH^- is the hydroxide ion and Fe^{3+} is ferric iron. Residual H_2O_2 decomposes into water and oxygen in the subsurface and any remaining iron precipitates out of groundwater as Fe^{3+}. When introduced to water containing chlorinated solvents, the hydroxyl radical reacts to form CO_2, H_2O, and Cl^-.

The hydroxyl radical created is a powerful oxidizing agent, second only to elemental fluorine in its reactivity and capable of treating DNAPL or sorbed-phase contamination. In addition, minor agitation produced during the reaction between H_2O_2 and Fe^{2+} can assist in transferring sorbed or immobile contamination into the dissolved phase, where it can be treated more effectively. These treatment capabilities are what make Fenton's Reagent effective for source area treatment.

Because Fenton's Reagent is capable of releasing sorbed-phase contamination from saturated soil particles into the dissolved phase, a dramatic increase in contaminant concentrations is typical following an injection; however, the increase is temporary. Over a short period of time (days to weeks) the dissolved-phase contaminant is treated with the excess reagent, resulting in decreased contaminant concentrations, although minor amounts of contaminant re-adsorption to

soil may occur. Recent studies have demonstrated that any depletion of the native microbial population stemming from oxidant injection is temporary and could lead to longer term enhancement by releasing sorbed-phase carbon compounds from soil, making them more bio-available.

The reaction between H_2O_2 and Fe^{2+} is vigorous and can produce significant amounts of off-gassing, causing injected material to force its way up and onto the ground surface. Because of this tendency for the material to surface, modified iron catalysts have been created to slow down the reaction between H_2O_2 and Fe^{2+} to a more controlled pace. Slowing down the reaction controls the off-gassing process, creating more favorable conditions for the injected material to remain below ground. In addition to a slower, more controlled reaction, the modified Fenton's Reagent does not require pH adjustments, as with conventional Fenton's Reagent where acidic conditions are necessary to maintain ferrous iron concentrations. Some modified Fenton's Reagent formulas are effective at neutral pH and result in a less than 25°F-temperature increase during field applications.

Multiple applications of Fenton's Reagent may be required to achieve treatment goals. Other chemical compounds in the subsurface such as metals, sulfide, and TOC, can exhibit an oxidant demand causing a fortuitous use of the oxidant. In addition, where the subsurface is heterogeneous, it is difficult to circulate the oxidizing solution throughout the different zones of contamination. Higher permeability zones are treated much faster due to preferential flow also creating a need for multiple applications.

A key component of this technology is the proprietary injection process (Patent #5,525,008) of *In situ* Oxidative Technologies, Inc. (ISOTEC) of Champaign, Illinois. With conventional Fenton's Reagent, the effective implementation of the reaction requires adjusting the treatment zone to a pH of 3 to 5, adding the iron catalyst ($FeSO_4$) and H_2O_2 slowly. If the pH is too high, the iron will precipitate as iron hydroxide ($Fe(OH)_3$) and catalytically decomposes the H_2O_2, generating intense heat and pressure due to the violent exothermic reaction. ISOTEC uses chelated iron and buffering agents to reduce this reaction. As compared to conventional Fenton's Reagent, which requires acidic conditions (pH~3), the ISOTEC process is effective at neutral (pH~7) conditions. This is an important consideration in full-scale application since acidifying an aquifer is typically impractical. However, carbonate minerals also react vigorously with the reagent, resulting in higher reagent requirements and in many cases precluding application to limestone aquifers or soils. Dissolved carbonate in water, existing primarily as bicarbonate ion, also reacts with reagent to form a free radical trap that can also reduce oxidation efficiency. High carbonate/bicarbonate conditions are not expected at FEW.

Another variation on the classic Fenton's process has been developed by another Illinois company – BioManagement Services of Tinley Park. The company's patent-pending BIOX process uses magnesium peroxide to create the H_2O_2 that oxidizes the contaminants. This process has field evidence to indicate that its reaction is significantly less exothermic than the conventional Fenton's reaction, raising temperatures only 6 to 10ºF rather than nearly 100ºF. In addition, the oxygen not used up in the oxidation process is available for the remaining soil microbes and may provide a biostimulation component of the remediation. The proprietary BIOX chemicals are injected into the subsurface using a patented direct-injection delivery (DID) system using high-velocity, low-volume fluid dynamics to liquefy the soil in front of the injector probe. The probe is then advanced into the subsurface by hand to depths as great as 13 feet. This injection system allows more dense spacing of injection points for better contact with the

soils. The injection process was modified to include the use of a direct-push rig to reach maximum depths of 22 feet. These limited depths may also be of concern at FEW, and an auger drill rig at greater cost may, therefore, be required to inject the BIOX chemicals to the desired depths or into the desired lithologies.

Capital, reagent, and O&M costs are typically higher for Fenton's Reagent injection than for $KMnO_4$, but the results, especially in areas of groundwater TCE concentrations in the thousands of µg/L, are fast, with verifiable results in treatment time frames that are measured in months as opposed to years.

2.4.4.3 Air/Ozone Sparging with C-Sparger™ System

The C-Sparger™ is an off-the-shelf system that relies on chemical oxidation of contaminants using ozone to degrade dissolved chlorinated hydrocarbons such as TCE, the DCE isomers, and vinyl chloride from groundwater (Table 2-4b). Ozonation remediates the chlorinated VOCs in groundwater by reducing the toxicity of the compounds by breaking the chlorine bond to form nontoxic, mineralized compounds including H_2O, CO_2, and Cl^-. C-Sparger™ injection provides 100 percent ozone, instead of the 21 percent oxygen of air sparging, to dechlorinate TCE, PCE, and other chlorinated hydrocarbons, unlike conventional air sparging, which is generally not capable of reducing the toxicity, mobility, or volume through treatment of such compounds.

Due to its microsparge air injectors, the C-Sparger™ produces microscopic bubbles in groundwater, much smaller than those produced in conventional air sparging systems. These smaller bubbles travel more easily through the microscopic soil pores in the saturated zone and reduce the time required to both dissolve the contained oxygen and reach downgradient contamination. In addition, the C-Sparger™ uses these smaller bubbles to encapsulate ozone molecules so that the ozone can move more readily through the aquifer than indirect ozone injection or with other ozone delivery methods. The pressurized system allows the microfine bubbles that transport encapsulated ozone to infuse the formation without fracturing it.

Design of the system and depth locations of sparge points is governed by subsurface heterogeneities. Airflow through the saturated zone may not be uniform. Where the subsurface is heterogeneous, higher permeability zones are cleaned up much faster due to preferential flow. Significant layering of low permeability material above the sparge point can significantly reduce the area of influence of the sparge point, impeding the oxidation and stripping capability of the system.

2.4.4.4 Chemical Reduction

In situ chemical reduction follows a similar premise as chemical oxidation, in which the delivery of a chemical reductant is introduced to the contaminated media to destroy the contaminants or to convert them to innocuous compounds commonly found under natural settings (Table 2-4b). Similarly, it is useful for source area mass reduction and intercepting of plumes to remove mobile contaminants. Common reductive chemicals used in remedial scenarios are dithionite (sodium hydrosulfite), sodium sulfite, calcium polysulfide, sodium borohydride, and gaseous hydrogen sulfide. Other common reductants include metabisulphate and ferrous sulfate, but may require post-treatment neutralization.

Similar to chemical oxidation, this process may not be cost-effective for high contaminant concentrations because of the large amounts of reductive agent required. Similarly, reductive chemicals will be consumed by noncontaminant species, which increases treatment cost and creates the potential for forming undesirable byproducts.

Chemical reductants such as gaseous hydrogen sulfide are powerful reagents, but are difficult and very dangerous to handle. Until recently, data regarding effectiveness in remediating chlorinated VOCs were limited – field demonstrations focus on effectiveness for hexavalent chromium.

Amonette *et al.* (1994) investigated the efficiency of dithionite in creating a subsurface reduction zone. Based on the column study, the reduced aquifer barrier created in this way could maintain a reducing environment for about 80 pore volumes before being reoxidized by groundwater. Within a week, approximately 90 percent of the carbon tetrachloride had been destroyed, while only minor losses of carbon tetrachloride occurred in the oxidized sediment during the same time period. Of the carbon tetrachloride destroyed, less than 10 percent was converted to trichloromethane, and no dichloromethane was detected.

At Fort Lewis, Washington, dithionite was evaluated for its efficiency in removing TCE from groundwater (Field Hydrology and Chemistry Group 2001). Products of TCE dechlorination showed that 99.5 to 100 percent was occurring via reductive elimination, producing chloroacetylene, acetylene, and ethylene. A bench-scale test of calcium polysulfide for TCA and DCE degradation was conducted at the Denver Federal Center, Colorado. The results of this test were negative and did not achieve the desired result.

2.4.5 Permeable Reactive Barriers

There are three types of PRBs commonly used. In a continuous PRB, treatment material is distributed across the entire path of the contaminated groundwater, as was constructed at SS7. In the case of granular iron, the iron has a hydraulic conductivity greater than many aquifers and thus should not significantly alter the natural groundwater flow path or velocity. The second type, the funnel-and-gate design, is currently installed at the Denver Federal Center, using a sheet pile funnel to direct flow to iron gates. The third type, the reaction cell, is a modified funnel-and-gate design with the reactive medium placed in a constructed "cell" of steel or concrete, with water piped into the system by gravity flow or pumping. The continuous permeable wall has been the most common configuration used recently in the United States, while the funnel-and-gate and reaction cell are still more commonly used in Europe.

A permeable zone of iron granules, other minerals, or organic materials can be designed to create a reactive treatment barrier oriented to intercept and remediate a contaminant plume. This barrier allows the passage of water while degrading contaminants. The following focused *in situ* groundwater technologies are discussed in this section:

- Additional ZVI by trenching
- Additional ZVI by injection
- Additional ZVI in reaction cell
- E-barrier
- Bark mulch biowall

2.4.5.1 Additional Zero Valent Iron by Trenching

As iron is oxidized, a chlorine atom is removed from the compound by one or more reductive dechlorination mechanisms, using electrons supplied by the oxidation of iron. The iron granules react in the process, but the metal disappears so slowly that the remediation barriers can be expected to remain effective for many years, possibly even decades.

Installation of a ZVI PRB by trenching requires the use of trenching machines that have been developed for installing underground utilities and constructing french drains and interceptor trenches (Table 2-4b). The most widely available utility trenching machines have depth capability of less than 25 feet, while some specialized machines used for interceptor well construction can excavate up to 30 to 40 feet. These machines incorporate a mechanism to temporarily shore the trench behind the cutter in a more or less continuous operation until the backfill is placed in the trench. Excavation with these specialized machines may lower the cost of PRB installation. Typical practice is to increase the PRB thickness by mixing the ZVI with sand to enhance hydraulic conductivity, facilitate construction, and/or to minimize construction costs. In an ideal homogeneous soil, as much as 400 tons of iron can be placed in a trench in one day. However, the presence of boulders severely limits the utility of this and other techniques and may require additional excavation approaches to complete installation. Trench-box trenching, with a sheet-pile starter trench, was used for installation of the SS7 PRB in 1999.

Procedures similar to shoring of the trench and use of an appropriate slurry or steel sheet piling are required for excavation to greater depths and also allow greater flexibility of design and quick installation. The most common liquid used for trench shoring is guar gum (naturally occurring carbohydrate polymer derived from guar beans) because it is biodegradable and would not lead to plugging of the wall with residual slurry material. The slurry exerts hydraulic pressure against the trench walls and acts as shoring to prevent collapse. Once the excavation and backfilling are complete, an enzyme breaker can be added to the trench to expedite biodegradation of the slurry and the reestablishment of permeability. The slurry would not affect the final permeability of the *in situ* soil or ZVI backfill materials.

ZVI PRBs are a method of passive remediation, with no ongoing energy input and limited maintenance following installation, no required surface structures other than monitoring wells following installation. Contaminants are not brought to the surface, therefore, there are no disposal requirements or disposal costs for treated wastes.

Factors that may limit process the applicability and effectiveness include:

- Passive treatment walls may lose their reactive capacity, requiring replacement of the reactive medium.
- Passive treatment wall permeability may decrease due to precipitation of metal salts.
- Depth and width of barrier.
- Limited to a subsurface lithology that has a continuous aquitard at a depth that is within the vertical limits of trenching equipment.
- Cost of treatment is medium.
- Biological activity or chemical precipitation may limit the permeability of the passive treatment wall.

- Plume must be very well characterized and delineated.
- Does not control or remediate the plume already present down gradient of the wall installation.
- Limited field data concerning longevity of wall reactivity or loss of permeability due to precipitation or biofouling.
- Proprietary licensing fee for use of ZVI.

2.4.5.2 Additional Zero Valent Iron by Injection

Limitations of conventional, trenched PRB construction are primarily implementability issues, and the challenges of placing ZVI at depths greater than 15 to 20 feet below the water table in heterogeneous lithologies (Table 2-4b). Direct injection of ZVI has the potential to address zones of deeper contamination, as well as to laterally extend the existing PRB in a comparatively cost-effective manner.

Jet-grouted iron injections with a rotary drill rig can create patterned, overlapping, iron-filled voids that essentially create a PRB without the need for trenching and soil removal. Voids are kept open through the injection of a biopolymer slurry consisting of a natural, biodegradable, nontoxic, food-grade guar gum. As mentioned above, this slurry is commonly used in slurry wall construction of conventional ZVI PRBs. Although the residual guar would eventually break down naturally in groundwater, a natural enzyme "breaker" is added to the slurry before installation to speed the biodegradation process. The iron is injected after the void is formed, displacing most of the slurry inside the void. This jetted soil and the displaced slurry are captured as they flow from the void and will be disposed of by an IDW subcontractor. Occasionally, residual guar has acted as a nutrient to stimulate microbial activity in the saturated zone upgradient of the PRB, with resultant biofouling. However, careful measuring and thorough mixing of the enzyme breaker should prevent this problem.

Advantages of this approach over ZVI emplacement by trenching is that there is no need to excavate and dispose of contaminated soil and it offers aquifer access at greater depths, although a significant amount of liquid IDW is generated during the injection process. Other factors that may limit the process applicability and effectiveness include:

- Passive treatment walls may lose their reactive capacity, requiring re-emplacement of the reactive medium.
- Difficult to ensure connectivity of the ZVI PRB when installed with jet grouting.
- Passive treatment wall permeability may decrease due to precipitation of metal salts.
- Width of barrier.
- Cost of treatment is medium.
- Biological activity or chemical precipitation may limit the permeability of the passive treatment wall.
- Plume must be very well characterized and delineated.

- Does not control or remediate the plume already present downgradient of the wall installation.
- Limited field data concerning longevity of wall reactivity or loss of permeability due to precipitation or biofouling.
- Proprietary licensing fee for use of ZVI.

2.4.5.3 Additional Zero Valent Iron by Deep Soil Mixing

Deep soil mixing (DSM) is a soil improvement technique normally used to construct cutoff or retaining walls and treat soils *in situ* (Table 2-4b). This is accomplished with a series of overlapping stabilized soil columns (typically 24- to 36-inch diameter). The stabilized soil columns are formed by a series of two to four mixing shafts guided by a crane-supported set of leads. As the mixing shafts are advanced into the soil, reagent, grout, or slurry is pumped through the hollow stem of the shaft and injected into the soil at the tip. The auger flights and mixing blades on tie shafts blend the soil with reagents, grout, or slurry in a pug mill. The mixing shafts are positioned to overlap one another and form a continuously mixed overlapping column. When the design depth is reached, the augers are withdrawn and the mixing process is repeated on the way to the surface. Field quality assurance/quality control (QA/QC) samples are retrieved from the wall for testing (every 100 linear feet of the DSM wall from each day's work). These samples are taken by a special sampling tool at mid-depth of the DSM column immediately following installation.

Geo-Con, a Denver DSM contractor, completed 7,350 linear feet of groundwater barrier to a depth of 37 feet bgs at Rocky Mountain Arsenal in 1999 using this technique. At Hill AFB near Ogden, Utah, a 1,330-foot-long barrier was completed in 1996 using this technology. However, both of these DSM barriers were designed to be impermeable walls, not PRBs.

In situ Fixation, Inc.'s (I-SF) Dual Auger® mixing system consists of alternate sections of auger flights and mixing blades that rotate in opposite directions to pulverize the soil and blend in the appropriate volume of treatment reagent. The mix proportions, volume, and injection pressures of the reagent are continuously controlled and monitored by an electronic instrumentation system. The electronic monitoring system sustains strict quality control of the reagent expended, thus assuring that the correct ratio of reagents to soil is maintained. If during the installation process the contaminants present in the soil have a tendency to become airborne (i.e., vapors), a hood and filter system can be added to the Dual Auger® mixing system, therefore eliminating the possibility of contaminants escaping into the atmosphere.

I-SF was the first company to inject and evenly distribute fine iron particles into the soil in a slurry batch process utilizing an auger. The fine iron particles consisted solely of carefully sized metallic ZVI. In this application, iron, steam, and hot air were simultaneously injected into the soil during mixing. The steam and air quickly removed the majority of the VOCs, and the injected ZVI continued the reaction process where a reducing chemical state resulted in the dechlorination of the remaining VOCs. The amount of ZVI was determined by residence time analyses and column testing, just as for a trenched or injected PRB. The ultimate result of this reaction process was the *in situ* removal of more than 98 percent of the chlorinated VOCs from the soil.

Once in place, the DSM barrier requires little O&M and should remain reactive for many years. It has similar limitations to those listed above for the injected PRB.

2.4.5.4 Electrical Barrier

Recent research conducted at Colorado State University has demonstrated that groundwater contaminants can be treated using flow-through electrolytic reactors (E-barriers) (Sale *et al.* 2001) (Table 2-4b). This is built upon the concept of an *in situ* PRB, in that the process involves application of low intensity direct electrical current across electrode pairs imposing oxidizing conditions at the positive electrode and reducing conditions at the negative electrode. Oxidation and reduction reactions occur sequentially via electrolytic process such as electro-osmosis and ion migration. Contaminants migrate toward respective electrodes depending upon their charge (Sale *et al.* 2001).

Sequential oxidation and reduction has the potential to address a wide range of contaminants including mixtures that are difficult to address with current technologies. The method itself is environmentally benign in that no chemicals or gases are introduced and no byproducts are released. The approach is fundamental in that chlorinated hydrocarbons are held together by shared pairs of electrons, so the addition or removal of electrons provides a direct means of driving chlorinated solvents and other common contaminants to environmentally innocuous compounds (e.g., carbon dioxide, water, and chloride). Furthermore, rates of chemical transformation can be modified remotely by adjusting applied voltage.

Installation of a panel through a plume would be challenging in deep and/or thick aquifers. In general, from a construction perspective, shallow applications would be the most feasible.

In waters containing high alkalinity, scale formation at the negative electrode may inhibit degradation of contaminants. Success in high carbonate environments would require effective measures to minimize and/or periodically remove scale from the negative electrode, such as reversing the potential to remove the inorganic precipitates.

E-barrier is an innovative technology with limited field testing and may be expensive to install and operate at full scale. The current field-scale installation in Plume C is being conducted by Colorado State University (Sale *et al.* 2001).

2.4.5.5 Bark Mulch Biowall

AFCEE completed pilot-scale testing of a permeable reactive biowall in August 2000 at Offutt AFB near Omaha, Nebraska (USEPA 2002b) (Table 2-4b). Field tests were conducted to determine the efficacy of organic mulch as an electron donor for promoting biological reductive dechlorination of groundwater contaminated with TCE. Mulch was selected as the electron donor for the biowall due to evidence of reductive dechlorination under an adjacent agricultural field where the soil contains a high level of naturally occurring organic carbon. The low cost associated with obtaining mulch was also considered.

The pilot test took place at a site used between 1942 and 1945 to manufacture military aircraft. The resulting groundwater contamination consists of a 3,000-foot plume with TCE concentrations reaching 2.2 milligrams per liter (mg/L). Soil in the area comprises alluvial silt and clay, with groundwater located approximately 6 feet bgs. Hydrologic testing indicated that the underlying 30-foot aquifer has an average flow velocity of 84 feet per year, a gradient of 0.01 foot/foot, and a hydraulic conductivity of 3.5 feet per day.

Mulch was generated on site using shredded trees and leaves, mixed with coarse sand in a 50:50 ratio to enhance the permeability and stability of the biowall. Using a continuous trencher, a 1-foot-thick wall was installed and filled simultaneously to a length of 100 feet and depth of 23 feet. Two upgradient, four downgradient, and two control wells were sampled in five events during the 31-month pilot test.

Sampling results indicated depressed oxygen concentrations and oxygen-reduction potentials due to the consumption of organic matter and oxygen by aerobic bacteria. Nitrate and sulfate levels also declined. Methane production was observed, providing further evidence of the establishment of reducing conditions. Over 31 months of treatment, the mean TCE removal 20 feet downgradient of the biowall was approximately 70 percent. Upgradient TCE concentrations were variable (0.3 to 2.1 mg/L), but downgradient TCE concentrations were consistently between 0.2 and 0.6 mg/L. The ratio of *cis*-1,2-DCE to TCE downgradient of the wall increased by a factor of 820 after five months of treatment. This ratio subsequently dropped as *cis*-1,2-DCE was converted to vinyl chloride, ethene, and ethane. The control plot showed no decrease in TCE concentrations.

Demonstration findings suggest that this technology is appropriate at sites with shallow (less than 8 feet) groundwater and biowalls extending less than 30 feet bgs. Costs for installing the Offutt AFB biowall were approximately $140 to $360 per linear foot. If not generated on site (at no cost), mulch for applications at other sites is estimated to cost approximately $20 per cubic yard.

Performance data from the Offutt AFB pilot study indicated that the biowall is a low-maintenance, cost-effective, *in situ* treatment wall technology. Based on these results, a full-scale 500-foot biowall was installed at Offutt AFB in July 2001. Additional performance data for this technology were collected over the next two years during full-scale operations. Prior studies by others indicate that a mulch-based biowall will last approximately 10 years.

AFCEE also constructed a 500-foot-long, 25-foot-deep mulch biowall at Altus AFB, Oklahoma, in 2002, and the technology is being considered for implementation at two additional USAF sites. Such a wall has been suggested for pilot testing in one of the Zone D TCE plumes at FEW.

2.4.6 Electrical Resistance Heating with SVE

The *in situ* electrical resistance heating technology to be discussed in this section is electrical resistance heating (ERH) combined with soil vapor extraction (SVE) (Table 2-4b). ERH treats contamination in the subsurface by passing an electrical current through the soil matrix, including the groundwater. The passage of an electrical current generates heat due to electrical resistance from the soil. Soil moisture boils into steam that travels to vapor recovery wells for vapor extraction and removal. Contaminants with a boiling point below or close to that of water are removed from the subsurface primarily by a combination of volatilization and steam stripping.

The innovation combines an emerging technology, ERH, with a baseline technology, SVE. ERH was developed to remediate soils contaminated with VOCs and semivolatile organic compounds (SVOCs) and is designed to enhance the removal of contaminants from the subsurface during SVE. ERH is especially suited to sites where permeability is low and contaminants are tightly bound to clays, making removal solely by SVE difficult. In addition, this technology is capable of reducing contaminant concentrations to below MCLs.

Heating is largely dependent on soil moisture; soils of low permeability and high water content are preferentially heated. Heating also raises the vapor pressure of VOCs and SVOCs, increasing their volatilization and concomitant removal from the soil via vapor extraction. As soil is heated, it dries and creates steam, which increases the permeability of the formation (this may be beneficial in low permeability materials), and strips contaminants that may not be removed via simple SVE.

Six-phase heating (SPH), a form of *in situ* ERH, uses conventional single-phase transformers to convert standard three-phase electricity into six-phase electricity, producing an improved subsurface heat distribution. This electricity is applied to the subsurface via electrodes. Each phase is delivered to a single electrode, which can be installed either vertically to specific depths, or horizontally, underneath buildings and/or buried utilities. Electrodes are placed in the ground in an arranged array, such as a hexagon, to provide a uniform distribution of electrical current. Current flows along a straight-line path between the electrodes and fans out slightly in the vertical and horizontal directions. The result of this electrical current distribution is even heat generation in the subsurface that leads to uniform steam production and VOC volatilization throughout the treatment volume. The vapor extraction well, which removes the contaminants, air, and steam from the subsurface, is located in the center of the hexagon. Alternative extraction (venting) configurations may be applied.

The advantages of SPH include:

- Significantly more power delivered to the bulk soil and less at the electrodes than other resistive heating techniques (such as three-phase heating).
- Conventional utility power transformers are used at a relatively low capital cost as compared to other electrical heating techniques.
- Permeable soils are not required as for SVE and most other heating methods.
- Six-phase current is less affected by grain size than three- or single-phase current, therefore it is effective in clay.

ERH can be an effective remediation technology to treat sites contaminated with VOCs such as PCE; TCE; DCE; 1,1,1-TCA; and fuel compounds that possess boiling points below or close to that of water. The media to receive treatment can be either saturated soil and groundwater, where steam is created allowing the contaminants to be stripped, or the overlying unsaturated soil (unsaturated soil typically contains 3 to 10 percent moisture, even in arid climates), where generated heat can initiate contaminants volatilization.

Subsurface sorbed-phase contamination that exists in areas with complex geology, low soil permeability, and low groundwater velocity can present serious challenges for treatment effectiveness. Unlike other technologies, ERH is not limited in the subsurface by distribution or groundwater flow since all areas selected in the treatment zone are affected by the passage of the electrical current. DNAPL residual saturation that can produce asymptotic results for pump-and-treat systems does not pose difficulties for ERH since all subsurface material, groundwater and soil, are heated uniformly. ERH is a fast-acting technology since it does not rely on groundwater velocity, and contaminant removal is controlled by delivering electrical current and the vapor extraction.

ERH was chosen by the U.S. Army Corps of Engineers for a Design Verification Study (DVS) in Operable Unit B (OUB) at Fort Richardson in Anchorage, Alaska. The lithology at OUB consists of dense, low permeability, heterogeneous glacial tills. Three stacked aquifers exist between 8 to 40 feet bgs. The site impact from chlorinated compounds—1,1,2,2-tetrachloroethane (PCA), TCE, and PCE—extended to at least 35 feet bgs. Impacts from the PCA were as high as 16,000 mg/kg in soil and 1,900 mg/L in groundwater.

Prior studies indicated that, without heating, SVE could take up to 10 years to reach OUB cleanup goals. ERH was selected over steam injection and radio frequency heating as the preferred heating enhancement because it more efficiently delivers energy to the subsurface. The purpose of the DVS was to evaluate the ability of SPH to accomplish the following goals:

- Quickly reach subsurface temperatures of 100 degrees Centigrade (°C)
- Maintain these temperatures throughout the test period
- Significantly increase contaminant removal rates
- Provide documented soil remediation results

Three hexagonal SPH arrays were operated sequentially for a period of six weeks each. Arrays 1 and 2 measured 27 feet in diameter, while Array 3 was 40 feet in diameter. All three arrays were designed and installed to heat the subsurface interval of 8 to 40 feet bgs.

Soil and groundwater within each array were heated to 100°C during the initial two weeks of operations. The arrays were then operated for an additional four weeks to allow boiling of the stacked aquifers and steam stripping of the soil matrix. Pre- and post-treatment soil sampling were performed inside and outside of each array. Sampling extended outside the arrays to a distance of 40 percent of the array diameters.

Results for Arrays 1 and 2 showed an average VOC removal of 96 to 97 percent with a 98 to 99 percent reduction of PCA concentrations. Results for Array 3 indicated an average VOC reduction of 44.5 percent. However, seven of 12 soil samples removed from the interior of Array 3 contained VOCs at concentrations below detection limits, and the average reduction of VOCs from the interior of Array 3 was 96.7 percent.

ERH successfully increased subsurface temperatures to the boiling point of water within days and held that temperature throughout the design verification period. Treatment at Arrays 1 and 2 extended beyond the arrays by at least 40 percent of the array diameters, but was limited to the array diameter at Array 3. The DVS indicated that ERH is an effective technology for removing chlorinated solvents from saturated soil in very short time frames.

2.4.7 Phytoremediation

Phytoremediation is an emerging passive *in situ* technology that uses plants and their associated rhizospheric microorganisms to remove, degrade, or contain chemical contaminants located in soil and groundwater (Table 2-4b). Researchers have found that plants can be used to treat most contaminants classes, including petroleum hydrocarbons, chlorinated solvents, pesticides, metals, radionuclides, and explosives. Plant species are selected for phytoremediation based on their potential to evapotranspirate groundwater, the degradative enzymes they produce, their growth rates and yield, the depth of their root zone, and their ability to bioaccumulate contaminants.

Despite the diversity of phytoremediation technologies, its application is limited by a number of factors. Phytoremediation can only work at sites that are well suited for plant growth. This means that the concentration of pollutants cannot be toxic to the plants, and the pollution cannot be so deep in the soils or groundwater that plant roots cannot reach it. As a result, phytoremediation may be a good strategy for sites conducive to plant growth with shallow contamination.

Researchers have been investigating the possibility of using trees in the genus *Populus* to hydraulically contain and ultimately remediate plumes of TCE in groundwater. In addition, managers at several DoD and Superfund hazardous waste sites have planted *Populus* species in an effort to treat groundwater contaminated with chlorinated solvents. The genus *Populus* includes a number of species of trees such as poplars, cottonwoods, and aspens. *Populus* is a member of the *Salicaceae* family, which also includes willows. There are around 30 species of *Populus* distributed around the Northern Hemisphere, with eight species indigenous to North America and others that have been introduced. In addition, *Populus* sp. have the ability to cross within the genus both in the wild and through controlled breeding, so there are a large number of potential hybrids.

Due to their ability to readily form hybrids, poplars have been crossed by foresters for years in order to maximize growth rates and yield. Hybrid poplars were originally bred and grown as a cash crop for such uses as pulpwood and as a renewable energy source, but because of their rapid growth rates and high evapotranspiration rates, they make ideal candidates for phytoremediation. Two species of poplars, *Populus deltoides* (eastern cottonwood) and *Populus trichocarpa* (black cottonwood), are commonly crossed for use in phytoremediation. *Populus trichocarpa x deltoides,* have leaves that are about four times as large as the leaves of parent plants. Increasing leaf size increases the potential evapotranspiration rates of these trees due to increased total leaf surface area. Another common cross that has been used in phytoremediation studies is *P. deltoides x P. nigra* (black poplar). This cross is sometimes referred to as *P. x euramericana* due to the original distribution of the two species, the black poplar in Europe and the eastern cottonwood in North America.

Poplar trees have been found to degrade TCE through phytotransformation, where the tree metabolizes the contaminants; phytovolatilization, where the contaminant is extracted by the tree roots then evapotranspired; and phytostimulation, where the tree root zone provides an environment for enhanced microbial biodegradation. Recent studies have demonstrated that poplars volatilize 90 percent of the TCE extracted by their roots through evapotranspiration; therefore, contaminants are not concentrated in the tree leaves.

Poplars have a life span of approximately 35 years and are fast growing, typically requiring five years to mature. The trees grow easily from cuttings; therefore, the use of tree “whips” for the initial plantings can be easy and inexpensive. Tree roots can extend to approximately 10 feet bgs. Poplars are able to treat a wide variety of organic contaminants and can withstand high levels of contaminants (approximately 25 to 50 ppm for TCE).

Poplars can also provide hydraulic control of groundwater contaminant plumes. Healthy trees can act as extraction wells intersecting groundwater flow, changing flow direction, or creating an upward gradient. However, since trees are solar driven and biological, as opposed to mechanical, pumping rates will vary with tree age and species, as well as time of day, time of year, amounts of solar radiation, and other climatic and geographic factors. As a result, pumping

rates will be highly site-specific, but include a wide range of pumping rates, from 1.6 gallons per day per tree (gpd/tree) for a young tree to 53 gpd/tree for a 5-year-old poplar.

In spite of these advantages, poplars will always be slower than mechanical treatments for groundwater remediation due to the growth and maturity period. In addition, depending on site conditions, a large surface area may be required for tree planting, eliminating the possibility of future land use. Another limitation of poplars is their requirement for shallow soils near streams and groundwater at depths of less than 20 feet.

2.4.8 Contaminant Flushing

Contaminant flushing or mobilization involves the injection of agents to remove and disperse sorbed chemicals and/or precipitates. Also, harmless solvents can be injected to increase the dissolution of the chemicals into groundwater (Table 2-4b). The following focused *in situ* groundwater technologies are discussed in this section:

- Surfactants
- Solvents

2.4.8.1 Surfactants

Surfactants are typically long-chain organic molecules derived from petroleum products. Sodium polyphosphates are dry materials commonly used to treat clay-plugging problems in water wells. Common polyphosphates include sodium acid pyrophosphate (SAPP), tetrasodium pyrophosphate (TSPP), sodium tripolyphosphate (STP), and sodium hexametaphosphate (SHMP). SHMP is also commonly known by the commercial trade name Calgon™. Several proprietary surfactants – PM-30 and CB-4 – have recently been used with some success (Alford and Cullimore 1999). The major advantages to surfactants and dispersal agents is their minimal site disturbance and their ability to be added to existing upgradient monitoring wells.

The use of such chemicals is easily implemented and may be applied in conjunction with, prior to, or after the physical/mechanical processes discussed above. In addition, they could be used in either shallow or deep groundwater. However, removal and/or prevention of precipitates is very difficult. Some agents may only cause lag in precipitate production as opposed to prevention. Other limitations of adding agents include the possibility that dispersal agents may coat iron in existing PRB, inhibiting chemical reduction capabilities.

BioSolve® is a patented, nonhazardous, biodegradable, liquid surfactant-based formulation being utilized as both a standalone technology and as an amendment to existing processes, such as “hi vac” extraction processes, pump-and-treat systems, bioremediation enhancement, and others.

The BioSolve® approach liberates the free-phase organic contaminant from the matrix by increasing contaminant solubility and encapsulating it in a micellular emulsion. BioSolve® also reduces interfacial tensions; thus, increasing matrix transmissivity and extraction capabilities at recovery points (surface tension reduced from 72 to 31 dyne per centimeter [dyne/cm] in a study performed by the University of Alabama). The resulting contaminant/BioSolve® solution can then be pumped to the surface for treatment. Contaminant mass removal of 80-plus percent can be achieved utilizing BioSolve®. As an added function, BioSolve® can stimulate the bioremediation of any remaining residual organic by increasing contaminant bioavailability.

The BioSolve® process may be implemented in a variety of ways using either batch, continuous, or semicontinuous systems, depending upon site specifics and existing infrastructure. The use of BioSolve® is effective in both *in situ* and *ex situ* remediation of DNAPLs and light non-aqueous phase liquids (LNAPLs). BioSolve® significantly reduces operating and maintenance costs and accelerates site closure. The BioSolve® approach reduces the total volume of water pumped in order to remove contaminants by increasing effluent contaminant concentration, thereby saving both time and disposal costs.

Because BioSolve® is designed to liberate and mobilize contaminants from the soil matrix, the potential exists for unwanted mobilization in systems where proper steps for hydraulic control are not taken. In addition, whenever dealing *in situ*, site characteristics such as geology and proximity to sensitive receptors (such as fisheries, watersheds, etc.) could also pose limitations.

BioSolve® does not contain enzymes, bacteria, or nutrients; therefore, to realize the secondary benefit of BioSolve's residual biodegradation capabilities; indigenous red microbial populations and aerobic conditions must exist or must be artificially introduced to the site. A possible benefit in this scenario, however, is that BioSolve® is compatible with most types of commercially produced microbes and that BioSolve® will actually enhance their performance. However, the effect of these agents on ZVI is unknown. Bench-scale testing would be required to determine the impact of the agents on ZVI before they could be used.

2.4.8.2 Solvents

Solvent extraction is accomplished by contacting soil with a solvent, separating the soil and solvent, and regenerating the solvent for reuse. To be successful, the extraction solvent should have a high solubility for the contaminant and low solubility in the waste matrix. Typical solvents include liquefied gas (propane or butane), supercritical CO_2 fluid, triethylamine, or proprietary organic fluids. The extraction solvent is well mixed with the contaminated matrix to allow contaminants to transfer to the solvent. The clean matrix and solvent are then separated by physical methods, such as gravity decanting or centrifuging. Distillation regenerates the solvent, which is then returned for reuse in the extraction process.

The following factors may limit the process applicability and effectiveness:

- Spent solvent must be regenerated and reused.
- Organically bound metals can be extracted along with the target organic pollutants, which restricts handling of the residuals.
- The presence of detergents and emulsifiers can unfavorably influence the extraction performance.
- Traces of solvent may remain in the treated solids, so the toxicity of the solvent is an important consideration.
- Solvent extraction is generally least effective on very high molecular weight organic and very hydrophilic substances.
- High moisture content reduces process efficiency and increases complexity of residuals management.

- Lithologies such as clays or silts with low hydraulic conductivities may limit delivery or dispersion of solvents through contaminant plume.
- Debris greater than 60 millimeters in diameter typically must be removed prior to processing.
- The effect of these agents on ZVI is unknown; bench-scale testing would be required to determine the impact of the agents on ZVI before they could be used.

2.4.9 Groundwater and Vapor Extraction

The following focused *ex situ* groundwater and/or vapor extraction technologies are discussed in this section and on Table 2-4b:

- Pumping
- Dual-phase extraction
- Two-phase extraction
- Air sparging with SVE
- Groundwater recirculation wells with SVE

2.4.9.1 Pumping

Groundwater pump-and-treat systems involve extracting contaminated water through the use of pumping wells. The extracted water is treated above ground with technologies such as air stripping, ultraviolet (UV) oxidation, or liquid-phase carbon adsorption and re-injected into the ground or discharged into a surface stream. Some of the advantages of pumping include:

- Pumping has been shown to be very effective in capturing and containing a contaminant plume.
- Sites where minimal sorption to soil particles has occurred, the contaminants are in a mobile, dissolved state, and the subsurface hydrogeology is relatively homogeneous are ideal for pump-and-treat remediation (Nyer 1993).
- Pumping is the most widely used extraction method for very soluble VOCs like gasoline.
- Pumping is one of the most readily available and most competitively priced technologies in a majority of localities.

Although conventional pumping technology has often been selected for site cleanup, it also has some serious limitations, as follows:

- The degree of contaminant removal is highly dependent on the chemical nature of the contaminant and subsurface geology.
- TCE is a DNAPL, meaning that it is denser than water and, when undissolved, tends to exist in pools in the bottom of an aquifer or sorbed to soil particles within the aquifer. Note: There is no documented presence of TCE DNAPL at FEW, although residual DNAPL is suspected in localized areas of SS7.

- Difficulties with contaminant chemistry and hydrogeology may increase the cost and time required to adequately remediate the site.
- Pump-and-treat has a high degree of uncertainty associated with low permeability aquifers and efforts of desorption.

Pump-and-treat methods that can remove dissolved fuel hydrocarbons or dissolved TCE may be less successful at removing sorbed TCE or pools of non-aqueous TCE in equilibrium with the groundwater. In these conditions, more TCE will dissolve into the aqueous phase as the groundwater concentrations are reduced during site remediation. This results in a continuous cycle of slow dissolution from the non-aqueous to the aqueous phase that could take many years to fully treat. Simple calculations for a variety of typical situations show that predicted cleanup times range from a few years to tens, hundreds, and even thousands of years (Kavanaugh *et al.* 1994). However, returning the groundwater to TCE drinking water standards may not be possible at some sites.

In addition, all of the ideal hydrogeologic conditions are rarely found for chlorinated VOCs like TCE, and non-ideal conditions can reduce the effectiveness of the pump-and-treat method. In some conventional pump-and-treat projects, two-thirds of the non-aqueous phase liquids (NAPLs) may not be extracted from the aquifer. Even enhanced pumping systems, such as vacuum-enhanced pumping (dual-phase extraction), have a maximum removal efficiency of 50 to 80 percent (Bedient *et al.* 1994).

2.4.9.2 Dual-Phase Extraction

Dual-phase vacuum extraction consists of pumping groundwater while simultaneously applying a vacuum to the well bore. It is basically a technology combining a groundwater pumping system and an SVE system into a single well, rather than in separate, single-purpose wells. A dual-phase system generally consists of a bottom inlet, controllerless, pneumatic pump in each extraction well, with all of the pumps powered by a single compressor located in the treatment system building. Each wellhead is fitted with a tee fitting in which a vacuum can be applied to one side and water discharged from the other. The vacuum for each well is supplied by a vacuum pump or blower, equipped to pass the vapors through carbon or a bioreactor, located in the treatment building. Some advantages to dual-phase extraction include:

- It can be added to existing pump-and-treat systems to recover more groundwater in, and strip vapors from, higher yielding aquifers.
- It is more effective than SVE or pumping alone for heterogeneous clays and fine sands.
- Use of dual-phase extraction with pumping can shorten the cleanup time at a site.

Factors that may limit the applicability and effectiveness of the process include:

- Lower permeability formations have the potential to leave isolated lenses of undissolved product in the formation.
- Combination with complementary technologies (e.g., pump-and-treat) may be required to recover groundwater from high-yielding aquifers.
- Dual-phase extraction requires separate water treatment and vapor treatment systems.

- With two "pumping" technologies and separate liquid and vapor-phase treatment systems, it is more expensive than either pumping alone or SVE alone.

Typical installation activities require connection of a power supply, pump installation, piping and vacuum system leveling, connection to the extraction well(s), and connection of vapor- and liquid-phase discharge connections to final treatment process(es).

2.4.9.3 Two-Phase Extraction

Two-phase extraction effectively combines two processes: vacuum-enhanced recovery and bioventing into a single pumping system, eliminating one of the limitations of the dual-phase system. Vacuum-enhanced recovery utilizes negative pressure to create a partial vacuum that extracts free product, groundwater, and vapors from the subsurface. Bioventing is forced aeration to accelerate *in situ* bioremediation of hydrocarbons and NAPLs.

Two-phase extraction uses a vacuum source applied to an extraction tube within a well to increase groundwater removal rates and to volatilize and extract that portion of contaminant from the sorbed or free product phases. Since a mixed vapor/liquid column is extracted from the well, the two-phase extraction technology allows a single piece of equipment (a high-vacuum source) to remove contaminants in both the liquid and vapor phases. The advantages of two-phase extraction technology include the following:

- Groundwater is extracted without the use of downhole pumps, wiring, or controls.
- Groundwater flow rates are increased.
- The water table is depressed, allowing for increased VOC extraction potential.
- Vacuum lift of water is not a limiting factor in the application of the technology.
- Under certain soil conditions, the extracted water may be amended with biological enhancements, aerated, and re-injected into the subsurface.
- System is modular, skid-mounted, and easy to install.
- System has the potential to reduce treatment costs by reducing the duration of treatment and thereby reducing life-cycle costs.

To extract both groundwater and soil vapor from a single extraction well, the two-phase extraction system uses a vacuum pump to apply a vacuum through an adjustable central extraction tube, often called a "straw" or "slurp tube," which extends down the well. Soil vapor drawn into the well by the vacuum provides for a vapor stream at the bottom tip of the extraction tube, which entrains both contaminated groundwater and vapor and lifts them to the ground surface. As the groundwater moves up the tube, more than 90 percent of the VOCs in the liquid phase are transferred to the vapor phase. The vapor and water phases are then separated at the surface in a knockout tank. The water phase generally requires only carbon polishing prior to discharge, provided that the contaminants can be adsorbed onto carbon. The vapor phase is then subjected to treatment (based on contaminant characteristics, mass loadings, and economics) with carbon, bioremediation, resin regeneration, catalytic oxidation, or other vapor-phase treatment prior to release.

During a USEPA site evaluation, the performance of the technology was proven to depend on the characteristics of the soil at the site. The system has several limitations, as follows:

- The system only works as designed at sites with low permeabilities (typically with groundwater yields of less than 10 liters/minute).
- At higher yields, the system is not able to maintain a stable air/water interface and converts to extracting only groundwater.
- The movement of air through the subsurface may enhance biological degradation of contaminants.
- The vacuums required for extraction may cause excessive soil dehydration, limiting biological activity normally stimulated by bioventing.

A two-phase extraction pilot test was conducted in 1995 at FEW Plume C, and the results indicated that it removed twice the daily contaminant mass of pumping alone or dual-phase, vacuum-enhanced pumping (see Section 1.3.3.3). A 40-well, two-phase extraction system with a BioTrol® bioreactor groundwater treatment unit has been operating at the WDEQ West Laramie Leaking Aboveground or Underground Storage Tank (LAUST) site since 1997, treating a minimum of 30 gallons per minute (gpm) of gasoline- and diesel fuel-contaminated groundwater.

2.4.9.4 Air Sparging with Soil Vapor Extraction

SVE is a technique which has been successful in the removal of VOCs and NAPLs in the unsaturated (i.e., vadose) zone. However, since SVE involves applying a vacuum pressure to remove contaminated air from the subsurface, any contamination in the saturated zone is not remediated using SVE alone.

Air sparging, when used in conjunction with SVE, has been shown to be effective in removing contaminants from both the saturated and unsaturated zones. It has also been effective in stimulating biological degradation by providing an electron acceptor, oxygen, to the indigenous microbes. Air sparging involves injecting air into the saturated zone of an aquifer, which enhances volatilization of VOCs and certain NAPLs. The volatilized contaminants are then captured in the unsaturated zone by an SVE system.

A main benefit of air sparging as a remediation technology is the enhancement of the mass transfer rate from liquid and/or adsorbed phase to vapor phase. Mass transport is the primary mechanism governing removal of VOCs from an aquifer, but it is often limited by the ability of VOCs to move from dissolved and soil-adsorbed phases to the vadose zone. Air sparging allows for the displacement of water-filled pores with sparged air, which induces mechanical mixing of the groundwater and enhances the rate of adsorbed and residual NAPL dissolution. Under quiescent groundwater conditions there is minimal contact between air and contaminants. Air sparging increases this contact time thereby facilitating mass transfer of adsorbed and dissolved VOCs.

Another benefit of air sparging is enhanced biodegradation of contaminants. Through dissolved oxygen injection, air sparging induces aerobic biodegradation of many VOCs, especially petroleum hydrocarbons in the unsaturated zone. In a contaminated zone, dissolved oxygen levels are often depressed (less than 2 mg/L) since microorganisms are using the contaminants as carbon sources and in the process are consuming all of the oxygen. With increased oxygen, the organisms become more active with higher rates of degradation. Biodegradation has been found

to lower extracted VOC concentrations, reduce vapor treatment costs, and allow for less chance of contaminant migration as sparged vapors enter the vadose zone. However, this benefit is of limited use with TCE because most dechlorination of TCE occurs in anaerobic environments.

The limitations of air sparging are summarized in Table 2-5. From this table, it can be seen that aquifers most amenable to air sparging remediation are those that are unconfined, contain highly fractured bedrock, have homogeneous soils with an organic carbon fraction less than 2 percent, have a permeability greater than 10^{-3} centimeters per second (cm/s), and are located at least 1.5 meters bgs.

2.4.9.5 Groundwater Recirculation Wells with SVE

Groundwater circulating wells (GCWs) with in-well air stripping can remove VOCs from an aquifer without extracting groundwater from the subsurface for aboveground treatment. GCWs with in-well air stripping integrate principles of groundwater recirculation and air stripping. A single well simultaneously circulates water and strips volatile contaminants from the water stream. The system converts groundwater contamination into a vapor stream that can be treated at the surface.

This in-well vapor stripping process requires specially designed wells. A GCW is open to the subsurface at two levels; one well screen draws in groundwater, and the second well screen returns the groundwater to the formation after it has been treated within the well. The treated water returns to the aquifer, and the VOC-laden air stream is directed to an off-gas treatment unit. Two types of GCWs with in-well air stripping are on the market. In both, VOCs partition into the air phase, and only the air phase is extracted for treatment.

In the first type of GCW, water is circulated by simple air-lift pumping (i.e., injected air changes the local density of water and induces flow from non-aerated regions). In GCWs that use air-lift pumping, the extraction zone always is below the recharge zone, and the injected air that induces flow also creates a concurrent vapor stripper. The extent of volatilization is controlled by Henry's Law. Although a cocurrent stripper cannot remove as much contamination as a countercurrent vapor stripper, high removal efficiencies are possible by designing systems with high air-to-water ratios (AWRs). With a typical AWR of 30:1, most wells treating chlorinated solvents should be able to remove 80 to 98 percent of the VOCs in a single pass through the system.

The second type of GCW uses a more traditional approach, pumping groundwater with a submerged pump. The treatment system may be installed in the well or in a subsurface vault. Because the vault system allows more design flexibility, it is more common than the true in-well air stripper. This type of system is not limited to cocurrent air strippers and may be able to achieve higher stripping efficiencies than the air-lift pump systems.

In homogeneous aquifers, a recharge zone located vertically above an extraction zone should create a toroidal circulation pattern around the well and have a minimal impact on groundwater levels. Thus, it can be used in areas that are sensitive to groundwater elevation changes, such as wetlands, perennial springs and sole-source aquifers.

The formation of a circulation cell depends on the ability of the extraction zone to capture the discharge from the recharge zone. Flow patterns in the aquifer will depend on the hydraulic gradients — both natural gradients and those created by the GCW — as well as on the three-dimensional hydraulic conductivity of the aquifer. To ensure circulation, it is essential that the

extraction and recharge zones are located within the same aquifer and that no aquitards exist to restrict flow between them.

As groundwater cycles through the well, VOCs are removed continuously. Remediation is accomplished without extracting groundwater, lowering the groundwater table, or generating the volumes of wastewater typical of most pump-and-treat systems. There is no need for an aboveground air stripper or storage tanks to contain treated water prior to disposal or reinjection. Because groundwater never leaves the subsurface, there is no need for surface level infiltration galleries or reinjection wells. This minimizes aboveground space requirements. Also, because the groundwater never is withdrawn from the subsurface, most states do not require a reinjection permit to operate the system.

Mass is removed by in-well air strippers, and GCWs tend to hydraulically isolate the area to be flushed. Thus, the technology may be ideally suited to some types of "hot spot" remediation. Rather than flushing the contaminated zone with groundwater drawn from uncontaminated zones, GCWs recycle treated water. Therefore, GCWs do not generate large volumes of contaminated groundwater that then must be treated or discharged.

GCWs also induce both horizontal and vertical groundwater flow. By altering normal flow directions, this technology may enhance the desorption of contaminants from soil, mobilizing contaminants and facilitating treatment. GCWs that discharge to the vadose zone potentially can accelerate aquifer restoration by flushing source contaminants from the capillary fringe. GCWs also may enhance vertical flow through a stratified system in which high concentrations of contaminants are bound in lower-permeability layers. However, inducing vertical flow is not always desirable. The vertical pumping action of a GCW can affect the distribution of other chemical components such as salts, carbon dioxide, and metals. These changes may affect the geochemistry of the aquifer.

Depending on the volatility of the contaminants and the physical design of the GCW, groundwater may need to pass though the in-well air stripper many times before treatment objectives are achieved. The average number of treatment cycles possible will depend on the capture efficiency of the well, its pumping rate, and groundwater velocity. In some cases, meeting treatment objectives using only in-well stripping may not be cost-effective.

If GCW systems are not properly designed, it is possible to mobilize contaminants from a source zone to the recharge area. If the contamination zone initially is smaller than the recirculation zone of the GCW, it is possible the GCW will spread contamination to previously uncontaminated zones.

2.4.10 *Ex situ* Treatment

The following focused *ex situ* groundwater treatment technologies are discussed in this section and on Table 2-4b:

- Air stripping
- Liquid-phase carbon adsorption
- UV oxidation
- Vapor-phase bioreactor

EPA has identified the first three items above as presumptive treatment technologies for TCE and other VOCs because of their recognized effectiveness and relative cost-effectiveness. Bioreactors are conventional technologies used at wastewater treatment plants.

2.4.10.1 Air Stripping

Air stripping is a technology in which VOCs are partitioned from groundwater by greatly increasing the surface area of the contaminated water exposed to air. Types of aeration methods include packed towers, diffused aeration, tray aeration, and spray aeration.

Air stripping involves the mass transfer of VOCs from water to air. For groundwater remediation, this process is typically conducted in a packed tower or aeration trays. The typical packed tower air stripper includes a spray nozzle at the top of the tower to distribute contaminated water over the packing in the column, a fan to force air countercurrent to the water flow, and a sump at the bottom of the tower to collect decontaminated water. Auxiliary equipment that can be added to the basic air stripper includes an air heater to improve removal efficiencies for low volatility compounds; automated control systems with sump level switches and safety features, such as differential pressure monitors, high sump level switches, and explosion-proof components; and air emission control and treatment systems, such as activated carbon units, catalytic oxidizers, or thermal oxidizers. Packed tower air strippers are installed either as permanent installations on concrete pads or on a skid or a trailer. Packed tower air strippers were tested during the SS7 extraction and treatment pilot test in 1995.

Aeration trays strip VOCs by bubbling air into a series of trays through which contaminated water flows. A series of holes in each tray are designed to ensure air-water contact without the need for any packing materials. The baffles and multiple trays ensure adequate residence time for stripping to occur. Aeration trays are typically sold as continuously operated skid-mounted units. The advantages offered by aeration trays are considerably lower profiles (less than 6 feet high) than packed towers (15 to 40 feet high), where height may be a problem, and the ability to modify performance or adapt to changing feed composition by adding or removing trays. The discharge air from aeration trays can be treated using the same technology as for packed tower air discharge treatment.

Air strippers can be operated continuously or in a batch mode where the air stripper is intermittently fed from a collection tank. The batch mode ensures consistent air stripper performance and greater energy efficiency than continuously operated units because mixing in the storage tanks eliminates any inconsistencies in feed water composition.

A major problem encountered with air strippers is inorganic or biological fouling of the equipment, which reduces the airflow rate. Fouling is caused by oxidation of minerals in the feed water, such as iron and magnesium (e.g., iron greater than 5 ppm, hardness greater than 800 ppm), by precipitation of calcium, and by biological growth on the packing material. Systems require periodic cleaning and may require pretreatment.

2.4.10.2 Liquid-Phase Carbon Adsorption

Granulated activated carbon (GAC) adsorption is a full-scale technology in which groundwater is pumped through a series of vessels containing activated carbon to which dissolved contaminants adsorb. When the concentration of contaminants in the effluent from the bed exceeds a certain

level, the carbon can be regenerated in place; removed and regenerated at an off-site facility; or removed and disposed of. Carbon used for explosives- or metals-contaminated groundwater probably cannot be regenerated and should be removed and properly disposed of. Adsorption by activated carbon has a long history of use in treating municipal, industrial, and hazardous wastes. GAC is being used for groundwater treatment in the FEW Zone B plume.

The two most common reactor configurations for liquid-phase carbon adsorption systems are the fixed bed and the pulsed or moving bed. The fixed-bed configuration is the most widely used for adsorption from liquids. Suspended solids in a liquid stream may accumulate in the column, causing an increase in pressure drop. When the pressure drop becomes too high, the accumulated solids must be removed, for example, by backwashing. The solids removal process necessitates adsorber downtime and may result in carbon loss and disruption of the mass transfer zone. Pretreatment for removal of solids from streams to be treated is, therefore, an important design consideration.

Carbon can be used in conjunction with steam reforming. Steam reforming is a technology designed to destroy halogenated solvents (such as TCE, carbon tetrachloride [CCl_4], and trichloromethane [$CHCl_3$]) adsorbed on activated carbon by reaction with superheated steam in a commercial reactor.

Limitations of GAC are typical of sorption remediation technologies. The chemical characteristics of the contaminants must be known prior to implementation. In many cases, pretreatment may be required to ensure the treatment's effectiveness. Costs are high if used as the primary treatment for groundwater with high concentrations of contaminants. Therefore, GAC is typically phased in after a different technology is used. Some degradation products, such as vinyl chloride and smaller molecules, are not sorbed well. Consequently, they must be monitored carefully.

All spent carbon eventually needs to be disposed of in landfills or regenerated and there are few regeneration facilities. Although activated carbon is a well-established technology for removing organic compounds, its use in the removal of inorganic contaminants has not been as widespread due to its low capacity as well as the difficulty of regeneration and cost of disposal. Carbon used for some contaminants (e.g., explosives or metals) may not be regenerated. If used to remove radioactive contamination from groundwater, GAC does not reduce radio-toxicity.

Major design variables for liquid-phase carbon applications are empty bed contact time (EBCT), usage rate, and system configuration. Particle size and hydraulic loading are often chosen to minimize pressure drop and reduce or eliminate backwashing. System configuration and EBCT have an impact on carbon usage rate.

2.4.10.3 Ultraviolet Oxidation

UV oxidation is a contaminant destruction process that oxidizes organic and explosive constituents by the addition of strong oxidizers and irradiation with UV light through proprietary high-powered, medium-pressure UV lamps (up to 30 kilowatt [kW]) that emit high-energy UV radiation through a quartz sleeve into contaminated groundwater. The oxidation reactions are achieved through the synergistic action of UV light in combination with ozone (O_3) and/or H_2O_2 to form hydroxyl radicals, which oxidize dissolved contaminants. The success of the process is based on the fact that the rate constants for the reaction of the OH• radicals with most organic

pollutants are very high. Hydroxyl radicals typically react one million to one billion times faster than chemical oxidants such as O_3 or H_2O_2. When the reaction is complete, the contaminants have been converted into water, CO_2, and, if the contaminant was chlorinated, residual chloride. UV oxidation processes can be configured in batch or continuous flow modes, depending on the throughput under consideration.

The main advantage of UV oxidation is that it is a destruction process, as opposed to air stripping or liquid-phase carbon adsorption, for which contaminants are extracted and concentrated in a separate phase. If complete mineralization is achieved, the final products of oxidation are CO_2, water, and salts. Although, when UV/O_3 is used on VOCs, the contaminants may be volatilized (e.g., "stripped") rather than destroyed, necessitating removal from the off-gas by activated liquid-phase carbon adsorption or catalytic oxidation.

A major consideration of UV oxidation is that the aqueous stream to be treated by UV oxidation should be relatively free of heavy metal ions (less than 10 mg/L) and insoluble oil or grease to minimize the potential for fouling of the quartz sleeves. Furthermore, the aqueous stream being treated must provide for good transmission of UV light (high turbidity causes interference). This factor can be critical for UV/H_2O_2 than UV/O_3. (Turbidity does not affect direct chemical oxidation of the contaminant by H_2O_2 or O_3.) In addition, free radical scavengers (e.g., excessive dosages of chemical additives) can inhibit contaminant destruction efficiency.

Costs may be higher than competing technologies because of energy requirements and storage/handling of oxidizers require special safety precautions.

Design and operational parameters include contact or retention time, oxidizer influent dosages, pH, temperature, UV lamp intensity, and various catalysts.

2.4.10.4 Vapor-Phase Bioreactor

For a broad range of influent flow rates and contaminant concentration levels, a fluidized bed reactor (FBR) system is often the most economical treatment choice. Their successful operating experience has ranged from 5 to 4,000 gpm, providing high performance at low capital and operating cost. Aerobic, anaerobic, and anoxic designs are available, and a portable version of an Envirogen vapor-phase bioreactor system was utilized in the 1995 two-phase pilot test at the head of Plume C (USAF 1996b).

Biofiltration is the process of treating a contaminated gas stream in a biologically active packed bed. Biofilters or bioreactors have been used to treat malodorous gases at wastewater treatment plants since the early 1950s and are now being used to treat a wide range of waste gases, including VOCs. Bioreactors are first "seeded" with the appropriate microorganism for degrading the target contamination such as TCE. This stage typically lasts between one and three weeks, depending upon the species of microorganism. Once the microorganisms reach an acceptable concentration, the waste stream is passed through the packed bed reactor. As long as contaminant concentrations remain fairly stable, little maintenance is required to sustain the vapor-phase treatment. However, on occasion when the system has to be shut down for routine maintenance, the microorganisms must be fed an alternative diet (typically monosodium glutamate [MSG] or similar nutrient), or they will die and produce sludge on the floor of the reactor. In this case, the system will need to be cleaned and "re-seeding" will have to occur.

Envirogen's FBR is a fixed-film reactor column that fosters the growth of microorganisms on a hydraulically fluidized bed of media, usually sand or activated carbon. The fluidized media provides an extremely large surface area on which a film of microorganisms can grow, thus a high concentration of biomass - usually two to five times greater than in conventional activated sludge bioreactors - provides the system's high volumetric efficiency in a small footprint. This system:

- Treats a variety of contaminants,
- Is capable of handling both hydraulic and organic shock loads,
- Produces high-quality effluent,
- Has a small footprint,
- Requires minimal operator attention,
- Is cost-effective with low capital and O&M costs, and
- Generates minimal biosludge.

The BioTrol®'s biological aqueous treatment system (BATS) is a patented biological system that treats contaminated groundwater and process water. The system uses naturally occurring microbes; in some instances, however, a specific microorganism may be added. This technique, known as microbial amendment, is important if a highly toxic or recalcitrant target compound is present. The amended microbial system removes both the target contaminant and the background organic carbon. A BioTrol® unit has been operating at the WDEQ West Laramie LAUST site since 1996, treating a minimum of 30 gpm of gasoline- and diesel fuel-contaminated groundwater extracted by a 40-well, two-phase extraction system.

Contaminated water enters a mix tank, where the pH is adjusted and inorganic nutrients are added. If necessary, the water is heated to an optimum temperature with a heater and a heat exchanger, to minimize energy costs. The water then flows to the bioreactor, where the contaminants are biodegraded.

The microorganisms that degrade the contaminants are immobilized in a multiple-cell, submerged, fixed-film bioreactor. Each cell is filled with a highly porous packing material to which the microbes adhere. For aerobic conditions, air is supplied by fine bubble membrane diffusers mounted at the bottom of each cell. The system may also run under anaerobic conditions.

As water flows through the bioreactor, the contaminants are degraded to biological end-products, predominantly CO_2 and water. The resulting effluent may be discharged to a POTW or reused on site. In some cases, discharge with an NPDES permit may be possible.

The BATS may be applied to a wide variety of wastewaters, including groundwater, lagoons, and process water. Contaminants amenable to treatment include pentachlorophenol (PCP), creosote components, gasoline and fuel oil components, chlorinated hydrocarbons, phenolics, and solvents. Other potential target waste streams include coal tar residues and organic pesticides. The BATS may also be effective for treating certain inorganic compounds such as nitrates; however, this application has not yet been demonstrated. The system does not treat metals; therefore, a pre-processing module to extract metals would be required if metals are to be removed.

The BATS was accepted into the Superfund Innovative Technology Evaluation (SITE) Demonstration Program in 1989. The system was demonstrated under the SITE Program from

July to September 1989 at the MacGillis and Gibbs Superfund site in New Brighton, Minnesota. The system operated continuously for six weeks at three different flow rates. For the SITE demonstration, the BATS yielded the following results:

- Reduced PCP concentrations from about 45 ppm to 1 ppm or less in a single pass.
- Produced minimal sludge and no PCP air emissions.
- Mineralized chlorinated phenolics.
- Eliminated groundwater biotoxicity.
- Appeared to be unaffected by low concentrations of oil and grease (about 50 ppm) and heavy metals in groundwater.
- Required minimal operator attention.

The treatment cost per 1,000 gallons was $3.45 for a 5-gpm pilot-scale system and $2.43 for a 30-gpm system.

2.4.11 Discharge of Treated Water

The following focused *ex situ* treated water discharge options are discussed in this section and on Table 2-4b:

- Reinjection
- Surface streams
- POTW

2.4.11.1 Reinjection

Reinjection is a commonly used wastewater discharge technique, although less commonly used than either discharge to a surface drainage or discharge to a POTW. The reason for its lesser use include the substantive requirements for underground injection control (UIC). However, due to water rights issues, reinjection is normally preferred by the State Engineer's Office. In addition, reinjection is the only one of the three discharge technologies that can assist in hydraulic control of contaminant plume migration. Reinjection wells have been used to create a hydraulic mound that either can drive contaminants downgradient towards extraction wells, or if injected at the leading edge of a plume, can reduce or reverse the gradient in that area and in effect create a hydraulic barrier.

As with all groundwater extraction technologies, low permeability soils reduce the effectiveness of infiltration/percolation of reinjected water. These systems can be designed to increase infiltration, but the capital equipment and O&M will increase correspondingly. For example, a single contaminated groundwater extraction and reinjection system currently operating at Pueblo Chemical Depot in Pueblo, Colorado, includes 41 extraction wells and 53 injection wells. These differences in numbers of extraction and reinjection/infiltration wells are due to the higher extraction well flow rates and the lower reinjection well infiltration/percolation rates in the silts and clayey sands of the shallow aquifer.

Reinjection using an upgradient infiltration trench, instead of wells, was the discharge technology selected for the 1995 extraction-and-treatment pilot test at FEW SS7. The objective of this discharge technology was, in part, to drive the contaminated groundwater toward the collection trenches, thus speeding recovery times in the low-permeability aquifer and maintaining a "closed-loop" extraction-and-treatment system.

In any *ex situ* groundwater discharge system, protection from freezing is required to below the depth of the frost line. This means that all extraction and reinjection piping and well-head connections must be placed below a depth of 5 feet bgs in the Cheyenne area. Frequent O&M of the system is also required and is considerably more labor intensive for injection wells than for surface or POTW discharge due to the potential for biofouling. Biofouling is common in wells pumping aerated/oxygenated water into the aquifer due to the presence of naturally occurring aerobic bacteria in the saturated zone. Treatment of biofouling may require annual inspections, treatment with chlorine solutions, and redevelopment (surging and pumping) of the wells.

2.4.11.2 Surface Streams

Discharge to a surface drainage is a standard wastewater discharge technique, more commonly used than either reinjection or discharge to a POTW. The advantages include the ability to use unpressurized, gravity-flow discharge lines, the addition to the surface system of water to maintain minimum stream flows, and the potential for reductions in surface contaminant concentrations through dilution. This discharge technology is currently being used for the FEW Zone B treatment system discharge.

Unless an existing NPDES permit is available that covers the discharge point to the surface drainage, substantive requirements of an NPDES permit would need to be met to discharge the treated water on site. An actual NPDES permit would only be required for off-site discharge, which is not anticipated. Other than meeting substantive requirements of the permit, discharge to a surface drainage has few limitations, although it will require O&M to maintain the discharge pipeline and control vegetation at the outfall. In addition, if the treatment system is to operate in the winter months, the discharge pipeline and outfall must be protected from freezing or ice buildup.

2.4.11.3 Publicly Owned Treatment Works

Discharge to a POTW is a standard wastewater discharge technique, more commonly used than reinjection, but less common than discharge to a surface drainage. The advantages include the possibility of using unpressurized, gravity-flow discharge lines, and proximity to FEW sewer lines at most locations within Zone D. This discharge technology is not currently being used for treated water discharge at FEW.

The use of this discharge technology requires approval by the City of Cheyenne to discharge treated water into the municipal system because the FEW sewage is treated at the municipal POTW. In the past, the city has refused CERCLA waste from FEW at both the municipal POTW and the municipal landfill. The City of Cheyenne has allowed only short-duration, limited-volume discharges, but does not have the capacity for larger, long-term discharges to the POTW. Other limitations include requiring O&M to maintain the discharge pipelines and, if the treatment system is to operate in the winter months, the discharge pipelines must be buried below the frost line to protect them from freezing.

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An initial screening of technologies based on their general applicability to conditions at FEW is summarized in Table 3-1 and discussed below in Section 3.1. Remedial technologies and process options were evaluated and retained or rejected from further consideration on the basis of USEPA's three screening criteria—effectiveness, implementability, and relative cost. This evaluation is presented in Table 3-2 and discussed in more detail in the sections following Section 3.1.

In some instances, even though a technology had potential applicability to Zone D groundwater, it was subsequently rejected based on data obtained from Zone D treatability studies (USAF 1996d, 2003f, 2003g).

3.1 APPLICATION OF THE TECHNOLOGIES AND PROCESS OPTIONS TO THE ZONE D PLUMES

As shown in Table 3-1, the *in situ* and *ex situ* treatment technologies and process options may be applicable only to specific portions of the groundwater plumes that constitute Zone D. The application of these technologies may be limited by their:

- Impacts on existing interim treatment systems, such as the SS7 PRB;
- Lack of implementability under some topographic, hydrogeologic, or endangered species constraints;
- Lack of effectiveness due to higher TCE concentrations than the technology can treat;
- Lack of cost-effectiveness due to lower concentrations than a costly technology is designed to treat; or
- Need to use the technology in combination with other technologies, such as combining groundwater pumping, *ex situ* air stripping, and discharge to a surface stream, to form a "treatment system" (as opposed to a "remedial alternative"), since none of these components can function independently of the other two to treat TCE-contaminated groundwater.

To account for these differences in the applicability of the groundwater technologies, the Zone D groundwater plumes have been subdivided into areas of concern (AOCs). No "plume head" AOC is shown for either Plume A or Plume E because there are no longer high concentration residual TCE indicated by monitoring at the former source areas of these two plumes. The references to low, moderate, and high concentrations of TCE as they apply to Zone D groundwater are relative but in general correspond to concentration ranges of less than 100 µg/L, 100 to 800 µg/L, and greater than 800 µg/L, respectively. The AOCs for each plume are shown across the top of Table 3-1 and depict:

- Plume A
  - Shallow Plume – shallow, low TCE concentration area of plume
  - Intermediate Plume – deeper, low TCE concentration area of plume
  - Creek Intercept – area of plume discharging into Diamond Creek

- Spill Site 7
  - Upgradient of PRB
  - Downgradient of PRB
  - Intermediate Plume
- Plume B
  - Plume Head – area of high residual TCE concentrations
  - Shallow Plume – shallow, low TCE concentration area of plume
  - Intermediate Plume – deeper, low TCE concentration area of plume
  - Creek Intercept – area of plume potentially discharging into Crow Creek
- Plume C
  - Plume Head – area of high residual TCE concentrations
  - Shallow Plume – shallow, low to moderate TCE concentration area of plume
  - Intermediate Plume – deeper, low TCE concentration area of plume
  - Hot Spot – several moderate TCE concentrations areas in the center of the plume corresponding to the former SS2, FPTA2, and the ADW
  - Creek Intercept – area of plume discharging into Crow Creek
- Plume E
  - Shallow Plume – shallow, moderate TCE concentration area of plume
  - Intermediate Plume – deeper, low TCE concentration area of plume
  - Creek Intercept – area of plume potentially discharging into Crow Creek

The application constraints for the remedial technologies delineated in Table 3-1 will be used to aid the screening of the technologies in the following sections.

3.2 GENERAL COSTING OF TECHNOLOGIES

Costs for each of the technologies in this section are normalized, where appropriate. The process of normalizing the capital and O&M costs associated with different technologies is complex given the variability of specific site conditions, such as area and concentration of contaminants.

For example, when attempting to normalize a pump-and-treat system versus an ERH system, site data must be taken into account. The cost of an ERH system is primarily based on area. Whether the contaminant concentration is 5 parts per billion (ppb) or 5,000 ppb, the same capital and O&M costs will apply. However, the costs associated with a pump-and-treat system are based on flow rate, area, and contaminant concentration. There is no way to "normalize" pump-and-treat costs versus ERH costs, unless costs for the two technologies were developed for a specific area. For this FS, not all technologies were applied and evaluated for all plumes. Therefore, normalization of costs was applied when possible for the following sections.

There may also be some economics-of-scale if the same technology is selected for both an intermediate zone and a shallow-zone alternative in the same part of a single plume. However, these incremental cost differences should be small when compared to net present value costs and are not utilized for this technology screening.

3.3 MONITORED NATURAL ATTENUATION

The use of MNA is a common method for remediating contaminants in groundwater. With reference to USEPA's MNA guidance (USEPA 1999), sites where the contaminant plumes are no longer increasing in extent, or are shrinking, would be the most appropriate candidates for MNA remedies. The screening of this technology is summarized in Table 3-2.

Effectiveness (low): Due to the longer timeframe required to remediate groundwater contamination, the natural attenuation period is substantially longer than for active treatment methods. Therefore, the effectiveness is considered to be low.

Implementability (technical – high, administrative – low): MNA is a passive, *in situ* approach avoiding substantial design, capital, and O&M costs. It can be applied almost anywhere quickly, unobtrusively, and cost-effectively. However, the natural attenuation period can be substantially longer than for other technologies due to the time required for groundwater contamination to naturally attenuate.

Cost (capital – low, O&M – high): The capital cost for this method is low since only the construction of monitoring wells is required. However, the O&M costs for maintaining and monitoring those wells may be high due to the long period of time required for MNA to remediate a site.

This technology is Retained due to high technical implementability and its low capital cost as described in Table 3-2.

3.4 BIOSTIMULATION AND BIOAUGMENTATION

The following focused *in situ* groundwater technologies are screened in this section:

- Anaerobic biostimulation using nutrient enhancement
- HRC®
- Anaerobic bioaugmentation (SiREM KB-1™) with nutrients (iSOC™; ORC®)
- Aerobic biostimulation using biosparging
- Aerobic biostimulation using iSOC/iMOX™
- Aerobic bioaugmentation (Cl-Out™) with oxygen (iSOC™; ORC®)

3.4.1 Anaerobic Biostimulation using Nutrient Enhancement

The use of anaerobic biostimulation using nutrient enhancement is an increasingly conventional treatment method for removing contaminants from groundwater via biostimulation. The screening of this technology is summarized in Table 3-2.

Effectiveness (moderate): Using nutrients to enhance biodegradation by indigenous microorganisms can initiate the reduction of contaminants *in situ*. Anaerobic biostimulation is an increasingly conventional, relatively low-cost technology that is ideally suited to long-term passive treatment of contaminants.

Evidence suggests there is competition between microorganisms that efficiently degrade contaminants (reductive dehalogenators) and those that do not (methanogens) where the less efficient microbes compete for the use of hydrogen in the metabolism of compounds other than the contaminants (i.e., methanogens use hydrogen to convert CO_2 to methane). This competition could produce a rapid consumption of hydrogen that does not result in a significant decrease in contaminant concentrations, therefore multiple applications will be required.

Molasses injections were delivered during a pilot test and full-scale installation at two USEPA sites to reduce concentrations of chlorinated solvents (USEPA 2000a, 2000b). At a site located in Emeryville, California, molasses injection created conditions favorable for the reduction of TCE, DCE, and vinyl chloride in the subsurface. During an 18-month full-scale operation, average concentrations of TCE decreased by 99 percent from more than 3,000 µg/L to 4 µg/L. At another site located in Williamsport, Pennsylvania, reducing conditions were created in only some of the wells where molasses was injected. After 18 months of operation, encouraging results were observed at only one well location where TCE concentrations in groundwater decreased by 90 percent from 67 µg/L to 6.7 µg/L.

Implementability (technical – moderate, administrative – low): This technology is a passive, *in situ* approach avoiding substantial design, capital, and O&M costs. It can be applied almost anywhere very quickly, unobtrusively, and cost-effectively. Injection applications are relatively non-invasive, allowing undisturbed operation of facilities during treatment installation and offering lack of visibility during the working phase.

Where the subsurface is heterogeneous, it could be difficult to circulate the nutrient solution throughout the different zones of contamination. Higher permeability zones may be treated more rapidly due to preferential flow and better distribution of the nutrients to the indigenous microbes. In addition, multiple injections may be required over a short time period; therefore, this option is moderately implementable. Administrative implementability is low since this is not a proven technology.

It is possible that this technology could be used near ZVI after bench testing proves its compatibility.

Cost (capital – low to moderate, O&M – high): The cost for this technology would be expensive for multiple applications; $4.20 per 1,000 gallons of water for a plume containing a maximum TCE concentrations of 1,000 µg/L compared to $8.90 per 1,000 gallons for conventional pump-and-treat (Quinton et al. 1997). Typically, this technology requires several applications. However, the implementation at the field scale would cost less than LTM costs of unassisted natural attenuation, 25 to 50 percent the cost of a conventional air sparging system with vapor recovery, and 50 percent the cost of a pump-and-treat system.

O&M costs may be considered high because technology normally requires subsequent injections. This technology would be feasible for long-term, large plume application, but adding stimulants can become very labor intensive.

This technology is Rejected due to the availability of other anaerobic technologies that work more rapidly or provide greater effectiveness.

3.4.2 Hydrogen Release Compound

The use of HRC® is a common treatment method for removing contaminants from groundwater via biostimulation. The screening of this technology is summarized in Table 3-2.

Effectiveness (low to moderate): HRC® is a passive, *in situ* approach that is currently utilized in more than 400 soil and groundwater restoration projects in the United States to treat chlorinated solvents. HRC® enhances microbial reductive dechlorination, has been used to treat a variety of contaminants, and is highly effective at enhancing degradation of chlorinated hydrocarbons such as TCE.

When in the subsurface, HRC® has a time-release feature that slowly releases lactic acid into contaminated environments for one to three years. In this manner, HRC® purposefully allows for prolonged periods of enhanced biodegradation of anaerobically degradable contaminants to occur. Simultaneous or sequential applications of HRC® with ORC™ can produce improved results in the treatment of chlorinated aliphatic hydrocarbons. HRC® treats the higher order chlorinated aliphatic hydrocarbons as ORC™ treats the breakdown products.

Because HRC® is used to supply hydrogen necessary for biodegradation, it will be moderately effective if the indigenous microbial population is not capable of degrading contaminants at the site. As with other biological treatments, effectiveness is highly dependent upon aquifer biocontent, permeability, site hydrology, DO content, pH, and depth, aerial extent, type, concentration, and biodegradability of contaminants. The low effectiveness is assigned due to results of the Zone D bench-scale test (USAF 2003g) that indicated site conditions were not conducive to degrade TCE all the way to ethene. The test indicated degradation "stalled" at DCE.

Implementability (technical – high, administrative – high): HRC® is a passive, *in situ* approach avoiding substantial design, capital, and O&M costs. It has high acceptance by regulatory agencies and it can be applied almost anywhere very quickly, unobtrusively, and cost-effectively. Injection applications are relatively non-invasive, allowing undisturbed operation of facilities during treatment installation and offering lack of visibility during the working phase.

Where the subsurface is heterogeneous, it could be difficult to circulate the HRC® solution throughout the different zones of contamination. Higher permeability zones may be treated more rapidly due to preferential flow and better distribution of the HRC® to the indigenous microbes; therefore, this technology is moderately implementable.

The technology should not be added to existing monitoring wells due to depleted HRC® residual chemical that cannot be easily removed. This technology is proprietary with only one vendor for the compound.

Cost (capital – moderate, O&M – high): Unlike engineered active treatment systems, continuous mechanical O&M is eliminated, dramatically reducing overall O&M costs. At the field scale, the overall costs are generally less than LTM costs of unassisted natural attenuation, 25 to 50 percent the cost of a conventional air sparging system with vapor recovery, and 25 percent the cost of a pump-and-treat system. The typical capital cost for this process is moderate, approximately $6 per

pound of chemical, or $2.25 per 1,000 gallons treated (Regenesis 2002). O&M costs may be considered high if a significant number of additional injections are needed at six to 12-month intervals. However, Regenesis has produced a new material—HRC-X™—that costs approximately 50 percent more per pound than standard HRC® but has a potential life of 36 months, instead of six to 12 months. If an FEW site can be remediated in 36 months or less, this new HRC-X™ would be worth considering to reduce O&M costs.

As described in Table 3-2, this technology is Rejected due to its low in as demonstrated during bench-scale treatability tests at FEW (USAF 2003g). However, this technology has demonstrated moderate to high effectiveness in treating chlorinated VOCs at hundreds of sites in the United States, moderate to high implementability, moderate costs, and short cleanup time for relatively low concentration (less than 100 µg/L) sites.

3.4.3 Anaerobic Bioaugmentation with Nutrient Enhancement

The use of anaerobic bioaugmentation with nutrient enhancement is a common treatment method for removing contaminants from groundwater via bioaugmentation. The screening of this technology is summarized in Table 3-2.

Effectiveness (moderate): This technology is relatively new, but has proven to be effective at some sites contaminated with chlorinated VOCs, including USAF installations in Texas, Nevada, and Delaware. Bioaugmentation can establish anaerobic dechlorinating bacteria at sites to stimulate reduction of contaminants by increasing dechlorinator population densities or to accelerate biodegradation rates to meet treatment goals. An example of a specific bacteria isolated to enhance biodegradation is the SiREM KB-1™ dechlorinator. This bacteria is a safe, natural microbial consortia that has demonstrated the ability to remediate chlorinated contaminants under diverse field conditions.

HRC® is an effective electron donor proven to accelerate contaminant biodegradation by the SiREM KB-1™ dechlorinator. The iMOX™ infuser is not a proven technology for KB-1 nutrient enhancement during bioaugmentation; however, this technology is currently being tested in Zone D and is considered moderately effective.

Implementability (technical – high, administrative – low): This technology is a passive, *in situ* approach avoiding substantial design, capital, and O&M costs. It can be applied almost anywhere very quickly, unobtrusively, and cost-effectively. Inoculation of microbes and injection/infusion applications of nutrients are relatively non-invasive, allowing undisturbed operation of facilities during treatment and offering lack of visibility during the working phase. Because a single inoculation is required to establish a strong microbial population, this option is highly implementable. However, nutrient addition (O&M) may be required at regular intervals.

It is possible that this technology could be used near ZVI after bench testing proves its compatibility. iMOX™ and HRC® are currently being tested in Zone D, thus anaerobic bioaugmentation with nutrient enhancement may be used near ZVI after bench testing. Since this is not a familiar technology to the regulators, it is assigned a low administrative implementability.

Cost (capital – low to moderate, O&M – low): The capital cost for this technology is relatively low. It is estimated to cost approximately $1,500 per 20,000 gallons of water. O&M requires nutrient addition at one- to three-year intervals for HRC® or continuously with six-month gas cylinder replacement and minimal equipment to maintain for iMOX™, plus monitoring costs.

This technology is Retained due to its moderate effectiveness, high technical/low administrative implementability, and low to moderate cost as described in Table 3-2.

3.4.4 Aerobic Biostimulation using Biosparging

The use of oxygen enhancement with biosparging is a common treatment method for removing contaminants from groundwater via biostimulation. The screening of this technology is summarized in Table 3-2.

Effectiveness (low): Biodegradation through oxygen enhancement with biosparging is primarily designed to treat VOCs by creating aerobic conditions and promoting microbial growth. Homogeneous sandy soils contribute to the efficiency of this technology since the contact of air, groundwater, and soil is increased, hence promoting biodegradation. Effectiveness is highly dependent upon aquifer permeability, site hydrology, dissolved oxygen content, pH, and depth, areal extent, type, concentration, and biodegradability of contaminants. The process has low effectiveness in treating chlorinated VOCs such as TCA and TCE; however, it maybe effective for degradation products such as DCE.

Implementability (technical – moderate, administrative – low): The moderate implementability of small-diameter air injection points allows flexibility in the design and construction of a remediation system. Oxygen enhancement with biosparging is typically used in conjunction with SVE or bioventing to enhance removal of the volatile component under consideration.

There are some technology limitations. The technology requires complex monitoring of nutrients such as carbon, oxygen, phosphorous, and nitrogen in order to optimize its operation. Low groundwater velocities and moderate dissolved concentrations are required for proper biological growth and hydrocarbon degradation. Since this is an aerobic process, it is not for use near the PRB due to oxidation of iron. Also, the technology requires new blowers and wells.

Biosparging is a widely used and accepted technology. However, administrative implementability is low because the technology is not able to treat site contaminants.

Cost (capital – moderate, O&M – moderate): Cost estimates are moderate at $40 to $80 per 1,000 gallons of groundwater treated. Variables affecting the cost are the nature and depth of the contaminants (Van Deuren *et al.* 1997). The O&M cost for this process is also moderate due to maintenance of injection equipment.

This technology is Rejected due to its low effectiveness, low implementability, and moderate cost as described in Table 3-2.

3.4.5 Aerobic Biostimulation using iSOC/iMOX™

The use of iSOC/iMOX™ is a new treatment method for removing contaminants from groundwater via co-metabolism. The screening of this technology is summarized in Table 3-2.

Effectiveness (low)**:** This technology is still under development, but performance information regarding treatment of groundwater contaminated with chlorinated VOCs is poor based on results of the Zone D Groundwater Treatability Study (USAF 2003f). As with other *in situ* biodegradation processes, the success of this technology is highly dependent upon soil and chemical properties. Typically, aerobic degradation is faster than anaerobic degradation for some VOCs such as DCE, DCA, and vinyl chloride.

Implementability (technical – high, administrative – unknown): The iSOC™ system has been used extensively to oxygenate and aerobically bioremediate fuel-contaminated groundwater and is designed to fit into existing monitoring wells. The non-electric iSOC™ can be operated in remote locations without nearby power lines or a portable electric generator. The iMOX™ system has been used less extensively for providing a hydrocarbon source like methane or methane gas to anaerobic groundwater plumes to degrade contaminants such as TCE, the DCE isomers, and vinyl chloride. However, introducing oxygen gas through the iSOC™ infuser and a carbon source (e.g., propane, methane, or butane gas) through the iMOX™ infuser into a single well to stimulate aerobic microbial co-metabolism is an innovative application, and documentation is limited. Although the system is highly technically implementable, it has unknown administrative implementability.

***Cost (capital – low, O&M – low)*:** The capital cost for co-metabolic treatment is relatively low. Results from a treatability study investigating the effectiveness of the single well application technique indicate $4,100 per iSOC™ unit (USAF 2003f). The cost per well for equipment and installation would be $10,000. O&M costs consist of approximately $350 per unit per year for gas refill and cylinder rental (USAF 2003f). The overall O&M would be $500 per year per well for materials in addition to monitoring costs.

This technology is Rejected due to its low effectiveness as demonstrated in the Zone D Groundwater Treatability Study (USAF 2003f) as described in Table 3-2.

3.4.6 Aerobic Bioaugmentation (Cl-Out™) with Oxygen (iSOC™; ORC®)

The use of aerobic bioaugmentation with oxygen enhancement is a relatively innovative treatment method for removing contaminants from groundwater via both bioaugmentation and biostimulation. The screening of this technology is summarized in Table 3-2.

Effectiveness (moderate): This technology is relatively new, but has proven to be effective at some sites contaminated with chlorinated VOCs. In many cases, indigenous microorganisms do not have the ability to completely degrade a specific contaminant. Bioaugmentation can establish a microbial community at a site to stimulate degradation of contaminants by increasing population density, or to accelerate biodegradation rates to meet treatment goals. An example of a specific aerobic bacteria isolated to enhance biodegradation is Cl-Out™.

Cl-Out™ has been used in remediation of groundwater affected by dry cleaning, metals manufacturing, printing, and electronics manufacturing industries to remediate chlorinated VOCs including carbon tetrachloride; 1,1,2,2-PCA; PCE; TCA; TCE; and vinyl chloride.

ORC® and iSOC™ have primarily been used to remediate groundwater containing BTEX, petroleum hydrocarbons, nitroaromatics, chloroaromatics, jet fuel, DCE, and vinyl chloride. When ORC® is used, the aerobic degradation rate of contaminants is increased 10 to 1,000 times over typical natural attenuation approaches. Therefore, ORC® is highly effective for providing oxygen to subsurface microbial environments.

Implementability (technical – moderate, administrative – low): This technology is a passive, *in situ* approach avoiding substantial design, capital, and O&M costs. It can be applied almost anywhere very quickly, unobtrusively, and cost-effectively. The Cl-Out™ system is designed for standalone application or for augmentation of existing treatments, including vapor stripping,

sparging, excavation, and dual-phase extraction technologies. Injection applications are relatively non-invasive, allowing undisturbed operation of facilities during treatment installation and offering lack of visibility during the working phase. Multiple injections may be required to establish a strong microbial population; therefore, this option is moderately implementable. Cl-Out™ may, however, have a low administrative implementability because it is not a proven technology.

ORC® is highly accepted by regulatory agencies and can be applied almost anywhere very quickly and unobtrusively. Since ORC® is an insoluble powder, it can be packaged in socks composed of a specially designed filter fabric. These "filter socks" are contacted with contaminated groundwater via an array of wells or trenches. ORC® can also be mixed directly with water to form a slurry for permanent injection applications in the saturated zone. Usually only one application is necessary depending on rebound and regulatory demands. However, as with other biological treatments, effectiveness is highly dependent upon aquifer permeability, site hydrology, DO content, pH, and depth, aerial extent, type, concentration, and biodegradability of contaminants. Therefore, the ORC® portion of this technology is highly implementable from a technical standpoint.

The iSOC™ system has been used extensively to oxygenate and aerobically bioremediate fuel-contaminated groundwater and is designed to fit into existing monitoring wells. The non-electric iSOC™ can be operated in remote locations with neither nearby power lines nor a portable electric generator. Therefore, the iSOC™ portion of this technology is highly implementable from a technical standpoint.

Cost (capital – low to high, O&M – low to high): The typical cost for co-metabolic treatment using Cl-Out™ is relatively low to moderate. The unit cost is $1,500 per drum-equivalent of Cl-Out™. Each drum of hydrated Cl-Out™ can treat up to 50,000 gallons of contaminated water. However, due to non-uniform subsurface distribution, it is recommended that a treatment rate of one drum for every 20,000 gallons of contaminated groundwater (Saul 2002). This results in an approximate cost of $75 per 1,000 gallons of contaminated groundwater. O&M costs are low, however, additional applications would increase O&M costs.

The typical cost, both capital and O&M, for ORC® application is moderate, approximately $6 per pound of chemical or $8.00 per 1,000 gallons treated (Regenesis 2002). However, O&M costs may be considered high if a significant number of additional applications of ORC® are needed. At the field scale, the overall costs are generally less than LTM costs of unassisted natural attenuation, 25 to 50 percent the cost of a conventional air sparging system with vapor recovery, and 25 percent the cost of a pump-and-treat system.

The capital cost for iSOC™ oxygen enhancement is relatively low. Preliminary results from a pilot study investigating the effectiveness of the single well application technique indicate $4,100 per iSOC™ unit. O&M costs consist of approximately $350 per unit per year for gas refill and cylinder rental (USAF 2003f).

This technology is Rejected due to its moderate effectiveness, moderate to low implementability, and low to high cost as described in Table 3-2.

3.5 CHEMICAL OXIDATION AND REDUCTION

The following focused *in situ* groundwater technologies are screened in this section:

- $KMnO_4$
- Fenton's Reagent
- Chemical reduction
- Air/ozone sparging with C-Sparger™ system

3.5.1 Potassium Permanganate

The use of $KMnO_4$ is a common treatment method for removing contaminants from groundwater via chemical oxidation. The screening of this technology is summarized in Table 3-2.

Effectiveness (high): USAF and the National Aeronautic and Space Administration (NASA) have evaluated the effectiveness of $KMnO_4$ on groundwater contaminated with TCE at the former Apollo Launch Complex at Cape Canaveral, Florida. Preliminary results with $KMnO_4$ show a removal efficiency of greater than 99 percent of the TCE in several monitoring wells throughout the treatment zone.

A treatability study evaluating the effectiveness of $KMnO_4$ injection in decreasing TCE concentrations has been conducted in Plume C at FEW (USAF 2003f). Results indicate a reduction in contaminant concentrations of approximately 350 µg/L to nondetect levels.

Highly effective treatment of groundwater contaminants by $KMnO_4$ is dependent on its distribution in the subsurface, which is dependent on site-specific conditions such as geology and hydrogeology. The rate and extent of degradation of chlorinated organics through chemical oxidation are dictated by the properties of the chemical itself and its susceptibility to oxidative degradation, in addition to matrix conditions including pH, temperature, the concentration of oxidant, and the concentration of other oxidant-consuming substances such as natural organic matter and reduced minerals.

The characteristic purple-colored groundwater observed in monitoring wells near injection points is presumed to indicate that the reaction is continuing. This can also serve as a useful tracer of subsurface migration pathways.

Implementability (technical – high, administrative – high): $KMnO_4$ is readily available, inexpensive, and results in generation of innocuous materials such as CO_2, manganese dioxide solids, potassium, and chloride. The chemistry of the process is well known and has been widely used in wastewater treatment applications. The injection process is easily applied and controlled, and treatment and reaction times are rapid; therefore, its technical implementability is high.

$KMnO_4$ is relatively stable and more persistent in the subsurface than other oxidants such as Fenton's Reagent or H_2O_2; as a result, it can migrate by diffusive processes. Moreover, the stable nature of $KMnO_4$ facilitates a high administrative implementability.

The potential for toxicity to organisms from a $KMnO_4$ solution limits the location of an injection site to areas at FEW at least an estimated 200 feet upgradient from any surface water bodies. This is because of the potential surface water expression within nearby creeks.

Cost (capital – low to moderate, O&M – none): Cost comparisons generated after field demonstrations to remediate TCE indicate moderate costs for *in situ* chemical oxidation using $KMnO_4$ (range from $363 to $778 per pound of TCE treated). Typical cost for injection of $KMnO_4$ is approximately $66 per injection point. The chemical cost for $KMnO_4$ is lower than for Fenton's Reagent, although the total chemical cost for remediation may be greater because a greater quantity of $KMnO_4$ may be required for treatment. Injection costs are dependent on the equipment used (e.g., direct push). These costs would increase if direct push cannot be used because of resistant layers. O&M costs are low to moderate, depending on the number of chemical injections that are required to remediate the site-specific area.

This technology is Retained for further evaluation due to its high effectiveness, high implementability, and low to moderate costs as described in Table 3-2.

3.5.2 Fenton's Reagent

The use of Fenton's Reagent is a common treatment method for removing contaminants from groundwater via chemical oxidation. The screening of this technology is summarized in Table 3-2.

Effectiveness (high): Fenton's Reagent has been used to treat DNAPL, sorbed-phase, and dissolved-phase VOC contamination. Field applications have generally reported favorable results in significantly reducing the mass of contaminants in short time periods. The hydroxyl radical created is a powerful oxidation agent and is capable of treating sorbed-phase contamination. In addition, minor agitation produced during the reaction between H_2O_2 and ferrous iron can assist in transferring sorbed or immobile contamination into the dissolved phase, where it can be treated more effectively. Hence, Fenton's Reagent is highly effective for source area treatment.

Effective treatment of groundwater contaminants by Fenton's Reagent is dependent on its distribution in the subsurface, which is dependent on site-specific conditions such as geology and hydrogeology. In addition, the rate and extent of degradation of chlorinated organics through chemical oxidation are dictated by the properties of the chemical itself and its susceptibility to oxidative degradation, in addition to matrix conditions including pH, temperature, the concentration of oxidant, and the concentration of other oxidant-consuming substances such as natural organic matter and reduced minerals.

Implementability (technical – moderate, administrative – low): ISOTEC employs a modified process utilizing a patented chelated organometallic catalysts that maintains neutral pH conditions (e.g., 5 to 8); therefore, no acidification of the aquifer is required as with conventional Fenton-based processes. These reagents are highly mobile in the subsurface and resist precipitation and soil adsorption. This results in efficient hydroxyl radical generation throughout the plume, unlike conventional Fenton's catalysts that are consumed near the point of injection. However, the use of a patented process available from only one supplier reduces technical implementability to moderate.

Oxidation by Fenton's Reagent requires contact with the contaminant and a good distribution of the chemical. Carbon and sulfur in soil/water can also consume the oxidizer. Strong oxidizers such as Fenton's Reagent should not be used near the PRB due to oxidation of the iron.

Health and safety concerns are reduced with the ISOTEC process due to the use of low concentration of oxidizers (typically less than 10 percent H_2O_2) and low pressure injection, which results in minimal (less than 25°F) temperature increase. This modified process should help in agency approval, but the cost of this patented process could reduce administrative implementability to low.

Cost (capital – high, O&M – none): The price of implementation could be expected to range from $20 per pound of contaminant for large, less intensely contaminated areas to several hundred dollars per pound for smaller, highly contaminated areas (Bryant and Wilson 1999). A typical cost for injection of Fenton's Reagent is approximately $80.26 per injection point. Fenton's Reagent is inexpensive, but more costly than H_2O_2 or $KMnO_4$.

The capital cost of $750,000 per acre includes materials and installation for three injections into TCE concentrated groundwater of 7,000 µg/L. O&M costs are none since only monitoring costs are required.

This technology is Retained due to its ability to remove high concentrations of TCE in groundwater, making it highly effective, and its moderate implementability.

3.5.3 Chemical Reduction

The use of reducing agents is a new treatment method for removing contaminants from groundwater via chemical reduction. The screening of this technology is summarized in Table 3-2.

Effectiveness (unknown): Historically, the target contaminant group for chemical redox is inorganics. The most common applications of chemical reduction are reducing chromium (VI) to chromium (III) in preparation for hydroxide precipitation, oxidizing arsenic (III) to arsenic (V) to reduce toxicity and improve removal by subsequent processes, and oxidizing cyanide to produce CO_2 and nitrogen (N_2) (Field Hydrology and Chemistry Group 2001). Treatment effectiveness is generally 90 to 99 percent reduction in contaminant mass, and treatment time is typically days.

The rate and extent of degradation of chlorinated organics through chemical reduction are dictated by the properties of the chemical itself and its susceptibility to reductive degradation, in addition to matrix conditions including pH, temperature, the concentration of reductant, and the concentrations of other reductant-consuming substances. The technology can be used but may be less effective for non-halogenated VOCs and SVOCs, fuel hydrocarbons, and pesticides.

Recent studies have shown dithionite may be effective in reducing concentrations of chlorinated compounds such as carbon tetrachloride (Amonette et al. 1994) and TCE (Field Hydrology and Chemistry Group 2001). However, its effectiveness is unknown pending the completion of current bench-scale testing conducted at a federal site outside of FEW.

Implementability (technical – unknown, administrative – unknown): Chemical reduction is a full-scale, well-established technology used for *ex situ* disinfection of drinking water and wastewater, and it is a common treatment for chromium (reduction of Cr (VI) to Cr (III) prior to precipitation) wastes, but treatment of chlorinated solvents is still at the bench- and pilot-scale stage. The technical and administrative implementability of this technology at the full scale is presently unknown, pending the evaluation of bench-scale test results of calcium polysulfide used to degrade TCE, TCA, and DCE currently being conducted at a federal site outside of FEW.

Based on similar application methods of *in situ* chemical oxidation, this technology requires minimal design and equipment, and contractors should be available locally.

Costs (capital – unknown, O&M – none): Costs for *in situ* chemical reduction range from $0.60 to $1.00 per 1,000 gallons of groundwater treated (NFESC 2004). O&M costs are low to moderate, depending on the number of injections required for remediation.

This technology is Rejected due to its unknown effectiveness and unknown implementability.

3.5.4 Air/Ozone Sparging with C-Sparger™ System

The use of C-Sparger™ is a new treatment method for removing contaminants from groundwater via oxidation and *in situ* air stripping. The screening of this technology is summarized in Table 3-2.

Effectiveness (low to moderate)*:* The C-Sparger™ system relies on chemical oxidation of contaminants using ozone to degrade dissolved chlorinated hydrocarbons such as TCE, the DCE isomers, and vinyl chloride. Ozonation remediates the chlorinated VOCs in groundwater by reducing the toxicity of the compounds through treatment by breaking the chlorine bond to form nontoxic, mineralized compounds including water, carbon dioxide, and chlorine ions.

The C-Sparger™ process consists of a combination of *in situ* air stripping with encapsulated ozone to oxidize contaminants and has been moderately effective in reducing chlorinated VOC concentrations in groundwater. Matrix conditions including pH, temperature, the concentration of oxidant, and the concentration of other oxidant-consuming substances such as natural organic matter and reduced minerals may affect the effectiveness.

A treatability study of the C-Sparger™ system has been conducted in Plume C at FEW (USAF 2003f). Concentrations between 300 and 500 µg/L were treated at levels as low as 50 µg/L, and the target goal of MCLs (5 µg/L) was not obtained. There is uncertainty at FEW whether this low effectiveness is attributable to the limitations in the technology, site conditions, or the recurring O&M issues experienced during the treatability study.

Implementability (technical – moderate, administrative – moderate)**:** The C-Sparger™ is a moderately implementable system for remediating chlorinated solvents at small, urban dry cleaning sites, but is relatively unknown to most agencies. Each site has a unique set of hydrogeologic characteristics and each application of the C-Sparger™ technology must be designed and engineered for that site, requiring the installation of sparge wells and airline trenches. The off-the-shelf C-Sparger™ system is convenient for pilot-scale tests and is moderately simple to install. This is, however, a proprietary system with only one vendor. Ozone is a very strong oxidizer, but conversely, is highly corrosive to metals and cannot be used near the PRB due to iron oxidation. In addition, the system requires frequent O&M of sparging equipment.

Because the gases are generated by the control unit, there are no liquids to mix or inject. Administrative implementability is moderate due to its limited documented use at multiple sites.

Cost (capital – moderate, O&M – moderate)**:** Based on data from the Zone D treatability study conducted at FEW (USAF 2003f), the typical cost for conventional air sparging is moderate. The cost for eight sparge points, system control unit, in addition to associated drilling/trenching,

is approximately $40,000. The O&M cost of the FEW system has been moderate, based on the frequent maintenance required.

This technology is Rejected for further consideration due to its low effectiveness, as demonstrated in the Zone D Treatability Study (USAF 2003f). However, elsewhere, this technology has been shown to have moderate effectiveness, moderate implementability, and moderate cost as described in Table 3-2.

3.6 PERMEABLE REACTIVE BARRIER

The following focused *in situ* groundwater technologies are screened in this section:

- Additional ZVI by trenching
- Additional ZVI by injection
- Additional ZVI by deep soil mixing
- E-barrier
- Bark mulch biowall

3.6.1 Additional Zero Valent Iron by Trenching

The use of ZVI in a PRB is now a relatively common treatment method for removing contaminants from groundwater via chemical reduction. This technology is presently in place at the Denver Federal Center. The screening of this technology is summarized in Table 3-2.

Effectiveness (high): There are more than 40 full-scale installations and more than 50 pilot-scale demonstrations of a ZVI PRB in the United States, including the PRB at FEW SS7. These applications have been highly effective in remediation of chlorinated contaminants such as PCE, TCE, *cis*-1,2-DCE, vinyl chloride, TCA, and DCA.

However, the rate and extent of degradation of chlorinated organics within the ZVI through chemical reduction are dictated by the properties of the contaminant itself and its susceptibility to reductive degradation, in addition to matrix conditions including pH, temperature, the concentration of reductant, and the concentration of other reductant-consuming substances. Generally, there is a longer period of time for treatment than active systems.

Implementability (technical – moderate, administrative – high): This technology requires significant design and field efforts to install. In addition, trenches are limited to depths reached by excavation equipment and, therefore, can be used only in shallow groundwater. Previous applications of a ZVI PRB at FEW SS7 have successfully reduced concentrations of TCE and associated daughter products to below the MCL. Therefore, technical implementability is moderate and administrative implementability is high.

Cost (capital – high, O&M – none): The capital cost for a ZVI PRB is higher than that of a standard reactive barrier (assuming a barrier thickness of 4 feet) due to significant mobilization and construction costs. In addition, the proprietary licensing fee for using ZVI in a remediation strategy is approximately 15 percent of the iron cost (EnviroMetal Technologies 2003). The ZVI is relatively expensive and a major cost factor.

Because this system is passive, there are minimal operational costs, with the exception of monitoring costs, and no need for groundwater extraction. There are no O&M costs unless precipitation or biofouling occurs.

This technology is Retained as a potential technology to extend the length, and possibly the depth, of the existing SS7 PRB and the stream intercept areas of the other Zone D plumes.

3.6.2 Additional Zero Valent Iron by Injection

The use of ZVI in a PRB is now a relatively common treatment method for removing contaminants from groundwater via chemical reduction, although injection of ZVI is a new method of installation. The screening of this technology is summarized in Table 3-2.

Effectiveness (limited information): There are few full-scale installations and pilot-scale demonstrations of injected/hydrofractured ZVI PRB in the United States. These applications have shown conflicting results for effectiveness in remediation of chlorinated organics such as PCE; TCE; *cis*-1,2-DCE; vinyl chloride; 1,1,1-TCA; and 1,1-DCA. The Plume E pilot test of a jet-grouted PRB has shown TCE reductions ranging from 45 to 96 percent in its first six months of operation.

The rate and extent of degradation of chlorinated organics within the ZVI through chemical reduction are dictated by the properties of the contaminant itself and its susceptibility to reductive degradation, in addition to matrix conditions including pH, temperature, the concentration of reductant, and the concentration of other reductant-consuming substances. Generally, there is a longer period of time for treatment than active systems.

Implementability (technical – low, administrative – low): This technology requires significant design and field efforts to install, and a large construction staging area is required. Injection/hydrofractured borings can reach greater depths than a probe or trench, and this is one of the only technologies available to deepen the SS7 PRB. This technology generates large volumes of IDW, both solid and liquid, that need to be managed. There are only two vendors available for additional ZVI by jet grouting and one for deep hydrofracturing. A pilot test is currently underway at Plume E. This technology is limited to areas of low to moderate chlorinated VOC concentrations due to its relatively thin ZVI (compared to a trenched PRB). Therefore, due to relatively few uses of the injected/hydrofractured ZVI technology, both technical and administrative implementability are low.

Cost (capital – high, O&M – low): Complete cost data are not available, but preliminary data from the Plume E pilot test indicates high capital costs attributed to significant ZVI waste, very high mobilization cost, and high IDW management/disposal costs, possibly in excess of the method of installation by trenching. In addition, the proprietary licensing fee for using ZVI in a remediation strategy is approximately 15 percent of the cost of the iron (EnviroMetal Technologies 2003). However, O&M costs are correspondingly low.

This technology is Retained as a potential technology to extend the length and depth of the existing SS7 PRB and the stream intercept areas of the other Zone D plumes.

3.6.3 Additional Zero Valent Iron by Deep Soil Mixing

The addition of ZVI by DSM has been used in a few instances for treatment of chlorinated VOCs. The screening of this technology is summarized in Table 3-2.

Effectiveness (moderate): This technology has proven to be moderately effective in a few applications of ZVI by itself and more than 98 percent effective when used with hot air and steam during iron mixing.

The rate and extent of degradation of chlorinated organics within the ZVI through chemical reduction are dictated by the properties of the contaminant itself and its susceptibility to reductive degradation, in addition to matrix conditions including pH, temperature, the concentration of reductant, and the concentration of other reductant-consuming substances.

Implementability (technical – moderate, administrative – low): The additional ZVI by DSM requires significant design and field effort to install, and the number of contractors with the proper equipment and experience is limited. Therefore, the additional ZVI by DSM is considered only moderately technically implementable.

This technology has not been implemented in many full-scale PRBs in North America. As a result, regulatory agencies may have limited experience with its use for chlorinated VOCs and is considered to have a low administrative implementability.

Cost (capital – high, O&M – none): In addition to a licensing fee for use of the iron, the ZVI is relatively expensive and a major cost factor. There are significant mobilization and construction costs associated with a ZVI PRB. However, O&M costs are correspondingly low, but there are additional costs for monitoring.

This technology is Retained due to its potential applicability to lengthening or deepening the SS7 PRB.

3.6.4 Electrical Barrier

The use of an E-barrier is a new treatment method for removing contaminants from groundwater via sequential oxidation and reduction. The screening of this technology is summarized in Table 3-2.

Effectiveness (moderate to high): The rate and extent of degradation of chlorinated organics within the E-barrier through chemical oxidation/reduction are dictated by the properties of the contaminant itself and its susceptibility to oxidative/reductive degradation, in addition to matrix conditions including pH, temperature, the concentration of oxidant/reductant, and the concentration of other oxidant/reductant-consuming substances.

This innovative technology is currently undergoing a Plume C pilot test, but results are not yet available. However, moderate to high treatment efficiency has been demonstrated for TCA, PCE, TCE, arsenic, and nitrate within saturated or unsaturated soils, sludges, and sediments in bench-scale testing. Bench-scale tests indicate more than 90 percent removal of TCE with minimal degradation products sustained in column and tank reactors for periods in excess of three years (Sale et al. 2001). This process is especially unique due to its ability to work in low-permeability as well as high-permeability soils and is applicable to a broad range of organic and inorganic contaminants. The process may be enhanced through the use of surfactants or reagents

to increase contaminant removal rates at the electrodes. There are no chemicals or gases required, and no byproducts are released.

Implementability (technical – low, administrative – moderate): This technology requires significant design and field efforts to install and has one supplier, Colorado State University. This technology is an innovative technology with limited field testing and cannot be used near the ZVI. Trenches are limited to depths reached by excavating equipment; thus, it can be used only in shallow groundwater. Conversely, the *in situ* process has no need for groundwater extraction. Therefore, the technical implementability is low and the administrative implementability is considered to be moderate, pending completion of current pilot testing.

Cost (capital – high, O&M – moderate): Complete cost data are not available because most sites have been demonstration and pilot scale. Preliminary cost data provided by Colorado State University indicates electrical power O&M costs associated with driving transformations are moderate (e.g., $0.03 to 0.001 per day per square foot), and the capital costs of the E-barrier are high, $300 per square foot (e.g., equivalent cost of electrodes are estimated to be 20 to 40 percent of ZVI cost). Construction costs would be high due to generation of large quantities of IDW (water and soil) that require treatment and/or disposal. Proprietary costs must also be considered, since there is only one vendor.

This technology is Retained pending results of the Plume C pilot study being conducted by Colorado State University.

3.6.5 Bark Mulch Biowall

The use of a bark mulch biowall is an innovative treatment method for removing contaminants from groundwater. The screening of this technology is summarized in Table 3-2.

Effectiveness (unknown): Bark mulch biowall may have a more limited life span than the ZVI PRB. There are no chemicals or gases required, but no byproducts may be released. A Zone D pilot test may demonstrate effectiveness at FEW. At Offutt AFB, a biowall reduced TCE in groundwater from 2,100 µg/L to greater than 200 µg/L and did not reach MCLs.

Implementability (technical – low, administrative – moderate): Implementability requires significant design and field effort to install. This process is very construction intensive and trench support will be needed. The trenches are limited to depths reached by excavation equipment and, therefore, can be used only in shallow groundwater. This is an *in situ* process with no need for groundwater extraction. Although this is a very new technology, agencies may accept it for a Zone D pilot test.

Cost (capital – high, O&M – none): There are significant construction costs of $4.20 per 1,000 gallons of treated water, compared to $8.90 per 1,000 gallons for a conventional pump-and-treat system using air stripping and GAC (Quinton et al. 1997). There are no O&M costs, except for monitoring costs, unless precipitation or biofouling occurs or replacement of the mulch is needed.

This technology is Retained if a pilot study of the technology is implemented at FEW and Rejected if the study is not approved.

3.7 ELECTRICAL RESISTANCE HEATING

The use of ERH is an innovative treatment method for removing contaminants from groundwater in low-permeability soils. The screening of this technology is summarized in Table 3-2.

Effectiveness (moderate to high): ERH can remove sorbed-phase VOCs as well as liquid-phase VOCs because groundwater and vapor-phase VOCs are heated to 100ºC and volatilized. An SVE system is required to capture these VOCs. The effectiveness is based on its use at other sites where 99 percent removal efficiencies have been reached for chlorinated VOCs.

Implementability (technical – moderate, administrative – low): ERH requires significant field effort to install and is available through limited vendors. ERH is one of a few limited technologies available to treat fine-grained, low-permeability soils and is an *in situ* process that has no need for groundwater extraction. However, the process requires a vapor extraction and *ex situ* treatment system and cannot be used near utility lines, groundwater extraction systems, or iron PRBs that could be impacted by heat or vapors.

ERH may be rejected by agencies because it is a complex, high energy-use technology and is therefore assigned a low administrative implementability.

Cost (capital – high, O&M – high): There are significant combined capital construction and O&M costs of costs of $2 million per half acre. Capital costs include heating electrodes and an SVE system. The O&M will result in very high energy costs in addition to monitoring costs and are therefore expensive for large treatment areas. However, the time period of system operation is short (months rather than years), and there is minimal equipment to maintain after initial use.

This technology is Retained due to its ability to treat high concentrations of VOCs in low permeability sediments, typical characteristics of the SS7 area.

3.8 PHYTOREMEDIATION

The use of phytoremediation with hybrid poplar trees is an innovative method for removing contaminants from groundwater and soils. The screening of this technology is summarized in Table 3-2.

Effectiveness (moderate): Hybrid poplar trees can be utilized in riparian areas with shallow groundwater up to 20 feet bgs. Phytoremediation is a passive, solar-driven treatment through the use of metabolism/transpiration by plants. Although phytoremediation by poplars is faster than natural attenuation, it is slower than mechanical treatments. The root depth is approximately 10 feet bgs and are therefore usable in areas with a shallow water table. Phytoremediation has fewer air and water emissions than *ex situ* systems.

Phytoremediation has been proven to be capable of treating a wide variety of organic contaminants; however, only in the dissolved phase. The trees have also been shown to withstand fairly high concentrations of TCE before reaching toxicity levels (approximately 25 to 50 ppm). However, trees are subject to disease and animal consumption and growth may be limited by the supply of water, oxygen, and nutrients.

Due to its frequent field use for hydraulic control and phytoremediation of chlorinated VOCs, including use at Carswell AFB in Texas, hybrid poplar trees have been considered as moderately effective for use at FEW.

Implementability (technical – high, administrative – low): The use of phytoremediation as a treatment technology requires equipment, trees, and labor readily available from local landscapers/tree nurseries. Site-specific conditions at FEW may require the use of an auger drill rig to drill boreholes in which the trees would be planted, providing a permeable pathway for the roots to grow and extract groundwater. In addition, planting trees in semiarid environments, such as at FEW, may require the installation of a small irrigation system before the tree roots are established. Phytoremediation cannot be used near ZVI due to the potential for root penetration and channeling through the ZVI.

This technology would have a higher public acceptance due to aesthetics, but regulatory agencies may have limited experience with its use for chlorinated VOCs, and is therefore assigned a low administrative implementability.

Cost (capital – moderate, O&M – moderate): One estimate of capital costs of phytoremediation at Carswell AFB in Fort Worth, Texas, included: wholesale cost of trees (does not include delivery or installation costs) = $0.20/tree for whips; subsurface fine biomass = $60,000 (Harvey 2002); plus costs for additional monitoring well construction.

Ecolotree's and Applied and Natural Science, Inc.'s cost estimate of a poplar tree phytoremediation system included: installation of trees at 1,450 trees/acre = $12,000 to $15,000; predesign investigations = $15,000; design, site visit = $5,000; soil cover and amendments = $5,000; transportation to site = $2.14/mile; for a total of approximately $50,000 per acre, although the predesign and design costs would not change substantially for a site of greater than one acre.

O&M costs for this site = $1,500/acre with irrigation; $1,000/acre without irrigation; pruning (assume every other year) = $500; and harvest (during harvest years every 5 years) = $2,500; for a total average annual cost of $2,200 per year per irrigated acre, excluding monitoring costs.

This technology is Retained. This technology may prove effective in removing contamination at creek intercepts of the contaminant plumes where depths to groundwater are shallow (between 3 to 10 feet bgs).

3.9 CONTAMINANT MOBILIZATION

The following focused *in situ* groundwater technologies are screened in this section:

- Surfactants
- Solvents

3.9.1 Surfactants

The use of surfactants and dispersal agents is a common water well method for removing piped fines during well redevelopment, but is much less frequently used in remediation. The screening of this technology is summarized in Table 3-2.

Effectiveness (low): The effectiveness of these chemicals is moderate to high for soil fines and precipitates in water wells. However, the chemicals may coat the particles of ZVI in existing PRBs at SS7 and Plume E, inhibiting its effectiveness to treat chlorinated VOC contamination. The effect of ZVI on these chemicals is unknown.

Implementability (technical – low, administrative – moderate): Surfactants and dispersal agents are generally implemented at relatively low concentrations of 250 to 500 mg/L and may be added to existing monitoring wells. Dispersal agents such as the polyphosphates should always be implemented simultaneously with a biocide such as hypochlorite because polyphosphates act as a food source for iron bacteria (Driscoll 1986). Surfactants must be removed from groundwater through extraction, treatment, and possible reuse for maximum effectiveness. Due to the unknown effects of these agents and bacteria on ZVI, the technical implementability is low and the administrative implementability is moderate.

Cost (capital – moderate to high, O&M – moderate to high): Chemicals utilized in this application are relatively inexpensive, and the typical cost for this treatment is considered to be moderate to high because the chemicals must be combined with an extraction system to be effective. Surfactants and dispersal agents are generally inexpensive to use because only relatively low concentrations of 250 to 500 mg/L are required. However, the longevity of these chemicals is questionable, therefore the O&M cost for frequent, multiple applications may be high.

This technology is Rejected due to the requirement for use of the technology with an extraction and treatment/recycling system.

3.9.2 Solvents

The use of solvents is an uncommon treatment method for removing contaminants from groundwater. The screening of this technology is summarized in Table 3-2.

Effectiveness (low): Usually, a harmless solvent is injected to dissolve TCE sorbed to soil particles in the groundwater to increase the effectiveness of an extraction system. When this technology is utilized in low permeability areas, it may decrease the radius of influence.

Implementability (technical – low, administrative – moderate): This technology can be easily added to existing monitoring wells. However, it must be used with a pumping system for removing TCE from groundwater. Solvents must be removed from groundwater through extraction, treatment, and possible reuse for maximum effectiveness. For these reasons, there is low technical implementability.

This process may be used near ZVI after bench testing. Solvent injection was used successfully for DNAPL at other USEPA Region 8 sites and is assumed to have a moderate administrative implementability.

Cost (capital – moderate to high, O&M – moderate to high): The capital cost to utilize solvent injection is moderate if used alone. It is a much higher cost when utilized with pumping. There will also be monitoring costs.

This technology is Rejected due to the requirement for use of the technology with an extraction and treatment/recycling system.

3.10 GROUNDWATER AND VAPOR EXTRACTION

The following focused *ex situ* groundwater and/or vapor extraction technologies are screened in this section:

- Pumping
- Dual-phase extraction
- Two-phase extraction
- Air sparging with SVE
- Groundwater recirculation wells with SVE

3.10.1 Pumping

The use of TCE-contaminated groundwater recovery by pumping of extraction wells is a common treatment method for removing contaminants from groundwater. The screening of this technology is summarized in Table 3-2.

Effectiveness (moderate): The potential effectiveness of a pump-and-treat system is dependent on several factors, including soil properties (e.g., capillary forces, effective porosity, moisture content, organic content, hydraulic conductivity, and texture); nature of the release (e.g., initial date of occurrence, duration, volume, and rate); geology; and hydrogeologic regime (e.g., depth to water table, groundwater flow direction, and gradient).

The Zone D pilot test demonstrated that conventional well pumping was half as effective as the two-phase system.

Implementability (technical – moderate, administrative – moderate): The extraction system components and experienced contractors are readily available for the technical implementability of pumping. Although this is a commonly used groundwater extraction technology, it may not be able to extract sorbed VOCs unless the system is cycled. This is a USEPA presumptive remedy for chlorinated VOCs in groundwater and has been accepted for use in Zone B. This system may affect nearby wells or water rights if large volumes of water are to be removed, and it cannot be used near ZVI. For these reasons, there is a moderate implementability of this technology.

Cost (capital – high, O&M – high): The capital cost for pumping is $100,000 per acre based on Zone B costs. O&M costs are $80,000 per year, plus monitoring costs, and some representative costs are $1,000 to $10,000 per month for a total fluids recovery system. These costs illustrate the relative magnitudes of the various recovery options available, system sizing, and additional mineral or biological treatment. Key cost factors for total fluids recovery include treatment additives, installation of permanent equipment, equipment and pump maintenance and engineering costs. The typical cost for total fluids recovery is medium to high (Van Deuren *et al.* 1997).

This technology is Retained as the presumptive technology for TCE-contaminated groundwater remediation.

3.10.2 Dual-Phase Extraction

The use of dual-phase extraction is a less common treatment method for removing contaminants from groundwater via liquid- and vapor-phase recovery. The screening of this technology is summarized in Table 3-2.

Effectiveness (moderate): Groundwater SVE is achieved by conventional pumping with a vacuum applied to the well casing. Dual-phase extraction can be designed to provide hydraulic control of a plume. The Zone D pilot test showed that this technology is half as effective as two-phase extraction.

Implementability (technical – moderate, administrative – low): The extraction system components and experienced contractors are readily available for the technical implementability of dual-phase extraction. It also provides added vapor extraction to a conventional pump-and-treat system. This system may affect nearby wells or water rights if large volumes of water are to be removed, and it cannot be used near ZVI. Dual-phase extraction does not require permits for both groundwater disposal and vapor emissions on site, but substantive permit requirements would have to be met. Therefore, this technology has a moderate implementability.

There are no known uses of dual-phase extraction in USEPA Region 8. The Plume C pilot test results indicated no advantage of this technology over pumping; thus, this dual-phase extraction has a low administrative implementability.

Cost (capital – high, O&M – high): Dual-phase extraction is typically three times more expensive than pumping alone, depending upon the size of the system, due to the need for dual *ex situ* groundwater and vapor extraction and treatment systems. The capital cost of approximately $300,000 per acre is based on RACER™ costs. O&M would cost $80,000 per year, which costs 50 percent higher than pumping alone, plus monitoring costs. Similar to pumping, the system requires frequent O&M and protection from freezing.

This technology is Rejected because it costs three times that of pumping alone, and based on the pilot test at Plume C, is no more effective.

3.10.3 Two-Phase Extraction

The use of two-phase extraction is a treatment method for removing contaminants from groundwater via liquid- and vapor-phase recovery. The screening of this technology is summarized in Table 3-2.

Effectiveness (moderate): Groundwater extraction is accomplished by a vacuum applied to the inside of the well casing. Similar to dual-phase extraction, two-phase extraction can be designed to provide hydraulic control of a plume. The pilot study in Plume C (USAF 1006d) indicated that two-phase extraction is twice as effective in terms of contaminant reduction (in pounds removed per day) as pumping and dual-phase extraction.

Implementability (technical – moderate, administrative – moderate to high): The extraction system components and experienced contractors are readily available for the technical implementability of two-phase extraction. Other contaminants of concern, such as metals, may be treated with add-on modules. This system may affect nearby wells or water rights if large volumes of water are to be removed, and it cannot be used near ZVI. Two-phase extraction may also require permits for both groundwater disposal and vapor emissions and, therefore, has a

moderate technical implementability. Two-phase extraction has been successfully pilot tested at Plume C and has a high administrative implementability.

Cost (capital – high, O&M – high): Two-phase extraction is generally labor intensive due to the need for *ex situ* groundwater and vapor extraction and treatment systems. The capital cost would be $550,000 per acre based on the Plume C - Zone D pilot test. Similar to pumping, the system requires frequent O&M and protection from freezing. O&M costs of $80,000 per year, plus monitoring costs would be anticipated.

This technology is Retained due to the success of a Plume C pilot test (USAF 1996c).

3.10.4 Air Sparging with Soil Vapor Extraction

The use of air sparging with SVE is a common treatment method for removing contaminants from groundwater via aeration and vapor recovery for *ex situ* treatment. The screening of this technology is summarized in Table 3-2.

Effectiveness (low): Conventional air stripping provides only stripping of volatiles, but no bioremediation benefit for chlorinated VOCs. The *in situ* air sparging effectiveness is generally poor for chlorinated VOCs. Effectiveness also depends on the ability of the sparged air to move through the aquifer, which is poor in the fines-dominated systems characteristic of FEW.

Implementability (technical – moderate, administrative – low): Air sparging is a commonly used groundwater treatment technology for VOCs. The process strips VOCs from groundwater with no *ex situ* groundwater treatment, permits, or disposal required. The system components and experienced contractors are readily available for the technical implementability of air sparging.

There is little impact on nearby wells or water rights from air sparging, however, it cannot be used near ZVI. This system requires an *ex situ* vapor treatment system and may require an emissions permit. The administrative implementability is low due to the lack of effectiveness of the technology for chlorinated VOCs.

Cost (capital – high, O&M – high): There are dual installation costs for air sparging and a separate SVE. Capital costs for an air sparging/SVE system per acre are approximately $250,000. The O&M costs are also high due to frequent O&M and protection from freezing. The costs are $100,000 per year, plus monitoring costs.

This technology is Rejected from further consideration due to its similarity to air/ozone sparging technology and its low effectiveness as demonstrated in the Zone D Treatability Study (USAF 2003f).

3.10.5 Groundwater Recirculation Wells with Soil Vapor Extraction

The use of groundwater recirculation wells with SVE is an innovative treatment method for removing contaminants from *in situ* groundwater, then recovering the contaminants in the vapor-phase for *ex situ* treatment. The screening of this technology is summarized in Table 3-2.

Effectiveness (low): This technology can efficiently remove VOCs from shallow- and intermediate-depth groundwater simultaneously. However, groundwater recirculation wells with SVE is not effective in low permeability areas and may prevent the formation of vertical circulation cells.

Implementability (technical – low, administrative – low): This technology can strip VOCs from groundwater with no *ex situ* groundwater treatment, permits, or disposal required. There is significantly more effort required for groundwater recirculation than single-screen pumping wells, and it cannot be used near ZVI. It requires a more complex design and installation than alternative technologies, and it does not guarantee meeting ARARs.

One advantage is that there is little impact on nearby wells or water rights. However, this system requires an *ex situ* vapor treatment system and may require an emissions permit. The implementability of this technology is low from a technical and administrative standpoint.

Cost (capital – high, O&M – moderate): There is a high capital cost because each well is twice the cost of a conventional extraction well. An additional cost of installing SVE recovery must also be considered. O&M costs less than pumping, but still requires frequent O&M and protection from freezing, in addition to monitoring costs.

This technology is Rejected due to its complexity and its low administrative implementability.

3.11 *EX SITU* TREATMENT

The following focused *ex situ* groundwater treatment technologies are screened in this section:

- Air stripping
- Liquid-phase carbon adsorption
- UV oxidation
- Vapor-phase bioreactor

3.11.1 Air Stripping

The use of air stripping is a common treatment method for removing volatile contaminants from groundwater. The screening of this technology is summarized in Table 3-2.

Effectiveness (high): Air strippers are very effective at reducing chlorinated VOCs to MCLs. Removal efficiencies around 99 percent are typical for towers that have 15 to 20 feet of packing and are removing compounds amenable to stripping. Removal efficiencies can be improved by adding a second air stripper in series with the first, heating the contaminated water, increasing the air/liquid ratio, or heating the air.

Implementability (technical – high, administrative – moderate): Air strippers are the most commonly used technology for chlorinated VOCs, and equipment is readily available. The major problem encountered with packed tower air strippers is fouling of the packing, which reduces the airflow rate. Fouling is caused by oxidation of minerals in the feed water, such as iron and magnesium, by precipitation of calcium, and by biological growth on the packing material. This can be solved in small-capacity systems by using stacked tray strippers, but these are limited in maximum size and large-capacity systems must use packed towers. Thermal units for treating air stripper emissions can be used as a source of heat. The performance of aeration tanks can be improved by adding chambers, trays, or by increasing the air supply, depending on the design of the tank. This technology has been used successfully in USEPA Region 8, but was less successful at SS7.

Cost (capital – moderate, O&M – high): A cost of $42,000 (per RACER™) for stacked tray system capable of treating 30 gpm. Frequent O&M is required at $80,000 per year, plus monitoring costs. A major operating cost of air strippers is the electricity required for the groundwater pump, sump discharge pump, and air blower. The power rating of the groundwater pump and discharge pump depends on the pressure head and pressure drop across the column and should be obtained from pump curves. As a generalized rule, pumps in the 1- to 20-gpm-range require from 0.33 to 2 horsepower (HP); from 20 to 75 gpm, power ratings are 1 to 5 HP; and from 100 to 600 gpm, power ratings range from 5 to 30 HP. A rough method of estimating blower motor power assumes that each foot of air stripper diameter requires 1.5 HP. The initial cost for air stripping system is relatively low, but annual O&M costs are approximately $75,000 per year (Van Deuren *et al.* 1997).

This technology is Retained due to its ability to remove high concentrations of TCE in groundwater, making it highly effective, and its high/moderate implementability.

3.11.2 Liquid-Phase Carbon Adsorption

The use of GAC is a common treatment method for removing contaminants from extracted groundwater. The screening of this technology is summarized in Table 3-2.

Effectiveness (high): GAC is very effective at reducing chlorinated VOCs to MCLs. Adsorption by activated carbon has a long history of use as a treatment for municipal, industrial, and hazardous waste streams. The concepts, theory, and engineering aspects of the technology are well developed. It is a proven technology with documented performance data. Liquid-phase carbon adsorption is a relatively nonspecific adsorbent and is effective for removing many organic, explosive, and some inorganic contaminants from liquid and gaseous streams.

The target contaminant groups for liquid-phase carbon adsorption are hydrocarbons, SVOCs, and explosives. Limited effectiveness may be achieved on halogenated VOCs and pesticides. Liquid-phase carbon adsorption is effective for removing contaminants at low concentrations (less than 10 mg/L) from water at nearly any flow rate and for removing higher concentrations of contaminants from water at lower flow rates.

Implementability (technical – moderate, administrative – high): Liquid-phase carbon adsorption is particularly effective for polishing water discharges from other remedial technologies to attain regulatory compliance. Liquid-phase carbon adsorption systems can be deployed rapidly, and contaminant removal efficiencies are high. Logistic and economic disadvantages arise from the need to transport and decontaminate spent carbon. GAC equipment is readily available, but GAC must be regenerated frequently for high COC water/air, and pretreatment of the water is required for metals and anions. GAC systems have been used frequently in USEPA Region 8, and one is currently being used in Zone B.

Cost (capital – moderate, O&M – high): Capital costs are approximately $40,000 for a GAC unit capable of treating 30 gpm. Frequent O&M and replacement of GAC (depending upon the change-out schedule) are required at $35,000 per year, plus monitoring costs. Costs associated with GAC are dependent on waste stream flow rates, type of contaminant, concentrations, and site and timing requirements. Costs are lower with lower concentration levels of a contaminant of a given type and at higher flow rates. At flow rates of 0.1 million gallons per day (mgd), costs increase to $1.20 to $6.30 per 1,000 gallons treated (Van Deuren *et al.* 1997).

This technology is Retained due to its ability to remove high concentrations of TCE in groundwater, making it highly effective, and its moderate/high implementability.

3.11.3 Ultraviolet Oxidation

The use of UV oxidation is a common secondary treatment method for removing contaminants from potable water and wastewater. The screening of this technology is summarized in Table 3-2.

Effectiveness (high): UV oxidation is an innovative groundwater treatment technology that has been used in full-scale groundwater treatment applications for more than 10 years. Currently, UV oxidation processes are in operation in more than 15 full-scale remedial applications. A majority of these applications are for groundwater contaminated with petroleum products. UV oxidation has been proven effective at reducing chlorinated VOCs to MCLs for moderate concentrations of COCs in large volumes of water.

Implementability (technical – low, administrative – moderate): A wide range of UV oxidation system sizes are commercially available. Single-lamp benchtop reactors that can be operated in batch or continuous modes are available for the performance of treatability studies. Pilot- and full-scale systems are available to handle higher throughput (e.g., 1,000 to 1 mgd). UV oxidation is a complex technology requiring substantially more design/equipment as COC concentration increases; pretreatment is required for metals and anions. It is not a commonly used technology in USEPA Region 8.

Cost (capital – high, O&M – very high): UV oxidation costs range between $0.10 to $10.00 per 1,000 gallons treated. Additional costs for O&M are also comparatively high. Factors that influence the cost to implementing UV oxidation include (Van Deuren *et al.* 1997):

- Types and concentration of contaminants (as they affect oxidizer selection, oxidizer dosage, UV light intensity, and treatment time);
- Degree of contaminant destruction required;
- Desired water flow rates; and
- Requirements for pretreatment and/or post-treatment.

This technology is Rejected due to its complexity and very high operating cost.

3.11.4 Vapor-Phase Bioreactor

The use of a liquid- and/or vapor-phase bioreactor is a less common treatment method for removing contaminants from extracted groundwater or vapor via a bioinnoculated reactor. The screening of this technology is summarized in Table 3-2.

Effectiveness (moderate): A vapor-phase bioreactor is effective at reducing chlorinated VOCs to lower concentrations, but may have some difficulty reaching MCLs. The technology requires microbial processes, and very high VOC concentrations may be toxic to microbes.

Implementability (technical – moderate, administrative – moderate): Vapor-phase bioreactor is a commonly used wastewater treatment technology, but lesser used technology for chlorinated VOCs. It is generally used for liquid-phase treatment although vapor-phase is available. The

system components are readily available for the technical implementability of this treatment system, but vendors are limited. Other COCs, such as metals, may be treated with add-on modules. However, pretreatment to prevent fouling is required for any groundwater containing a high concentration of minerals.

Vapor-phase bioreactors have been used infrequently in USEPA Region 8, but this technology was used successfully in the Plume C - Zone D pilot test for vapor treatment.

Cost (capital – moderate, O&M – high): This technology's capital cost will be $243,000 per RACER™ for a BioTrol® unit capable of treating 30 gpm. Frequent O&M is required in addition to protection from freezing, costing $50,000 per year, plus monitoring costs.

This technology is Retained due to the success of a Plume C pilot test (USAF 1996c).

3.12 DISCHARGE OF TREATED WATER

The following focused *ex situ* treated water discharge options are screened in this section:

- Reinjection
- Surface streams
- POTWs

3.12.1 Reinjection

The use of reinjection is a less common treatment method for returning treated groundwater to the saturated zone. The screening of this technology is summarized in Table 3-2.

Effectiveness (low): This technology discharges treated water which must meet MCLs before it is released to nearby injection wells or an infiltration gallery for return to the aquifer. Low-permeability soil reduces the effectiveness of percolation/infiltration into the soil.

Implementability (technical – moderate, administrative – low): This is a commonly used wastewater discharge technique. However, the technology requires new wells, pumps, and piping and has a moderate technical implementability due to the relatively low hydraulic conductivities in Zone D. This technology is preferred by the State Engineer's Office due to the lessened impact on water rights. However, this technology has a low administrative implementability due to the lengthy permit requirements of the UIC program prior to reinjection into the Ogallala Aquifer.

Cost (capital – high, O&M – high): The capital cost is relatively high due to the injection wells. There are also continuing pumping costs, high O&M costs (including protection from freezing), plus monitoring costs.

This technology is Rejected due to its low administrative implementability.

3.12.2 Surface Streams

The use of pumping or gravity-draining treated water to the surface water system is a commonly used technology in wastewater treatment. The screening of this technology is summarized in Table 3-2.

Effectiveness (high): Discharge to a surface water body will need to be treated to substantive NPDES requirements before discharge. However, gravity-draining treated water to surface water is very effective.

Implementability (technical – high, administrative – moderate): This technology is a commonly used wastewater discharge technique. There are surface drainages near each plume at FEW, and the technology can be easily gravity drained; thus, having a high technical implementability.

This process is currently being used for the Zone B treatment system discharge. There is more water in Zone D, and substantive requirements of an NPDES permit would be required to discharge treated water. Discharge to surface streams has a moderate administrative implementability.

Cost (capital – low, O&M – moderate): The capital cost for this technology is low due to only needing a drain line. O&M costs are required for drain lines and for vegetation control at outfalls, in addition to monitoring costs.

This technology is Retained due to its current success in Zone B.

3.12.3 Publicly Owned Treatment Works

The use of pumping or gravity-draining groundwater to a POTW is a common treatment method for treating groundwater, but is used much less frequently for disposal of treated water because it must be treated twice. The screening of this technology is summarized in Table 3-2.

Effectiveness (high): This technology has been used for numerous similar sites in Wyoming by WDEQ and has proven to be effective.

Implementability (technical – high, administrative – low): Utilization of a POTW is a common wastewater discharge technique. There are sewer lines near each plume at FEW, and the treatment can be gravity drained from most sites. This technology requires approval from the City of Cheyenne. In the past, the City of Cheyenne POTW has rejected waste from CERCLA sites, specifically from FEW groundwater remediation. Currently, the primary reason is the POTW cannot handle large quantity, continuous discharges because of capacity limitations. Therefore, the administrative implementability is low.

Cost (capital – moderate, O&M – moderate): The cost for a sewer line, including manholes at each connection, is considered to be moderate. This technology requires frequent O&M for sewer lines and protection from freezing, plus monitoring costs and discharge fees.

This technology is Rejected due to its low administrative implementability as it cannot large quantity, continuous discharges.

3.13 SURFACE WATER TREATMENT

Surface water treatment options include channel drop structures, instream fountains, indoor water cascade and instream bubblers. Each of these options is discussed further in the following sections.

3.13.1 Channel Drop Structures

Channel drop structures are typically used to increase surface area of the water, which increases aeration and volatilization of contaminants such as TCE. Creating turbulence by forcing water over a drop structure increases the surface area of the water.

Effectiveness (moderate): Channel drop structures are an effective way of creating turbulence within a stream flow. The use of aeration to volatize contaminants is a proven technology that is used widely. A rating of "moderate" is given to this technology due to the existence of more aggressive volatilization technologies.

Implementability (technical – high, administrative – high): Channel drop structures can be built of several kinds of materials. Concrete and river rock are two materials that can be utilized to create an effective drop structure. The design and build of such a structure is simple and takes little time compared to other volatilization technologies. This option is also the least intrusive to the natural environment surrounding the creek.

Cost (capital – low, O&M – very low): Channel drop structure costs range between $35,000 and $60,000 for three to four structures. O&M associated with this option is minimal as only debris clearing is required.

This technology is Retained due to its simplicity, low level of intrusion on the environment, and low cost.

3.13.2 Instream Fountain

Instream fountains are typically used to increase aeration of the water, which increases volatilization of contaminants such as TCE. Creating turbulence by spraying water into the air increases the aeration of the water.

Effectiveness (moderate): Instream fountains are an effective way of increasing aeration within a stream flow. The use of aeration to volatize contaminants is a proven technology that is used widely. A rating of "moderate" is given to this technology due to the existence of more aggressive volatilization technologies.

Implementability (technical – high, administrative – moderate): Instream fountains can be installed fairly easily; however, O&M issues exist with the mechanical workings of the fountain. The design and build of such a structure is simple and takes little time compared to other volatilization technologies. This option is minimally intrusive to the natural environment surrounding the creek.

Cost (capital – moderate, O&M – low): Instream fountain costs range between $45,000 and $80,000, depending upon the location of electricity. O&M associated with this option is low as maintenance of the mechanical workings of the fountain is required.

This technology is Rejected due to its O&M component and moderate capital costs.

3.13.3 Indoor Water Cascade

Water cascades are used to increase aeration of the water, which increases volatilization of contaminants such as TCE. Creating turbulence by forcing water over a cascade increases the

aeration of the water. The cascade would have to be built indoors due to the freezing temperatures and delicacy of the mechanical components.

Effectiveness (high): Water cascades are an effective way of increasing aeration within water flow. The use of aeration to volatize contaminants is a proven technology that is used widely. A rating of "high" is given to this technology due to the indoor, heated component of the design. Increased temperature improves the rate of volatilization of the TCE.

Implementability (technical – high, administrative – high): Water cascades require a moderate complexity within the design. The addition of a structure further complicates the design. This option is intrusive to the natural environment surrounding the creek due to the requirement of heavy equipment and the structure.

Cost (capital – high, O&M – moderate): Water cascade costs range between $55,000 and $100,000, depending upon the location of electricity and the design. O&M associated with this option is moderate with costs ranging from $500 to $800 monthly.

This technology is Rejected due to its environmental intrusiveness and cost.

3.13.4 Instream Bubbler

Bubblers are used to increase aeration of the water, which increases volatilization of contaminants such as TCE. Creating turbulence by forcing bubbles through the water increases the aeration of the water.

Effectiveness (moderate): Bubblers are an effective way of increasing aeration within water flow. The use of aeration to volatize contaminants is a proven technology that is used widely. A rating of "moderate" is given to this technology due to the instream placement of the bubbler. By placing a panel with many small orifices instream, the technology opens itself to many environmental influences that may not be favorable.

Implementability (technical – moderate, administrative – moderate): Bubblers require a moderate complexity within the design due to the outside influences. The plugging factor is a risk that must be considered during the design. This option is intrusive to the natural environment, requiring some a small structure to house parts.

Cost (capital – moderate, O&M – moderate): Bubbler costs range between $65,000 and $90,000, depending upon the location of electricity and the design. O&M associated with this option is moderate with frequent inspections.

This technology is Rejected due to its environmental intrusiveness and cost.

3.14 RETAINED TECHNOLOGIES AND PROCESS OPTIONS FOR ZONE D PLUMES

As shown in Table 3-3, the retained *in situ* and *ex situ* treatment technologies and process options may be applicable only to specific portions of the groundwater plumes that constitute Zone D.

3.15 TECHNOLOGY SELECTION AND RATIONALE FOR ZONE D PLUMES

The application of the technologies in Table 3-3 to the AOCs for each plume may be limited by:

- Impacts on existing interim treatment systems, such as the SS7 PRB;
- Lack of implementability under some topographic, hydrogeologic, or endangered species constraints;
- Lack of effectiveness due to higher TCE concentrations than the technology can treat;
- Lack of cost-effectiveness due to lower concentrations than a costly technology is designed to treat; or
- Need to use the technology in combination with other technologies, such as combining groundwater pumping, *ex situ* air stripping, and discharge to a surface stream, to form a "treatment system" (as opposed to a "remedial alternative"), since none of these components can function independently of the other two to treat TCE-contaminated groundwater.

These applicability constraints will be utilized to aid in the selection of technologies for each AOC in each plume as part of the development of the remedial alternatives. A summary of the technology selection and rationale for each plume are presented in Tables 3-4 through 3-9. In the case of SS7, this plume has been sub-divided into two areas for the purpose of determining applicable technologies. These areas, referred to as SS7 East and SS7 West, are presented in Tables 3-5 and 3-6, respectively. SS7 East represents the eastern portion of the plume within the vicinity of the existing PRB while SS7 West represents the remainder of the plume. This distinction is made based upon hydrogeologic data which indicates a shallow groundwater divide in the central portion of SS7, as illustrated in Figure 5-1 of Volume II. Furthermore, these areas are differentiated based upon groundwater flow. In SS7 East groundwater flows to the northeast and is treated by the existing PRB before reaching Diamond Creek; whereas, groundwater within SS7 West flows to the west reaching Diamond Creek untreated. Additionally, application of technologies in SS7 East is limited by their compatibility with the existing PRB, as discussed in Table 3-5 (e.g., injection of oxidants would counteract the desired effect of reduction induced by the ZVI PRB). Rationale contained within Tables 3-5 and 3-6 helps document the applicability of technologies at SS7 treated as a single area for development of the alternatives as discussed in Section 5.

As stated in Section 1.2.2, Hydrogeologic Setting, and discussed in Volume II, Groundwater Modeling, two principal hydrogeologic zones are recognized, shallow and intermediate. Distinction between these zones is related to depth (shallow being the upper 20 feet of groundwater and intermediate approximately 20 to 50 feet below the water table); but primarily the distinction is made based on hydrogeologic properties with the intermediate zone typically being 1.5 orders-of-magnitude lower in hydraulic conductivity. This difference in hydraulic properties requires that these zones be approached differently in terms of remediation.

During initial preparation of this FS, a technical implementability issue was identified for the intermediate zone. The basic premise was that the intermediate zone could not be effectively remediated (neither technologically nor cost effectively) due to limiting hydraulic challenges in extracting groundwater or injecting remedial agents into the low-permeability geologic material. A similar discussion was presented with technical rationale in the *Supplemental Zone C FS*

(USAF 2003d). The Zone C FS demonstrated that groundwater could not reasonably be extracted from the intermediate, low-permeability zones without the wells going perpetually dry. However, injection of a chemical oxidant, $KMnO_4$, could feasibly treat the intermediate zone; although, it would likely require an increased density of injection points. Application of this oxidant technology to effectively treat the contaminants (albeit in the shallow zone) is documented in the *Zone D Treatability Studies* (USAF 2003f). As a result of this recent work, the technical implementability issue for Zone D was mitigated to accommodate treatment of the intermediate zone.

This section consists of the development, detailed analysis, and comparison of the alternatives selected for Plume A, exclusive of SS7. SS7 is evaluated in a separate section (Section 5) due to its separate source and relatively high TCE concentrations.

4.1 DEVELOPMENT OF ALTERNATIVES

The following alternatives have been developed for the Plume A shallow zone. The "A" designation for each of these alternatives refers to Plume A.

- Alternative 1A – No Action
- Alternative 2A – Institutional Controls
- Alternative 3A – MNA
- Alternative 4A – Groundwater Extraction and *Ex situ* Treatment
- Alternative 5A – Localized Bioaugmentation and MNA

All of the alternatives presented would result in concentrations on site above health-based levels, therefore, a site review would be required no less frequent than every five years. Additionally, all of the alternatives would be subject to institutional controls, including stipulations to evaluate potential risk if future buildings are to be constructed overlying higher concentration areas of the groundwater plumes, and none of the alternatives would result in off-site discharge. As such, substantive permit requirements would be met, but actual permits would not be required.

There is no surface water treatment option included for Plume A. Plume A contributes to Diamond Creek, which has no current TCE regulatory limit due to its 3B Classification. Diamond Creek intersects Crow Creek, a Class 2AB creek, which has a current regulatory limit of 2.7 µg/L. Modeling demonstrates that the contaminant load to Diamond Creek from Plume A is not significant enough to require surface water treatment.

With limited treatment options for the intermediate zone, the FS alternatives have been structured and developed to focus on addressing contaminants in the shallow groundwater where most of the contaminant mass exists and hydraulic properties are not as much of a limiting factor. Following discussion of the shallow zone remedial alternatives in subsequent sections, natural attenuation time frames, and simulations of active treatment for the intermediate zone are presented. Treatment methods of the intermediate zone are focused on MNA and $KMnO_4$ injection. This approach has been taken with the understanding that a selected alternative for the shallow zone would also incorporate one of the options for the intermediate zone, including:

- No Action (possibly with monitoring)
- Institutional Controls
- MNA
- Chemical Oxidation ($KMnO_4$)

For all of the alternatives, the proposed monitoring approaches are regarded as baseline assumptions for the purposes of scoping monitoring needs and to provide a basis for FS cost estimates. Actual monitoring needs would be evaluated as the design of the selected alternative progresses.

Waste streams generated during implementation of the alternatives include soil from drill cuttings and trench excavation, water from monitoring well development and purging, and spent carbon from liquid-phase treatment of extracted, vacuum-stripped groundwater. In general, these wastes would be managed consistent with current USEPA-approved waste management practices at FEW.

4.1.1 Alternative 1A – No Action

The No Action Alternative assumes no further action be taken regarding contaminants in groundwater. No institutional controls, such as legal/management control or LTM, would be implemented. This alternative is required by NCP for baseline comparison purposes.

4.1.2 Alternative 2A – Institutional Controls

This alternative consists of Institutional Controls to limit access and future development of groundwater and limit risk from indoor air in buildings that may be constructed overlying the groundwater plumes. Because this alternative does not allow unrestricted use and unlimited exposure, this alternative would be subject to review not less than every five years.

4.1.2.1 Process Description

Prohibit the use of groundwater within the plume, other than for environmental monitoring or testing, as long as contaminant concentrations exceed the RAO.

Require installation of sub-slab vapor venting systems on any new construction over or adjacent to the groundwater plume.

4.1.2.2 Rationale

At sites where contaminants are left in place at levels that do not allow unrestricted use, Land Use Controls (LUCs) are used to ensure that the contaminants do not pose an unacceptable risk to human health or the environment. LUCs consist of institutional and/or physical controls.

4.1.2.3 Conceptual Design

The following actions and restrictions shall be implemented and maintained until unrestricted use and unlimited exposure is achieved.

Employ USAF administrative procedures to track all development activity at FEW to ensure that no project violates the terms of any use restriction for Plume A.

Update the Base General Plan. The General Plan implements “zoning-like” requirements at FEW. Air Force Instructions require this comprehensive planning document for the establishment and maintenance of administrative and physical controls. The General Plan resides in the office of the Base Community Planner. The USAF will develop a map to be included in the General Plan showing the extent of groundwater contamination related to the plume. The following restrictions will be incorporated into the General Plan and cross-referenced to this map:

- No use of groundwater impacted within Plume A, other than for environmental monitoring or testing, until Class I, Wyoming Ground Water Standards (MCLs) are met for TCE and it's degradation products.
- Any development over or adjacent to the groundwater plume shall incorporate sub-slab vapor ventilation systems.

The USAF will notify the regulatory agencies at least 45 days in advance of any Base proposal for a major land use change inconsistent with the use restrictions and assumptions described herein, any anticipated action that may disrupt the effectiveness of the LUCs, any action that might alter or negate the need for the LUCs, or any anticipated transfer of the property subject to the LUCs (consistent with CERCLA Section 120(h)).

4.1.2.4 Performance Monitoring

The USAF will conduct periodic monitoring (at least annually) and take prompt action to restore, repair or correct any LUC deficiency or failure identified. The USAF will notify the USEPA and the State within two weeks upon discovery of any activity that is inconsistent with the LUC objectives or use restrictions, or any action that may interfere with the effectiveness of the LUCs.

The USAF will fully comply with and be accountable for the LUCs identified herein and will timely submit to the USEPA and the State an annual monitoring report (AMR) on the status of the LUCs, including the operation and maintenance, and monitoring thereof, and how any LUC deficiency or inconsistent use has been addressed.

The AMR shall be filed in the Administrative Record and Information Repository.

The AMR is not be subject to approval and/or revision by the USEPA and the State and will be provided to each for informational purposes only.

The USAF is responsible for implementing (to the degree controls are not already in place), monitoring, maintaining, and enforcing the identified LUCs. If the USAF determines that it cannot meet specific LUC requirements, it is understood that the remedy may be reconsidered and that additional measures may be required to ensure the protection of human health and the environment. The USAF shall obtain the concurrence of the USEPA and the state prior to terminating any LUC Objective or modifying LUC Implementation Actions in a manner inconsistent with the listed LUC Objectives.

All aspects of the performance monitoring would be reviewed during the five-year review of the ROD for Zone D Groundwater.

4.1.3 Alternative 3A – Monitored Natural Attenuation

According to USEPA guidance (USEPA 1999), the most important considerations regarding the suitability of MNA as a remedy include:

- Whether the contaminants are likely to be effectively addressed by natural attenuation processes;
- Stability of the groundwater contaminant plume and its potential for migration; and

- Potential for unacceptable risks to human health or environmental resources by the contamination.

MNA should not be considered where such an approach would result in either plume migration or impacts to environmental resources that would be unacceptable. Therefore, sites where the contaminant plumes are no longer increasing in extent, or are shrinking, would be the most appropriate candidates for MNA.

Groundwater sampling data and numerical modeling results suggest that Plume A, exclusive of SS7, is relatively stable and is shrinking in size and contaminant mass (Volume II and Sections 4.1.3.1 and 5.4.1 and Figure 5-21 of the Zone D Groundwater RI [USAF 2003a]). Modeled results for Alternative 3A (MNA) are shown on Figure 4-1.

Based on these results, MNA is identified as a viable alternative. This alternative is also subject to institutional controls, as described in Section 4.1.2 to limit access and future development of groundwater.

4.1.3.1 Process Description

Natural attenuation is comprised of biological, chemical, and physical processes that reduce contaminant mass, toxicity, mobility, volume, and/or concentration without the application of actively engineered remediation techniques. Processes of attenuation within Zone D include:

- Hydrodynamic dispersion
- Adsorption
- Biodegradation
- Volatilization

Hydrodynamic dispersion is a process by which dissolved contaminants migrating with groundwater tend to spread out from the path that would be expected solely from advective transport. This phenomenon is caused by mechanical mixing (dilution) and diffusion.

Adsorption is a process by which dissolved contaminants partition from the liquid to the solid phase and is considered to have a significant affect on the rate of migration of certain contaminants in groundwater. Contaminants that are adsorbed on to the solid matrix (soils or other geologic materials) in the saturated zone migrate at a slower rate than the advective transport rate. The adsorption rate for a given chemical is usually described by its soil-water distribution coefficient, K_d. The higher the K_d value, the more retarded (less mobile) the chemical.

Biodegradation is a process by which certain types of contaminants dissolved in water are consumed by indigenous microorganisms. The process of biodegradation ultimately transforms contaminants into innocuous byproducts.

Volatilization is a process by which organic chemicals are transferred from the liquid (dissolved phase in water) or solid (adsorbed on soil) phase to a gas (soil vapor or the atmosphere). In general, the tendency of a chemical to volatilize depends on its physical properties (vapor pressure and Henry's Law constant) and environmental factors such as temperature, pressure, and the available pathways.

Natural attenuation is a remedy that combines these natural processes to achieve remediation objectives with a comprehensive monitoring program. Monitoring results are used to calculate the rate of natural attenuation occurring at the site, which is then compared to contaminant removal rates estimated from previously obtained site characterization data and groundwater modeling predictions.

4.1.3.2 Rationale

Groundwater sampling data indicate that TCE concentrations are decreasing throughout Plume A, which suggests that natural attenuation is occurring at the site. TCE concentrations in groundwater samples collected as part of the Zone D RI (Sections 4.1.3.1 and 5.4.1 and Figure 5-21, USAF 2003a) and the MNA groundwater modeling for the Zone D FS (Volume II) suggest that:

- Plume A-1, which originates at the WSA, is stable and receding and the source area has similar TCE concentration levels as the downgradient plume, indicating that there is no longer an effective source.
- Plume A-2, which originates from SS4, is also stable and receding with the eastern lateral extent at MW-99 shrinking from 32 to 2.25 µg/L (i.e., now below the RAO) between 1992 and 2001.
- In both sub-plumes, TCE concentrations in wells with historical data show a decreasing trend.
- The presence of *cis*-1,2-DCE concentrations at detectable levels indicates that at least some biodegradation is occurring.
- The maximum 2001 TCE concentration in Plume A, exclusive of SS7, was 102.2 µg/L.
- Average TCE half-lives of 6 to 8 years have been estimated for Plume A.

Based on results of MNA groundwater modeling presented in Volume II, the time for TCE concentrations throughout the entire plume to be naturally attenuated to 5 µg/L from present conditions is estimated to be approximately 50 years. Modeled results for Alternative 3A (MNA) are shown on Figure 4-1. LTM would allow for continued evaluation of contaminant migration and effectiveness of this alternative.

4.1.3.3 Conceptual Design

The MNA program would be designed to accomplish the following:

- Validate conclusions of the Zone D RI and MNA groundwater modeling;
- Monitor contaminant migration;
- Monitor temporal and spatial changes in TCE concentrations to document decreasing trends;
- Monitor changes in the shape, size, and/or position of the TCE plume;
- Evaluate the effectiveness of natural attenuation processes to reduce contaminant mass and limit migration; and

- Assess the degree to which site-specific RAOs are being met and evaluate the need for additional remediation.

For FS estimating purposes, the MNA design consists of 12 existing shallow zone wells.

4.1.3.4 Performance Monitoring

An LTM program would be developed for the full extent of the MNA period until RAOs are achieved. The program would be reviewed and modified accordingly as new data are obtained during the monitoring period. The following describes the monitoring network and analytical protocol that would be part of the MNA alternative.

Groundwater Monitoring

The network of monitoring will be adjusted and located according to the most appropriate design to measure the effectiveness of each of the chosen treatment alternatives. The monitoring well network would tentatively consist of 12 existing wells in the following locations (Plate 1):

- In-plume—MW-003, MW-005, MW-006, MW-146, MW-164B, MW-165B
- Downgradient—MW-130, MW-144R, MW-145
- Creek intercept—MW-129, MW-311, MW-1003

Monitoring would occur until established groundwater standards are met in each area. Samples would be collected according to the monitoring plan developed for each alternative during the design phase. No new monitoring wells are assumed.

Surface Water Monitoring

Groundwater sampling and modeling results indicate that TCE concentrations in Plume A-1 groundwater may be attenuated to below 5 µg/L before reaching Diamond Creek, a Class 3B stream (Section 5.4.1 and Figure 5-21 of the Zone D Groundwater RI [USAF 2003a]). Plume A-2 does not reach a stream. Based on modeling (Figure 5-1), the TCE concentrations at MW-311 are currently the highest in Plume A and currently exceed MCLs, but the surface water TCE concentrations do not exceed 5 µg/L. In order to monitor the accuracy of the modeling, however, a surface water monitoring network is proposed that would include the following locations:

- Plume intercept—D2.3
- Upstream—D1
- Downstream—D2.8

The plume intercept monitoring point would document surface water directly impacted by discharge from Plume A. An upstream location would serve as a reference point to establish whether any reported concentrations in surface water at the plume intercept are in fact attributable to the plume and not an upstream source. The downstream location would help to define the extent of the TCE-plume intercept, as well as potentially documenting the attenuation of the TCE in surface water. For purposes of the FS, it is assumed that existing surface water stations would be used and no new locations established.

Analytical Protocol

All LTM wells would be sampled and analyzed for those analytes listed in Table 4-1 to evaluate the effectiveness of MNA at achieving the RAOs for Zone D. In addition to standard water quality parameters and water level measurements, the list includes only VOCs, specifically those for TCE and its degradation products (e.g., DCE isomers and vinyl chloride). MNA, in situations where biodegradation is a dominant process, typically requires additional parameters for documenting MNA. However, at FEW, natural attenuation is understood to be a function of processes such as dilution, volatilization, and adsorption; biodegradation is not recognized as a primary attenuation process. Therefore, monitoring trends of only TCE and its degradation products is deemed to be effective for evaluating MNA. This is consistent with the monitoring protocol established for the MNA remedy selected in Zone A (USAF 2003b).

Sampling Frequency and Duration of Monitoring

Results of MNA groundwater modeling (Volume II) suggest that TCE concentrations in groundwater will attenuate to 5 μg/L from present conditions in approximately 50 years.

The sampling frequency would be quarterly for three years, annually through Year 30, then every five years thereafter until RAOs are achieved. It is recognized that during the design and implementation phase, modifications to the sampling frequency (and analyte list) may be required. This sampling frequency would be optimized through time but is assumed to be consistent throughout the remedial time frame for conservative estimating purposes.

4.1.4 Alternative 4A – Groundwater Extraction and *Ex situ* Treatment

This alternative would provide the USEPA "presumptive remedy" for chlorinated VOC contamination in groundwater for Zone D TCE Plume A. Because Plume A can be remediated within 20 years without the application of MNA according to the Plume A model (Volume II and Figure 4-3), no "MNA" was required as part of this alternative. Modeled results for Alternative 4A (Groundwater Extraction and Treatment Method) are shown on Figure 4-3.

The following sections provide a process description, rationale for selection, conceptual design, and process monitoring plan of the groundwater extraction and treatment alternative. This alternative is also subject to institutional controls, as described in Section 4.1.2, to limit access and future development of groundwater.

4.1.4.1 Process Description

This alternative would include four technologies: groundwater extraction, groundwater treatment, treated water discharge, and institutional controls. Institutional controls were discussed in Section 4.1.2, and groundwater extraction, treatment, and disposal are discussed in the following sections.

Groundwater Extraction and Treatment

Groundwater extraction and treatment involves the extraction of contaminated groundwater, aboveground treatment to remove TCE and its degradation products, and discharge of the treated

groundwater. Plume A chlorinated VOC contamination in the shallow zone generally consists of VOCs present in two different phases: dissolved in the groundwater and sorbed to soil particles.

Under static conditions, each of these phases would often be close to equilibrium with little net contaminant transfer between phases. Groundwater extraction creates an area of lowered head within the aquifer and induces groundwater to flow toward the point of extraction. This increased gradient causes groundwater to flow through the aquifer at higher than natural velocities and in directions different than the natural flow direction, replacing contaminated water with "clean" water.

Groundwater extraction upsets the equilibrium between these phases and results in a mass transfer from the sorbed phase to the dissolved phase, which is continuously or cyclically extracted. The extraction process typically continues until the contaminant concentrations in the nondissolved phases are reduced to a point in which mass transfer is not significant enough to overcome the forces that hold the contaminant in the other phases (e.g., adsorption onto soil particles, diffusion-limited, etc.).

Extraction systems typically consist of a network of extraction points (e.g., wells), a collection and conveyance system, a water treatment system, a discharge method, and a monitoring system. An effective monitoring program is essential to provide long-term effectiveness of the system and to evaluate whether the goals and objectives of the remedy are being met.

The methods for groundwater extraction, treatment, and discharge were selected following the identification and screening of remedial technologies and process options as presented in Section 2.4. The methods chosen include:

- Vertical wells for extraction assuming two-phase extraction as the extraction method;
- Liquid-phase carbon adsorption for *ex situ* treatment of TCE-contaminated groundwater;
- Vapor-phase bioreactor for *ex situ* treatment of TCE-contaminated vapors; and
- Discharge of treated groundwater to surface drainage.

The rationale for selection of these technologies is discussed in the following section.

Monitored Natural Attenuation

There would be no MNA involved in this alternative. Based upon modeling results (Figure 4-3), the shallow plume would be remediated after the 20 years of extraction and treatment is completed.

4.1.4.2 Rationale for Alternative

As discussed in Sections 1.3.3 and 2.4.8.2, groundwater extraction and treatment was pilot tested at the head of Zone D Plume C during the fall of 1995 (USAF 1996d). The site was selected in order to compare the effectiveness of three extraction technologies at the very high TCE concentration head of Plume C. Tests of conventional pump-and-treat, dual-phase extraction, and two-phase extraction were run during the pilot test. The pump-and-treat technology was tested for six days, dual-phase extraction for 12 days, and two-phase extraction for 47 days. During this period, the influent and effluent TCE concentrations were analyzed for each technology, the total TCE mass (liquid-phase plus vapor-phase) removed by each technology

was determined, and an average daily TCE mass removal rate was calculated. Based on these calculations, pump-and-treat and dual-phase extraction each extracted 0.011 pound of TCE per day, while two-phase extraction removed 0.023 pound per day, of which 98 percent of the mass occurred in the vapor phase. Thus, the two-phase system removed twice as much contaminant mass per day as each of the other two technologies.

In addition to its effectiveness, two-phase extraction has a greater potential for groundwater removal in lower permeability formation materials than does conventional pumping. As stated in the conclusions of the pilot test report (USAF 1996b):

> "The difference in groundwater extraction between pump-and-treat, dual-phase, and two-phase was moderate at this site…[because] The moderately productive formation ($K=10^{-2}$-10^{-3} cm/sec) yielded significant flow even under standard pump-and-treat conditions. A tighter formation ($K<10^{-3}$ cm/sec) would likely show more dramatic differences in flow between the extraction methods."

The hydraulic conductivities calculated for Plume A are generally much less than 10^{-3} centimeters per second (cm/sec). In addition to the greater extraction rate of two-phase in tight formations, the pilot test report (USAF 1996b) also states that:

> "Two-phase is likely to be more cost effective in tighter formations, and pump-and-treat or traditional (low vacuum) dual-phase is likely to be more cost effective in more productive formations… Advantages of two-phase typically include treatment (stripping) of the groundwater during the extraction process; larger dewatered area in a given well, which allows greater treatment zone and contaminant mass removal; very simple downhole equipment (pipe only); and no external compressor required to operate the pump."

Two-phase is more effective in tight formations because, even if the well has been pumped dry of groundwater, the applied high vacuum can still remove vapors from VOCs sorbed to soil particles (i.e., SVE). At the very low groundwater extraction rates expected in Plume A areas away from Diamond Creek, this vacuum extraction should remove more contaminant mass from vapors than from groundwater extraction. The much greater effectiveness for two-phase in a pilot test run specifically in Zone D and the greater groundwater removal rate in tight formations form the rationale for its selection over conventional pump-and-treat.

During the pilot test discussed above, treatment with a vapor-phase bioreactor and liquid-phase GAC was also successfully tested, as discussed in Sections 1.3.3 and 2.4.9.4. The phases were treated/tested separately because only the liquid-phase was produced during the pump-and-treat test. However, because two-phase extraction produces both a liquid-phase and a vapor-phase contaminant stream, a single treatment system that simultaneously remediates liquid and vapor streams is preferable to separate treatment systems for each phase. Separate systems increase O&M and double influent and effluent (emissions) sampling and analysis efforts. In addition, if one part of a two-part treatment system is not operating, the other system also has to be shut down, requiring twice the number of automated controls. Finally, an FBR does not require the frequent cleaning of an air stripper or the replacement of the reactive medium of a GAC system. Therefore, a combination liquid-phase GAC and vapor-phase FBR was selected for detailed analysis and costing of the extraction and treatment alternative.

4.1.4.3 Conceptual Design

A groundwater extraction and treatment system would be implemented to remove TCE-contaminated groundwater from portions of Plume A that exceed the MCL of 5 µg/L. The following assumptions were made for purposes of preparing a conceptual design of the system (based on Year 2001 data):

- The dimensions of Plume A exceeding 5 µg/L are approximately 3,700 feet long, up to 1,700 feet wide, and up to 25 feet bgs in the shallow zone.
- The maximum TCE concentration is 102.2 µg/L.
- Approximately 37 kg of dissolved TCE are present in Plume A.
- The Zone D groundwater model (Figure 4-2) was used to estimate the number and placement of extraction wells, well pumping rates, and time required to reduce TCE concentrations to 5 µg/L (Figure 4-3) throughout the shallow zone.
- Well locations in the model (Figure 4-2) were optimized to recover the contaminant plume in the shortest possible time without completely dewatering the aquifer, which eliminated wells located in the very low hydraulic conductivity central portion of the plume.
- Model simulations using more than this optimum number of wells (Figure 4-2) indicated no added recovery or time benefit.

Objectives of a groundwater extraction and treatment system therefore include:

- Achieve the RAO of restoring groundwater to beneficial use and reduce TCE and degradation concentrations in groundwater to 5 µg/L;
- Operate the extraction and treatment system in an effective and efficient manner;
- Operate the extraction wells in a manner that reduces the potential for dewatering the aquifer;
- Discontinue extraction from wells where TCE concentrations have been reduced to 5 µg/L; and
- Validate the conclusions of groundwater modeling.

Conceptual Design Approach

A configuration of 103 extraction wells was selected to provide an extraction system capable of pumping a majority of the plume in a reasonable amount of time (Figures 4-2 and 4-3). This configuration of wells was selected through an iterative modeling process involving comparison of results for various scenarios where different numbers and placements of wells were evaluated.

The following assumptions were made to evaluate this alternative using the Zone D groundwater model (see Volume II):

- Extraction wells are screened only in the shallow aquifer zones;

- Extraction wells were simulated using the MODFLOW Drain package, where the bottom of the drain is specified near the bottom of the aquifer layer and the conductance of the drain cell is specified as much greater than the surrounding formation, thus flow into the drain is limited by the formation conductivity and not the drain conductance; and
- Flow condition is simulated as steady state.

Groundwater modeling results indicate that an extraction system consisting of up to 103 extraction wells could feasibly be operated at a total extraction rate of 40 gpm in the shallow aquifer. Groundwater modeling simulations of more than 103 wells resulted in large areas of very thin to partially dry saturated thickness due to aquifer dewatering. In the three-dimensional transport model, MT3D, the areas of very low saturated thickness were converted to inactive cells. Therefore, the contaminated groundwater could not be transported to the extraction wells in these areas. Model simulations using more than 103 wells indicated no added benefit.

Based on this model, the extraction and treatment system would require 20 years to remediate the shallow plume to a TCE concentration of 5 μg/L.

Extraction System

To extract a majority of the plume in the shallow aquifer zone, the extraction system would consist of 103 new, 4-inch wells screened from static groundwater level to the total shallow aquifer depth of contamination ranging from 20 to 30 feet bgs. The conceptual design is presented in Figure 4-2. Based on pump tests conducted at FEW and groundwater modeling, the 103 extraction wells are anticipated to have a combined production rate of approximately 40 gpm. However, actual extraction rates for individual wells would be optimized in the field as part of system start-up.

The wells would be equipped with small-diameter, two-phase “straws” that discharge below grade through lateral pipelines to a collection pipeline that would carry extracted groundwater to the treatment facility. All piping would be placed at least 4 feet below ground to prevent freezing. Extraction system components are summarized in Table 4-4.

Aboveground Treatment System

The anticipated influent flow rate at any one time would be approximately 40 gpm and the treatment system would be designed to treat up to 50 gpm. The treatment plant would be designed to treat the extracted groundwater to meet the RAO and substantive requirements of an NPDES permit. Pretreatment, such as iron precipitation to achieve the substantive requirements of an NPDES permit, does not appear to be necessary. The groundwater would be pumped with the liquid-ring pump to a liquid-vapor separator, with the liquid then treated with GAC and the vapor with a bioreactor. Following treatment, effluent would be released to a surface discharge point at a maximum discharge rate of 50 gpm. A one-month startup and testing period would be required to inoculate the bioreactor, adjust the pH, add inorganic nutrients, and grow the microbes to their operating volume of biomass.

The treatment plant would be placed in an enclosed, heated treatment building with a concrete-bermed floor. Electrical power would be obtained from the existing FEW electrical supply grid.

Treatment and discharge components are summarized in Table 4-4. A conceptual design for the groundwater extraction and treatment system is included as Figure 4-2.

4.1.4.4 Performance Monitoring

A performance monitoring plan would be a required component of the groundwater extraction and treatment alternative and should be considered for planning and budgeting purposes. The performance monitoring plan would describe a groundwater monitoring program for the shallow groundwater extraction system extending over a 20-year period. The performance monitoring plan should be reviewed and modified accordingly as new data are obtained during and after operation of the extraction system. Goals for the performance monitoring program at Plume A include:

- Monitor contaminant migration;
- Monitor temporal and spatial changes in TCE concentrations to document decreasing trends;
- Monitor changes in the shape, size, and/or position of the TCE plume;
- Evaluate the effectiveness of groundwater extraction and treatment to reduce TCE concentrations throughout the plume to 5 μg/L;
- Optimize groundwater extraction and treatment system performance;
- Confirm that system effluent standards are being met; and
- Assess the degree to which site-specific RAOs are being met and evaluate the need for additional remediation.

Groundwater Monitoring

The performance and compliance monitoring network would tentatively consist of the following types of sample locations:

- In-plume—MW-003, MW-005, MW-006, MW-146, MW-164B, MW-165B
- Downgradient—MW-130, MW-144R, MW-145
- Creek intercept—MW-129, MW-311, MW-1003
- Influent from the extraction well system
- Effluent from the treatment system

Monitoring of the shallow zone would continue until established groundwater standards are met in the treatment area. Samples would be collected according to the monitoring plan developed for each alternative during the design phase. The network of monitoring would be adjusted and located according to the most appropriate design to measure the effectiveness of each of the chosen treatment alternatives. No new monitoring wells were assumed.

Surface Water Monitoring

See Section 4.1.3.4 for details of the surface water monitoring program.

Analytical Protocol

All performance monitoring points would be sampled and analyzed for those analytes listed in Table 4-2 to evaluate the effectiveness of groundwater extraction and treatment at achieving the RAOs for Plume A. The list includes parameters that may relate to potential precipitates or discharge requirements. In addition to laboratory analyses, groundwater elevations and water quality parameters would also be measured.

Sampling Frequency and Duration of Monitoring

It is anticipated that the groundwater extraction and treatment system would remediate the shallow aquifer groundwater in approximately 20 years. Therefore, the performance monitoring program sampling duration is based on a 20-year monitoring period. The sampling frequency would be consistent with that presented in Section 4.1.3.4.

Performance Monitoring Program Review

The performance monitoring program would be periodically reviewed and modified to optimize the program and its effectiveness. Groundwater and operational data collected during sampling events would be used as the basis for program modifications. Sampling frequency and monitoring point locations would be evaluated using groundwater modeling and/or trend analysis techniques to evaluate whether a reduction in sampling events and/or locations would be appropriate. Over time, plume shrinkage may dictate the elimination of monitoring points to optimize the program.

4.1.5 Alternative 5A – Localized Bioaugmentation and Monitored Natural Attenuation

This alternative would provide bioaugmentation for local areas of higher concentration chlorinated VOC contamination in groundwater, followed by MNA to reduce concentrations throughout the plume. The following sections provide a process description, rationale for selection, conceptual design, and process monitoring plan. This alternative would also be subject to institutional controls, as described in Section 4.1.2, to limit access and future development of groundwater.

4.1.5.1 Process Description

The following section describes bioaugmentation and MNA portions of the alternative in more detail.

Bioaugmentation

Bioaugmentation is the addition of laboratory-grown microbial cultures to a system for the purpose of performing a specific operational task. The process of bioaugmentation has been used for decades in industrial operations such as food production and wastewater treatment. Adding microbes to contaminated groundwater systems for the purpose of remediation is an innovative process that is currently being implemented at hazardous waste sites.

In many cases, indigenous microorganisms at hazardous waste sites do not have the ability to completely degrade a specific contaminant. Bioaugmentation can establish a consortium of microorganisms to stimulate reduction of contaminants by introducing effective species for complete contaminant degradation, increasing population densities, or accelerating biodegradation rates to meet treatment goals. As microorganisms are added to the subsurface, electron donors (nutrients) can also be added to help establish the microbial population and assist the growth process.

The anaerobic bacterium *Dehalococcoides ethenogenes* is currently the only known organism that can completely dechlorinate PCE and TCE to ethene via dehalorespiration (Magnuson *et al.* 2000; Maymó-Gatell *et al.* 1997; Damborsky 1999; Duhamel *et al.* 2002). For other organisms that have demonstrated the ability to reductively dechlorinate PCE and TCE, the dechlorination is incomplete with the end product being *cis*-1,2-DCE (Maymó-Gatell *et al.* 1997; Suyama *et al.* 2001; Wild *et al.* 1997; Damborsky 1999; Magnuson *et al.* 2000; Duhamel *et al.* 2002).

Bioaugmentation in Zone D would require that microbes be injected into the subsurface. However, before the injection of the microbes, anaerobic conditions must be established in the aquifer to maintain and support cell growth. Anaerobic conditions are established by injecting a mixed solution of oxygen scavenger, vitamins, ZVI, and slow-release lactate (e.g., HRC®) into the area where the microbes will be augmented. Under ideal conditions, the introduced species will thrive and maintain, creating a population of microbes able to degrade site-specific contaminants.

After established, the microbial consortium degrades TCE to ethene through reductive dechlorination processes. The microbes would continue to grow in the injected area creating zones of treatment, depending on the injection radius of influence, which is expected to be similar to the radius of influence observed during the Zone D $KMnO_4$ treatability study since similar injection procedures are followed. These treatment zones are anticipated since complete injection coverage is not expected due to the Zone D lithology. Although *Dehalococcoides* strains can migrate in aquifers (Major *et al.* 2002; Cox *et al.* 2002), the rate of migration is typically slower than groundwater velocities. Therefore, the extent of migration and activity of migrating cells is most likely dependent on the distribution of mixed oxygen scavenger solution, dissolved electron donors, and contaminants.

Monitored Natural Attenuation

Refer to Section 4.1.3.1 for the process description of MNA. Following active treatment of portions of the plume, the remainder of the contaminants would be allowed to naturally attenuate.

4.1.5.2 Rationale for Alternative

The following section discusses the rationale for the combination of bioaugmentation and MNA at Plume A. Unlike other Zone D plumes with a narrow, downgradient creek intercept zone, Plume A parallels Diamond Creek and is in contact with the surface water system over an extended stream length. Bioaugmentation was selected for this alternative over chemical oxidation using $KMnO_4$ in order to avoid the possibility that $KMnO_4$ could seep into this surface water system and cause the creek to appear purple or to experience increased Mn levels.

Bioaugmentation

Bioaugmentation is relatively new, but has proven to be effective at some sites contaminated with chlorinated VOCs, including USAF installations in Texas, Nevada, and Delaware. It is a passive, *in situ* that can be applied almost anywhere very quickly and unobtrusively. Inoculation of microbes and injection/infusion applications of nutrients are relatively non-invasive, allowing undisturbed operation of facilities during treatment and offering lack of visibility during the working phase. A single inoculation is required to establish a strong microbial population, however, nutrient addition (O&M) may be required at regular intervals.

Bioaugmentation can establish anaerobic dechlorinating bacteria at sites to stimulate reduction of contaminants by increasing dechlorinator population densities or to accelerate biodegradation rates to meet treatment goals. The augmented bacteria is a safe and natural microbial consortia that has demonstrated the ability to remediate chlorinated contaminants under diverse field conditions.

Based on the preliminary data received from the supplemental bioaugmentation study that was performed at SS7 and Plume A (Appendix A), it is suspected that conditions within the test area are generally aerobic; however, the presence of anaerobic bacteria and *cis*-1,2-DCE indicate that weak or dormant areas of anaerobic activity exist. In support of this preliminary conclusion, *Dehalococcoides* bacteria were detected in nine of 10 groundwater samples collected from monitoring wells as displayed on Figure A-1, Appendix A, with detections ranging from 4 to 100 percent detection intensity. Because microbial dechlorination in Zone D may be experiencing a "stall" at *cis*-1,2-DCE, it is possible that the strain of *Dehalococcoides* necessary to degrade TCE to ethene is not present, or if present, the population has been weakened due to poor anaerobic living conditions. Both of these possibilities support the use of bioaugmentation in Zone D.

Monitored Natural Attenuation

Groundwater sampling data indicate that TCE concentrations are decreasing throughout Plume A, which suggests that natural attenuation is occurring at the site, as discussed in Section 4.1.3.2. TCE concentrations in groundwater samples were collected as part of the Zone D RI (USAF 2003a) and the MNA groundwater modeling for the Zone D FS (Volume II).

Based on results of MNA groundwater modeling presented in Volume II, the time for TCE concentrations throughout the entire plume to be naturally attenuated to 5 µg/L from present conditions would be approximately 50 years. Modeled results for Alternative 5A are shown on Figure 4-5. LTM would allow for continued evaluation of contaminant migration and effectiveness of this alternative.

4.1.5.3 Conceptual Design

The following sections describe the design of the proposed alternative.

Bioaugmentation

The conceptual design for bioaugmentation assumes that at shallow depths (20 to 40 feet bgs), approximately half of the injection locations would have dedicated injection wells installed to the

anticipated depths using a casing advance-type drilling method, and the other half would be installed using direct-push methods.

Proposed bioaugmentation treatment areas are displayed on Figure 4-4. The final 14-acre area of application of bioaugmentation in Plume A was derived from an iterative process of evaluating variably sized treatment areas and comparing cleanup times. Areas of approximately 6 and 8 acres covering the two portions of Plume A where TCE concentrations exceed 100 µg/L (Figure 4-4) were evaluated to assess the effectiveness of applying the technology to a larger overall area. Estimated cleanup times for the larger area scenarios were no different (Volume II). Bioaugmentation modeling results for Plume A are shown on Figure 4-5, and the system components are listed in Table 4-5. The modeling assumptions that were made to evaluate the effectiveness of this technology using the Zone D groundwater model are provided in Volume II.

The depth of the treatment area is estimated to be 20 to 40 feet bgs. Existing monitoring wells that are located in the vicinity of the injection area and are screened across the shallow aquifer zone may require installation of a packer within the well casing to deter loss of injected material through migration up the casing.

Where direct-push drilling and injection is achievable, a direct-push drill rig would be used to install injection rods and screens to predetermined depths at designated injection locations. The direct-push injection system is designed to allow for pressure injection and introduction of material directly into the aquifer, with no permanent equipment installed. A 1- to 1.25-inch outer diameter stainless steel casing with an expendable tip is driven into the subsurface via the drill rig. Solid sections of 4- to 5-foot-long casing are added behind the initial drive rod and advanced until the desired injection depth is reached. Upon reaching this depth, the drill rods are pulled upwards to expose the portion of the borehole to receive injections.

In order to fully saturate the target zone with injected material and limit the need for vertical migration of microbes and reagents, it may be possible that direct-push injections be delivered to two different depth intervals within the water-bearing zone. Depth intervals would be determined using historical geologic boring logs. Injection depths may also be adjusted vertically during injection to achieve an ideal level of flow.

In areas of the plume where the lithology is not ideal for using direct-push injection, 1- to 1.5-inch diameter injection wells would be installed using a casing advance-type drilling method (e.g., dual-wall percussion hammer or sonic).

The Zone D Treatability Study (USAF 2003f) indicated that injection rates of 1.5 to 3 gpm with pressures of 10 psi are sufficient to distribute the $KMnO_4$ approximately 20 feet radially from each injection location. This is supported in both the field observations (USAF 2003f) and subsequent numerical modeling (USAF 2004). A similar distribution of injected nutrients is also expected when implementing bioaugmentation. Unlike $KMnO_4$, nutrients injected for bioaugmentation are not expected to move significant distances downgradient due to advective transport. Therefore, an injection grid with points spaced 20 feet apart in the transverse direction and 20 feet in the longitudinal direction was utilized during remedial alternative development.

Separate injection events are required to first establish favorable anaerobic conditions, then introduce the microbes. During the first event, a mixture of oxygen scavenger, vitamins, ZVI, and slow release lactate would be injected. Once stable anaerobic conditions are achieved, microbes are injected into the same locations as the reagent mixture.

The microbes and corresponding reagents would be injected under pressure to obtain the broadest lateral, as well as vertical, saturation of the contaminated zone. The zones of saturation from each of the injection points would be designed to overlap to provide complete coverage of the target interval. Some adjustment of the injection points would most likely be required to ensure complete coverage.

Solutions would be injected at a rate of approximately 1.5 to 3 gpm under pressures of approximately 10 pounds per square inch (psi) to obtain the broadest lateral and vertical saturation of the contaminated zone, while reducing the potential for material surfacing. Final injection pressure and rate would be determined in the field based on the aquifer response to pressure injection. Pumps, hoses, and fittings used to transfer reagents from the mixing tank to the injection locations would be sealed to eliminate leaks onto the ground surface.

Monitored Natural Attenuation

The MNA system design for Plume A is discussed in detail in Section 4.1.3.3.

4.1.5.4 Performance Monitoring

A performance monitoring plan would be a required component of the localized bioaugmentation and MNA alternative and should be considered for planning and budgeting purposes. The performance monitoring plan would describe a groundwater monitoring program for the shallow zone extending over a 35-year period.

Performance Monitoring Goals

The goals for the performance monitoring program at Plume A are the same as those described in Section 4.1.3.4.

Analytical Protocol

All performance monitoring points would be sampled and analyzed for those analytes listed in Table 4-1. Additional details are consistent with Section 4.1.4.4.

Sampling Frequency and Duration of Monitoring

It is anticipated that the full-plume bioaugmentation system would remediate the shallow aquifer groundwater in approximately 35 years. The sampling frequency would be consistent with that presented in Section 4.1.4.4.

Performance Monitoring Program Review

The performance monitoring program would be periodically reviewed and modified to optimize the program and its effectiveness, as discussed in Section 4.1.4.4.

4.1.6 Intermediate Zone Options

This section discusses the following options developed for the intermediate-depth portion of Plume A:

- Option 1A-INT – No Action
- Option 2A-INT – Institutional Controls
- Option 3A-INT – MNA
- Option 4A-INT – Localized Chemical Oxidation and MNA

The first two options—Option 1A-INT, No Action, and Option 2A-INT, Institutional Controls—for the intermediate zone of Plume A are identical in name and description to Alternative 1A, No Action, and Alternative 2A, Institutional Controls, for the shallow zone of Plume A. Therefore, the development of those intermediate-zone options assumes that all of the discussion in Sections 4.1.1 and 4.1.2 apply and will not be repeated in this section.

For the purposes of cost estimating, the value associated with the most conservative intermediate MNA option is presented. Due to variations in length of the different shallow zone alternatives, the institutional controls and 5-Year Reviews associated with the intermediate MNA costs differ. For a complete list of costs associated with each, individual intermediate option, refer to Volume III.

4.1.6.1 Option 3A-INT – Monitored Natural Attenuation

According to USEPA guidance (USEPA 1999), the most important considerations regarding the suitability of MNA as a remedy include:

- Whether the contaminants are likely to be effectively addressed by natural attenuation processes;
- Stability of the groundwater contaminant plume and its potential for migration; and
- Potential for unacceptable risks to human health or environmental resources by the contamination.

Groundwater sampling data and numerical modeling results suggest that the intermediate zone at Plume A is relatively stable and is shrinking in size and contaminant mass (Volume II). Based on these results, MNA is identified as a viable alternative. This alternative is also subject to institutional controls, as described in Section 4.1.2, to limit access and future development of groundwater.

Process Description

Natural attenuation is comprised of biological, chemical, and physical processes that reduce contaminant mass, toxicity, mobility, volume, and/or concentration without the application of actively engineered remediation techniques. For details, see Section 4.1.3.

Based on results of MNA groundwater modeling presented in Volume II, the time for TCE concentrations throughout the entire plume to be naturally attenuated to 5 µg/L from present conditions is estimated to be approximately 120 years. Modeled results for Option 3A-INT

(MNA) are shown on Figure 4-6. LTM would allow for continued evaluation of contaminant migration and effectiveness of this alternative.

Conceptual Design

Refer to Section 4.1.3.2 for conceptual design of the MNA program. For the intermediate zone, only four monitoring wells are proposed for FS estimating purposes.

Performance Monitoring

Performance monitoring would consist of groundwater monitoring, as discussed in the following paragraphs.

Groundwater Monitoring. The LTM monitoring well network would be similar to that for the shallow zone of Plume A. Monitoring of the intermediate zone would occur until established groundwater standards are met in the zone. Four existing intermediate-depth monitoring wells were assumed.

Analytical Protocol. All performance monitoring points would be sampled and analyzed for those analytes listed in Table 4-1. Refer to Section 4.1.3.4 for additional details concerning the analytical protocol.

Sampling Frequency and Duration of Monitoring. Results of MNA groundwater modeling (Volume II) suggest that TCE concentrations in groundwater will attenuate to 5 µg/L from present conditions in approximately 120 years. Therefore, the proposed LTM program sampling duration would be based on a 120-year monitoring period. The sampling frequency would be consistent with that presented in Section 4.1.3.4.

4.1.6.2 Option 4A-INT – Localized Chemical Oxidation and MNA

This option provides chemical oxidation using $KMnO_4$, followed by MNA, to treat the low-concentration groundwater found in the intermediate zone of Plume A. The following sections provide a process description, rationale for selection, conceptual design, and process monitoring plan of this intermediate-zone option. This alternative is also subject to institutional controls, as described in Section 4.1.2, to limit access and future development of groundwater.

Process Description

The following paragraphs describe the technologies included in this alternative—chemical oxidation and MNA.

Potassium Permanganate. *In situ* chemical oxidation consists of delivering of a chemical oxidant to contaminated media (groundwater or soil) to destroy the contaminants or convert them to innocuous compounds commonly found in natural settings. $KMnO_4$ is a strong oxidant that can effectively break the carbon-carbon bonds in chlorinated VOCs such as TCE, DCE, and vinyl chloride. Recent studies have demonstrated that $KMnO_4$ may be more effective at treating moderate to low levels of dissolved groundwater contamination rather than DNAPL and significant sorbed-phase material located in source areas.

$KMnO_4$ is received from a chemical distributor in the form of a dry, crystalline, purple powder. The powder is mixed with water at the treatment site to achieve the desired aqueous concentration. The purple color acts as a built in indicator for the unreacted oxidant, since reacted chemical is reddish brown. The brown color indicates the presence of MnO_2 byproduct, which also can be naturally present in soil, may cause a reduction in aquifer permeability.

MnO_2 is a brown solid that can precipitate out of solution and cause a reduction in aquifer permeability. Concern over permeability loss due to precipitation is thought to be greatest for sites with high concentrations of contaminants or DNAPL, to which a high concentration of $KMnO_4$ is delivered for treatment. However, following more precise delivery methods in areas of moderate to low levels of contamination with no DNAPL, MnO_2 solids can be discrete and agglomerated micron-sized particles that remain mobile in groundwater. The current assessment of methods to deliver $KMnO_4$ so that MnO_2 solids remain mobile in groundwater and, therefore, do not cause a permeability loss, is to apply a less concentrated, better distributed $KMnO_4$ solution to plumes with moderate to low levels of dissolved contaminants. As demonstrated during recent field-scale treatability studies at Zone D, permeability loss from MnO_2 precipitation in already low permeability aquifers was avoided by delivering a series of small volumes of low concentration (1 percent by weight) $KMnO_4$ solution at a large number of injection locations.

The radius of influence of the $KMnO_4$ injection during the Zone D treatability study was determined to be more significant than expected. Immediately after injection, $KMnO_4$ was observed in all of the wells within the test area, except for one crossgradient temporary well. In addition, eight weeks after the second injection and one day after the third injection, $KMnO_4$ was observed in a test boring located approximately 70 feet downgradient of the injection area, suggesting that $KMnO_4$ is moving with groundwater flowing away from the injection zone and that the radius of influence from injection is not solely dependant on injection pressure.

$KMnO_4$ must be thoroughly distributed throughout the contaminated zone to decrease contaminant concentrations. Higher permeability zones are cleaned up faster due to preferential flow and better distribution. During the Zone D Treatability Study, the direct-push pressure injection process proved to be an effective method of delivering and distributing $KMnO_4$ into the subsurface (USAF 2002e); however, successful drilling using the direct-push drill rig was sporadic in Zone D, indicating that auger drilling may be required within some areas of the plume.

Multiple applications of $KMnO_4$ may be required to offset the effects of natural oxidant demand and adsorption. The oxidant is consumed during oxidation of other naturally occurring compounds such as sulfide, metals, or total organic carbon.

Monitored Natural Attenuation. Refer to Section 4.1.3.1 for a process description of natural attenuation.

Rationale for Alternative

The rationale for the retention of each technology included in this alternative is discussed in the following paragraphs.

Potassium Permanganate. Based on the Zone D $KMnO_4$ Treatability Study observation, it was assumed that the injection technique using small volumes and low concentration of $KMnO_4$ is

successful in avoiding permeability loss due to MnO_2 precipitation. Using the results from the Zone D Treatability Study, a preliminary plan and conceptual design for a chemical oxidation and monitoring treatment alternative were developed. The $KMnO_4$ Treatability Study is applicable for the following reasons:

- The geology at the Treatability Study site is very similar to that observed in the proposed injection area.
- Findings of the Zone D $KMnO_4$ Treatability Study indicate that this technology is effective in reducing TCE concentrations from 357 µg/L to nondetect. The highest TCE concentration recently observed in the intermediate zone of Plume A was 71.04 µg/L (MW-311M).

In addition to the results of the $KMnO_4$ Treatability Study, contaminant concentrations to be treated with $KMnO_4$ are low enough to where the majority of the contamination present is expected to be in the dissolved-phase rather than the sorbed-phase, making the plume area conducive to treatment with $KMnO_4$.

The proposed treatment area of approximately 2 acres is an optimization of the area in an attempt to treat the area of the highest observed TCE concentrations in the intermediate zone and remove the most contaminant mass. Thus, the cleanup time for the intermediate zone of Plume A is 110 years (Table 4-7).

Monitored Natural Attenuation. Based on results of groundwater modeling presented in Volume II, the time for TCE concentrations throughout the entire plume to be locally treated and then naturally attenuated to 5 µg/L is estimated to be approximately 110 years. This time frame is only 10 years less than for MNA alone. Modeled results for Option 4A-INT are shown on Figure 4-8.

Conceptual Design

The goals and design concepts for the $KMnO_4$ and MNA options for the intermediate zone are discussed in the following paragraphs.

Potassium Permanganate. Direct-push drilling and injection would be used for a portion of the treatment based on localized drilling conditions. Injection locations at intermediate depths would consist of dedicated injection wells and no direct-push injections. If *in situ* treatment is the selected alternative, additional applicable information that becomes available from the Plume C Treatability Study would be incorporated into the final design.

Plume A encompasses a relatively large area; therefore, only the higher concentration portion of the plume would be treated with $KMnO_4$ to remove contaminant mass and accelerate MNA. The treatment area is approximately 2 acres and is displayed on Figure 4-7. The depth of the treatment area is estimated to be 40 to 50 feet bgs in the intermediate aquifer. Existing monitoring wells that are located in the vicinity of the injection area and are screened across both the shallow and intermediate aquifer zones may require installation of a packer within the well casing to deter loss of injected $KMnO_4$ through migration up the casing and into the shallow aquifer zone.

Where direct-push drilling and injection is achievable, a direct-push drill rig would be used to install injection rods to predetermined depths at injection locations. The direct-push injection

system is designed to allow for pressure injection and introduction of material directly into the aquifer, with no permanent equipment installed. A 1- to 1.25-inch outer diameter stainless steel casing with an expendable tip is driven into the subsurface via the drill rig. Solid sections of 4- to 5-foot-long casing are added behind the initial drive rod and advanced until the desired injection depth is reached. Upon reaching this depth, the drill rods are pulled upwards to expose the portion of the borehole to receive injections.

In order to fully saturate the target zone with $KMnO_4$ solution and limit the need for vertical migration of the oxidants, it may be possible that direct-push injections can be delivered to two different depth intervals within the water-bearing zone. Depth intervals would be determined using geologic boring logs. Injection depths may also be adjusted vertically during injection to achieve an ideal level of flow.

In areas of the plume where the lithology is not ideal for using direct-push injection, 1- to 1.5-inch diameter injection wells would be installed using a casing advance-type drilling method (e.g., dual-wall percussion hammer or sonic).

Spacing of injection locations was determined from the Zone D Treatability Study (USAF 2003f) and the subsequent modeling performed for the planned Zone A Treatability Study (USAF 2004). The Zone D Treatability Study (USAF 2003f) indicated that injection rates of 1.5 to 3 gpm with pressures of 10 psi are sufficient to distribute the $KMnO_4$ approximately 20 feet radially from each injection location. This is supported in both the field observations (USAF 2003f) and subsequent numerical modeling (USAF 2004). Modeling results indicate injection locations may be conservatively spaced 40 feet between points in the transverse direction of the $KMnO_4$ plume and 80 feet in the longitudinal direction. The simulated distribution is the combined result of the initial injection under pressure and subsequent advective and dispersive transport of the $KMnO_4$. This spacing of injection points simulated during the Zone A modeling provides limited overlap in the simulated zones of treatment. Based on this limited overlap and uncertainties in the amount and variation of natural oxidant throughout FEW, and given the heterogeneity in hydrogeologic conditions, a more conservative grid spacing is recommended to ensure adequate subsurface distribution of the injected $KMnO_4$ and overlap of the zones of treatment for each injection location. A factor of conservatism on the order of two was applied such that an injection grid with points spaced 20 feet between points in the transverse direction and 40 feet in the longitudinal direction was utilized during remedial alternative development.

Various chemicals in soil and groundwater, such as total organic carbon, metals, and sulfur compounds, can exhibit an oxidant demand, consuming $KMnO_4$, and therefore, reducing its effectiveness on oxidizing contaminants. Because of this excess oxidant demand and the potential for desorption, 1.5 applications of oxidant would be delivered to the subsurface to verify that enough material is delivered to sufficiently reduce contaminant mass. However, the recent $KMnO_4$ Treatability Study at FEW has demonstrated that the oxidant persistence is longer than expected (USAF 2003f), suggesting there are not significant concentrations of other compounds that would exhibit an oxidant demand at the test site. Groundwater monitoring data collected after the first treatability study injection suggests that fewer applications may be required to achieve treatment objectives.

Based on contaminant concentrations detected previously at the site, an approximately 1 percent (by weight) solution of $KMnO_4$ would need to be delivered into the subsurface during the first application. The final amount of oxidant delivered would be decided in the field, and would be

based on the rate of flow established during injection at each borehole. Per application, approximately 200 gallons of a 1 percent solution of $KMnO_4$ would be injected into the subsurface at each injection location. Total volume of oxidant and pounds of dry $KMnO_4$ required are provided in Volume III.

$KMnO_4$ would be injected under pressure to obtain the broadest lateral, as well as vertical, saturation of the contaminated zone. The zones of saturation from each of the injection points would be designed to overlap to provide complete coverage of the target interval. Some adjustment of the injection points would most likely be required to ensure complete coverage. Once injection is complete, advective flow of groundwater should transport the oxidant downgradient where it would continue to oxidize contaminants until all of the oxidant is expended.

The $KMnO_4$ solution would be injected at a rate of approximately 3 to 10 gpm under pressures of approximately 10 to 40 psi to obtain the broadest lateral and vertical saturation of the contaminated zone, while reducing the potential for oxidant surfacing. Based on recent work performed in Zone D Plume C, this injection rate is assumed feasible. Final injection pressure and rate would be determined in the field based on the aquifer response to pressure injection. Pumps, hoses, and fittings used to transfer the oxidant from the mixing tank to the injection locations would be sealed to eliminate oxidant leaks onto the ground surface. A list of the components associated with the $KMnO_4$ treatment is presented in Table 4-6.

In situ chemical treatment and MNA modeling results are shown in Figure 4-8. The modeling assumptions that were made to evaluate the effectiveness of this technology using the Zone D groundwater model are provided in Volume II.

Monitored Natural Attenuation. Refer to Section 4.1.3.2 for a discussion of the conceptual design of an MNA program.

Performance Monitoring

Performance monitoring would consist of groundwater monitoring, as discussed in the following paragraphs.

Monitoring Network. The LTM monitoring well network would be similar to that for the shallow zone of Plume A. Monitoring of the intermediate zone would occur until established groundwater standards are met in the zone. Four intermediate-depth monitoring wells are assumed.

Analytical Protocol. All performance monitoring points would be sampled and analyzed for those analytes listed in Table 4-1. Refer to Section 4.1.3.2 for additional details concerning the analytical protocol.

Sampling Frequency and Duration of Monitoring. Results of MNA groundwater modeling (Volume II) suggest that TCE concentrations in groundwater will attenuate to 5 µg/L from present conditions in approximately 110 years. Therefore, the proposed LTM program sampling duration is based on a 110-year monitoring period. The sampling frequency would be consistent with that presented in Section 4.1.3.2.

4.2 DETAILED ANALYSIS OF ALTERNATIVES

A general summary of the Plume A remedial alternatives is provided in Table 4-7. Individual analysis and assessment of each of these groundwater remedial alternatives with respect to the nine evaluation criteria are presented in this section. The first two (Overall Protection and Compliance with ARARs) are threshold criteria. Alternatives are evaluated for whether they provide protectiveness or comply with ARARs. Alternatives must be both protective and comply with ARARs to be considered for a remedy. The next five are balancing criteria, where the relative tradeoffs among the criteria are evaluated. These first seven criteria are further described in Table 4-3. The final two are modifying criteria, in which the state and the community express whether they support or oppose the alternatives, which are evaluated by the end of the public comment period.

Summaries of the detailed analyses are presented in Tables 4-8 and 4-9. Following the individual analysis is a comparative analysis among the groundwater alternatives. The comparative analysis assesses the relative performance of each groundwater alternative with respect to each criterion.

4.2.1 Alternative 1A – No Action

The No Action Alternative assumes no further action would be taken for groundwater at Zone D. This alternative is required by NCP and selected for detailed analysis so that it may be used as a baseline for comparative analysis of the risk and cost associated with other alternatives. Although there is no capital cost involved with this alternative, the future costs and liabilities associated with exposure risks are unknown. Although expected, the No Action Alternative does not take into account natural attenuation of the groundwater plume through time.

4.2.1.1 Overall Protection of Human Health and the Environment

Although the BRA identified no unacceptable threat to human health or the environment under current groundwater conditions, this alternative does not include a means to monitor or assess protection of human health or the environment. Therefore, the No Action Alternative is not protective of human health and the environment.

4.2.1.2 Compliance with ARARs

The No Action Alternative will not comply with ARARs.

4.2.1.3 Long-Term Effectiveness

The potential risk of exposure to groundwater would continue to exist with this alternative. Untreated TCE contamination remains in groundwater. Therefore, the No Action Alternative does not provide long-term effectiveness.

4.2.1.4 Reduction of Toxicity, Mobility, and Volume

Since no active treatment of groundwater is undertaken, there would not be an active reduction of toxicity, mobility, or volume. However, over time the groundwater plume would be expected to naturally attenuate.

4.2.1.5 Short-Term Effectiveness

Because no action for groundwater is taken, there would be no additive short-term exposure to the community or workers.

4.2.1.6 Implementability

There would be no implementation concerns associated with the No Action Alternative for groundwater.

4.2.1.7 Cost

The No Action Alternative for groundwater incurs no cost. The cost associated with long-term liability would be unknown.

4.2.2 Alternative 2A – Institutional Controls

The Institutional Controls Alternative assumes that legal and/or physical controls would be implemented for groundwater at Zone D. This alternative has limited capital cost, but the future costs and liabilities associated with exposure risks can only be estimated. Although expected, the Institutional Controls Alternative does not take into account natural attenuation of the groundwater plume through time.

4.2.2.1 Overall Protection of Human Health and the Environment

The Institutional Controls Alternative would protect human health and the environment through implementation and enforcement of administrative controls described in Section 4.1.2. No unacceptable short-term or cross-media impacts would be expected.

4.2.2.2 Compliance with ARARs

The Institutional Controls Alternative would comply with potential action and location specific ARARs. It would not comply with the potential chemical-specific ARAR of the federal MCL for TCE of 5 µg/L. This alternative would not comply with ARARs requiring monitoring of releases (i.e., 40 CFR Part 264).

4.2.2.3 Long-Term Effectiveness and Permanence

The untreated TCE contamination in groundwater would continue to exist at Zone D. This alternative offers a level of protection through the regulation of groundwater use as discussed in Section 4.1.2. Controls would be implemented to limit or exclude use of the groundwater and thus reduce the potential for exposure. These controls would be contained in the General Plan and are a

long-term and reliable management control, enforced by USAF within the installation boundaries. The groundwater plume would be expected to naturally attenuate over time.

4.2.2.4 Reduction of Toxicity, Mobility and Volume

The contaminated groundwater would not be treated to reduce the toxicity, mobility, or volume. However, over time, the groundwater plume would be expected to naturally attenuate.

4.2.2.5 Short-Term Effectiveness

This alternative does not include a remediation component, so there would be no additive short-term exposure to the community or workers.

4.2.2.6 Implementability

This alternative would be easy to implement, technically and administratively. Documentation in the General Plan and coordination with installation personnel, as discussed in Section 4.1.2, would be a reliable management control that would be easy to implement.

4.2.2.7 Cost

Costs of this alternative would include updates and changes to the General Plan, community and educational programs, reporting, and management and administrative efforts. Capital costs associated with this alternative are estimated to be $18,484. Total O&M costs (e.g., five-year review, annual plan updates, and site closure) are estimated to be $2,387 annually. Present value cost is $61,181. The detailed cost estimate is provided in Volume III.

4.2.3 Alternative 3A – Monitored Natural Attenuation

Alternative 3A, MNA, assumes that LTM of natural attenuation processes that reduce TCE concentrations over time would be implemented for groundwater at Plume A. Institutional controls are included in the alternative to prevent the use of groundwater for human consumption prior to the end of the MNA period.

4.2.3.1 Overall Protection of Human Health and the Environment

With institutional controls, Alternative 3A would adequately protect human health and the environment through natural attenuation processes that reduce TCE concentrations over time.

The human health BRA results indicate that TCE contamination in the groundwater at Plume A would not pose an unacceptable threat to human health under current conditions. An unacceptable risk may be posed if residences were built on the site and used the groundwater for drinking, washing, and other domestic uses; but this is considered unlikely because municipal supplies are available. Or, unacceptable risk may be encountered with the construction of new buildings over moderate to high concentrations of TCE in groundwater. However, this risk can be mitigated through design additions such as a sub slab depressurization system.

By comparing historical and current site data, TCE concentrations are not expected to exceed MCLs at the furthest downgradient monitoring wells. In addition, Diamond Creek is a Class 3B

stream, which means it has no contaminant standards for VOCs. Long-term groundwater monitoring would allow continued evaluation of contaminant migration and natural attenuation. No unacceptable short-term or cross-media impacts are expected.

4.2.3.2 Compliance with ARARs

With institutional controls, the use of MNA as a remedial alternative for contaminated groundwater in Zone D would comply with all potential location- and action-specific ARARs. The chemical-specific ARAR would be achieved after 50 years. No permits would be needed for this alternative.

4.2.3.3 Long-Term Effectiveness

The MNA alternative would rely on the effectiveness of natural processes to reduce contaminant concentrations and minimize contaminant migration over time. Data indicating that TCE concentrations are decreasing suggest that natural attenuation due to dispersion, adsorption, biodegradation, and volatilization may be occurring at the site. Natural attenuation processes are expected to reduce contaminant concentrations to MCLs over time. Continued monitoring would provide a reliable means to assess the residual concentrations. Institutional controls would limit or prevent the use of groundwater and eliminate the exposure pathway.

No clear remaining source of TCE was found during the Zone D Sources RI (USAF 2002a), and it is presumed to have been exhausted and no longer will contribute contaminants to groundwater. Results of groundwater modeling for Plume A estimate the time for TCE concentrations throughout the entire groundwater plume to be naturally attenuated to 5 μg/L from present conditions in approximately 50 years.

4.2.3.4 Reduction of Toxicity, Mobility, and Volume

Natural attenuation parameters suggest that there is potential for reductive dechlorination of chlorinated organic compounds, such as TCE, within the contaminated portions of groundwater in Zone D. In general, site conditions appear to favor aerobic mechanisms, based on DO levels and oxidation-reduction potential. Detection of DCE, a reductive degradation product of TCE, indicates that some degree of reductive dechlorination has occurred at the site.

The heterogeneity of the shallow and intermediate aquifer zones at Zone D, indicated by its discontinuous geologic units and variation in hydraulic conductivity, enhances the potential for hydrodynamic dispersion. Over time, the process of dispersion will cause further mixing of the TCE groundwater plume with clean groundwater.

The known soil-water distribution coefficient for TCE (K_d = 0.252) suggests that the contaminant may be slightly retarded in groundwater by particle adsorption. As a relative comparison, inorganics in groundwater are typically strongly adsorbed and much less mobile than dissolved organics such as TCE.

4.2.3.5 Short-Term Effectiveness

Minimal potential exists for worker exposure to contaminants within the groundwater plume; however, protective measures including on-site monitoring and appropriate personal protective

equipment (PPE) would be used. No short-term impacts to the community, workers, or the environment would occur.

Soil spoils from drilling will be placed in soil containers, covered or sealed, and transported to a Class C landfill. Because the soil will be contained, the community does not incur incremental risk associated with disposal, but could incur a slight incremental risk due to increased traffic.

Although TCE concentrations in groundwater samples collected during previous investigations at Zone D suggest that the leading edge of the groundwater plume is stable or may be receding, and TCE concentrations within the plume are diminishing, groundwater modeling efforts estimate the time to achieve MCLs within Plume A would be approximately 50 years.

4.2.3.6 Implementability

The O&M of an MNA system at the site would be minimal. MNA would require no construction because a sufficient monitoring well network already exists in Zone D. There would be no O&M or replacement activities other than maintaining the monitoring wells. Long-term management of the monitoring program, periodic site reviews to confirm the completeness of sample data, and to verify the effectiveness of the alternative would be easy to implement.

Administrative feasibility assumes approval for the use of this technology by federal, state, and local agencies. Currently, USEPA supports the use of natural attenuation at many sites contaminated by chlorinated organics. The availability of TSD services and capacity would not be an issue since natural attenuation is a passive remedial technology that does not require removal, aboveground treatment, or disposal of contaminated media.

4.2.3.7 Cost

Costs of Alternative 3A would include an LTM plan, changes to the General Plan, community and educational programs, reporting, and management and administrative efforts. There are no capital costs associated with this alternative due to the availability of numerous existing monitoring wells. Total O&M costs that include LTM data collection, analysis, evaluation, and reporting costs, are estimated to be about $2.6 million over the 50-year life of the alternative. These costs are outputs of RACER™ and reflected in present value dollars in Volume III. Present value cost is approximately $1.1 million. The detailed cost estimate is provided in Volume III.

4.2.4 Alternative 4A – Groundwater Extraction and *Ex situ* Treatment

Alternative 4A assumes that groundwater extraction and treatment would reduce TCE concentrations to RAOs, then long-term groundwater monitoring, and legal and/or physical institutional controls would be used to complete the remediation of groundwater in untreated portions of Plume A. The future O&M costs, LTM costs, and potential liabilities associated with exposure risks can only be estimated. Based on groundwater modeling, this alternative requires 20 years of extraction and treatment.

4.2.4.1 Overall Protection of Human Health and the Environment

Alternative 4A would protect human health and the environment by removing and treating the contaminated groundwater, enforcement of the LTM program, and the administrative controls described in Section 4.1.2.

The human health BRA results indicate that TCE contamination in the groundwater at Zone D would not pose an unacceptable threat to human health under current conditions. An unacceptable risk may be posed if residences were built on the site and used the groundwater for drinking, washing, and other domestic uses; but this is considered unlikely because municipal supplies are available. Or, unacceptable risk may be encountered with the construction of new buildings over moderate to high concentrations of TCE in groundwater. However, this risk can be mitigated through design additions such as a sub slab depressurization system.

By comparing historical and current site data, TCE concentrations currently exceed MCLs at the furthest downgradient monitoring wells. The groundwater extraction and treatment alternative would be designed to remove contaminant concentrations exceeding MCLs through groundwater extraction. The contaminants present in the extracted groundwater would be removed by phase separation and then destroyed by a bioreactor, providing long-term protection. Treated groundwater discharge would be monitored to demonstrate compliance with effluent goals that protect water quality. No unacceptable short-term or cross-media impacts are expected.

4.2.4.2 Compliance with ARARs

Alternative 4A would comply with potential action- and location-specific ARARs and with the potential chemical-specific ARAR of the federal MCL for TCE of 5 µg/L at the end of the LTM period. This alternative complies with the USEPA preference for treatment and ARARs requiring monitoring of releases (i.e., 40 CFR Part 264).

4.2.4.3 Long-Term Effectiveness

The extraction and treatment alternative relies on the effectiveness of groundwater extraction and hydraulic control to reduce contaminant concentrations and minimize contaminant migration over time. Modeling indicates that TCE concentrations within the plume would decrease to 5 µg/L within 20 years with 103 extraction wells pumping at a combined rate of approximately 40 gpm.

This alternative offers a level of protection through the treatment and monitoring of groundwater contaminant concentration and flow, as discussed in Section 4.1.4, and by regulating groundwater use, as discussed in Section 4.1.2.

4.2.4.4 Reduction of Toxicity, Mobility, and Volume

Alternative 4A would reduce contaminant concentrations and minimize contaminant migration over time through groundwater extraction and hydraulic control. The contaminated groundwater would be treated for 20 years to reduce the toxicity and volume of the groundwater contamination.

4.2.4.5 Short-Term Effectiveness

The estimated time to meet RAOs for this alternative is 20 years. Adsorption- and diffusion-limited conditions may be achieved quickly, and pulsing of the extraction system may be needed.

This alternative includes a remediation component but there would be no additive short-term exposure to the community. However, treatment system construction and O&M and LTM workers would use protective measures such as on-site monitoring and appropriate PPE while conducting intrusive, construction, or disposal activities within the plume area. Therefore, minimal potential exists for exposure to contaminants.

Soil spoils from drilling and construction will be placed in soil containers, covered or sealed, and transported to a Class C landfill. Because the soil will be contained, the community does not incur incremental risk associated with disposal, but could incur a slight incremental risk due to increased traffic.

4.2.4.6 Implementability

Technology approval by federal, state, and local agencies would be anticipated due to the "presumptive remedy" nature of Alternative 4A. Construction and O&M of a groundwater extraction and treatment system and installation of monitoring wells at the site is technically feasible and could easily be implemented. The groundwater extraction and treatment alternative would require extraction well installation, treatment system construction, discharge to a tributary of Crow Creek, O&M of the treatment system, and groundwater and treatment system monitoring. The equipment and personnel for performing these tasks are widely available. Management of the O&M program would be required to allow proper and effective system operation. Periodic site reviews would be conducted to confirm the completeness of data and to verify the effectiveness of the alternative.

4.2.4.7 Cost

Costs of Alternative 4A would include capital costs for the extraction and treatment system design and construction, changes to the General Plan, community and educational programs, reporting, and management and administrative efforts. Capital costs associated with this alternative are estimated to be $2.0 million. Total O&M costs that include extraction and treatment system O&M, and reporting costs are estimated to be about $9.6 million over the 20-year life of the alternative. These costs are outputs of RACER™ and reflected in present value dollars in Volume III. Present value cost is approximately $7.4 million. A summary of costs is provided in Table 4-8, and a detailed cost estimate is provided in Volume III.

4.2.5 Alternative 5A – Localized Bioaugmentation and Monitored Natural Attenuation

Alternative 5A assumes that a combination of localized bioaugmentation, long-term groundwater monitoring (Alternative 3A), and legal and/or physical institutional controls (Alternative 2A) would be implemented for groundwater. The future O&M costs, LTM costs, and potential liabilities associated with exposure risks can only be estimated. Based on groundwater modeling, this alternative requires 35 years of bioaugmentation and MNA of the groundwater plume to complete remediation.

4.2.5.1 Overall Protection of Human Health and the Environment

Alternative 5A would protect human health and the environment by *in situ* treatment of the contaminated groundwater with bioaugmentation, enforcement of the LTM program, and the administrative controls described in Section 4.1.2.

The human health BRA results indicate that TCE contamination in the groundwater at Zone D would not pose an unacceptable threat to human health under current conditions. An unacceptable risk may be posed if residences were built on the site and used the groundwater for drinking, washing, and other domestic uses; but this is considered unlikely because municipal supplies are available. Or, unacceptable risk may be encountered with the construction of new buildings over moderate to high concentrations of TCE in groundwater. However, this risk can be mitigated through design additions such as a sub slab depressurization system.

By comparing historical and current site data, TCE concentrations currently exceed MCLs at the furthest downgradient monitoring wells. The bioaugmentation/MNA alternative would be designed to destroy contaminant concentrations exceeding MCLs primarily through *in situ* groundwater treatment. No unacceptable short-term or cross-media impacts are expected.

4.2.5.2 Compliance with ARARs

Alternative 5A would comply with potential action- and location-specific ARARs and with the potential chemical-specific ARAR of the federal MCL for TCE of 5 µg/L at the end of the 35-year treatment/LTM period. This alternative complies with the USEPA preference for treatment and ARARs requiring monitoring of releases (i.e., 40 CFR Part 264).

4.2.5.3 Long-Term Effectiveness

The bioaugmentation/MNA alternative relies primarily on the effectiveness of *in situ* groundwater treatment to reduce contaminant concentrations and minimize contaminant migration over time. Modeling indicates that TCE concentrations within the plume would decrease within 10 years to less than 5 µg/L in the treated areas, but would leave some areas with concentrations below 50 µg/L outside the treated areas. Continued natural attenuation of the plume would reduce TCE concentrations near 50 µg/L to less than 5 µg/L in the untreated areas during an additional 25 years (Year 35).

This alternative offers a level of protection through the *in situ* treatment and monitoring of groundwater contaminant concentration and flow, as discussed in Section 4.1.5, and by regulating groundwater use, as discussed in Section 4.1.2.

4.2.5.4 Reduction of Toxicity, Mobility, and Volume

Alternative 5A would reduce contaminant concentrations and minimize contaminant migration over time through *in situ* treatment. The contaminated groundwater would be treated for 10 years by bioaugmentation to reduce the toxicity and volume of the groundwater contamination to the RAO. After treatment, the remaining areas of the groundwater plume would be expected to naturally attenuate to ARARs in an additional 25 years.

4.2.5.5 Short-Term Effectiveness

The estimated time to meet RAOs for Alternative 5A is 35 years, although it is likely that RAOs in many areas treated by bioaugmentation would be met within 10 years.

This alternative includes a remediation component, but there would be no additive short-term exposure to the community. However, bioaugmentation injection workers and LTM workers would use protective measures such as on-site monitoring and appropriate PPE while conducting intrusive activities within the plume area. Therefore, minimal potential exists for exposure to contaminants.

Soil spoils from drilling will be placed in soil containers, covered or sealed, and transported to a Class C landfill. Because the soil will be contained, the community does not incur incremental risk associated with disposal, but could incur a slight incremental risk due to increased traffic.

4.2.5.6 Implementability

Approval of Alternative 5A by federal, state, and local agencies would be anticipated to be difficult because the technology has had no previous use in pilot tests or IRAs in Zone D. Injection of bioaugmentation microbes and stimulants and installation of monitoring wells at the site are technically feasible and could be easily implemented. The equipment and personnel for performing these tasks are readily available in the Rocky Mountain Region.

A bioaugmentation injection system design would be prepared as discussed in Section 4.1.5, an LTM plan would be prepared for the 35-year LTM period, and documentation would be provided in the General Plan as discussed in Section 4.1.2.

4.2.5.7 Cost

Costs of this alternative would include capital costs for bioaugmentation design and implementation, preparation of the LTM plan, changes to the General Plan, community and educational programs, reporting, and management and administrative efforts. Capital costs associated with this alternative are estimated to be about $11.8 million. Total O&M costs that include LTM data collection, analysis, evaluation, and reporting costs are estimated to be about $2.3 million over the 35-year life of the alternative. These costs are outputs of RACER™ and reflected in present value dollars in Volume III. Present value cost is approximately $12.3 million. The detailed cost estimate is provided in Volume III.

4.2.6 Intermediate Zone Options

This section presents the individual analysis and assessment of each intermediate zone option with respect to the seven evaluation criteria, as described above. For a summary of this analysis, see Table 4-3.

For detailed analysis of Option 1A-INT, No Action, and Option 2A-INT, Institutional Controls, see Sections 4.2.1 and 4.2.2, respectively.

4.2.6.1 Option 3A-INT – Monitored Natural Attenuation

Option 3A-INT, MNA, assumes that LTM of natural attenuation processes that reduce TCE concentrations over time would be implemented for groundwater in the intermediate zone at Plume A. Institutional controls are included in the alternative to prevent the use of groundwater for human consumption prior to the end of the MNA period.

Overall Protection of Human Health and the Environment

With institutional controls, MNA in the intermediate zone protects human health and the environment under current conditions through natural attenuation processes. No unacceptable short-term or cross-media impacts are expected.

Compliance with ARARs

With institutional controls, the use of MNA in the intermediate zone complies with all potential action- and location-specific ARARs, but would not comply with the potential chemical-specific ARAR of the federal MCL for TCE of 5 µg/L until near the end of the 120-year monitoring period. MNA complies with ARARs requiring monitoring of releases. No discharge permits would be required for this alternative.

Long-Term Effectiveness

Natural processes will reduce contaminant levels in groundwater to RAOs over time. Continued monitoring provides a reliable means to assess the residual concentrations and manage the risk posed by the residual. Institutional controls would limit or prevent use of the intermediate-zone groundwater. This process would produce no untreated residual contamination. Minimal operation and maintenance of wells and groundwater sampling are required.

Reduction of Toxicity, Mobility, and Volume

Toxicity, mobility, and volume of TCE would be reduced over time from natural attenuation of contaminants in groundwater. TCE levels would be reduced to RAOs in intermediate zone groundwater in approximately 120 years. No residuals would be present in groundwater at completion, and attenuation would be irreversible.

Short-Term Effectiveness

No additional risk to site workers and the environment would occur because there is no construction of a treatment system. There is also no increased risk to workers, the community, or the environment during implementation. Time to achieve RAOs within the intermediate zone at Plume A is estimated to be approximately 120 years.

Soil spoils from drilling will be placed in soil containers, covered or sealed, and transported to a Class C landfill. Because the soil will be contained, the community does not incur incremental risk associated with disposal, but could incur a slight incremental risk due to increased traffic.

Implementability

This option is easy to implement and should not create schedule delays. Passive technologies such as MNA do not require removal, aboveground treatment, or TSD services. Monitoring the effectiveness is simple, and FEW administrative requirements to accommodate this option would include modifying the General Plan.

Cost

Costs of this option would include an LTM plan, changes to the General Plan, community and educational programs, reporting, and management and administrative efforts. There are no capital costs associated with this alternative due to the availability of numerous existing monitoring wells. Total O&M costs that include LTM data collection, analysis, evaluation, and reporting costs are estimated to be about $4.5 million over the 120-year life of the alternative. These costs are outputs of RACER™ and reflected in present value dollars in Volume III. Present value cost is approximately $0.7 million. A summary of the costs is provided in Table 4-9, and a detailed cost estimate is provided in Volume III.

4.2.6.2 Option 4A-INT – Localized Chemical Oxidation and MNA

Option 4A-INT, chemical oxidation and MNA, assumes that a combination of chemical oxidation, long-term groundwater monitoring, and legal and/or physical institutional controls would be implemented for intermediate-zone groundwater in Plume A. The future O&M costs, LTM costs, and potential liabilities associated with exposure risks can only be estimated.

Overall Protection of Human Health and the Environment

Comparing historical and current site data, TCE concentrations currently exceed RAOs in some intermediate-zone monitoring wells. This chemical oxidation/MNA option would protect human health and the environment by *in situ* treatment of the contaminated groundwater with chemical oxidizers, application of an LTM program, and enforcement of institutional controls. The option would be designed to destroy contaminant concentrations exceeding RAOs through a combination of *in situ* groundwater treatment and MNA. No unacceptable short-term or cross-media impacts would be expected.

Compliance with ARARs

This option would comply with potential action- and location-specific ARARs and with the potential chemical-specific ARAR of the federal MCL for TCE of 5 µg/L at the end of the LTM period. It would also comply with the USEPA preference for treatment of contaminated groundwater (i.e., 40 CFR Part 264). No discharge permits would be required for this option.

Long-Term Effectiveness and Permanence

Active treatment would reduce the TCE concentrations in the intermediate-zone groundwater to 50 µg/L in approximately six months. Natural processes would reduce the TCE concentration in groundwater to the RAO approximately 110 years after completion of active treatment. Continued monitoring provides a reliable means to assess the treatment effectiveness.

Institutional controls would limit or prevent use of groundwater. Greater operation and maintenance than the MNA option would occur only during the six-month treatment period.

Reduction of Toxicity, Mobility and Volume

Toxicity, mobility, and volume of TCE would be reduced over time from active treatment of groundwater and natural processes. TCE concentrations in groundwater would be reduced to RAOs in intermediate-zone groundwater in approximately 110 years, and the treatment process would be irreversible.

Short-Term Effectiveness

There would be minimal additional risk to site workers and the environment during the construction phase involving drilling and injection of chemicals. Soil spoils from drilling will be placed in soil containers, covered or sealed, and transported to a Class C landfill. Because the soil will be contained, the community does not incur incremental risk associated with disposal, but could incur a slight incremental risk due to increased traffic. There would be no increased risk to workers, the community, or the environment during the implementation phase, which would involve only groundwater sampling. The time to achieve RAOs is estimated to be approximately 110 years.

Implementability

This option is easy to implement and chemical oxidation is a proven and reliable technology. The chemical oxidation compound ($KMnO_4$) is readily available, as are the conventional well drilling and installation techniques that would be used. Schedule delays should not be expected due to lack of availability since multiple drilling contractors and $KMnO_4$ suppliers are available. Competitive bids can be obtained and monitoring the effectiveness is simple. Administrative requirements would include preparing a treatment system design and LTM plan and modifying the General Plan.

Cost

Costs of this alternative would include capital costs for chemical oxidation design and implementation, preparation of the LTM plan, changes to the General Plan, community and educational programs, reporting, and management and administrative efforts. Capital costs associated with this alternative are estimated to be $1.9 million. Total O&M costs that include LTM data collection, analysis, evaluation, and reporting costs are estimated to be about $3.6 million over the 35-year life of the alternative. These costs are outputs of RACER™ and reflected in present value dollars in Volume III. Present value cost is approximately $2.5 million. A summary of the costs is provided in Table 4-8. The detailed cost estimate is provided in Volume III.

4.3 COMPARATIVE ANALYSIS

The first seven sections compare the following alternatives for the shallow Plume A groundwater:

- Alternative 1A – No Action
- Alternative 2A – Institutional Controls
- Alternative 3A – MNA
- Alternative 4A – Groundwater Extraction and *Ex situ* Treatment
- Alternative 5A – Bioaugmentation and MNA

One section also compares the following options for intermediate-zone groundwater at Plume A:

- Option 1A-INT – No Action
- Option 2A-INT – Institutional Controls
- Option 3A-INT – MNA
- Option 4A-INT – Localized Chemical Oxidation and MNA

Tables 4-10 and 4-11 present a comparison among the criteria for each shallow-zone alternative and intermediate-zone option for the groundwater of Plume A. The tables do not combine the shallow zone groundwater and the intermediate zone groundwater of the plume. Because the comparisons are relative to the other alternatives for this plume, they should not be used for comparison to other plumes or even to the shallow versus intermediate groundwater zones in Plume A.

4.3.1 Overall Protection of Human Health and the Environment

Alternative 1A, No Action, would be protective of human health and the environment under current conditions because no current unacceptable risk has been identified. However, because this alternative provides no means to monitor future contamination, it is not protective over the long term. Alternative 2A provides implementation and enforcement of administrative controls to prevent future use of the groundwater resource, but cannot monitor future conditions. Because Diamond Creek is a Class 3B stream and concentrations of TCE will attenuate naturally over long periods of time, MNA (Alternative 3A) provides long-term protection of human health and the environment through implementation of the LTM program and enforcement of institutional controls.

Extraction and treatment (Alternative 4A) would achieve RAOs (i.e., protection of human health and the environment) in the shortest time period in the surface groundwater zone through *ex situ* groundwater extraction and treatment. Bioaugmentation and MNA (Alternative 5A) would provide significant protection of human health and the environment due to implementation of treatment through bioaugmentation of two areas of the central plume, enforcement of the LTM program, and institutional controls, although the time to achieve RAOs would be longer than Alternative 4A.

Therefore, Alternatives 3A, 4A, and 5A would be protective of human health and the environment in both the short- and long-term (Table 4-10). Alternatives 1A and 2A cannot provide long-term protectiveness with any certainty and do not meet this threshold criterion.

4.3.2 Compliance with ARARs

The No Action Alternative would not comply with ARARs. The Institutional Controls Alternative would comply with potential action- and location-specific ARARs, but not with the potential chemical-specific groundwater ARAR of the federal MCL for TCE of 5 µg/L or with ARARs requiring monitoring of releases. Because these first two alternatives do not meet either threshold criterion, they are not carried through the remainder of the comparative analysis.

Alternatives 3A, 4A, and 5A would comply with potential action- and location-specific ARARs and with ARARs requiring monitoring of releases (i.e., 40 CFR Part 264). Alternative 3A would comply with the potential chemical-specific groundwater ARAR set at the federal MCL for TCE of 5 µg/L near the end of a 50-year LTM period, Alternative 4A after a 20-year period of continuous pumping and treating, and Alternative 5A after a 35-year *in situ* treatment and LTM period. Therefore, based on time to reach ARARs, Alternative 4A would be faster than Alternatives 5A and 3A (Table 4-10).

4.3.3 Long-Term Effectiveness and Permanence

Alternative 4A may achieve RAOs in the shortest time period (20 years) and would provide a high degree of long-term effectiveness and permanence because the contaminants would be permanently removed from the aquifer through groundwater removal and treatment (Figure 4-3, Table 4-10). However, pump-and-treat systems may not be able to remove all sorbed contamination from some low hydraulic conductivity lithologies. Alternative 5A is the next shortest period (35 years), and this alternative would provide the highest degree of long-term effectiveness and permanence because the contaminants would be permanently removed from the aquifer through biological treatment technologies that can remove even sorbed TCE from the aquifer (Figure 4-5). Alternative 3A has the longest remediation period (50 years) and would also remove the sorbed contaminants during this period (Figure 4-1). Therefore, all three alternatives would be effective and permanent.

4.3.4 Reduction of Toxicity, Mobility, and Volume Through Treatment

Alternative 3A, MNA, would not provide active treatment for contaminated groundwater, but over time, the groundwater plume would be expected to attenuate through natural processes that reduce the toxicity and volume of contamination. Alternative 4A would combine pumping to reduce shallow plume volume and hydraulic control to reduce mobility, with an active, *ex situ* treatment method to reduce plume toxicity. Alternative 5A would combine *in situ* bioaugmentation and MNA to reduce shallow plume toxicity. Therefore, although all three alternatives would provide contaminant reduction, Alternative 4A would provide faster reductions in the highest concentrations than Alternatives 5A and 3A (Table 4-10).

4.3.5 Short-Term Effectiveness

Alternative 3A, MNA, would not include an active remediation component so there would be no additive short-term impacts to the community or the environment, but LTM workers would be monitored to prevent exposure. The Alternative 4A extraction/treatment alternative would have no additive short-term exposure to the community, but both construction workers and treatment system O&M workers would have to be monitored to prevent short-term exposure. The

Alternative 5A bioaugmentation/MNA alternative would include no additive short-term exposure to the community, but both treatment and LTM workers would be monitored to prevent exposure. Therefore, Alternative 3A would provide the least exposure followed by Alternative 5A, then Alternative 4A.

Alternative 3A achieves RAOs in 50 years, Alternative 4A in 20 years, and Alternative 5A in 35 years. Therefore, Alternative 4A has the shortest remediation time, followed by Alternative 5A, then Alternative 3A.

"Averaging" the three sub-criteria (community protection, worker protection, and time to achieve RAOs) shows that all three alternatives have similar short-term effectiveness (Table 4-10).

4.3.6 Implementability

The MNA alternative (Alternative 3A) would be easy to implement technically, potentially requiring only new monitoring wells, but perhaps be more difficult administratively due to its reliance on natural processes to degrade the contaminants in groundwater. The extraction and treatment alternative (Alternative 4A) would be the most difficult alternative to implement technically, but may be more administratively acceptable since it is a USEPA presumptive remedy for contaminated groundwater. The bioaugmentation/MNA alternative (Alternative 5A) would be less difficult to implement technically than Alternative 4A, but perhaps more difficult administratively due to its limited previous use in USEPA Region 8.

Therefore, Alternative 3A would be the simplest to implement technically followed by Alternative 5A, then Alternative 4A. Administratively, Alternative 4A may be the easiest to implement, followed by Alternative 5A, then Alternative 3A (Table 4-10).

4.3.7 Cost

For quantitative cost comparisons, refer to Table 4-8; for qualitative comparisons, refer to Table 4-10. Alternative 3A has the lowest present value cost of the three shallow zone groundwater alternatives, Alternative 4A has the second lowest, and Alternative 5A has the highest.

4.3.8 Intermediate Zone Options

The following subsections compare these options for intermediate zone groundwater at Plume A:

- Option 1A-INT – No Action
- Option 2A-INT – Institutional Controls
- Option 3A-INT – MNA
- Option 4A-INT – Localized Chemical Oxidation and MNA

4.3.8.1 Overall Protection of Human Health and the Environment

No Action (Option 1A-INT) would be protective of human health and the environment under current conditions because no current unacceptable risk has been identified (Table 4-11). However, because this alternative provides no means to monitor future contamination, it would

not be protective over the long term. Institutional Controls (Option 2A-INT) would provide implementation and enforcement of administrative controls to prevent future use of the groundwater resource, but would not monitor future conditions.

Because Diamond Creek is a Class 3B stream and concentrations of TCE will attenuate naturally over long periods of time, MNA (Option 3A-INT) would provide protection of human health and the environment through implementation and enforcement of both the LTM program and institutional controls. However, the time to achieve RAOs would be longer than Option 4A-INT. $KMnO_4$ and MNA (Option 4A-INT) would achieve RAOs (i.e., protection of human health and the environment) in the shortest time period through injection of $KMnO_4$ solution into the intermediate zone, enforcement of the LTM program, and institutional controls.

Therefore, Options 3A-INT and 4A-INT would be protective of human health and the environment in both the short- and long-term (Table 4-11). However, Options 1A-INT and 2A-INT would not provide long-term protectiveness with any certainty and would not meet this threshold criterion.

4.3.8.2 Compliance with ARARs

The No Action option (Option 1A-INT) would not comply with ARARs. The Institutional Controls option (Option 2A-INT) would comply with potential action- and location-specific ARARs, but not with the potential chemical-specific groundwater ARAR of the federal MCL for TCE of 5 µg/L or with ARARs requiring monitoring of releases. Because these first two options would not meet this threshold criterion, they are not carried through the remainder of the comparative analysis (Table 4-11).

Options 3A-INT and 4A-INT would comply with potential action- and location-specific ARARs and with ARARs requiring monitoring of releases (i.e., 40 CFR Part 264). Option 3A-INT would comply with the potential chemical-specific groundwater ARAR set at the federal MCL for TCE of 5 µg/L near the end of a 120-year LTM period and Option 4A-INT after a combined 110-year *in situ* treatment and LTM period. Therefore, based on time to reach ARARs, Option 4A-INT would be faster than Option 3A-INT (Table 4-11).

4.3.8.3 Long-Term Effectiveness and Permanence

Option 4A-INT would reduce the highest concentrations from greater than 80 µg/L TCE to 5 µg/L in six months, leaving other areas of concentrations below 50 µg/L for an additional 110 years (Figure 4-7). This option would provide a higher degree of long-term effectiveness and permanence than Option 3A-INT because Option 3A-INT would leave higher TCE concentrations in groundwater at Plume A until near the end of the 120-year LTM period (Figure 4-6; Table 4-11).

4.3.8.4 Reduction of Toxicity, Mobility, and Volume Through Treatment

Option 3A-INT, MNA, would not provide active treatment for the contaminated groundwater, but over time (120 years), the plume would be expected to attenuate through natural processes that reduce the toxicity and volume of the contamination. Option 4A-INT would combine chemical oxidation to actively treat the highest concentrations in groundwater for six months, followed by natural attenuation to ARARs in 110 years. However, the use of active treatment in

Option 4A-INT would reduce the total time for remediation of the intermediate zone of Plume A by only 10 years over a 120-year MNA period (Table 4-11).

4.3.8.5 Short-Term Effectiveness

Option 3A-INT, MNA, would not include an active remediation component so there would be no additive short-term exposure to the community, but LTM workers would be monitored to prevent exposure. The Option 4A-INT chemical oxidation/MNA system would have no additive short-term exposure to the community, but chemical oxidation treatment and LTM workers would be monitored to prevent exposure. Option 3A-INT requires 120 years to achieve RAOs and Option 4A-INT 110 years, both statistically similar intervals. Therefore, Option 3A-INT would provide similar short-term effectiveness to Option 4A-INT (Table 4-11).

4.3.8.6 Implementability

Option 3A-INT, MNA, would be easy to implement technically, but may be more difficult administratively due to its reliance on natural processes to degrade the contaminants in groundwater. Option 4A-INT, chemical oxidation/MNA, would be more difficult to technically implement than Option 3A-INT, but perhaps less difficult administratively. Therefore, Option 3A-INT would be the simpler to implement technically, and Option 4A-INT may be more easily implemented administratively (Table 4-11).

4.3.8.7 Cost

For quantitative cost comparisons, refer to Table 4-9; for qualitative comparisons, refer to Table 4-11. Option 3A-INT has the lower present value cost, and Option 4A-INT has the higher of the two intermediate-zone groundwater options.

This section consists of the development, detailed analysis, and comparison of the alternatives selected for SS7.

5.1 DEVELOPMENT OF ALTERNATIVES

The following alternatives have been developed for the shallow zone of SS7, while the remainder of Plume A was discussed in Section 4. The "S" designation for each of these alternatives refers to SS7.

- Alternative 1S – No Action
- Alternative 2S – Institutional Controls
- Alternative 3S – Existing PRB and MNA
- Alternative 4S – Expansion of PRB, West PRB, and MNA
- Alternative 5S – Existing PRB, Localized Bioaugmentation, and MNA
- Alternative 6S – ERH with SVE and Chemical Oxidation (Disregard Existing PRB)

All of the alternatives presented would result in concentrations on site above health-based levels; therefore, a site review would be required no less frequent than every five years. Additionally, all of the alternatives would be subject to institutional controls, including stipulations to evaluate potential risk if future buildings are to be constructed overlying higher concentration areas of the groundwater plumes. Finally, none of the alternatives would result in off-site discharge. As such, substantive permit requirements would be met, but actual permits would not be required.

Pump-and-treat, USEPA's presumptive remedy for contaminated groundwater, was considered for an alternative to intercept the plume in local areas between the source area and Diamond Creek. However, the pumping model in the immediate vicinity of the creek, as shown in Figure 5-12 of Volume II and discussed in Section 5.3 of Volume II, "Other Simulated Alternatives," added no significant benefit to the use of a PRB and adds significantly to the O&M requirements of the alternative. In addition, a pump-and-treat system was constructed and operated at SS7 for one year (see Section 1.3.3.1) but was unsuccessful at restoring even part of the plume. This may have been due to the low overall hydraulic conductivity of the SS7 area, lower than in other Zone D plumes, which limits the effectiveness of pump-and-treat. In addition, because the existing IRA PRB is successfully remediating a portion of the plume, a pumping system could reverse the groundwater gradient through the PRB and reduce this effectiveness. Therefore, a pumping system was not proposed in any SS7 alternative.

Surface water treatment is included for SS7, which contributes to Diamond Creek. Due to its 3B Classification, Diamond Creek has no current TCE regulatory limit. However, Diamond Creek intersects Crow Creek, a Class 2AB creek with a current regulatory limit of 2.7 µg/L. Since historical concentrations of TCE measured in Diamond Creek near the SS7 intersect have exceeded the regulatory limit for Crow Creek, surface water treatment is required.

With limited treatment options for the intermediate zone, the FS alternatives have been structured and developed to focus on addressing contaminants in the shallow groundwater where most of the contaminant mass exists and hydraulic properties are not as much of a limiting factor. Following discussion of the shallow zone remedial alternatives in subsequent sections, natural attenuation time frames and active treatment simulations for the intermediate zone are

presented for the respective plumes. Contaminant reduction in the intermediate zone is focused on MNA and $KMnO_4$ injection. This approach has been taken with the understanding that a selected alternative for the shallow zone would also incorporate one of the options for the intermediate zone. These options would include:

- No Action (possibly with monitoring)
- Institutional Controls
- MNA
- Chemical Oxidation ($KMnO_4$)

For all of the alternatives, the proposed monitoring approaches are regarded as baseline assumptions for the purposes of scoping monitoring needs and to provide a basis for FS cost estimates. Actual monitoring needs would be evaluated as the design of the selected alternative progresses.

Waste streams generated during implementation of the alternatives include soil from drill cuttings and trench excavation, water from monitoring well development and purging, and spent carbon from liquid-phase treatment of extracted, vacuum-stripped groundwater. In general, these wastes would be managed consistent with current USEPA-approved waste management practices at FEW.

5.1.1 Alternative 1S – No Action

The No Action Alternative assumes no further action would be taken regarding contaminants in groundwater. No institutional controls, such as legal/management control or LTM would be implemented. This alternative is required by the NCP for baseline comparison purposes.

5.1.2 Alternative 2S – Institutional Controls

This alternative consists of physical and/or institutional controls to limit access and future development of groundwater and assess risk from indoor air if buildings are planned to be constructed overlying higher concentration areas of the groundwater plumes. Access to the groundwater would be controlled and activities inconsistent with the prescribed usage of the groundwater would be prohibited. Because this alternative does not allow unrestricted use and unlimited exposure, this alternative would be subject to review not less than every five years.

Refer to Section 4.1.2 for discussions of the Process Description, Rationale, Conceptual Design, and Performance Monitoring associated with Institutional Controls.

5.1.3 Alternative 3S – Existing Permeable Reactive Barrier and Monitored Natural Attenuation

Groundwater sampling data and numerical modeling results suggest that SS7 is stable or increasing in size and contaminant mass has not been significantly reduced upgradient of the existing PRB (Volume II and Sections 4.1.3.1, 5.4.1, and Figure 5-21 of the Zone D Groundwater RI [USAF 2003a]). However, VOC concentrations downgradient of the PRB are slowly decreasing from the PRB toward Diamond Creek. Based on these results, continued use of the SS7 IRA and its replacement after 30 and 60 years, together with MNA, is considered to

be a viable alternative. Modeled results for Alternative 3S (Existing PRB/MNA) are shown on Figure 5-1. This alternative would also be subject to institutional controls, as described in Section 5.1.2, to limit access and future development of groundwater.

5.1.3.1 Process Description

The alternative includes the existing PRB and MNA, as discussed in the following sections.

Permeable Reactive Barrier

A PRB is an emplacement of reactive treatment materials in the subsurface designed to intercept a contaminant plume, provide a preferential flow path through the reactive media, and chemically transform the contaminant(s) into environmentally acceptable forms to attain remediation concentration goals at points of compliance. Necessary information regarding contaminant concentration, contaminant degradation rate in the presence of the reactive substrate, and groundwater flow rate through the barrier must be known. This allows determination of the required residence time in the zone needed to achieve remedial goals, hence allowing calculation of the required thickness of the reactive zone. For additional details, see Sections 2.4.4 and 3.4.1.

Monitored Natural Attenuation

Refer to Section 4.1.3.1 for a process description of natural attenuation. As shown in Figure 5-1, portions of the SS7 plume crossgradient of the PRB will be allowed to naturally attenuate for between 60 and 80 years until they reach RAOs. Following passive remediation of the portions of the plume upgradient of the PRB during the first 90 years (three PRB lifetimes) of the 100-year LTM period, the remaining contaminants would be allowed to naturally attenuate for an additional 10 years before reaching RAOs.

5.1.3.2 Rationale for Alternative

The rationale for this alternative, which includes the existing PRB and MNA, is discussed in the following sections.

Permeable Reactive Barrier

The location of the existing PRB is depicted in Figure 5-1. Rationale for the present location, orientation, and life of the PRB included:

- The orientation of the existing PRB was oriented as nearly perpendicular to groundwater flow in this vicinity of SS7 as was possible.
- The existing PRB location was selected, in part, due to restrictions on construction in sensitive species habitat and, in part, to constructability problems on a steep slope.
- The existing PRB depth (15 feet below the historic low water level) was selected through agreement by the agencies to provide protection of Diamond Creek and Crow Creek surface water.

- The existing PRB configuration was selected through an iterative modeling process involving comparison of results for various scenarios where different placements of PRBs were evaluated.
- Groundwater contaminant data collected during LTM of the SS7 PRB indicate the existence of natural attenuation at SS7 (see Section 5.4.1 of the Zone D Groundwater RI [USAF 2003a]).
- Shallow-zone groundwater immediately downgradient of the PRB is being passively treated by the ZVI (USAF 2003e). TCE concentrations have been reduced by nearly 100 percent in wells immediately downgradient of the iron. Therefore, the PRB is destroying contaminant mass migrating through it from the highest concentration portion of the shallow plume.
- TCE concentrations are not expected to exceed the RAO at the furthest downgradient monitoring well (i.e., MW-172C) after Year 10.
- The modeling simulation (Volume II) estimated that the existing PRB would have a life of at least 30 years. Thereafter, the PRB would need to be replaced twice in order to treat the groundwater for approximately 100 years.

Based on results of groundwater modeling presented in Volume II and Figure 5-1, the time for TCE concentrations throughout the entire plume to flow through the PRB and be naturally attenuated to 5 μg/L from present conditions is estimated to be approximately 100 years. LTM would allow for continued evaluation of contaminant migration and effectiveness of this alternative.

Monitored Natural Attenuation

For a discussion of MNA results at SS7, see Section 5.4.1 of the Zone D Groundwater RI (USAF 2003a). Groundwater sampling data in the RI indicate that TCE concentrations are decreasing in wells in the southeastern portion of SS7 (the zone crossgradient from the PRB and not intercepted by the PRB), suggesting that natural attenuation, migration, and dilution are occurring in that area of the plume. TCE concentrations in LTM groundwater samples, summarized in Table 4-4 of the RI, indicate that:

- The leading edge of the SS7 plume at MW-172C has remained constant in the shallow zone of the aquifer, and concentrations have been reduced by an order of magnitude from 86 μg/L in 1992 to 8.3 μg/L in 2001.
- According to the model (Figure 5-1), TCE concentrations at the plume toe (MW-172C) will be reduced below RAOs before Year 10 and will remain below RAOs for the remainder of the MNA period.
- TCE concentrations at PRB crossgradient well MW-189 have been reduced by a factor of 2 (170 μg/L in 1993 to 82 μg/L in 2001), will be reduced below RAOs before Year 60 without additional treatment according to the model (Figure 5-1), and will remain below RAOs for the remainder of the MNA period.
- TCE concentrations at upgradient well MW-027 were reduced by an order of magnitude from 1,200 μg/L in 1986 to 103.4 μg/L in 1998 (after the SS7 pump-and-treat system

operation but before the construction of the PRB), will be reduced below RAOs before Year 40 without additional treatment according to the model (Figure 5-1), and will remain below RAOs for the remainder of the MNA period (Figure 5-1).

Based on results of additional groundwater sampling and MNA groundwater modeling presented in Volume II, the time for TCE concentrations throughout the shallow zone of the plume to be PRB-treated and naturally attenuated to 5 µg/L from present conditions is estimated to be approximately 100 years.

5.1.3.3 Conceptual Design

The existing PRB has been in place since 1999, therefore, no additional design is required for this alternative. PRB design, location, emplacement methodology, and estimated life expectancy were based on site characterization information. In 1999, trench box-supported trenching was used for installing the 569-foot-long SS7 PRB. This PRB was constructed in a 4-foot-wide trench excavated to 15 feet below the historic low water level. The historic low was selected in order to prevent exposure of the ZVI to vadose-zone atmospheric conditions and subsequent oxidation (rusting) of the iron. In Segment 1 of the SS7 PRB, the 4-foot trench was backfilled with a full 4 feet of 100 percent iron. Typical practice is to increase the PRB thickness by mixing the iron with sand to enhance hydraulic conductivity, facilitate construction, and/or to minimize construction costs. This practice was used in two of the three segments of the SS7 PRB, where an amount of iron equivalent to a 1-foot-thick was used in one segment and equivalent to 1.5 feet was used in another segment.

Monitored Natural Attenuation

An LTM program would be developed for the 100-year PRB treatment/MNA period. The LTM program would be reviewed and modified accordingly as new data are obtained during the 100-year monitoring period. The design for MNA at SS7 would be similar to that for Plume A in Section 4.1.3.2.

5.1.3.4 Performance Monitoring

Performance monitoring would consist of groundwater and surface water monitoring, as discussed in the following paragraphs.

Groundwater Monitoring

A long-term performance monitoring network has been established for the 30-year life of the SS7 PRB. The monitoring well network currently consists of annual or semiannual monitoring of the following wells (Plate 1):

- Upgradient of the PRB—PMW-101A/B, PMW-201A/B, PMW-301A/B
- Downgradient of the PRB—PMW-103A/B/C, PMW-203A/B/C, PMW-303A/B/C, MW-173B, MW-186, MW-700B, MW-702B, MW-707A/B, MW-708
- In-wall (within the PRB)—PMW-102, PMW-202, PMW-302
- Crossgradient—PMW-401, PMW-501

- In-plume—MW-151, MW-182, MW-190

Monitoring would occur until established groundwater standards are met in the shallow plume. However, this network may be adjusted and located according to the most appropriate design to measure the effectiveness of the chosen alternative. Samples would be collected according to the monitoring plan developed for each alternative during the design phase. No new monitoring wells were assumed.

Surface Water Monitoring

The surface water sampling associated with the existing IRA and LTM program (USAF 2003b) would be continued. In order to monitor the discharge from SS7 to Diamond Creek, the current surface water monitoring program for PRB performance at Stations D3, D3.5, D3.6, and D4 would be included in the performance monitoring program. Although optimization of that program may lead to changes, no additional surface water monitoring would be proposed.

Analytical Protocol

All performance monitoring points would be sampled and analyzed for those analytes listed in Table 4-1. Refer to Section 4.1.3.4 for additional details concerning the analytical protocol.

Sampling Frequency and Duration of Monitoring

Results of MNA groundwater modeling (Volume II and Figure 5-1) suggest that TCE concentrations in groundwater will attenuate to 5 µg/L from present conditions in approximately 100 years. Therefore, the proposed LTM program sampling duration is based on a 100-year monitoring period. The sampling frequency would be consistent with that presented in Section 4.1.3.2.

5.1.4 Alternative 4S – Extension of Existing Permeable Reactive Barrier, Western Permeable Reactive Barrier, and Monitored Natural Attenuation

This alternative provides extending the existing PRB to the east of its present location, constructing a new PRB along the western side of SS7, and MNA to remediate the SS7 plume. The following sections provide a process description, rationale for selection, conceptual design, and process monitoring plan of this "creek intercept" treatment alternative. This alternative would also be subject to institutional controls, as described in Section 5.1.2, to limit access and future development of groundwater.

5.1.4.1 Process Description

The following sections describe the PRB and MNA portions of the alternative in more detail.

Permeable Reactive Barrier

Refer to Section 5.1.3.1 for a process description of existing PRB.

Monitored Natural Attenuation

Refer to Section 4.1.3.1 for a process description of natural attenuation. Following passive treatment of portions of the plume with the PRBs, the remainder of the contaminants would be allowed to naturally attenuate.

5.1.4.2 Rationale for Alternative

The rationale for both new PRB construction and MNA is described in the following sections.

Permeable Reactive Barrier

PRB design, location, emplacement methodology, and estimated life expectancy are based on the site characterization information. Design criteria require that the entire plume must be directed through and remediated within the reactive zone of the barrier. The plume must not be able to pass over, under, or around the barrier, and the reactive zone must be capable of reducing the contaminant to concentration goals without rapidly plugging with precipitates or losing its reactivity.

The existing PRB extends to a depth of only 15 feet below the water table along a length of 568 feet of Diamond Creek between surface water monitoring stations D3.5 and D3.6. Groundwater modeling results have shown that extending this PRB another 300 feet to the east would minimize bypass of the PRB in the area between the PMW-401 and MW-189 monitoring wells. This bypass has been demonstrated by recently increasing TCE concentrations in MW-501 (USAF 2003e).

In addition, the modeling indicated that a groundwater divide exists in a line between SS7 MW-06 and MW-704. West of this divide, groundwater flows toward Diamond Creek in the stream reach between surface water monitoring stations D3 and D3.5. The model shows that groundwater in this area would not flow through the existing PRB and, therefore, needs another PRB or some alternate technology to treat this portion of SS7. The proposed PRB would have a length of 300 feet and a depth of 13 feet.

The proposed locations for the eastward extension of the existing PRB and the west PRB are depicted in Figure 5-2. This configuration was selected through an iterative modeling process involving comparison of results for various scenarios where different placements of PRBs were evaluated. Rationale for location, orientation, and life of these PRBs includes:

- The proposed orientation of the eastward extension of the existing PRB is oriented perpendicular to groundwater flow in this vicinity of SS7.
- The eastward extension is projected to the location of monitoring well MW-189. Thus, MW-189 may be utilized to assess contaminant flow around the east end of the wall in the similar manner as PMW-401 is utilized for the LTM.
- The eastward extension is the approximate eastward extent of concentrations of 100 μg/L or greater. Concentrations observed east of MW-189 are too low to justify using a ZVI PRB.

- The simulation estimated that the initial PRBs would have a life of at least 30 years. Thereafter, the PRBs would need to be replaced twice in order to treat the groundwater for 100 years.

An alternative technology for the proposed western PRB is a line of groundwater extraction wells to develop a hydraulic barrier rather than a PRB to prevent groundwater contamination migrating westward to the creek. Seven extraction wells were proposed along the western margin of SS7 east of Diamond Creek, and a long and narrow zone of hydraulic low was developed as the result of pumping. The low permeability of the aquifer and the need to minimize disturbance of the hydraulic flow pattern upgradient of the existing PRB necessitated the use of a low pumping rate, totaling 1.7 gpm.

Monitored Natural Attenuation

Refer to Section 4.1.3.2 for rationale for natural attenuation.

5.1.4.3 Conceptual Design

The conceptual design includes constructing two new PRBs and MNA.

Permeable Reactive Barrier

In a continuous PRB, treatment material would be distributed across the entire path of the contaminated groundwater, which is different from a funnel-and-gate system with an impermeable barrier pierced by treatment "gates." In 1999, trench box-supported trenching was used for installing the SS7 PRB. This was successfully implemented, but newer continuous trenching machines allow simultaneous excavation and backfilling without an open trench to moderate groundwater depths.

Continuous trenching is performed by a cutting chain immediately in front of a trench-box (boot) that extends the width and depth of the finished treatment zone. Both the cutting chain and boot are attached to the trenching machine. As the trencher moves forward, treatment material is added to the boot creating a continuous treatment zone. Trenchers are available to install treatment zones from 1 to 2 feet in width to depths of 25 feet. If necessary, additional passes along the trench can be made to install thicker walls. As implemented at the SS7 PRB, the PRB thickness may be optimized by mixing the ZVI with sand to enhance hydraulic conductivity, facilitate construction, and/or to minimize construction costs (Table 5-1).

Two *in situ* PRBs using granular ZVI would be implemented to treat TCE-contaminated groundwater at the intercept of the SS7 plume with Diamond Creek in order to minimize TCE concentrations in groundwater reaching the creek. This alternative would consist of a 300-foot-long eastward extension of the existing SS7 PRB and a 300-foot-long, newly installed PRB along the west side of SS7.

The location of this western PRB would be situated in an area in which numerical modeling (Volume II) indicates a potential for westward migration of contaminants from SS7 and may be a major contributor to the contamination observed at surface water sampling location D3. The following assumptions were made for purposes of preparing a conceptual design of the system (based on Year 2001 data):

- The zone to be remediated by the PRB in both proposed locations covers a length of approximately 600 feet (300 feet for each PRB).
- The 0.25-foot-thick ZVI section would extend throughout the 20 feet of saturated thickness of the shallow aquifer zone for both PRBs.
- The Zone D groundwater model was used to estimate the size and placement of the PRBs and the time required to reduce TCE concentrations to 5 μg/L in the area downgradient of the iron.
- A total of 375 cubic feet of granular iron would be utilized in each PRB.

Monitored Natural Attenuation

An LTM program would be developed for the 100-year PRB treatment/MNA period (Figure 5-3). The LTM program would be reviewed and modified accordingly as new data are obtained during the 100-year monitoring period. The design for MNA at SS7 would be similar to that for Plume A in Section 4.1.3.3.

5.1.4.4 Performance Monitoring

Performance monitoring would consist of groundwater and surface water monitoring, as discussed in the following paragraphs.

Groundwater Monitoring

See Section 5.1.3.4.

Surface Water Monitoring

See Section 5.1.3.4.

Analytical Protocol

All performance monitoring points would be sampled and analyzed for those analytes listed in Table 4-1. Refer to Section 4.1.3.2 for additional details concerning the analytical protocol.

Sampling Frequency and Duration of Monitoring

Results of MNA groundwater modeling (Volume II and Figure 5-1) suggest that TCE concentrations in groundwater will attenuate to 5 μg/L from present conditions in approximately 100 years. Therefore, the proposed LTM program sampling duration is based on a 100-year monitoring period. The sampling frequency would be consistent with that presented in Section 4.1.3.2.

5.1.5 Alternative 5S – Existing Permeable Reactive Barrier, Localized Bioaugmentation and Monitored Natural Attenuation

This alternative provides the existing PRB to protect the surface water interface of SS7 and a combination of bioaugmentation and MNA to address the chlorinated VOC contamination in groundwater for the upgradient plume at SS7. The following sections provide a process description, rationale for selection, conceptual design, and process monitoring plan of this groundwater alternative.

5.1.5.1 Process Description

The following sections describe the PRB, bioaugmentation, and MNA portions of the alternative in more detail.

Permeable Reactive Barrier

Refer to Section 5.1.3.1 for a process description of the existing SS7 PRB.

Bioaugmentation

Refer to Section 4.1.5.1 for a process description of bioaugmentation.

Monitored Natural Attenuation

Refer to Section 4.1.3.1 for the process description of natural attenuation.

5.1.5.2 Rationale for Alternative

The following sections discuss rationale for the combination of the existing PRB and bioaugmentation at SS7.

Permeable Reactive Barrier

The existing PRB extends to a depth of only 15 feet below the water table along a length of 568 feet of Diamond Creek between surface water monitoring stations D3.5 and D3.6. Groundwater modeling results have shown that the time frame for flow through the existing PRB and MNA to remediate the plume to MCLs is 100 years (see Section 5.1.3.2).

In addition, the modeling indicated that a groundwater divide exists in a line between SS7, MW-06 and MW-704. West of this divide, groundwater flows toward Diamond Creek in the stream reach between surface water monitoring stations D3 and D3.5. The model shows that groundwater in this area would not flow through the existing PRB and, therefore, needs another technology to treat this portion of SS7. One alternate technology that could remediate this portion of the plume is bioaugmentation, as discussed in the following section.

Bioaugmentation

The use of bioaugmentation at SS7 has a similar rationale to its use in Plume A. Therefore, the rationale is discussed in Section 4.1.5.2.

Monitored Natural Attenuation

Refer to Section 4.1.3.2 for rationale for natural attenuation.

5.1.5.3 Conceptual Design

The following sections describe the design of the proposed alternative (Table 5-2).

Permeable Reactive Barrier

The existing PRB was designed in 1998 as part of the SS7 IRA. Because this alternative assumes that no modifications would be made to this system and that a performance monitoring network has already been established, no additional design would be required.

Bioaugmentation

Refer to Section 4.1.5.3 for the conceptual design for bioaugmentation. Proposed bioaugmentation treatment areas are displayed on Figure 5-4. In the area of SS7 near the PRB, it is not necessary to establish reducing conditions, since an anaerobic environment has already been created by the PRB. Bioaugmentation modeling results for SS7 are shown on Figure 5-5. The modeling assumptions made to evaluate the effectiveness of this technology using the Zone D groundwater model are provided in Volume II. The final 8.5-acre area of application of bioaugmentation was derived from an iterative process of evaluating variably sized treatment areas and comparing cleanup times. Areas of 3.3 and 5.6 acres were evaluated to assess the effectiveness of applying the technology to a smaller, high concentration area compared to an overall larger area. Estimated cleanup times for the smaller area scenarios were greater than 60 years (Volume II).

Monitored Natural Attenuation

An LTM program would be developed for the 35-year bioaugmentation/PRB treatment/MNA period. The LTM program would be reviewed and modified accordingly as new data are obtained during the 35-year monitoring period. The design for MNA at SS7 would be similar to that for Plume A in Section 4.1.3.2.

5.1.5.4 Performance Monitoring

Performance monitoring will consist of both groundwater and surface water monitoring, as discussed in the following paragraphs.

Groundwater Monitoring

See Section 5.1.3.4.

Surface Water Monitoring

See Section 5.1.3.4.

Analytical Protocol

All performance monitoring points would be sampled and analyzed for those analytes listed in Table 4-1. Refer to Section 4.1.3.4 for additional details concerning the analytical protocol.

Sampling Frequency and Duration of Monitoring

Results of MNA groundwater modeling (Volume II and Figure 5-1) suggest that TCE concentrations in groundwater will attenuate to 5 µg/L from present conditions in approximately 35 years. Therefore, the proposed LTM program sampling duration would be based on a 35-year monitoring period. The sampling frequency would be consistent with that presented in Section 4.1.3.2.

5.1.6 Alternative 6S – Electrical Resistance Heating with Soil Vapor Extraction and Chemical Oxidation (Disregard Existing Permeable Reactive Barrier)

This alternative provides ERH for the highest concentration chlorinated VOC contamination in groundwater for SS7, chemical oxidation using Fenton's Reagent for the intermediate VOC concentrations, and $KMnO_4$ for the lower concentrations. The existing IRA (the SS7 PRB) would be disregarded in this alternative by leaving it in place and utilizing the ERH and chemical oxidation technologies in the same portions of the plume. Therefore, the iron may be oxidized by the heat of the ERH array or the oxidizing chemicals used for Fenton's Reagent and $KMnO_4$ injection. The following sections provide a process description, rationale for selection, conceptual design, and process monitoring plan of this treatment alternative. This alternative would also be subject to institutional controls, as described in Section 5.1.2, to limit access and future development of groundwater.

5.1.6.1 Process Description

The following paragraphs describe the technologies included in this alternative—ERH with SVE and chemical oxidation. This alternative assumes that the existing SS7 IRA PRB would be abandoned in place and would not provide any remediation benefit to SS7.

Electrical Resistance Heating

Refer to Section 2.4.6 for a description of SPH and ERH.

Fenton's Reagent

Refer to Section 2.4.4.2 for a complete description of Fenton's Reagent.

Fenton's Reagent must be thoroughly distributed throughout the contaminated zone to decrease contaminant concentrations. Higher permeability zones are cleaned up faster due to preferential flow and better distribution. During the Zone D Treatability Study, the direct-push pressure injection process proved to be an effective method of delivering and distributing $KMnO_4$ into the subsurface (USAF 2002), however successful drilling using the direct-push drill rig was sporadic in Zone D, indicating that auger drilling may be required within some areas of the plume. The injection process for Fenton's Reagent is similar to the $KMnO_4$ injection process with the

exception of aboveground equipment such as injection hoses, pumps, fittings, adapters, and mixing tanks.

Potassium Permanganate

Refer to Section 4.1.6.2 for the process description of $KMnO_4$.

5.1.6.2 Rationale for Alternative

The rationale for selecting each technology included in this alternative is discussed in the following paragraphs.

Electrical Resistance Heating

Refer to Section 2.4.6 for the remediation process of SPH, including a list of advantages of SPH over other ERH techniques.

ERH was chosen for the highest concentration portion of SS7 because the lithology at that location (Figure 5-6) consists of lower permeability clays and silts than the surrounding areas of Plume A. Modeling indicates that, without heating and chemical oxidation, the existing PRB could take up to 100 years to reach cleanup goals. ERH was selected for use in a 0.6 acre area, as discussed in Section 5.2.4 of Volume II.

Fenton's Reagent

Few technologies are capable of treating residual DNAPL particles or sorbed-phase contamination suspected to be found in source areas, or areas of high dissolved-phase contaminant concentrations. The hydroxyl free radical is a strong oxidizer and is capable of treating DNAPL or sorbed-phase contamination. In addition, minor agitation produced during the reaction between hydrogen peroxide and ferrous iron can assist in transferring sorbed or immobile contamination into the dissolved phase, where is can be treated more effectively. These treatment capabilities are what make Fenton's Reagent effective for high-concentration source area treatment. However, because Fenton's Reagent is not as effective as ERH in very low-conductivity soils, it was applied only to a 2.2-acre higher conductivity, but very high concentration, zone outside the limits of the ERH treatment zone (see Section 5.2.4 of Volume II).

Because Fenton's Reagent is injected in a similar manner as $KMnO_4$, the observations made during the Zone D $KMnO_4$ Treatability Study apply to Fenton's Reagent injection and are listed below.

- The lithology of the area to receive treatment and Plume C, where the $KMnO_4$ Treatability Study was conducted, are both within Zone D.
- The geology at the Treatability Study site is very similar to that observed in the proposed 3.7-acre injection area.
- Fenton's Reagent is a stronger oxidant than $KMnO_4$, and therefore is capable of oxidizing compounds that cannot be oxidized by $KMnO_4$.

- The radius of influence for Fenton's Reagent injection is expected to be similar to the radius of influence observed during the Zone D $KMnO_4$ Treatability Study.

Potassium Permanganate

Based on the Zone D $KMnO_4$ Treatability Study observation, it was assumed that the injection technique using small volumes and low concentration of $KMnO_4$ is successful in avoiding permeability loss due to MnO_2 precipitation. Using the results from the Zone D Treatability Study, a preliminary plan and conceptual design for a chemical oxidation and monitoring treatment alternative were developed. The $KMnO_4$ Treatability Study conducted in Plume C is applicable to SS7 for the following reasons.

- SS7 and Plume C, where the $KMnO_4$ Treatability Study was conducted, are both within Zone D.
- The geology at the Treatability Study site is very similar to that observed in the proposed 5.7-acre injection area at SS7 (see Section 5.2.4 of Volume II).
- Findings of the Zone D $KMnO_4$ Treatability Study indicate that this technology is effective in reducing TCE concentrations of 357 µg/L to nondetect. The highest TCE concentration recently observed in the portion of SS7 to be treated with $KMnO_4$ was 470 µg/L (SS7-MW35, January 2003).
- Findings of the $KMnO_4$ Treatability Study indicate that the area of impact (where $KMnO_4$ was detected) extends up to 70 feet downgradient and as far as 30 feet crossgradient.

In addition to the results of the $KMnO_4$ Treatability Study, contaminant concentrations within the portion of SS7 to be treated with $KMnO_4$ are low enough so that the majority of the contamination present is expected to be in the dissolved-phase rather than the sorbed-phase, making the plume area conducive to treatment with $KMnO_4$.

5.1.6.3 Conceptual Design

The conceptual design of the ERH, Fenton's Reagent, and $KMnO_4$ technologies is discussed in the following paragraphs. The proposed treatment area of 8.5 acres for Alternative 6S was an optimization of the area in an attempt to reduce the cleanup time (as discussed in Section 5.2.4 of Volume II). The resulting cleanup time for the shallow layer of SS7 was 35 years (Figure 5-7 and Table 5-5).

Electrical Resistance Heating

Five hexagonal SPH arrays would be operated sequentially for a period of six weeks each. Array 1 would be 60 feet in diameter; array 2, 50 feet in diameter; array 3, 40 feet in diameter; array 4, 60 feet in diameter; and array 5, 100 feet in diameter. These five arrays would cover an area of approximately 0.6 acres, as discussed in Section 5.2.4 of Volume II and shown on Figure 5-6. ERH modeling results for SS7 are shown on Figure 5-7.

All five arrays would be designed and installed to heat the subsurface interval. Soil and groundwater within each array will be heated to 100°C during the initial two weeks of

operations. The arrays will then be operated for an additional four weeks to allow boiling of the groundwater and steam stripping of the soil matrix.

Fenton's Reagent

The conceptual design for Fenton's Reagent injection assumes that at shallow depths (20 to 40 feet bgs) approximately half of the injection locations would have dedicated injection wells installed to the anticipated depths using a casing advance-type drilling method, and the other half would be installed using direct-push.

The acreage of the treatment area is 2.2 acres, as discussed in Section 5.2.4 of Volume II, and displayed in Figure 5-6. Fenton's Reagent modeling results for SS7 are shown on Figure 5-7.

The depth of the treatment area is estimated to be 20 to 40 feet bgs. Existing monitoring wells that are located in the vicinity of the injection area and are screened across the shallow aquifer zone may require installation of a packer within the well casing to deter loss of injected oxidant through migration up the casing.

Where direct-push drilling and injection is achievable, a direct-push drill rig would be used to install injection rods and screens to predetermined depths at designated injection locations. The direct-push injection system would be designed to allow for pressure injection and introduction of material directly into the aquifer, with no permanent equipment installed. A 1- to 1.25-inch outer diameter stainless steel casing with an expendable tip would be driven into the subsurface via the drill rig. Solid sections of 4- to 5-foot long casing would be added behind the initial drive rod and advanced until the desired injection depth is reached. Upon reaching this depth, the drill rods would be pulled upwards to expose the portion of the borehole to receive injections.

In order to fully saturate the target zone with Fenton's Reagent and limit the need for vertical migration of the oxidants, it may be possible that direct-push injections be delivered to two different depth intervals within the water-bearing zone. Depth intervals would be determined using historical geologic boring logs. Injection depths may also be adjusted vertically during injection to achieve an ideal level of flow.

In areas of the plume where the lithology is not ideal for using direct-push injection, 1- to 1.5-inch diameter injection wells would be installed using a casing advance-type drilling method (e.g., dual-wall percussion hammer or sonic).

The Zone D Treatability Study (USAF 2003f) indicated that injection rates of 1.5 to 3 gpm with pressures of 10 psi are sufficient to distribute the $KMnO_4$ approximately 20 feet radially from each injection location. This is supported in both the field observations (USAF 2003f) and subsequent numerical modeling (USAF 2004). A similar distribution of Fenton's Reagent is also expected when injected, although Fenton's Reagent has a much higher reactive capacity and is presumed to be expended more rapidly. Therefore, advective transport of the oxidant is expected to be much less than that of $KMnO_4$. With this in mind, an injection grid with points spaced 20 feet apart in the transverse direction and 20 feet in the longitudinal direction was utilized during remedial alternative development.

Various chemicals in soil and groundwater, such as TOC, metals, and sulfur compounds, can exhibit an oxidant demand, consuming Fenton's Reagent and therefore reducing its effectiveness on oxidizing contaminants. Because of this excess oxidant demand, two applications of oxidant

would be delivered to the subsurface to verify that enough material was delivered to sufficiently release and treat sorbed-phase and dissolved-phase contamination to reduce contaminant mass.

Modified Fenton's Reagent can consist of a site-specific chelated iron complex and stabilized H_2O_2 to be used as the oxidizer. Stabilized H_2O_2 typically used ranges in concentration from 5 to 20 percent.

Fenton's Reagent would be injected under pressure to obtain the broadest lateral and vertical saturation of the contaminated zone. The saturation zones from each injection point would be designed to overlap to provide complete coverage of the target interval. Some adjustment of the injection points would most likely be required to ensure complete coverage.

The Fenton's Reagent solution would be injected at a rate of approximately 1.5 to 3 gpm under pressures of approximately 10 psi to obtain the broadest lateral and vertical saturation of the contaminated zone, while reducing the potential for oxidant surfacing. Final injection pressure and rate would be determined in the field based on the aquifer response to pressure injection. Pumps, hoses, and fittings used to transfer the oxidant from the mixing tank to the injection locations would be sealed to eliminate oxidant leaks onto the ground surface.

Potassium Permanganate

The main difference between the application of $KMnO_4$ at Plume C and the conceptual design for SS7 is that direct-push drilling and injection may only be used for a portion of the treatment based on localized drilling conditions. For this reason, the conceptual design assumes that at shallow depths approximately half of the injection locations would have dedicated injection wells installed to the anticipated depths using a casing advance-type drilling method, and the other half using direct-push. Injection locations at intermediate depths would consist of dedicated injection wells and no direct-push injections. If *in situ* treatment is the selected alternative, additional applicable information that becomes available from the Zone D Treatability Study would be incorporated into the final design.

SS7 encompasses a relatively large area; therefore, only the higher concentration portion of the plume would be treated with $KMnO_4$ to remove contaminant mass and accelerate MNA. The $KMnO_4$ treatment area is approximately 5.7 acres, as discussed in Section 5.2.4 of Volume II, and is displayed on Figure 5-6. $KMnO_4$ modeling results for SS7 are shown on Figure 5-7.

The depth of the treatment area is estimated to be 20 to 40 feet bgs in the shallow aquifer. Existing monitoring wells that are located in the vicinity of the injection area and are screened across both the shallow and intermediate aquifer zones may require installation of a packer within the well casing to deter loss of injected $KMnO_4$ through migration up the casing and into the shallow aquifer zone.

Injection points would installed across the injection zone as described in the conceptual design for $KMnO_4$ in Section 4.1.6.2. Injection procedures would be similar to those described in the previous subsection for Fenton's Reagent.

Based on contaminant concentrations detected previously at the site, an approximately 1-percent (by weight) solution of $KMnO_4$ would need to be delivered into the SS7 subsurface during the first application. The final amount of oxidant delivered would be decided in the field and would be based on the rate of flow established during injection at each borehole. Per application, approximately 200 gallons of a 1-percent solution of $KMnO_4$ would be injected into the

subsurface at each injection location. Total volume of oxidant and pounds of dry $KMnO_4$ required are provided in Volume III.

The $KMnO_4$ solution would be injected at a rate of approximately 1- to 1.5-gpm under a pressure of approximately 10 psi, consistent with observations of the Zone D Treatability Study (USAF 2003f), to obtain the broadest lateral and vertical saturation of the contaminated zone, while reducing the potential for oxidant surfacing. Based on recent work performed in Zone D Plume C, this injection rate is assumed feasible. However, final injection pressure and rate would be determined in the field based on the aquifer response to pressure injection.

5.1.6.4 Performance Monitoring

Performance monitoring would consist of groundwater and surface water monitoring, as discussed in the following paragraphs. For ERH, pre- and post-treatment soil sampling would be performed inside and outside of each array. Sampling would be extended outside the arrays to a distance of 40 percent of the array diameters.

Groundwater Monitoring

The monitoring well network would tentatively consist of 12 selected wells, or their replacements if some wells were damaged by the ERH or Fenton's Reagent heating, in the following locations (Plate 1):

- Downgradient—MW-186, MW-700B, MW-702B, MW-707B, MW-708, MW-172C
- Crossgradient—MW-189, MW-067
- In-plume—MW-151, MW-182, MW-190, MW-027

Monitoring would occur until established groundwater standards were met in the shallow plume. However, this network may be adjusted and located according to the most appropriate design to measure the effectiveness of the chosen alternative. Samples would be collected according to the monitoring plan developed for each alternative during the design phase. No new monitoring wells were assumed.

Surface Water Monitoring

The surface water sampling associated with the existing IRA and LTM program (USAF 2003b) would be continued. In order to monitor the discharge from SS7 to Diamond Creek, the current surface water monitoring program for PRB performance at Stations D3, D3.5, D3.6, and D4 would be included in the performance monitoring program. Although optimization of that program may lead to changes, no additional surface water monitoring is proposed for in this FS.

Analytical Protocol

All performance monitoring points would be sampled and analyzed for those analytes listed in Table 4-1. Refer to Section 4.1.3.2 for additional details concerning the analytical protocol.

Sampling Frequency and Duration of Monitoring

Results of MNA groundwater modeling (Volume II and Figure 5-7) suggest that TCE concentrations in groundwater would attenuate to 5 µg/L from present conditions in approximately 35 years. Therefore, the proposed LTM program sampling duration is based on a 35-year monitoring period. The sampling frequency would be consistent with that presented in Section 4.1.3.2.

5.1.7 Intermediate Zone Options

This section discusses the following options developed for the intermediate-depth portion of SS7:

- Option 1S-INT – No Action
- Option 2S-INT – Institutional Controls
- Option 3S-INT – MNA
- Option 4S-INT – Localized Chemical Oxidation and MNA

The first two options—Option 1S-INT, No Action, and Option 2S-INT, Institutional Controls, for the intermediate zone of SS7 are identical in name and description to Alternative 1S, No Action, and Alternative 2S, Institutional Controls, for the shallow zone of SS7. Therefore, the development of those intermediate-zone options assumes that all of the discussion in Sections 5.1.1 and 5.1.2 applies and will not be repeated in this section.

For the purposes of cost estimating, the value associated with the most conservative intermediate MNA option is presented. Due to variations in length of the different shallow zone alternatives, the institutional controls and 5-Year Reviews associated with the intermediate MNA costs differ. For a complete list of costs associated with each, individual intermediate option, refer to Volume III.

5.1.7.1 Option 3S-INT – Monitored Natural Attenuation

According to USEPA guidance (USEPA 1999), the most important considerations regarding the suitability of MNA as a remedy include:

- Whether the contaminants are likely to be effectively addressed by natural attenuation processes;
- Stability of the groundwater contaminant plume and its potential for migration; and
- Potential for unacceptable risks to human health or environmental resources by the contamination.

Groundwater sampling data and numerical modeling results suggest that the intermediate zone at SS7 is relatively stable and is shrinking in size and contaminant mass (Volume II). Based on these results, MNA is identified as a viable alternative. This alternative would also be subject to institutional controls, as described in Section 5.1.2, to limit access and future development of groundwater.

5.1.7.2 Process Description

Refer to Section 4.1.3.1 for the process description of natural attenuation.

Based on results of MNA groundwater modeling presented in Volume II, the time for TCE concentrations throughout the entire plume to be naturally attenuated to 5 µg/L from present conditions is estimated to be approximately 290 years. Modeled results for Option 3S-INT (MNA) are shown on Figure 5-8.

5.1.7.3 Conceptual Design

An LTM program would be developed for the full extent of the MNA period until RAOs are achieved. The LTM program would be reviewed and modified accordingly as new data are obtained during the monitoring period. The following describes the LTM program goals, monitoring network, and analytical protocol that would be part of the MNA alternative.

The LTM program goals for the intermediate zone in Section 4.1.3 are identical to those for the shallow zone with the exception of surface water. Because the intermediate groundwater does not impact surface water, a surface water-related goal is not included.

5.1.7.4 Performance Monitoring

The groundwater monitoring, analytical protocol, sampling frequency, and duration of monitoring are discussed in the following paragraphs.

Groundwater Monitoring. The LTM monitoring well network would be similar to that for the shallow zone of SS7. Monitoring of the intermediate zone would occur until established groundwater standards are met in the zone. Four intermediate-depth monitoring wells are assumed. Surface water sampling would not be required for the intermediate zone because there are no surface water effects from intermediate zone contamination.

Analytical Protocol. All performance monitoring points would be sampled and analyzed for those analytes listed in Table 4-1. Refer to Section 4.1.3.4 for additional details concerning the analytical protocol.

Sampling Frequency and Duration of Monitoring. Results of MNA groundwater modeling (Volume II) suggest that TCE concentrations in groundwater will attenuate to 5 µg/L from present conditions in approximately 290 years with the addition of $KMnO_4$. Therefore, the proposed LTM program sampling duration is based on a 290-year monitoring period. For details, see Section 4.1.3.4.

5.1.7.5 Option 4S-INT – Localized Chemical Oxidation and Monitored Natural Attenuation

This option provides chemical oxidation using $KMnO_4$, followed by MNA, to treat the low-concentration groundwater found in the intermediate zone of SS7. The following sections provide a process description, rationale for selection, conceptual design, and process monitoring plan of this intermediate zone option. This alternative would also be subject to institutional controls, as described in Section 5.1.2, to limit access and future development of groundwater.

Process Description

For a process description of $KMnO_4$, see Section 4.1.6.2. For details of MNA, see Section 4.1.3.

Rationale for Alternative

For the rationale for using $KMnO_4$ and MNA for intermediate zone groundwater, see Section 4.1.6.2. The proposed treatment area of 0.65 acre for this zone was an optimization of the area in an attempt to treat the area of highest observed TCE concentrations in the intermediate zone and remove the most contaminant mass. Thus, the cleanup time for the intermediate layer of SS7 was 175 years (Table 5-4).

Conceptual Design

The concept of the designs for injected $KMnO_4$ and MNA for the intermediate zone are discussed in the following paragraphs.

Potassium Permanganate. SS7 encompasses a relatively large area; therefore, only the higher concentration portion of the plume would be treated with $KMnO_4$ to remove contaminant mass and accelerate MNA. The treatment area is approximately 0.65 acre and is displayed on Figure 5-8. The depth of the treatment area is estimated to be 40 to 50 feet bgs in the intermediate aquifer. For additional details, see Section 4.1.6.2.

In situ chemical treatment and MNA modeling results are shown in Figure 5-9. The modeling assumptions made to evaluate the effectiveness of this technology using the Zone D groundwater model are provided in Volume II.

Monitored Natural Attenuation. Refer to Section 4.1.3.2 for conceptual design of the MNA program. For the intermediate zone, only four wells are proposed for FS-estimating purposes.

Performance Monitoring

The groundwater monitoring, analytical protocol, sampling frequency, and duration of monitoring are discussed in the following paragraphs.

Groundwater Monitoring. The LTM monitoring well network would be similar to that for the shallow zone of SS7. Monitoring of the intermediate zone would occur until established groundwater standards are met in the zone. Four intermediate-depth monitoring wells are assumed. Surface water sampling would not be required for the intermediate zone because there are no surface water effects from intermediate zone contamination.

Analytical Protocol. All performance monitoring points would be sampled and analyzed for those analytes listed in Table 4-1. Refer to Section 4.1.3.4 for additional details concerning the analytical protocol.

Sampling Frequency and Duration of Monitoring. Results of MNA groundwater modeling (Volume II) suggest that TCE concentrations in groundwater will attenuate to 5 μg/L from present conditions in approximately 175 years with the addition of $KMnO_4$. Therefore, the proposed LTM program sampling duration is based on a 175-year monitoring period. For details, see Section 4.1.3.4.

5.1.8 Surface Water Treatment Options for Diamond Creek

Diamond Creek's 3B classification does not require that TCE be monitored; however, Diamond Creek intersects Crow Creek, which is a Class 2AB stream. Crow Creek's classification requires regulation of certain compounds, such as TCE. The current regulatory limit of TCE for Crow Creek is 2.7 µg/L. Historical data show that elevated concentrations of TCE in Diamond Creek can lead to the TCE standard in Crow Creek (Figure 1-2). Therefore, the following surface water treatment options are proposed for Diamond Creek prior to its confluence with Crow Creek.

To reduce the TCE concentrations in Diamond Creek, treatment options that will allow increased aeration within the creek were considered. The increased aeration would cause a higher rate of volatilization of the TCE, thus reducing the amount of TCE in the creek.

Due to protected vegetation and wildlife, the treatment technologies were narrowed to four options described in the following paragraphs. Ecological damage and destruction of critical habits range from minimal to no damage with these options.

Option 1S: Channel Drop Structures

Channel drop structures are weir-type panels that are placed in the streambed to allow a small area of pooling prior to an overflow. The overflow is obstructed with a concrete slope embedded with rocks to allow for the creation of turbulence. The turbulence created by the flow of the water over the rocks allows additional aeration to stream flow due to the increased surface area of the water.

This type of structure is relatively low in cost, would require very little maintenance, and would not require an outside power source. The disadvantage of this type of treatment option is that the effectiveness cannot fully be determined until after the structure is installed and analytical data can be obtained. The other disadvantage of this option is that there are limited areas with adequate gradient for the installation of such a structure.

Seasonal fluctuation of water flow is not an issue for the channel drop structures. The structures would be designed to increase surface area of the liquid flow by three, whether the flow is 10 cubic feet per minute (cfm) or less than 1 cfm. Freezing is not a factor since there would be no contribution of contaminated flow into Crow Creek if Diamond Creek was frozen.

One possible configuration for the drops would be to line the active channel with railroad ties, concrete walls, or some other material to create a flume for 25 to 50 feet upstream as needed. At the downstream end, a low wall of grouted rocks or stop logs would create a sill over which water would flow and create turbulence. The flume upstream of the sill would constrain the flow to the channel, thereby limiting flooding of channel margins and maximizing channel velocities. Three to four of these structures are estimated to cost between $35,000 and $60,000.

The required O&M for this option would be weekly inspection and removal of any impedances in the weir.

Option 2S: Instream Fountain

An instream fountain involves fixing a pump nears the stream that would remove water from an instream pool and recirculate it by means of a spray, or fountain, within the stream. The fountain would create turbulence and increase surface area of the water for additional aeration.

This option is moderate in expense; however, the mechanical aspect of this treatment requires moderate O&M activities. A power source for the pump would be in the form of solar energy, power taken off lines that may run parallel to the road crossing, or power ran from nearby buildings. A shed to protect batteries or transformers may be required near the location. The main disadvantage with this approach would be freezing during the months from approximately November to April. The estimated cost would vary with the power source used and would range from approximately $45,000 (with nearby electricity) to $80,000.

Option 3S: Indoor Water Cascade

A second mechanical means would entail pumping water to a structure in a small, heated building where it would vertically cascade over a series of baffles, bars, or other rough elements within a concrete housing. As with Option 2S, power would be required to run this system.

The advantage of this system would be the ability to design the effectiveness with regards to TCE removal. Disadvantages of this type of system include heating the structure to avoid freezing winter temperatures and higher O&M due to mechanical parts. Costs would range from $55,000 to $100,000 in capital, with monthly O&M fees ranging from $500 to $800.

Option 4S: Instream Bubbler

An instream bubbler includes a panel with small orifices placed in the stream. Air is pumped through the orifices and contacts the water flowing over top of the panel. The configuration required to control fouling and effectiveness involves a precast, concrete vault installed upstream of the road within the stream channel. The top of the vault would be near the current channel bottom elevation. A series of pipes would run from a compressor building to the bottom of the vault where air could be pumped through the orifices at a rate sufficient to volatilize the proper amount of TCE.

A small building to house the electric service and an air compressor would be required. Electric service tapped from nearby lines or brought in from nearby buildings would also be necessary. Freezing would not be expected to be a major problem with this option; however, frequent O&M would be required to prevent fouling. The estimated cost would be $65,000 to $90,000 if a power source was available.

A summary of the surface water treatment options is presented in Table 5-5a.

5.2 DETAILED ANALYSIS OF ALTERNATIVES

A general summary of the SS7 remedial alternatives is provided in Table 5-5. The individual analysis and assessment of each of these groundwater remedial alternatives with respect to the nine evaluation criteria are presented in this section. The first two (Overall Protection and Compliance with ARARs) are threshold criteria. Alternatives are evaluated for whether they provide protectiveness or comply with ARARs. Alternatives must be both protective and comply with ARARs to be considered for a remedy. The next five are balancing criteria, where the relative tradeoffs among the criteria are evaluated. These first seven criteria are further described in Table 4-3. The final two are modifying criteria, in which the state and the community express whether they support or oppose the alternatives, which are evaluated by the end of the public comment period.

Summaries of the detailed analyses are presented in Tables 5-6 and 5-7. Following the individual analysis is a comparative analysis among the groundwater alternatives. The comparative analysis assesses the relative performance of each groundwater alternative with respect to each criterion. The Institutional Controls Alternative would be incorporated into all of the alternatives.

5.2.1 Alternative 1S – No Action

The No Action Alternative assumes no further action would be taken for groundwater at Zone D. This alternative is required by the NCP and selected for detailed analysis so that it may be used as a baseline for comparative analysis of the risk and cost associated with other alternatives. Although there is no capital cost involved with this alternative, the future costs and liabilities associated with exposure risks are unknown. Although expected, the No Action Alternative does not take into account natural attenuation of the groundwater plume through time.

5.2.1.1 Overall Protection of Human Health and the Environment

Although the BRA identified no unacceptable threat to human health or the environment under current groundwater conditions, this alternative does not include a means to monitor or assess protection of human health or the environment. Therefore, the No Action Alternative would not be protective of human health and the environment.

5.2.1.2 Compliance with ARARs

The No Action Alternative would not comply with ARARs.

5.2.1.3 Long-Term Effectiveness

The potential risk of exposure to groundwater would continue to exist with this alternative, as untreated TCE contamination would remain in groundwater. Therefore, the No Action Alternative would not provide long-term effectiveness.

5.2.1.4 Reduction of Toxicity, Mobility, and Volume

Since no active treatment of groundwater would be undertaken, there would not be an active reduction of toxicity, mobility, or volume. However, over time, the groundwater plume would be expected to naturally attenuate.

5.2.1.5 Short-Term Effectiveness

Because no action for groundwater would be taken, there would be no additive short-term exposure to the community or workers.

5.2.1.6 Implementability

There would be no implementation concerns associated with the No Action Alternative for groundwater.

5.2.1.7 Cost

The No Action Alternative for groundwater would incur no cost. The cost associated with long-term liability would be unknown.

5.2.2 Alternative 2S – Institutional Controls

The Institutional Controls Alternative assumes that legal and/or physical controls would be implemented for groundwater at Zone D. This alternative has limited capital cost, but the future costs and liabilities associated with exposure risks can only be estimated. Although expected, the Institutional Controls Alternative does not take into account natural attenuation of the groundwater plume through time.

5.2.2.1 Overall Protection of Human Health and the Environment

The Institutional Controls Alternative would protect human health and the environment through implementation and enforcement of administrative controls described in Section 5.1.2. No unacceptable short-term or cross-media impacts would be expected.

5.2.2.2 Compliance with ARARs

The Institutional Controls Alternative would comply with potential action- and location-specific ARARs. It would not comply with the potential chemical-specific ARAR of the federal MCL for TCE of 5 µg/L, and this alternative would not comply with ARARs requiring monitoring of releases (i.e., 40 CFR Part 264).

5.2.2.3 Long-Term Effectiveness and Permanence

The untreated TCE contamination in groundwater would continue to exist at Zone D. This alternative would offer a level of protection through the regulation of groundwater use as discussed in Section 5.1.2. Controls would be implemented to limit or exclude use of the groundwater, thus reducing the potential for exposure. These controls would be contained in the General Plan and are a long-term and reliable management control, enforced by the USAF within the installation boundaries. The groundwater plume would be expected to naturally attenuate over time.

5.2.2.4 Reduction of Toxicity, Mobility and Volume

The contaminated groundwater would not be treated to reduce the toxicity, mobility, or volume. However, over time, the groundwater plume would be expected to naturally attenuate.

5.2.2.5 Short-Term Effectiveness

This alternative does not include a remediation component, so there would be no additive short-term exposure to the community or workers.

5.2.2.6 Implementability

This alternative would be easy to implement technically and administratively. Documentation in the General Plan and coordination with installation personnel, as discussed in Section 3.1.2, would be a reliable management control that would be easy to implement.

5.2.2.7 Cost

Costs for this alternative include a capital cost of $18,484, plus annual costs of $2,387 for updates. These costs are outputs of RACER™ and reflected in present value dollars in Volume III.

5.2.3 Alternative 3S – Existing Permeable Reactive Barrier and Monitored Natural Attenuation

Alternative 3S, Existing Permeable Reactive Barrier and MNA, assumes that the existing SS7 IRA PRB, long-term groundwater monitoring, and the Alternative 2 institutional controls would be implemented for groundwater in SS7. Future LTM costs, and potential liabilities associated with exposure risks, can only be estimated. In addition, the life of the existing PRB is only 30 to 35 years, or half the predicted 100-year MNA period for SS7, so the PRB is assumed to be replaced twice.

5.2.3.1 Overall Protection of Human Health and the Environment

The PRB/MNA alternative (Alternative 3S) would protect human health and the environment through treatment in the existing pilot PRB, implementation and enforcement of the LTM program described in Section 5.1.3, and administrative controls described in Section 5.1.2. No unacceptable short-term or cross-media impacts would be expected.

The human health BRA results indicate that TCE contamination in the groundwater at Zone D would not pose an unacceptable threat to human health under current conditions. An unacceptable risk may be posed if residences were built on the site and used the groundwater for drinking, washing, and other domestic uses; but this is considered unlikely because municipal supplies are available. Or, unacceptable risk may be encountered with the construction of new buildings over moderate to high concentrations of TCE in groundwater. However, this risk can be mitigated through design additions such as a sub slab depressurization system.

By comparing historical and current site data, TCE concentrations currently exceed MCLs at the furthest downgradient monitoring wells. The PRB/MNA alternative would be designed to destroy contaminant concentrations exceeding MCLs through *in situ* groundwater treatment.

5.2.3.2 Compliance with ARARs

The PRB/MNA alternative would comply with potential action- and location-specific ARARs. It would not comply with the potential chemical-specific ARAR of the federal MCL for TCE of 5 µg/L until near the end of the 100-year LTM period, but would reduce concentrations downgradient of the PRB near Diamond Creek to less than 50 µg/L by Year 20 (Figure 5-1).

This alternative complies with the USEPA preference for treatment and with ARARs requiring monitoring of releases (i.e., 40 CFR Part 264).

5.2.3.3 Long-Term Effectiveness

The untreated TCE contamination in groundwater would continue to exist at SS7 until the end of the 100-year LTM period. Modeling indicates that TCE concentrations within the high concentration area would decrease flow through by the PRB and monitoring of groundwater contaminant concentration and flow. This alternative would offer a level of protection through the *in situ* treatment and monitoring of groundwater contaminant concentration and flow, as discussed in Section 5.1.3, and by regulation of groundwater use as discussed in Section 5.1.2.

5.2.3.4 Reduction of Toxicity, Mobility, and Volume

Large volumes of contaminated groundwater would be treated by the existing PRB to reduce the toxicity and volume of the groundwater in the center of SS7. After 90 years of PRB treatment, the remaining plume would naturally attenuate in 10 years. The western portion of the groundwater plume not upgradient of the PRB would be expected to naturally attenuate in 80 years (Figure 5-1).

5.2.3.5 Short-Term Effectiveness

The estimated time to meet RAOs for Alternative 3S is 100 years. This alternative includes an existing remediation component so there would be no additive short-term exposure to the community. However, LTM workers would be monitored to prevent exposure. Therefore, minimal potential would exist for exposure to contaminants.

Soil spoils from drilling and construction will be placed in soil containers, covered or sealed, and transported to a Class C landfill. Because the soil will be contained, the community does not incur incremental risk associated with disposal, but could incur a slight incremental risk due to increased traffic.

5.2.3.6 Implementability

This alternative would be easy to implement technically because the PRB and the monitoring wells already exist and administratively due to the existence of the General Plan. An LTM Plan would be prepared for the 100-year LTM period as discussed in Section 5.1.3, and documentation would be provided in the General Plan as discussed in Section 5.1.2.

5.2.3.7 Cost

Costs of this alternative would include an LTM Plan, changes to the General Plan, community and educational programs, reporting, and management and administrative efforts. The initial capital costs for the existing PRB have already been spent and not included in this estimate; however, two replacements of the PRB are estimated to cost $6.1 million. Additional capital costs associated with this alternative are estimated to be low due to the availability of numerous existing monitoring wells. Total O&M costs that include LTM data collection, analysis, evaluation, and reporting costs are estimated to be about $4.6 million over the 100-year life of

the alternative. Present value cost is approximately $1.9 million. The detailed cost estimate is provided in Volume III.

5.2.4 Alternative 4S – Existing and Expansion of Permeable Reactive Barrier, Western Permeable Reactive Barrier and Monitored Natural Attenuation

Alternative 4S assumes that extending the existing PRB and constructing a second PRB would reduce TCE concentrations to Diamond Creek and, eventually, treat the entire SS7 plume. Downgradient treatment by flow through two PRBs, long-term groundwater monitoring, and legal and/or physical institutional controls (Alternative 2S) would be used to complete the remediation of groundwater in SS7. The future O&M costs, LTM costs, and potential liabilities associated with exposure risks can only be estimated. Based on groundwater modeling, this alternative would require 100 years of PRB treatment and natural attenuation of the groundwater plume to complete remediation in a 100-year time period.

5.2.4.1 Overall Protection of Human Health and the Environment

Alternative 4S would protect human health and the environment by *in situ* treatment of the contaminated groundwater with two PRBs, enforcement of the LTM program, and the administrative controls described in Section 5.1.2. No unacceptable short-term or cross-media impacts would be expected.

The human health BRA results indicate that TCE contamination in the groundwater at Zone D would not pose an unacceptable threat to human health under current conditions. An unacceptable risk may be posed if residences were built on the site and used the groundwater for drinking, washing, and other domestic uses; but this is considered unlikely because municipal supplies are available. Or, unacceptable risk may be encountered with the construction of new buildings over moderate to high concentrations of TCE in groundwater. However, this risk can be mitigated through design additions such as a sub slab depressurization system.

By comparing historical and current site data, TCE concentrations currently exceed MCLs at the furthest downgradient monitoring wells. The PRB/MNA alternative would be designed to destroy contaminant concentrations exceeding RAOs through *in situ* groundwater treatment.

5.2.4.2 Compliance with ARARs

Alternative 4S would comply with potential action- and location-specific ARARs and with the potential chemical-specific ARAR of the federal MCL for TCE of 5 µg/L at the end of the 100-year LTM period. This alternative would comply with the USEPA preference for treatment and ARARs requiring monitoring of releases (i.e., 40 CFR Part 264).

5.2.4.3 Long-Term Effectiveness and Permanence

The PRB/MNA alternative relies on the effectiveness of *in situ* groundwater treatment to reduce contaminant concentrations and minimize contaminant migration over time. Modeling indicates that TCE concentrations within the high concentration area would not decrease, except by natural attenuation, to 5 µg/L within the untreated, central area of the SS7 plume until the end of the

100-year MNA period. However, the alternative would treat downgradient concentrations near Diamond Creek to below 50 µg/L by Year 20 (Figure 5-3).

This alternative would offer a level of protection through the *in situ* treatment and monitoring of groundwater contaminant concentration and flow, as discussed in Section 5.1.4, and by regulation of groundwater use, as discussed in Section 5.1.2.

5.2.4.4 Reduction of Toxicity, Mobility and Volume

Alternative 4S would reduce contaminant concentrations and minimize contaminant migration over time through *in situ* treatment. The contaminated groundwater would be treated by flow through a PRB for 70 to 80 years to reduce the toxicity and volume of the groundwater contamination at the creek intercept (Figure 5-3). After PRB treatment, the groundwater plume would be expected to naturally attenuate to ARARs in an additional 20 years.

5.2.4.5 Short-Term Effectiveness

The estimated time to meet RAOs for Alternative 4S is 100 years, although it is likely that RAOs in some downgradient areas treated by PRB would be met within 20 years.

This alternative includes a remediation component, but there would be no additive short-term exposure to the community. However, PRB construction workers and LTM workers would use protective measures such as on-site monitoring and appropriate PPE while conducting intrusive and construction activities within the plume area. Therefore, minimal potential would exist for exposure to contaminants.

Soil spoils from drilling and construction will be placed in soil containers, covered or sealed, and transported to a Class C landfill. Because the soil will be contained, the community does not incur incremental risk associated with disposal, but could incur a slight incremental risk due to increased traffic.

5.2.4.6 Implementability

Technology approval of Alternative 4S by federal, state, and local agencies would be anticipated due to the successful use of PRBs in pilot tests and IRAs in Zone D. Construction of a PRB and installation of monitoring wells at the site are technically feasible and could be implemented with some difficulty (Figure 5-2). The equipment and personnel for performing these tasks are available in the Rocky Mountain Region. Periodic site reviews would be conducted to verify the effectiveness of the alternative.

A PRB design would be prepared as discussed in Section 5.1.4, an LTM Plan would be prepared for the 100-year LTM period, and documentation would be provided in the General Plan as discussed in Section 5.1.2.

5.2.4.7 Cost

Costs of this alternative would include capital costs for PRB design and implementation, preparation of the LTM Plan, changes to the General Plan, community and educational programs, reporting, and management and administrative efforts. Capital costs associated with

this alternative are estimated to be $15.3 million. Total O&M costs that include LTM data collection, analysis, evaluation, and reporting costs are estimated to be about $4.6 million over the 100-year life of the alternative. Present value cost is approximately $4.6 million. The detailed cost estimate is provided in Volume III.

5.2.5 Alternative 5S – Existing Permeable Reactive Barrier, Localized Bioaugmentation, and Monitored Natural Attenuation

Alternative 5S assumes that a combination of bioaugmentation, long-term groundwater monitoring, and institutional controls (Alternative 2S) would be implemented for groundwater in SS7. The future O&M costs, LTM costs, and potential liabilities associated with exposure risks can only be estimated. Based on groundwater modeling, this alternative would requires six months to establish reducing conditions and add microbes, followed by 20 years of bioactivity to reduce concentrations to MCLs in the treated zone, then an additional 15 years of MNA to complete the groundwater plume remediation.

5.2.5.1 Overall Protection of Human Health and the Environment

The PRB, bioaugmentation, and MNA alternative (Alternative 5S) would protect human health and the environment through treatment of the creek intercept with the existing PRB, bioaugmentation of the central plume as described in Section 5.1.5, enforcement of the LTM program, and institutional controls described in Section 5.1.2. No unacceptable short-term or cross-media impacts would be expected.

5.2.5.2 Compliance with ARARs

The PRB, bioaugmentation, and MNA alternative would comply with potential action- and location-specific ARARs and with the potential chemical-specific ARAR of the federal MCL for TCE of 5 µg/L at the end of the 35-year LTM period. This alternative would comply with the USEPA preference for treatment and ARARs requiring monitoring of releases (i.e., 40 CFR Part 264).

5.2.5.3 Long-Term Effectiveness

Some untreated TCE contamination in groundwater would continue to exist at SS7 until the end of the 35-year LTM period (Figure 5-5). However, the PRB, bioaugmentation, and MNA alternative would reduce the highest concentrations from greater than 20,000 µg/L TCE to less than 200 µg/L in 10 years and to below RAOs in the treated zone by Year 20, leaving small areas of concentrations below 50 µg/L for an additional 15 years of the MNA period. This alternative would offer a level of protection through the treatment and monitoring of groundwater contaminant concentration and flow, as discussed in Section 5.1.5, and by regulation of groundwater use, as discussed in Section 5.1.2.

5.2.5.4 Reduction of Toxicity, Mobility, and Volume

The PRB, bioaugmentation, and MNA alternative would treat the contaminated groundwater for 20 years to reduce the toxicity and volume of the groundwater contamination. After treatment,

the groundwater plume would be expected to naturally attenuate to ARARs in 15 additional years.

5.2.5.5 Short-Term Effectiveness

The PRB, bioaugmentation, and MNA alternative would include a remediation component, but there would be no additive short-term exposure to the community. However, bioaugmentation treatment and LTM workers would be monitored to prevent exposure.

Soil spoils from drilling and construction will be placed in soil containers, covered or sealed, and transported to a Class C landfill. Because the soil will be contained, the community does not incur incremental risk associated with disposal, but could incur a slight incremental risk due to increased traffic.

5.2.5.6 Implementability

The PRB, bioaugmentation, and MNA alternative would be the least difficult active treatment alternative to implement technically, but may have administrative implementability problems because bioaugmentation has not been pilot tested at FEW. A bioaugmentation treatment system design would be prepared as discussed in Section 5.1.3, an LTM Plan would be prepared for the 35-year LTM period, and documentation would be provided in the General Plan as discussed in Section 5.1.2.

5.2.5.7 Cost

Costs of this alternative would include capital costs for bioaugmentation design and implementation, preparation of the LTM Plan, changes to the General Plan, community and educational programs, reporting, and management and administrative efforts. Capital costs associated with this alternative are estimated to be $2.5 million and do not include replacement costs for a PRB since no replacement is planned. Total O&M costs that include LTM data collection, analysis, evaluation, and reporting costs are estimated to be about $2.3 million over the 35-year life of the alternative. Present value cost is $3.5 million. The detailed cost estimate is provided in Volume III.

5.2.6 Alternative 6S – Electrical Resistance Heating with Soil Vapor Extraction, Chemical Oxidation, and Monitored Natural Attenuation (Disregard Existing Permeable Reactive Barrier)

Alternative 6S assumes that ERH in the highest concentration zones of the plume and chemical oxidation using Fenton's Reagent and $KMnO_4$ in the areas outside the ERH would reduce TCE concentrations to MCLs within the treated zone. This alternative disregards the existing SS7 PRB IRA. Long-term groundwater monitoring and institutional controls would be used to complete the remediation of groundwater in SS7. The future O&M costs, LTM costs, and potential liabilities associated with exposure risks can only be estimated. Based on groundwater modeling, this alternative would requires six months of ERH and chemical oxidation to reduce central plume concentrations below 10 µg/L, followed by 85 years of natural attenuation of the groundwater plume to complete remediation in a 85-year time period.

5.2.6.1 Overall Protection of Human Health and the Environment

Alternative 6S would protect human health and the environment by *in situ* treatment of the contaminated groundwater with ERH, chemical oxidizers, enforcement of the LTM program, and the administrative controls described in Section 5.1.2.

The human health BRA results indicate that TCE contamination in the groundwater at Zone D would not pose an unacceptable threat to human health under current conditions. An unacceptable risk may be posed if residences were built on the site and used the groundwater for drinking, washing, and other domestic uses; but this is considered unlikely because municipal supplies are available. Or, unacceptable risk may be encountered with the construction of new buildings over moderate to high concentrations of TCE in groundwater. However, this risk can be mitigated through design additions such as a sub slab depressurization system.

By comparing historical and current site data, TCE concentrations currently exceed MCLs at the furthest downgradient monitoring wells. The ERH/chemical oxidation/MNA alternative would be designed to destroy contaminant concentrations exceeding MCLs through *in situ* groundwater treatment. No unacceptable short-term or cross-media impacts would be expected.

5.2.6.2 Compliance with ARARs

Alternative 6S would comply with potential action- and location-specific ARARs and with the potential chemical-specific ARAR of the federal MCL for TCE of 5 µg/L at the end of the 85-year LTM period (Figure 5-7). This alternative would comply with the USEPA preference for treatment and ARARs requiring monitoring of releases (i.e., 40 CFR Part 264).

5.2.6.3 Long-Term Effectiveness

The ERH/chemical oxidation/MNA alternative relies on the effectiveness of *in situ* groundwater treatment to reduce contaminant concentrations and minimize contaminant migration over time. Modeling indicates that TCE concentrations within the high concentration area would decrease within six months to less than 10 µg/L in the treated areas by using five large-diameter ERH hexagonal grids, 207 Fenton's Reagent injection points, and 309 $KMnO_4$ injection points, but would leave areas of concentrations below 800 µg/L outside the treated zone (Figure 5-6).

Continued contaminant reduction within the plume by natural attenuation would reduce the highest TCE concentrations to below 200 µg/L during the first 10 years of the MNA period, to less than 100 µg/L during an additional 10 years, and to 5 µg/L by Year 85.

This alternative would offer a level of protection through the *in situ* treatment and monitoring of groundwater contaminant concentration and flow, as discussed in Section 5.1.6, and by regulation of groundwater use, as discussed in Section 5.1.2.

5.2.6.4 Reduction of Toxicity, Mobility and Volume

Alternative 6S would reduce contaminant concentrations and minimize contaminant migration over time through *in situ* treatment. The contaminated groundwater would be treated for six months with ERH and chemical oxidation to reduce the toxicity and volume of the groundwater

contamination to a threshold level above the MCL. After treatment, the groundwater plume would be expected to naturally attenuate to ARARs in 85 years.

5.2.6.5 Short-Term Effectiveness

The estimated time to meet RAOs for Alternative 6S is 85 years, although it is likely that RAOs in many areas treated by chemical oxidation would be met within six months (Figure 5-7).

This alternative would include a remediation component, but there would be no additive short-term exposure to the community. However, ERH and chemical oxidation injection workers and LTM workers would use protective measures such as on-site monitoring and appropriate PPE while conducting intrusive activities within the plume area. Therefore, minimal potential would exist for exposure to contaminants.

Soil spoils from drilling will be placed in soil containers, covered or sealed, and transported to a Class C landfill. Because the soil will be contained, the community does not incur incremental risk associated with disposal, but could incur a slight incremental risk due to increased traffic.

5.2.6.6 Implementability

Technology approval of Alternative 6S by federal, state, and local agencies would be anticipated due to the successful use of chemical oxidation in pilot test at Plume C. However, the success of ERH has not been demonstrated at FEW, although it has been used successfully at other DoD sites. Injection of chemical oxidizers, construction of an ERH/SVE system, and installation of monitoring wells at the site are technically feasible and could be implemented with some difficulty. The equipment and personnel for performing the injection and SVE construction tasks are available in the Rocky Mountain Region. However, ERH, including SPH, requires a national specialty subcontractor, who is not available locally. Periodic site reviews would be conducted to verify the effectiveness of the alternative.

An injection system and PRB design (Figure 5-6) would be prepared as discussed in Section 5.1.6, an LTM Plan would be prepared for the 85-year LTM period, and documentation would be provided in the General Plan as discussed in Section 5.1.2.

5.2.6.7 Cost

Costs of this alternative would include capital costs for chemical oxidation and ERH/SVE design and implementation, preparation of the LTM Plan, changes to the General Plan, community and educational programs, reporting, and management and administrative efforts. Capital costs associated with this alternative are estimated to be $7.9 million. Total O&M costs that include LTM data collection, analysis, evaluation, and reporting costs are estimated to be about $4.1 million over the 85-year life of the alternative. Present value cost is $8.8 million. The detailed cost estimate is provided in Volume III.

5.2.7 Intermediate Zone Options

This section presents the individual analysis and assessment of each intermediate zone option with respect to the seven evaluation criteria, as described above. For a summary of this analysis, see Table 5.6.

For detailed analysis of Option 1S-INT, No Action, and Option 2S-INT, Institutional Controls, see Sections 5.2.1 and 5.2.2.

5.2.7.1 Option 3S-INT – Monitored Natural Attenuation

Option 3S-INT assumes that LTM of natural attenuation processes that reduce TCE concentrations over time would be implemented for groundwater in the intermediate zone at SS7. Institutional controls are included in the alternative to prevent the use of groundwater for human consumption prior to the end of the MNA period.

Overall Protection of Human Health and the Environment

With institutional controls, MNA in the intermediate zone would protect human health and the environment under current conditions through natural attenuation processes. No unacceptable short-term or cross-media impacts would be expected.

Compliance with ARARs

With institutional controls, the use of MNA in the intermediate zone would comply with all potential action- and location-specific ARARs, but would not comply with the potential chemical-specific ARAR of the federal MCL for TCE of 5 µg/L until near the end of the 290-year monitoring period. MNA would comply with ARARs requiring monitoring of releases.

Long-Term Effectiveness

Natural processes will reduce contaminant levels in groundwater to RAOs over time. Continued monitoring provides a reliable means to assess the residual concentrations and manage the risk posed by the residual. Institutional controls would limit or prevent use of the intermediate zone groundwater. No untreated residual contamination would be produced by this process and minimal O&M of wells and groundwater sampling would be required.

Reduction of Toxicity, Mobility, and Volume

Toxicity, mobility, and volume of TCE would be reduced over time from natural attenuation of contaminants in groundwater. TCE levels would be reduced to RAOs in intermediate zone groundwater in approximately 290 years. No residuals would be present in groundwater at completion, and attenuation is irreversible.

Short-Term Effectiveness

No additional risk to site workers and the environment would occur because there would be no construction of a treatment system. There would also be no increased risk to workers, the community, or the environment during implementation. Time to achieve RAOs within the intermediate zone at SS7 is estimated to be approximately 290 years.

Soil spoils from drilling will be placed in soil containers, covered or sealed, and transported to a Class C landfill. Because the soil will be contained, the community does not incur incremental risk associated with disposal, but could incur a slight incremental risk due to increased traffic.

Implementability

This option would be easy to implement and should not create schedule delays. Passive methods such as MNA do not require removal, aboveground treatment, or TSD services. Monitoring the effectiveness would be simple, and FEW administrative requirements to accommodate this option would include modifying the General Plan.

Cost

Costs of this option would include an LTM Plan, changes to the General Plan, community and educational programs, reporting, and management and administrative efforts. There are no capital costs associated with this alternative due to the availability of numerous existing monitoring wells. Total O&M costs that include LTM data collection, analysis, evaluation, and reporting costs are estimated to be about $11.5 million over the 290-year life of the alternative. Present value cost is $0.7 million. The detailed cost estimate is provided in Volume III.

5.2.7.2 Option 4S-INT – Localized Chemical Oxidation and MNA

Option 4S-INT assumes that a combination of chemical oxidation, long-term groundwater monitoring, and institutional controls would be implemented for intermediate zone groundwater in SS7. The future O&M costs, LTM costs, and potential liabilities associated with exposure risks can only be estimated.

Overall Protection of Human Health and the Environment

Comparing historical and current site data, TCE concentrations currently exceed RAOs in some intermediate-zone monitoring wells. This chemical oxidation/MNA option would protect human health and the environment by *in situ* treatment of the contaminated groundwater with chemical oxidizers, application of an LTM program, and enforcement of institutional controls. The option would be designed to destroy contaminant concentrations exceeding RAOs through a combination of *in situ* groundwater treatment and MNA. No unacceptable short-term or cross-media impacts would be expected.

Compliance with ARARs

This option would comply with potential action- and location-specific ARARs and with the potential chemical-specific ARAR of the federal MCL for TCE of 5 µg/L at the end of the LTM period. It would also comply with the USEPA preference for treatment of contaminated groundwater (i.e., 40 CFR Part 264). No discharge permits would be required for this option.

Long-Term Effectiveness and Permanence

Active treatment would reduce the TCE concentrations in the intermediate zone groundwater to 50 µg/L in approximately six months. Natural processes would reduce the TCE concentration in groundwater to the RAO approximately 175 years after completion of active treatment. Continued monitoring would provide a reliable means to assess the treatment effectiveness, and institutional controls would limit or prevent use of groundwater. Greater O&M than the MNA option would occur only during the six-month treatment method period.

Reduction of Toxicity, Mobility and Volume

Toxicity, mobility, and volume of TCE are reduced over time from active treatment of groundwater and natural processes. TCE concentrations in groundwater would be reduced to RAOs in intermediate zone groundwater in approximately 175 years, and the process would be irreversible.

Short-Term Effectiveness

There would be minimal additional risk to site workers and the environment during the construction phase involving drilling and injection of chemicals. Soil spoils from drilling will be placed in soil containers, covered or sealed, and transported to a Class C landfill. Because the soil will be contained, the community does not incur incremental risk associated with disposal, but could incur a slight incremental risk due to increased traffic. There would be no increased risk to workers, the community, or the environment during the implementation phase, which would involve only groundwater sampling. The time to achieve RAOs is estimated to be approximately 175 years.

Implementability

This option would be easy to implement and chemical oxidation is a proven and reliable technology. The chemical oxidation compound (KMnO4) is readily available, as are the conventional well drilling and installation techniques that would be used. Schedule delays should not be expected due to lack of availability since multiple drilling contractors and KMnO4 suppliers are available. Competitive bids can be obtained and monitoring the effectiveness would be simple. Administrative requirements would include preparing a treatment system design, LTM Plan, and modifying the General Plan.

Cost

Costs of this alternative would include capital costs for chemical oxidation design and implementation, preparation of the LTM Plan, changes to the General Plan, community and educational programs, reporting, and management and administrative efforts. Capital costs associated with this alternative are estimated to be $0.6 million. Total O&M costs that include LTM data collection, analysis, evaluation, and reporting costs are estimated to be about $5.3 million over the 175-year life of the alternative. Present value cost is $1.2 million. These costs may be reduced slightly if this option is utilized in combination with Alternative 6S due to reduced chem-ox, mobilization costs. The detailed cost estimate is provided in Volume III.

5.3 COMPARATIVE ANALYSIS

The first seven sections compare these alternatives for the shallow SS7 groundwater:

- Alternative 1S – No Action
- Alternative 2S – Institutional Controls
- Alternative 3S – Existing PRB and MNA
- Alternative 4S – Expansion of Existing PRB, Western PRB, and MNA

- Alternative 5S – Existing PRB, Bioaugmentation, and MNA
- Alternative 6S – ERH, Chemical Oxidation, and MNA (disregard existing PRB)

One section also compares the following options for intermediate zone groundwater at SS7:

- Option 1S-INT – No Action
- Option 2S-INT – Institutional Controls
- Option 3S-INT – MNA
- Option 4S-INT – Localized Chemical Oxidation and MNA

Tables 5-8 and 5-9 present a comparison among the criteria for each alternative/option comparison for the shallow zone and intermediate zone groundwater of SS7, respectively. The tables are for the shallow groundwater zone or the intermediate groundwater zone of each plume, but do not combine the two. Because the comparisons are relative to the other alternatives for this plume, they should not be used for comparison to other plumes or even to the shallow versus intermediate groundwater in SS7.

5.3.1 Overall Protection of Human Health and the Environment

No Action (Alternative 1S) would be protective of human health and the environment under current conditions because no current unacceptable risk has been identified. However, because this alternative would provide no means to monitor future contamination, it is not protective over the long-term. Institutional controls (Alternative 2S) would provide implementation and enforcement of administrative controls to prevent future use of the groundwater resource, but cannot monitor future conditions.

Because MNA alone was not considered for SS7 due to continuing high TCE concentrations at the plume head/source zone, but also because no unacceptable risk has been identified and concentrations of TCE will be reduced over long periods of time. The existing PRB and MNA (Alternative 3S) would provide protection of human health and the environment through treatment by an existing PRB and implementation and enforcement of both the LTM program and institutional controls.

Expansion of the existing PRB, construction of a new western PRB, and MNA (Alternative 4S) would provide protection of human health and the environment through a combination of two PRBs to protect the creek, enforcement of the LTM program, and institutional controls. Bioaugmentation and MNA (Alternative 5S) would provide significant protection of human health and the environment due to implementation of treatment method through bioaugmentation of the central plume, enforcement of the LTM program, and institutional controls. This alternative would achieve RAOs in the surface groundwater zone of the entire plume in the shortest time period. The ERH/chemical oxidation/MNA alternative (Alternative 6S) would disregard the existing PRB, but would not significantly improve the time for remediation of the shallow zone over Alternatives 3S and 4S. However, it would provide protection of human health and the environment through implementation of ERH in the highest concentration portions of SS7, treatment of the remaining high concentration area with chemical oxidation, enforcement of the LTM program, and institutional controls.

Therefore, Alternatives 3S, 4S, 5S, and 6S would be protective of human health and the environment in both the short- and long-term (Table 5-8). However, Alternatives 1S and 2S cannot provide long-term protectiveness with any certainty and do not meet this threshold criterion.

5.3.2 Compliance with ARARs

The No Action Alternative would not comply with ARARs. The Institutional Controls Alternative would comply with potential action- and location-specific ARARs, but not with the potential chemical-specific groundwater ARAR of the federal MCL for TCE of 5 µg/L or with ARARs requiring monitoring of releases. Because these first two alternatives do not meet this threshold criterion, they are not carried through the remainder of the comparative analysis.

Alternatives 3S, 4S, 5S, and 6S would comply with potential action- and location-specific ARARs and with ARARs requiring monitoring of releases (i.e., 40 CFR Part 264). Alternatives 3S and 4S would comply with the potential chemical-specific groundwater ARAR set at the federal MCL for TCE of 5 µg/L near the end of a 100-year LTM period; Alternative 5S after a 35-year *in situ* bioaugmentation and LTM period; and Alternative 6S after treatment with ERH and *in situ* chemical oxidation, then 85 years of MNA. Therefore, based on total time to comply with ARARs, Alternative 5S would comply in the shortest period and Alternatives 3S, 4S, and 6S in longer, but similar, periods (Table 5-8).

5.3.3 Long-Term Effectiveness and Permanence

In Alternative 3S, the untreated TCE contamination in groundwater would continue to exist at SS7 until near the end of the 100-year LTM period (Figure 5-1, Table 5-8). In Alternative 4S, the PRB expansion would reduce the highest plume TCE concentrations from 20,000 µg/L TCE to 5 µg/L during the 100 years of the MNA period (Figure 5-3).

In Alternative 5S, *in situ* bioaugmentation would be combined with MNA to reduce the highest plume TCE concentrations from 100 µg/L TCE to 5 µg/L in 10 years in the treated areas, with continuing treatment method by the existing PRB and MNA for an additional 25 years (Figure 5-5) and would provide the highest degree of long-term effectiveness and permanence because the contaminants are permanently removed from the aquifer through biological treatment method technologies that can remove even sorbed TCE from the aquifer. In Alternative 6S, *in situ* ERH/chemical oxidation would be combined with MNA to reduce the highest concentrations from greater than 20,000 µg/L TCE to less than 10 µg/L in six months in the treated areas, leaving small areas of concentrations below 50 µg/L for the 85 years of the MNA period (Figure 5-7).

5.3.4 Reduction of Toxicity, Mobility, and Volume Through Treatment

Alternative 3S would treat the contaminated groundwater for 90 years to reduce the toxicity and mobility of the groundwater contamination. After treatment, the groundwater plume would be expected to naturally attenuate to ARARs in 10 additional years of the 100-year MNA period. This differs little from the treatment method in the PRB expansion/MNA alternative, except that Alternative 4S would protect the creek after 20 years. Alternative 5S would treat the contaminated groundwater for 10 years to significantly reduce the toxicity of the groundwater

contamination, then for 25 additional years of treatment by the PRB. The untreated portion of the groundwater plume would be expected to naturally attenuate to ARARs in the 35 years of the MNA period. The active treatment period for "hot spots" using Alternative 6S would last only six months, but after treatment, the remainder of the groundwater plume would not be expected to naturally attenuate to ARARs for 85 years (Table 5-8).

5.3.5 Short-Term Effectiveness

Alternatives 3S and 4S would have no additive short-term exposure to the community, but both PRB construction workers and LTM workers must be monitored to prevent short-term exposure. Alternative 5S would have no additive short-term exposure to the community, but bioaugmentation injection workers and LTM workers must be monitored to prevent short-term exposure. Alternative 6S would have no additive short-term exposure to the community, but construction workers for the ERH system and PRB, chemical oxidation injection workers, treatment system O&M workers, and LTM workers must be monitored to prevent short-term exposure.

Therefore, Alternative 5S would provide the least exposure followed by Alternatives 3S and 4S, then finally Alternative 6S.

Alternative 3S achieves RAOs in 100 years, Alternative 4S in 100 years, Alternative 5S in 35 years, and Alternative 6S in 85 years. Therefore, Alternative 5S has the shortest remediation time, followed by Alternative 6S, then Alternatives 3S and 4S.

"Averaging" the three sub-criteria (community protection, worker protection, and time to achieve RAOs) shows that Alternative 5S has greater short-term effectiveness than the other three alternatives (Table 5-8).

5.3.6 Implementability

Alternative 3S would be the second least difficult alternative to implement technically and administratively. Alternative 4S would be the second most difficult active treatment alternative to implement technically, but the least difficult administratively due to the success of current SS7 PRB at FEW. Alternative 5S would be the least difficult to implement technically because only a single, simple technology—bioaugmentation—would be employed. However, few regulatory agencies have had experience with bioaugmentation and a treatability study at FEW is pending. Alternative 6S would be the most difficult alternative to implement technically and administratively, as few contractors have had experience with ERH or Fenton's Reagent, so national contractors must be utilized. In addition, few regulatory agencies have had experience with ERH, so administrative implementability could be difficult.

Therefore, Alternative 5S would be the simplest to implement technically followed by Alternative 3S, then Alternatives 4S and 6S. Administratively, Alternative 4S may be easiest to implement, followed by Alternative 5S, then Alternatives 3S and 6S (Table 5-8).

5.3.7 Cost

For cost comparisons, refer to Table 5-6; for qualitative comparisons, refer to Table 5-8. Alternative 3S has the lowest present value cost of the shallow zone groundwater treatment

alternatives, Alternative 4S has the second lowest, Alternative 5S has the second highest, and Alternative 6S has the highest.

5.3.8 Intermediate Zone Options

The following subsections compare options for intermediate zone groundwater at SS7:

- Option 1S-INT – No Action
- Option 2S-INT – Institutional Controls
- Option 3S-INT – MNA
- Option 4S-INT – Localized Chemical Oxidation and MNA

5.3.8.1 Overall Protection of Human Health and the Environment

No Action (Option 1S-INT) would be protective of human health and the environment under current conditions because no current unacceptable risk has been identified (Table 5-9). However, because this alternative would provide no means to monitor future contamination, it is not protective over the long-term. Institutional Controls (Option 2S-INT) would provide implementation and enforcement of administrative controls to prevent future use of the groundwater resource, but cannot monitor future conditions.

Because Diamond Creek is a Class 3B stream and concentrations of TCE in the intermediate zone will attenuate naturally over long periods of time, MNA (Option 3S-INT) would provide protection of human health and the environment through implementation and enforcement of both the LTM program and institutional controls. However, the time to achieve RAOs would be longer than Option 4S-INT. $KMnO_4$ and MNA (Option 4S-INT) would achieve RAOs (i.e., protection of human health and the environment) in the shortest time period through injection of $KMnO_4$ solution into the intermediate zone, enforcement of the LTM program, and institutional controls.

Therefore, Options 3S-INT and 4S-INT would be protective of human health and the environment in both the short- and long-term (Table 5-9). However, Options 1S-INT and 2S-INT cannot provide long-term protectiveness with any certainty and do not meet this threshold criterion.

5.3.8.2 Compliance with ARARs

The No Action option (Option 1S-INT) would not comply with ARARs. The Institutional Controls option (Option 2S-INT) would comply with potential action- and location-specific ARARs, but not with the potential chemical-specific groundwater ARAR of the federal MCL for TCE of 5 µg/L or with ARARs requiring monitoring of releases. Because these first two options do not meet this threshold criterion, they are not carried through the remainder of the comparative analysis (Table 5-9).

Options 3S-INT and 4S-INT would comply with potential action- and location-specific ARARs and with ARARs requiring monitoring of releases (i.e., 40 CFR Part 264). Option 3S-INT would comply with the potential chemical-specific groundwater ARAR set at the federal MCL for TCE

of 5 µg/L near the end of a 290-year LTM period, and Option 4S-INT after a combined 175-year *in situ* treatment and LTM period (Table 5-9).

5.3.8.3 Long-Term Effectiveness and Permanence

Option 4S-INT would reduce the highest concentrations from greater than 2,000 µg/L TCE to 10 µg/L in six months, leaving one very small area of concentrations below 300 µg/L and a larger, untreated area below 50 µg/L for MNA for an additional 175 years (Figure 5-10). This option would provide a higher degree of long-term effectiveness and permanence than Option 3S-INT because Option 3S-INT would leave high TCE concentrations in groundwater at SS7 for much of the 290-year LTM period (Figure 5-8; Table 5-9).

5.3.8.4 Reduction of Toxicity, Mobility, and Volume Through Treatment

Option 3S-INT, MNA, would not provide any active treatment method for the contaminated groundwater, but over time (290 years), the plume would be expected to attenuate through natural processes that reduce the toxicity of the groundwater. Option 4S-INT, chemical oxidation, would combine chemical oxidation to actively treat the highest concentrations in groundwater for six months, followed by natural attenuation to ARARs in 175 years. Thus, the use of treatment in Option 4S-INT would reduce the total time of toxicity of the plume by nearly half of the 290-year MNA-only period (Figures 5-8 and 5-10; Table 5-9).

5.3.8.5 Short-Term Effectiveness

Option 3S-INT would not include an active remediation component so there would be no additive short-term exposure to the community, but LTM workers would be monitored to prevent exposure. Option 4S-INT would have no additive short-term exposure to the community, but chemical oxidation treatment and LTM workers would be monitored to prevent exposure. However, Option 3S-INT requires 290 years and Option 4S-INT 175 years to achieve RAOs. Therefore, Option 4S-INT would provide better short-term effectiveness than Option 3S-INT (Table 5-9).

5.3.8.6 Implementability

Option 3S-INT would be easy to implement technically due to its need only for additional monitoring wells, but perhaps more difficult administratively. Option 4S-INT would be more difficult to implement technically than Option 3S-INT, but perhaps less difficult administratively due to its rapid reduction of the highest contaminant concentrations. Therefore, Option 3S-INT would be the simpler to implement technically and Option 4S-INT may be more easily implemented administratively (Table 5-9).

5.3.8.7 Cost

For cost comparisons, refer to Table 5-7; for qualitative comparisons, refer to Table 5-9. Option 3S-INT has the lower present value cost and Option 4S-INT has the higher of the two intermediate zone groundwater options.

This section consists of the development, detailed analysis, and comparison of the alternatives selected for Plume B. The "B" designation for each of these alternatives refers to Plume B.

6.1 DEVELOPMENT OF ALTERNATIVES

The following alternatives have been developed for Plume B. The "B" designation for each of these alternatives refers to Plume B.

- Alternative 1B – No Action
- Alternative 2B – Institutional Controls
- Alternative 3B – MNA
- Alternative 4B – Groundwater Extraction, *Ex situ* Treatment, and MNA
- Alternative 5B – Localized Chemical Oxidation and MNA

All of the alternatives presented would result in concentrations on site above health-based levels, therefore, a site review would be required no less frequent than every five years. Additionally, all of the alternatives would be subject to institutional controls, including stipulations to evaluate potential risk if future buildings are to be constructed overlying higher concentration areas of the groundwater plumes. Finally, none of the alternatives would result in off-site discharge. As such, substantive permit requirements would be met, but actual permits would not be required. A summary of the alternatives is in Table 6-4, and Table 6-5 contains a detailed analysis summary of the alternatives.

There is no surface water treatment option included for Plume B. Plume B contributes to Crow Creek, a Class 2AB creek, which has a current regulatory limit of 2.7 µg/L. Modeling demonstrates that the contaminant load to Crow Creek from Plume B is not significant enough to require surface water treatment.

With limited options for the intermediate zone, the FS alternatives have been structured and developed to focus on addressing contaminants in the shallow groundwater where most of the contaminant mass exists and hydraulic properties are not as much of a limiting factor. Following discussion of the shallow zone remedial alternatives in subsequent sections, natural attenuation time frames and simulations of active treatment for the intermediate zone are presented for the respective plumes. Contaminant reduction in the intermediate zone is focused on MNA and $KMnO_4$ injection. This approach has been taken with the understanding that a selected alternative for the shallow zone would also incorporate one of the options for the intermediate zone. These options would include:

- No Action (possibly with monitoring)
- Institutional Controls
- MNA
- Chemical Oxidation ($KMnO_4$)

For all of the alternatives, the proposed monitoring approaches are regarded as baseline assumptions for the purposes of scoping monitoring needs and to provide a basis for FS cost

estimates. Actual monitoring needs would be evaluated as the design of the selected alternative progresses.

Waste streams generated during implementation of the alternatives include soil from drill cuttings and trench excavation, water from monitoring well development and purging, and spent carbon from liquid-phase treatment of extracted, vacuum-stripped groundwater. In general, these wastes would be managed consistent with current USEPA-approved waste management practices at FEW.

6.1.1 Alternative 1B – No Action

The No Action Alternative assumes no further action would be taken regarding contaminants in groundwater. No institutional controls, such as legal/management control or LTM would be implemented. This alternative is required by the NCP for baseline comparison purposes.

6.1.2 Alternative 2B – Institutional Controls

This alternative would consist of physical and/or institutional controls to limit access and future development of groundwater and assess risk from indoor air if buildings are planned to be constructed overlying higher concentration areas of the groundwater plumes. Access to the groundwater would be controlled and activities inconsistent with the prescribed usage of the groundwater would be prohibited. Because this alternative would not allow unrestricted use and unlimited exposure, this alternative would be subject to review not less than every five years.

Refer to Section 4.1.2 for discussions of the Process Description, Rationale, Conceptual Design, and Performance Monitoring associated with Institutional Controls.

6.1.3 Alternative 3B – Monitored Natural Attenuation

As with Plume A (Section 4.1.3), groundwater sampling data and numerical modeling results suggest that Plume B is relatively stable and is shrinking in size and contaminant mass (Volume II and Sections 4.1.3.2, 5.4.2, and Figure 5-21 of the Zone D Groundwater RI [USAF 2003a]). Modeled results for Alternative 3B (MNA) are shown on Figure 6-1.

Based on these results, MNA would be considered a viable alternative. This alternative would also be subject to institutional controls, as described in Section 6.1.2, to limit access and future development of groundwater.

6.1.3.1 Process Description

Refer to Section 4.1.3.1 for the process description of natural attenuation.

6.1.3.2 Rationale for Alternative

Groundwater sampling data indicate that TCE concentrations are decreasing throughout most of Plume B, which suggests that natural attenuation is occurring at the site. TCE concentrations in groundwater samples collected as part of the Zone D RI (USAF 2003a), and MNA groundwater modeling for the Zone D FS (Volume II) suggest that:

- The leading edge of the plume has migrated to Crow Creek in the shallow zone of the aquifer, but only half as far in the intermediate zone (Figures 6-1 and 6-6).
- TCE concentrations in the shallow zone wells nearest Crow Creek (MW 176, MW-048, MW-288, and MW-289) do not currently exceed the MCLs for TCE or its degradation products (see Plate 1).
- TCE concentrations are not expected to exceed the current concentration of less than 10 µg/L at downgradient monitoring well MW-053 and at the Crow Creek intercept during a 65-year MNA period (Figure 6-1), indicating a stable or shrinking plume.
- TCE concentrations are decreasing throughout the length of the plume, from the original source area wells MW-105, MW-009, and MW-101 to plume toe wells MW-053, MW-292, and MW-293 (see detailed discussion in Section 4.1.3.2 of the Zone D RI [USAF 2003a]).
- *cis*-1,2-DCE concentrations, although still below the MCL of 70 µg/L, have increased in much of the plume to levels near those of TCE (in wells MW-009, MW-053, MW-095, MW-096, MW-101, MW-105, MW-292, and MW-293), indicating that active biodegradation of the TCE is occurring throughout the plume (see detailed discussion in Section 4.1.3.2 of the Zone D RI [USAF 2003a]).

Based on results of additional groundwater sampling and MNA groundwater modeling presented in Volume II and Figure 6-1, the time for TCE concentrations throughout the shallow zone of the plume to be naturally attenuated to 5 µg/L from present conditions is estimated to be 65 years. There has not been a documented exceedance of the WDEQ surface water standard for Crow Creek at the leading edge of Plume B. Modeling and mass loading calculations for this alternative are presented in Volume II, and based on these, there are no predicted future exceedances.

LTM would allow for continued evaluation of contaminant migration and effectiveness of this alternative.

6.1.3.3 Conceptual Design

Refer to Section 4.1.3.2 for conceptual design of the MNA program.

6.1.3.4 Performance Monitoring

Performance monitoring would consist of groundwater sampling, as discussed in the following paragraphs.

Groundwater Monitoring

The network of monitoring wells would be adjusted and located according to the most appropriate design to measure the effectiveness of each of the alternatives, but LTM at 12 existing wells has been assumed for Plume B. The monitoring well network would tentatively consist of selected wells in the following locations:

- Crossgradient—MW-101, MW-106, MW-103, MW-091

- Downgradient—MW-053, MW-289, MW-292, MW-293
- In-plume—MW-105, MW-009, MW-100, MW-096

Monitoring of shallow zone groundwater would occur until established groundwater standards are met in that zone. Samples would be collected according to the monitoring plan developed for this alternative during the design phase, and no new monitoring wells were assumed for Plume B.

Surface Water Monitoring

Groundwater sampling and modeling results indicate that TCE concentrations in groundwater would be attenuated to below 5 µg/L before reaching Crow Creek. However, for conservative FS estimating purposes, a surface water monitoring network is proposed that would include the following locations:

- Plume intercept
- Upstream
- Downstream

The plume intercept monitoring point would document any exceedance of the state surface water standards. An upstream location would serve as a reference point to establish whether any reported concentrations in surface water at the plume intercept are in fact attributable to the plume and not an upstream source. The downstream location would help to define the extent of the TCE-plume intercept, as well as potentially documenting the attenuation of the TCE in surface water. For purposes of the FS, it is assumed that existing surface water stations would be used and no new locations established.

Analytical Protocol

All performance monitoring points would be sampled and analyzed for those analytes listed in Table 4-1. Refer to Section 4.1.3.4 for additional details concerning the analytical protocol.

Sampling Frequency and Duration of Monitoring

Results of MNA groundwater modeling (Volume II and Figure 6-1) suggest that TCE concentrations in groundwater would attenuate to 5 µg/L from present conditions in approximately 65 years. Therefore, the proposed LTM program sampling duration is based on a 65-year monitoring period. The sampling frequency would be consistent with that presented in Section 4.1.3.4.

6.1.4 Alternative 4B – Groundwater Extraction, *Ex situ* Treatment and Monitored Natural Attenuation

This alternative provides the USEPA "presumptive remedy" for chlorinated VOC contamination in groundwater for Zone D TCE Plume B. The following sections provide a process description, rationale for selection, conceptual design, and process monitoring plan of the groundwater extraction and treatment alternative.

6.1.4.1 Process Description

Refer to Section 4.1.4.1 for the process description of groundwater extraction and treatment. Refer to Section 4.1.3.1 for the process description of MNA.

6.1.4.2 Rationale for Alternative

The rationale for Plume B is the same as that discussed for Plume A in Section 4.1.4.2.

Currently no exceedances of the surface water standard of 2.7 μg/L have been measured in Crow Creek. Under this alternative, mass loading calculations, as described in Volume II of the FS, indicate that there will be no future exceedances.

6.1.4.3 Conceptual Design

A groundwater extraction and treatment system would be implemented to remove TCE-contaminated groundwater from the portions of Plume B that exceed the MCL of 5 μg/L. The following assumptions were made for purposes of preparing a conceptual design of the system (based on 2001 data):

- The dimensions of the TCE plume exceeding 5 μg/L are approximately 4,400 feet long, up to 1,200 feet wide, and up to 20 feet bgs.
- The maximum TCE concentration is 888 μg/L in a temporary well located near the head of the plume.
- Approximately 48 kg of dissolved TCE are present.
- The Zone D groundwater model (Figure 6-2) was used to estimate the number and placement of extraction wells, well pumping rates, and time required to reduce TCE concentrations to 5 μg/L throughout the entire plume. The distribution of extraction wells would be localized within the zones of high hydraulic conductivity and highest contaminant mass. Extraction wells would not be located in the vicinity of well MW-086 due to lower permeability, which may preclude effective performance of the well. Therefore, this region of the plume would be treated using MNA.

Operational Goals

The goals for operating a groundwater extraction and treatment system at Plume B would be the same as those for Plume A in Section 4.1.4.3.

Conceptual Design Approach

A configuration of 23 extraction wells was selected to provide an extraction system capable of pumping a majority of Plume B in a reasonable amount of time and cost-effective manner (Figure 6-2). This configuration of wells was selected through an iterative modeling process involving comparison of results for various scenarios where different numbers and placements of wells were evaluated.

Groundwater modeling results indicate that it would not be feasible to extract and treat the entire plume. An extraction system consisting of up to 23 wells could feasibly be operated; however, a small portion of the plume within the intermediate/deep aquifer of Plume B cannot be extracted and would be remediated through another alternative (see Section 6.1.6).

Groundwater modeling simulations of more than 23 wells would result in large areas of very thin to partially dry saturated thickness due to aquifer dewatering. In the three-dimensional transport model, MT3D, the areas of very low saturated thickness were converted to inactive cells. Therefore, the contaminated groundwater could not be transported to the extraction wells in these areas. These results suggest that the downgradient portion of the plume is dominated by low permeability aquifer materials and conditions are not suitable for implementing extraction and treatment. Therefore, model simulations using more than 23 wells indicated no added benefit and were not feasible.

The assumptions were made to evaluate this alternative using the Zone D groundwater model are the same as those assumed for Plume A in Section 4.2.3.3. The extraction and treatment system would operate for 10 years (Figure 6-3). MNA would occur for an additional 20 years for the shallow zone.

Extraction System

The extraction system would consist of 23 new, 4-inch wells screened from static groundwater level to the bottom of the shallow zone at depths ranging from 20 to 40 feet bgs.

Based on groundwater modeling, the extraction wells would be anticipated to have a combined pumping rate of approximately 30 gpm. The wells would be two-phase wells, as described in Section 4.2.3.3.

Aboveground Treatment System

The anticipated influent flow rate at any one time would be approximately 30 gpm, and the treatment system would be designed to treat up to 40 to 50 gpm. The treatment plant would be designed to treat the extracted groundwater to meet the RAO and substantive requirements of an NPDES permit as discussed in Section 4.2.3.3. Following treatment, effluent would be released to surface discharge at a maximum discharge rate of 50 gpm. Treatment and discharge components are summarized in Table 6-1. A conceptual design for the groundwater extraction and treatment system is included as Figure 6-2.

Monitored Natural Attenuation

An LTM program would be developed for the 30-year MNA period. The LTM program would be reviewed and modified accordingly as new data are obtained during the monitoring period. The design for MNA would will be similar to that for Plume A in Section 4.1.3.2.

6.1.4.4 Performance Monitoring

A performance monitoring plan is a required component of the full plume groundwater extraction and treatment alternative should be considered for planning and budgeting purposes. The performance monitoring plan would describe a groundwater monitoring program for the

groundwater extraction system extending over a 10-year period, and a monitoring program for MNA extending over a 20-year period after extraction is discontinued. The performance monitoring plan should be reviewed and modified accordingly as new data are obtained during and after operation of the extraction system.

Performance Monitoring Goals

The goals for the performance monitoring program at Plume B would be the same as those for Plume A, exclusive of SS7, described in Section 4.2.3.3. However, instead of assessing the degree to which potential receptors in Diamond Creek are being protected from contamination, the protection of Crow Creek would be required. Performance monitoring would consist of groundwater, as discussed in the following paragraphs.

Groundwater Monitoring

The network of monitoring wells would be adjusted and located according to the most appropriate design to measure the effectiveness of the alternative, but LTM at 12 existing wells has been assumed for Plume B. The monitoring well network would tentatively consist of selected wells in the following locations:

- Crossgradient—MW-101, MW-106, MW-103, MW-091
- Downgradient—MW-053, MW-289, MW-292, MW-293
- In-plume—MW-105, MW-009, MW-100, MW-096

Monitoring of shallow zone groundwater would occur until established groundwater standards are met in that zone. Samples would be collected according to the monitoring plan developed for this alternative during the design phase, and no new monitoring wells were assumed for Plume B.

Surface Water Monitoring

Groundwater sampling and modeling results indicate that TCE concentrations in groundwater would be attenuated to below 5 µg/L before reaching Crow Creek. However, for conservative FS estimating purposes, a surface water monitoring network is proposed that would include the following locations:

- Plume intercept
- Upstream
- Downstream

The plume intercept monitoring point would document any exceedance of the state surface water standards. An upstream location would serve as a reference point to establish whether any reported concentrations in surface water at the plume intercept are in fact attributable to the plume and not an upstream source. The downstream location would help to define the extent of the TCE-plume intercept, as well as potentially documenting the attenuation of the TCE in surface water. For purposes of the FS, it is assumed that existing surface water stations would be used and no new locations established.

Analytical Protocol

All performance monitoring points would be sampled and analyzed for those analytes listed in Table 4-2 to evaluate the effectiveness of groundwater extraction and treatment at achieving the RAOs for Plume B. The list includes parameters that may relate to potential precipitates or discharge requirements. In addition to laboratory analyses, groundwater elevations and water quality parameters would also be measured.

Sampling Frequency and Duration of Monitoring

It is anticipated that the shallow plume groundwater extraction and treatment system would remediate a majority of groundwater in approximately 10 years (Figure 6-3). However, the remaining plume would require an additional 20 years to attenuate. Therefore, the performance monitoring program sampling frequency and duration would be based on a 30-year monitoring period. The sampling frequency would be consistent with that presented in Section 4.1.3.4.

6.1.5 Alternative 5B – Chemical Oxidation and Monitored Natural Attenuation

In situ chemical oxidation is based on the delivery of a chemical oxidant to contaminated media to destroy the contaminants or to convert them to innocuous compounds commonly found in nature. $KMnO_4$ is an effective oxidant typically applied to treat compounds such as PCE. $KMnO_4$ attacks the carbon-carbon bonds in chlorinated organic compounds. The following sections present a process description, rationale for selection, and conceptual design for the *in situ* chemical oxidation and MNA alternative for Plume B. This alternative would also be subject to institutional controls, as described in Section 6.1.2, to limit access and future development of groundwater.

6.1.5.1 Process Description

The processes for this alternative have been previously discussed, as indicated in the following sections.

Potassium Permanganate

For the process description of $KMnO_4$, refer to Section 4.1.6.2.

Monitored Natural Attenuation

For the process description of MNA, refer to Section 4.1.3.1.

6.1.5.2 Rationale for Alternative

From the Zone D $KMnO_4$ Treatability Study observation, it was assumed that the injection technique using small volumes and low concentration of $KMnO_4$ is successful in avoiding permeability loss due to MnO_2 precipitation. Using the results from the Zone D Treatability Study, a preliminary plan and conceptual design for a chemical oxidation and monitoring treatment alternative were developed. The $KMnO_4$ Treatability Study conducted in Plume C is applicable to Plume B for the following reasons:

- Plume B and Plume C, where the $KMnO_4$ Treatability Study was conducted, are both within Zone D.
- The geology at the Treatability Study site is very similar to that observed in the proposed injection area at Plume B.
- Findings of the Zone D $KMnO_4$ Treatability Study indicate that this technology is effective in reducing TCE concentrations of 357 µg/L to nondetect. The highest TCE concentration recently observed in Plume B was 102 µg/L (MW-009, January 2003), which is approximately one-third of the highest concentration observed at the Plume C Treatability Study site.

In addition to the results of the $KMnO_4$ Treatability Study, contaminant concentrations within Plume B are low enough so that the majority of the contamination present is expected to be in the dissolved-phase rather than the sorbed-phase, making the plume area conducive to treatment with $KMnO_4$.

The proposed treatment area of 2.6 acres for the shallow zone of Alternative 5B (Figure 6-4) corresponds to the treatment zone proposed for the intermediate zone of the aquifer (Figure 6-7). This zone is smaller than the originally planned area of application, in which concentrations greater than or equal to 100 µg/L covered approximately 4 acres. Optimization of the area was conducted in an attempt to minimize the area in order to maximize implementability. An assessment of the hydrologic conditions revealed that a comparatively higher hydraulic conductivity zone exists in the downgradient portion of the 100 µg/L zone compared to the source zone, facilitating a greater amount of contaminant dispersion and attenuation. Thus, the cleanup time for the shallow layer of Plume B remained at 35 years with a slightly reduced area of treatment (Volume II). Further reduction of the area was attempted by applying $KMnO_4$ to the just the head of the plume. This resulted in a reduction of $KMnO_4$ used, but the groundwater RAO time frame increased to 65 years, which is the same as the Alternative 3B time frame (Figure 6-1). Currently no exceedances of the surface water standard of 2.7 µg/L have been measured in Crow Creek. Under this alternative, mass loading calculations, as described in Volume II of the FS, indicate that there will be no future exceedances.

6.1.5.3 Conceptual Design

Refer to Section 5.1.6.3 and the subsection on $KMnO_4$ for a general description of the conceptual design.

Plume B encompasses a relatively large area; therefore, only the higher concentration portion of the plume would be treated with $KMnO_4$ to remove contaminant mass and accelerate MNA. The treatment area is approximately 2.6 acres and is displayed on Figure 6-4. The depth of the treatment area is estimated to be 20 to 40 feet bgs in the shallow aquifer and 50 to 70 feet bgs in the intermediate. System components are included in Table 6-2.

In situ chemical treatment and MNA modeling results are shown on Figures 6-4 and 6-5. The modeling assumptions made to evaluate the effectiveness of this technology using the Zone D groundwater model are provided in Volume II.

6.1.5.4 Performance Monitoring

Performance monitoring would consist of groundwater, as discussed in the following paragraphs.

Groundwater Monitoring

The network of monitoring wells would be adjusted and located according to the most appropriate design to measure the effectiveness of each of the chemical oxidation/MNA alternative, but LTM at 12 existing wells has been assumed for Plume B. The monitoring well network would tentatively consist of selected wells in the following locations:

- Crossgradient—MW-101, MW-106, MW-103, MW-091
- Downgradient—MW-053, MW-289, MW-292, MW-293
- In-plume—MW-105, MW-009, MW-100, MW-096

Monitoring of shallow zone groundwater would occur until established groundwater standards are met in that zone. Samples would be collected according to the monitoring plan developed for this alternative during the design phase, and no new monitoring wells were assumed for Plume B.

Surface Water Monitoring

Groundwater sampling and modeling results indicate that TCE concentrations in groundwater would be attenuated to below 5 µg/L before reaching Crow Creek. However, for conservative FS estimating purposes, a surface water monitoring network is proposed that would include the following locations:

- Plume intercept
- Upstream
- Downstream

The plume intercept monitoring point would document any exceedance of the state surface water standards. An upstream location would serve as a reference point to establish whether any reported concentrations in surface water at the plume intercept are in fact attributable to the plume and not an upstream source. The downstream location would help to define the extent of the TCE-plume intercept, as well as potentially documenting the attenuation of the TCE in surface water. For purposes of the FS, it is assumed that existing surface water stations would be used and no new locations established.

Analytical Protocol

All performance monitoring points would be sampled and analyzed for those analytes listed in Table 4-1. Refer to Section 4.1.3.4 for additional details concerning the analytical protocol.

Sampling Frequency and Duration of Monitoring

Results of groundwater modeling (Volume II) suggest that TCE concentrations in groundwater would attenuate to 5 μg/L following injection of the $KMnO_4$ in approximately 35 years. Therefore, the proposed LTM program sampling duration is based on a 35-year monitoring period. The sampling frequency would be consistent with that presented in Section 4.1.3.4.

6.1.6 Intermediate Zone Options

This section discusses the following options developed for the intermediate-depth portion of Plume B:

- Option 1B-INT – No Action
- Option 2B-INT – Institutional Controls
- Option 3B-INT – MNA
- Option 4B-INT – Localized Chemical Oxidation and MNA

The first two options—Option 1B-INT, No Action, and Option 2B-INT, Institutional Controls, for the intermediate zone of Plume B are identical in name and description to Alternative 1B, No Action, and Alternative 2B, Institutional Controls, for the shallow zone of Plume B. Therefore, the development of those intermediate-zone options assumes that all of the discussion in Sections 4.1.1 and 4.1.2 applies and will not be repeated in this section.

For the purposes of cost estimating, the value associated with the most conservative intermediate MNA option is presented. Due to variations in length of the different shallow zone alternatives, the institutional controls and 5-Year Reviews associated with the intermediate MNA costs differ. For a complete list of costs associated with each, individual intermediate option, refer to Volume III.

6.1.6.1 Option 3B-INT – Monitored Natural Attenuation

According to USEPA guidance (USEPA 1999), the most important considerations regarding the suitability of MNA as a remedy include:

- Whether the contaminants are likely to be effectively addressed by natural attenuation processes;
- Stability of the groundwater contaminant plume and its potential for migration; and
- Potential for unacceptable risks to human health or environmental resources by the contamination.

Groundwater sampling data and numerical modeling results suggest that the intermediate zone at Plume B is relatively stable and is shrinking in size and contaminant mass (Volume II). Based on these results, MNA is identified as a viable alternative. This alternative would also be subject to institutional controls, as described in Section 6.1.2, to limit access and future development of groundwater.

Process Description

Refer to Section 4.1.3.1 for the process description of natural attenuation.

Rationale for Alternative

Based on results of MNA groundwater modeling presented in Volume II, the time for TCE concentrations throughout the entire plume to be naturally attenuated to 5 µg/L from present conditions was estimated to be approximately 110 years. Modeled results for Option 3B-INT (MNA) are shown on Figure 6-6.

By comparing historical and current site data and interpreting groundwater modeling results, TCE concentrations are not expected to exceed the MCL at the furthest downgradient monitoring well (i.e., MW-053). LTM would allow for continued evaluation of contaminant migration and effectiveness of this alternative.

Conceptual Design

Refer to Section 4.1.3.2 for conceptual design of MNA.

Performance Monitoring

Performance monitoring would consist of groundwater monitoring, as discussed in the following paragraphs.

Groundwater Monitoring. The LTM monitoring well network would be similar to that for the shallow zone of Plume B. Monitoring of the intermediate zone would occur until established groundwater standards are met in the zone. Four intermediate-depth monitoring wells were assumed, likely including MW-111M, MW-105M, MW-100M, and MW-176A. Surface water sampling would not be required for the intermediate zone because there are no surface water effects from intermediate zone contamination.

Analytical Protocol. All performance monitoring points would be sampled and analyzed for those analytes listed in Table 4-1. For further discussion, see Section 4.1.3.2.

Sampling Frequency and Duration of Monitoring. Results of MNA groundwater modeling (Volume II) suggest that TCE concentrations in groundwater would attenuate to 5 µg/L from present conditions in approximately 110 years. Therefore, the proposed LTM program sampling duration is based on a 110-year monitoring period. For additional details, see Section 4.1.3.2.

6.1.6.2 Option 4B-INT – Localized Chemical Oxidation and MNA

This option provides chemical oxidation using $KMnO_4$, followed by MNA, to treat the low-concentration groundwater found in the intermediate zone of Plume B. The following sections provide a process description, rationale for selection, conceptual design, and process monitoring plan of this intermediate-zone option. This alternative would also be subject to institutional controls, as described in Section 6.1.2, to limit access and future development of groundwater.

Process Description

For a process description of $KMnO_4$ for intermediate zone groundwater, see Section 4.1.6.2. For details of MNA, see Section 4.1.3.

Rationale for Alternative

For the rationale for using $KMnO_4$ and MNA for intermediate zone groundwater, see Section 4.1.6.2. The proposed treatment area of 3.4 acres for this zone was an optimization of the area in an attempt to treat the area of the highest observed TCE concentrations in the intermediate zone and remove the most contaminant mass. Thus, the cleanup time for the intermediate layer of Plume B was 35 years (Table 6-4).

Conceptual Design

The concept of the designs for injected $KMnO_4$ and MNA for the intermediate zone are discussed in the following paragraphs.

Potassium Permanganate. Plume B encompasses a relatively large area; therefore, only the higher concentration portion of the plume would be treated with $KMnO_4$ to remove contaminant mass and accelerate MNA. The treatment area is approximately 2.1 acres and is displayed on Figure 6-7. The depth of the treatment area is estimated to be 40 to 50 feet bgs in the intermediate aquifer. For additional details, see Section 4.1.6.2 and Table 6-3.

In situ chemical treatment and MNA modeling results are shown in Figure 6-8. The modeling assumptions made to evaluate the effectiveness of this technology using the Zone D groundwater model are provided in Volume II.

Monitored Natural Attenuation. For the process description of MNA, refer to Section 4.1.3.1.

Monitoring Network. The LTM monitoring well network would be similar to that for the shallow zone of Plume B. Monitoring of the intermediate zone would occur until established groundwater standards were met in the zone. Four intermediate-depth monitoring wells were assumed, likely including MW-111M, MW-105M, MW-100M, and MW-176A. Surface water sampling would not be required for the intermediate zone because there are no surface water effects from intermediate zone contamination.

Analytical Protocol. All performance monitoring points would be sampled and analyzed for those analytes listed in Table 4-1. For further discussion, see Section 4.1.3.

Sampling Frequency and Duration of Monitoring. Results of MNA groundwater modeling (Volume II) suggest that TCE concentrations in groundwater would attenuate to 5 μg/L from present conditions in approximately 35 years with the addition of $KMnO_4$. Therefore, the proposed LTM program sampling duration would be based on a 35-year monitoring period. For details, see Section 4.1.6.2.

6.2 DETAILED ANALYSIS OF ALTERNATIVES

This section presents the individual analysis and assessment of each Plume B groundwater remedial alternative with respect to the nine evaluation criteria. The first two (Overall Protection and Compliance with ARARs) are threshold criteria. Alternatives are evaluated for whether they

provide protectiveness or comply with ARARs. Alternatives must be both protective and comply with ARARs to be considered for a remedy. The next five are balancing criteria, where the relative tradeoffs among the criteria are evaluated. These first seven criteria are further described in Table 4-3. The final two are modifying criteria, in which the state and the community express whether they support or oppose the alternatives, which are evaluated by the end of the public comment period. Following the individual analysis is a comparative analysis among the groundwater alternatives. The comparative analysis will assess the relative performance of each groundwater alternative with respect to each criterion.

The Institutional Controls Alternative would be incorporated into all of the alternatives. Costs associated with institutional controls have been added to the costs associated with each alternative.

6.2.1 Alternative 1B – No Action

The No Action Alternative assumes no further action would be taken for groundwater at Zone D. This alternative is required by the NCP and selected for detailed analysis so that it may be used as a baseline for comparative analysis of the risk and cost associated with other alternatives. Although expected, the No Action Alternative would not take into account natural attenuation of the groundwater plume through time.

6.2.1.1 Overall Protection of Human Health and the Environment

Although the BRA identified no unacceptable threat to human health or the environment under current groundwater conditions, this alternative would not include a means to monitor or assess protection of human health or the environment. Therefore, the No Action Alternative would not be protective of human health and the environment.

6.2.1.2 Compliance with ARARs

The No Action Alternative would not comply with ARARs.

6.2.1.3 Long-Term Effectiveness

The potential risk of exposure to groundwater would continue to exist with this alternative, and untreated TCE contamination would remain in groundwater. Therefore, the No Action Alternative would not provide long-term effectiveness.

6.2.1.4 Reduction of Toxicity, Mobility, and Volume

Since no active treatment of groundwater would be undertaken, there would not be an active reduction of toxicity, mobility, or volume. However, over time, the groundwater plume would be expected to naturally attenuate.

6.2.1.5 Short-Term Effectiveness

Because no action for groundwater would be taken, there would be no additive short-term exposure to the community or workers.

6.2.1.6 Implementability

There would be no implementation concerns associated with the No Action Alternative for groundwater.

6.2.1.7 Cost

The No Action Alternative for groundwater would incur no cost. The cost associated with long-term liability would be unknown.

6.2.2 Alternative 2B – Institutional Controls

The Institutional Controls Alternative assumes that legal and/or physical controls would be implemented for groundwater at Zone D. This alternative has limited capital cost, but the future costs and liabilities associated with exposure risks can only be estimated. Although expected, the Institutional Controls Alternative would not take into account natural attenuation of the groundwater plume through time.

6.2.2.1 Overall Protection of Human Health and the Environment

The Institutional Controls Alternative would protect human health and the environment through implementation and enforcement of administrative controls described in Section 6.1.2. No unacceptable short-term or cross-media impacts would be expected.

6.2.2.2 Compliance with ARARs

The Institutional Controls Alternative would comply with potential action- and location-specific ARARs. It would not comply with the potential chemical-specific ARAR of the federal MCL for TCE of 5 µg/L. This alternative would not comply with ARARs requiring monitoring of releases (i.e., 40 CFR Part 264).

6.2.2.3 Long-Term Effectiveness and Permanence

The untreated TCE contamination in groundwater would continue to exist at Zone D. This alternative would offer a level of protection through the regulation of groundwater use as discussed in Section 6.1.2. Controls would be implemented to limit or exclude use of the groundwater and thus reduce the potential for exposure. These controls would be contained in the General Plan and are a long-term and reliable management control, enforced by the USAF within the installation boundaries. The groundwater plume would be expected to naturally attenuate over time.

6.2.2.4 Reduction of Toxicity, Mobility and Volume

The contaminated groundwater would not be treated to reduce the toxicity, mobility, or volume. However, over time, the groundwater plume would be expected to naturally attenuate.

6.2.2.5 Short-Term Effectiveness

This alternative would not include a remediation component, so there would be no additive short-term exposure to the community or workers.

6.2.2.6 Implementability

This alternative would be easy to implement technically and administratively. Documentation in the General Plan and coordination with installation personnel, as discussed in Section 6.1.2, would be a reliable management control that would be easy to implement.

6.2.2.7 Costs

Costs for this alternative include a capital cost of $18,484, plus annual costs of $2,387 for updates. These costs are outputs of RACER™ and reflected in present value dollars in Volume III.

6.2.3 Alternative 3B – Monitored Natural Attenuation

Alternative 3B assumes that both long-term groundwater monitoring and institutional controls would be implemented for groundwater in Plume B. The future LTM costs and potential liabilities associated with exposure risks can only be estimated. Unlike Alternative 2, however, the MNA alternative would take into account natural attenuation of the groundwater plume through time.

6.2.3.1 Overall Protection of Human Health and the Environment

The MNA alternative would protect human health and the environment through implementation and enforcement of both the LTM program described in Section 6.1.3 and the administrative controls described in Section 6.1.2. No unacceptable short-term or cross-media impacts would be expected.

6.2.3.2 Compliance with ARARs

The MNA alternative would comply with potential action- and location-specific ARARs. It would not comply with the potential chemical-specific ARAR of the federal MCL for TCE of 5 µg/L until near the end of the 65-year LTM period (Figure 6-1). This alternative would comply with ARARs requiring monitoring of releases (i.e., 40 CFR Part 264).

6.2.3.3 Long-Term Effectiveness and Permanence

The untreated TCE contamination in groundwater would continue to exist at Plume B until the end of the 65-year LTM period. This alternative would offer a level of protection through the monitoring of groundwater contaminant concentration and flow, as discussed in Section 6.1.3, and by regulation of groundwater use, as discussed in Section 6.1.2. LTM and institutional controls would be implemented to monitor, limit, and/or exclude use of the groundwater and thus reduce the potential for exposure.

6.2.3.4 Reduction of Toxicity, Mobility, and Volume

The contaminated groundwater would not be treated to reduce the toxicity, mobility, or volume. However, over time, the groundwater plume would be expected to naturally attenuate.

6.2.3.5 Short-Term Effectiveness

This alternative would not include a remediation component, so there would be no additive short-term exposure to the community, but LTM workers would be monitored to prevent exposure.

Soil spoils from drilling will be placed in soil containers, covered or sealed, and transported to a Class C landfill. Because the soil will be contained, the community does not incur incremental risk associated with disposal, but could incur a slight incremental risk due to increased traffic.

6.2.3.6 Implementability

This alternative would be easy to implement technically and administratively. An LTM Plan would be prepared for the 65-year LTM period, as discussed in Section 6.1.3, and documentation would be provided in the General Plan, as discussed in Section 6.1.2.

6.2.3.7 Cost

Costs of this alternative would include an LTM Plan, changes to the General Plan, community and educational programs, reporting, and management and administrative efforts. There are no capital costs associated with this alternative due to the availability of numerous existing monitoring wells. Total O&M costs that include LTM data collection, analysis, evaluation, and reporting costs are estimated to be about $4.5 million over the 65-year life of the alternative. Present value cost is approximately $1.6 million. The detailed cost estimate is provided in Volume III.

6.2.4 Alternative 4B – Groundwater Extraction, *Ex situ* Treatment, and Monitored Natural Attenuation

Alternative 4B assumes that a combination of groundwater extraction and treatment, long-term groundwater monitoring (Alternative 3B), and institutional controls (Alternative 2) would be implemented for groundwater in Plume B. The future O&M costs, LTM costs, and potential liabilities associated with exposure risks can only be estimated. Based on groundwater modeling, this alternative would require 10 years of extraction and treatment, followed by 20 years of natural attenuation of the groundwater plume to complete remediation.

6.2.4.1 Overall Protection of Human Health and the Environment

Alternative 4B would protect human health and the environment through implementation of the groundwater extraction and treatment system described in Section 6.1.4, enforcement of the LTM program described in Section 6.1.3, and the administrative controls described in Section 6.1.2. No unacceptable short-term or cross-media impacts would be expected.

6.2.4.2 Compliance with ARARs

Alternative 4B would comply with potential action- and location-specific ARARs and with the potential chemical-specific ARAR of the federal MCL for TCE of 5 µg/L at the end of the 30-year LTM period. This alternative would comply with the USEPA preference for treatment and ARARs requiring monitoring of releases (i.e., 40 CFR Part 264), and this alternative would meet substantive NPDES discharge requirements.

6.2.4.3 Long-Term Effectiveness and Permanence

The untreated TCE contamination in groundwater would continue to exist at Plume B until the end of the 30-year LTM period (Figure 6-3). However, the extraction and treatment system would reduce the highest concentrations from greater than 500 µg/L TCE to 50 µg/L in 10 years, leaving small areas of concentrations below 50 µg/L for an additional 10 years and below 10 µg/L for the final 10 years of the MNA period. This alternative would offer a level of protection through the treatment and monitoring of groundwater contaminant concentration and flow, as discussed in Section 6.1.4, and by regulation of groundwater use, as discussed in Section 6.1.2.

6.2.4.4 Reduction of Toxicity, Mobility, and Volume

The contaminated groundwater would be treated for 10 years to reduce the toxicity and volume of the groundwater contamination. After treatment, the groundwater plume would be expected to naturally attenuate to ARARs in 20 years.

6.2.4.5 Short-Term Effectiveness

This alternative would include a remediation component, but there would be no additive short-term exposure to the community. However, treatment system O&M and LTM workers would be monitored to prevent exposure.

Soil spoils from drilling and construction will be placed in soil containers, covered or sealed, and transported to a Class C landfill. Because the soil will be contained, the community does not incur incremental risk associated with disposal, but could incur a slight incremental risk due to increased traffic.

6.2.4.6 Implementability

This alternative would be difficult to implement technically due to the requirement to design and install a large-scale, dual-tube, extraction well system in the shallow groundwater, to install extraction piping in a number of trenches, and to connect this extraction system to a treatment system, which must also be installed by the contractor. However, all of this construction can be accomplished by experienced local contractors and the equipment is readily available. Administratively, this alternative may be easily implemented due its status as the EPA "presumptive remedy" for contaminated groundwater and to its success in a treatability study at the head of Plume C. An O&M Plan would be prepared for the two-phase extraction system and the bioreactor treatment system as discussed in Section 6.1.4, an LTM Plan would be prepared

for the 30-year LTM period as discussed in Section 6.1.3, and documentation would be provided in the General Plan as discussed in Section 6.1.2.

6.2.4.7 Cost

Costs of this alternative would include capital costs for the extraction and treatment system design and construction, preparation of the LTM Plan, changes to the General Plan, community and educational programs, reporting, and management and administrative efforts. Capital costs associated with this alternative are estimated to be $1.2 million. Total O&M costs that include extraction and treatment system O&M, LTM data collection, analysis, evaluation, and reporting costs are estimated to be about $6.8 million over the 30-year life of the alternative. Present value cost is $5.4 million. A summary of the costs is provided in Table 6-2. The detailed cost estimate is provided in Volume III.

6.2.5 Alternative 5B – Chemical Oxidation and Monitored Natural Attenuation

Alternative 5B assumes that a combination of chemical oxidation, long-term groundwater monitoring (Alternative 3B), and legal and/or physical institutional controls (Alternative 2B) would be implemented for groundwater in Plume B. The future O&M costs, LTM costs, and potential liabilities associated with exposure risks can only be estimated. Based on groundwater modeling, this alternative would require six months of chemical oxidation, followed by 35 years of natural attenuation of the groundwater plume to complete remediation.

6.2.5.1 Overall Protection of Human Health and the Environment

Alternative 5B would protect human health and the environment through implementation of the chemical oxidation system described in Section 6.1.5, enforcement of the LTM program described in Section 6.1.3, and the administrative controls described in Section 6.1.2. No unacceptable short-term or cross-media impacts would be expected.

6.2.5.2 Compliance with ARARs

Alternative 5B would comply with potential action- and location-specific ARARs and with the potential chemical-specific ARAR of the federal MCL for TCE of 5 µg/L at the end of the 35-year LTM period. This alternative would comply with the USEPA preference for treatment and ARARs requiring monitoring of releases (i.e., 40 CFR Part 264).

6.2.5.3 Long-Term Effectiveness and Permanence

The untreated TCE contamination in groundwater would continue to exist at Plume B until the end of the 35-year LTM period. However, the chemical oxidation system would reduce the highest concentrations from greater than 500 µg/L TCE to 50 µg/L in six months, leaving small areas of concentrations below 50 µg/L for an additional 30 years and below 10 µg/L for the final five years of the MNA period (Figure 6-5). This alternative would offer a level of protection through the treatment and monitoring of groundwater contaminant concentration and flow, as discussed in Section 6.1.5, and by regulation of groundwater use, as discussed in Section 6.1.2.

6.2.5.4 Reduction of Toxicity, Mobility and Volume

The contaminated groundwater would be treated for six months to reduce the toxicity and volume of the groundwater contamination. After treatment, the groundwater plume would be expected to naturally attenuate to ARARs in 35 years.

6.2.5.5 Short-Term Effectiveness

This alternative would include a remediation component, but there would be no additive short-term exposure to the community. However, chemical oxidation treatment and LTM workers would be monitored to prevent exposure.

Soil spoils from drilling will be placed in soil containers, covered or sealed, and transported to a Class C landfill. Because the soil will be contained, the community does not incur incremental risk associated with disposal, but could incur a slight incremental risk due to increased traffic.

6.2.5.6 Implementability

This alternative would be relatively easy to implement technically due to the ready availability of the required chemicals and of local contractors with previous experience in injecting $KMnO_4$. This alternative should also be easy to implement administratively due to its proven effectiveness in treating shallow groundwater TCE contamination at other sites and its successful use in a treatability study in Plume C.

This alternative would be a moderately easy active treatment alternative to implement technically and administratively. A chemical oxidation treatment system design would be prepared as discussed in Section 6.1.5, an LTM Plan would be prepared for the 35-year LTM period as discussed in Section 6.1.3, and documentation would be provided in the General Plan as discussed in Section 6.1.2.

6.2.5.7 Cost

Costs of this alternative would include capital costs for chemical oxidation design and implementation, preparation of the LTM Plan, changes to the General Plan, community and educational programs, reporting, and management and administrative efforts. Capital costs associated with this alternative are estimated to be $0.9 million. Total O&M costs that include LTM data collection, analysis, evaluation, and reporting costs are estimated to be about $3.3 million over the 35-year life of the alternative. Present value cost is approximately $2.4 million. A summary of the costs is provided in Table 6-2. The detailed cost estimate is provided in Volume III.

6.2.6 Intermediate Zone Options

This section presents the individual analysis and assessment of each intermediate zone option with respect to the seven evaluation criteria, as described above. For a summary of this analysis, see Table 6-6.

For detailed analysis of Option 1B-INT, No Action, and Option 2B-INT, Institutional Controls, see Section 6.2.1 and 6.2.2.

6.2.6.1 Option 3B-INT – Monitored Natural Attenuation

Option 3B-INT assumes that LTM of natural attenuation processes that reduce TCE concentrations over time would be implemented for groundwater in the intermediate zone at Plume B. Institutional controls would be included in the alternative to prevent the use of groundwater for human consumption prior to the end of the MNA period.

Overall Protection of Human Health and the Environment

With institutional controls, MNA in the intermediate zone would protect human health and the environment under current conditions through natural attenuation processes. No unacceptable short-term or cross-media impacts would be expected.

Compliance with ARARs

With institutional controls, the use of MNA in the intermediate zone would comply with all potential action- and location-specific ARARs, but would not comply with the potential chemical-specific ARAR of the federal MCL for TCE of 5 µg/L until near the end of the 110-year monitoring period. MNA would comply with ARARs requiring monitoring of releases. There would be no need to meet the substantive requirements of an NPDES discharge permit for this alternative.

Long-Term Effectiveness

Natural processes will reduce contaminant levels in groundwater to RAOs over time. Continued monitoring would provide a reliable means to assess the residual concentrations and manage the risk posed by the residual. Institutional controls would limit or prevent use of the intermediate zone groundwater, and this process would produce no residual contamination. Minimal O&M of wells and groundwater sampling would be required.

Reduction of Toxicity, Mobility, and Volume

Toxicity, mobility, and volume of TCE would be reduced over time from natural attenuation of contaminants in groundwater. TCE levels would be reduced to RAOs in intermediate zone groundwater in approximately 110 years, and no residuals would be present in groundwater at completion. The attenuation would be irreversible.

Short-Term Effectiveness

No additional risk to site workers and the environment would occur because there is no construction of a treatment system. There would also be no increased risk to workers, the community, or the environment during implementation. Time to achieve RAOs within the intermediate zone at Plume B was estimated to be approximately 110 years.

Soil spoils from drilling will be placed in soil containers, covered or sealed, and transported to a Class C landfill. Because the soil will be contained, the community does not incur incremental risk associated with disposal, but could incur a slight incremental risk due to increased traffic.

Implementability

This option would be easy to implement and should not create schedule delays. Passive methods such as MNA do not require removal, aboveground treatment method, or TSD services. Monitoring the effectiveness would be simple, and administrative requirements to accommodate this option would include modifying the General Plan.

Cost

Costs of this option would include an LTM Plan, changes to the General Plan, community and educational programs, reporting, and management and administrative efforts. There would be no capital costs associated with this alternative due to the availability of numerous existing monitoring wells. Total O&M costs that include LTM data collection, analysis, evaluation, and reporting costs are estimated to be about $3.9 million over the 110-year life of the alternative. Present value cost is about $0.7 million. The detailed cost estimate is provided in Volume III.

6.2.6.2 Option 4B-INT – Localized Chemical Oxidation and MNA

Option 4B-INT assumes that a combination of chemical oxidation, long-term groundwater monitoring, and legal and/or physical institutional controls would be implemented for intermediate zone groundwater in Plume B. The future O&M costs, LTM costs, and potential liabilities associated with exposure risks can only be estimated.

Overall Protection of Human Health and the Environment

Comparing historical and current site data, TCE concentrations currently exceed RAOs in some intermediate-zone monitoring wells. This chemical oxidation/MNA option would protect human health and the environment by *in situ* treatment of the contaminated groundwater with chemical oxidizers, application of an LTM program, and enforcement of institutional controls. The option would be designed to destroy contaminant concentrations exceeding RAOs through a combination of *in situ* groundwater treatment and MNA. No unacceptable short-term or cross-media impacts would be expected.

Compliance with ARARs

This option would comply with potential action- and location-specific ARARs and with the potential chemical-specific ARAR of the federal MCL for TCE of 5 µg/L at the end of the LTM period. It would also comply with the USEPA preference for treatment of contaminated groundwater (i.e., 40 CFR Part 264). No discharge permits would be required for this option.

Long-Term Effectiveness and Permanence

Active treatment would reduce the TCE concentrations in the intermediate zone groundwater to 50 µg/L in approximately six months. Natural processes would reduce the TCE concentration in groundwater to the MCL approximately 35 years after completion of active treatment. Continued monitoring would provide a reliable means to assess the treatment effectiveness, and institutional controls would limit or prevent use of groundwater. Greater operation and

maintenance than the MNA option would occur only during the six-month treatment method period.

Reduction of Toxicity, Mobility and Volume

Toxicity, mobility, and volume of TCE would be reduced over time from active treatment of groundwater and natural processes. TCE concentrations in groundwater would be reduced to RAOs in intermediate zone groundwater in approximately 35 years, and the process would be irreversible.

Short-Term Effectiveness

There would be minimal additional risk to site workers and the environment during the construction phase involving drilling and injection of chemicals. Soil spoils from drilling will be placed in soil containers, covered or sealed, and transported to a Class C landfill. Because the soil will be contained, the community does not incur incremental risk associated with disposal, but could incur a slight incremental risk due to increased traffic. There would be no increased risk to workers, the community, or the environment during the implementation phase, which would involve only groundwater sampling. The time to achieve RAOs is estimated to be approximately 35 years.

Implementability

This option would be easy to implement and chemical oxidation is a proven and reliable technology. The chemical oxidation compound ($KMnO_4$) is readily available, as are the conventional well drilling and installation techniques that would be used. Schedule delays should not be expected due to lack of availability since multiple drilling contractors and $KMnO_4$ suppliers are available. Competitive bids can be obtained and monitoring the effectiveness would be simple. Administrative requirements would include preparation of a treatment system design, an LTM Plan, and modifying the General Plan.

Cost

Costs of this alternative would include capital costs for chemical oxidation design and implementation, preparation of the LTM Plan, changes to the General Plan, community and educational programs, reporting, and management and administrative efforts. Capital costs associated with this alternative are estimated to be $1.5 million. Total O&M costs that include LTM data collection, analysis, evaluation, and reporting costs are estimated to be approximately $1.3 million over the 35-year life of the alternative. Present value cost is $2.0 million. This cost may be reduced slightly, if this option is utilized in combination with Alternative 5B due to reduced chem-ox mobilization costs. The detailed cost estimate is provided in Volume III.

6.3 COMPARATIVE ANALYSIS

The first seven sections compare these alternatives for the shallow Plume B groundwater:

- Alternative 1B – No Action

- Alternative 2B – Institutional Controls
- Alternative 3B – MNA
- Alternative 4B – Groundwater Extraction and *Ex situ* Treatment
- Alternative 5B – Chemical Oxidation and MNA

One section also compares the following options for intermediate zone groundwater at Plume B:

- Option 1B-INT – No Action
- Option 2B-INT – Institutional Controls
- Option 3B-INT – MNA
- Option 4B-INT – Localized Chemical Oxidation and MNA

Tables 6-7 and 6-8 present a comparison among the criteria for each alternative/option comparison for the shallow zone and intermediate zone groundwater of Plume B, respectively. The tables are for the shallow groundwater zone or the intermediate groundwater zone of each plume, but do not combine the two. Because the comparisons are relative to the other alternatives for this plume, they should not be used for comparison to other plumes or even to the shallow versus intermediate groundwater in Plume B.

6.3.1 Overall Protection of Human Health and the Environment

No Action (Alternative 1B) would be protective of human health and the environment under current conditions because no current unacceptable risk has been identified. However, because this alternative would provide no means to monitor future contamination, it is not protective over the long term. Alternative 2B would provide implementation and enforcement of administrative controls to prevent future use of the groundwater resource, but cannot monitor future conditions. Because the extent of Plume B appears to be stable or shrinking, passive bioremediation currently appears to be occurring throughout the shallow plume, TCE concentrations in monitoring wells at the Crow Creek intercept are below MCLs, no unacceptable risk has been identified, and concentrations of TCE would be reduced over long periods of time, MNA (Alternative 3B) would provide protection of human health and the environment through implementation and enforcement of both the LTM program and institutional controls.

Extraction/treatment method/MNA (Alternative 4B) would also provide protection of human health and the environment through a combination of *ex situ* groundwater extraction and treatment method, MNA, and institutional controls. This alternative would achieve RAOs in the surface groundwater zone of the entire plume in the shortest time period, but only five years shorter than Alternative 5B. Chemical oxidation and MNA (Alternative 5B) would provide protection of human health and the environment due to implementation of treatment through chemical oxidation of the plume head and central plume, enforcement of the LTM program, and institutional controls.

Therefore, Alternatives 3B, 4B, and 5B would be protective of human health and the environment in both the short- and long-term (Table 6-7). However, Alternatives 1B and 2B cannot provide long-term protectiveness with any certainty and do not meet this threshold criterion.

6.3.2 Compliance with ARARs

The No Action Alternative (Alternative 1B) would not comply with ARARs. The Institutional Controls Alternative (Alternative 2B) would comply with potential action- and location-specific ARARs, but not with the potential chemical-specific groundwater ARAR of the federal MCL for TCE of 5 µg/L or with ARARs requiring monitoring of releases. Because these first two alternatives do not meet this threshold criterion, they are not carried through the remainder of the comparative analysis.

Alternatives 3B, 4B, and 5B would comply with potential action and location specific ARARs and with ARARs requiring monitoring of releases (i.e., 40 CFR Part 264). Alternative 3B would comply with the potential chemical-specific groundwater ARAR set at the federal MCL for TCE of 5 µg/L near the end of a 65-year LTM period; Alternative 4B after a 10-year treatment period and 20-year LTM period (30 years); and Alternative 5B after six months of treatment and a 35-year *in situ* treatment and LTM period (35 years). Therefore, based on time to reach ARARs, Alternative 4B would be slightly faster than Alternative 5B and twice as fast as Alternative 3B (Table 6-7).

6.3.3 Long-Term Effectiveness and Permanence

Alternative 4B may achieve RAOs in the shortest time period (30 years) and would provide a high degree of long-term effectiveness and permanence because the contaminants would be permanently removed from the aquifer through groundwater removal and treatment (Figure 6-3; Table 6-7). However, pump-and-treat systems may not be able to remove all sorbed contamination from some low hydraulic conductivity lithologies. Alternative 5B is the next shortest period (35 years), and this alternative would provide the highest degree of long-term effectiveness and permanence because the contaminants would permanently removed from the aquifer through biological treatment technologies that can remove even sorbed TCE from the aquifer (Figure 6-5). Alternative 3B has the longest remediation period (65 years), but would also remove the sorbed contaminants during this period and is currently providing remediation of the TCE contamination in the shallow Plume B aquifer (Figure 6-1). Therefore, all three alternatives would be effective and permanent.

6.3.4 Reduction of Toxicity, Mobility, and Volume Through Treatment

Alternative 3B, MNA, would not provide active treatment for the contaminated groundwater, but over time, the groundwater contamination can be expected to attenuate through natural processes that are already at work reducing the toxicity of the shallow Plume B groundwater. Alternative 4B would combine pumping to reduce shallow plume mobility and volume with an active, *ex situ* treatment method to reduce plume toxicity in 10 years plus 20 years of MNA. Alternative 5B would combine *in situ* chemical oxidation to very quickly reduce shallow plume toxicity in six months from a small volume of the plume, then MNA for 35 years to reduce the very low residual groundwater contamination concentrations. In addition, Alternative 5B may have a beneficial impact on the intermediate zone due to a combination of the density of $KMnO_4$ solution and the downward groundwater gradients from the shallow to the intermediate zone. Therefore, all three alternatives would provide contaminant reductions. Alternative 5B would provide a much faster reduction in the highest concentrations than Alternative 4B, and Alternative 4B would be twice as fast as Alternative 3B (Table 6-7).

6.3.5 Short-Term Effectiveness

Alternative 3B, MNA, would not include an active remediation component, so there would be no additive short-term impacts to the community or the environment, but LTM workers would be monitored to prevent exposure. The Alternative 4B extraction/treatment alternative would have no additive short-term exposure to the community, but construction workers and treatment system O&M workers must be monitored to prevent short-term exposure. The Alternative 5B chemical oxidation/MNA alternative would include no additive short-term exposure to the community, but both treatment and LTM workers would be monitored to prevent exposure. Therefore, Alternative 3B would provide the least exposure followed by Alternative 5B, then Alternative 4B.

Alternative 3B achieves RAOs in 65 years, Alternative 4B in 30 years, and Alternative 5B in 35 years. Therefore, Alternative 4B and Alternative 5B have similar remediation times then Alternative 3B.

"Averaging" the three sub-criteria (community protection, worker protection, and time to achieve RAOs) shows that Alternative 5B has greater short-term effectiveness than the other two alternatives (Table 6-7).

6.3.6 Implementability

The MNA alternative (Alternative 3B) would be easy to implement technically, potentially requiring only new monitoring wells, but perhaps be more difficult administratively due to its natural attenuation of the contaminated groundwater. However, due to the stability of the contamination in Plume B and the evidence for current bioremediation, administrative implementability may be greater than in other Zone D plumes. The extraction and treatment/ MNA alternative (Alternative 4B) would be the most difficult alternative to implement technically, but relatively easy administratively as it is a USEPA presumptive remedy for contaminated groundwater. The chemical oxidation/MNA alternative (Alternative 5B) would be less difficult to implement technically than Alternative 4B and likely less difficult administratively due to its success in FEW treatability studies.

Therefore, Alternative 3B would be the simplest to implement technically followed by Alternative 5B, then Alternative 4B. Administratively, Alternative 5B may be easiest to implement, followed by Alternative 4B, then Alternative 3B (Table 6-7).

6.3.7 Cost

For quantitative cost comparisons, refer to Table 6-5; for qualitative comparisons, refer to Table 6-7. Alternative 3B has the lowest present value cost of the three shallow-zone groundwater alternatives, Alternative 4B has the highest, and Alternative 5B has the second lowest.

6.3.8 Intermediate Zone Options

The following subsections compare these options for intermediate zone groundwater at Plume B:

- Option 1B-INT – No Action
- Option 2B-INT – Institutional Controls

- Option 3B-INT – MNA
- Option 4B-INT – Localized Chemical Oxidation and MNA

6.3.8.1 Overall Protection of Human Health and the Environment

No Action (Option 1B-INT) would be protective of human health and the environment under current conditions because no current unacceptable risk has been identified (Table 6-8). However, because this alternative would provide no means to monitor future contamination, it would not be protective over the long term. Institutional Controls (Option 2B-INT) would provide implementation and enforcement of administrative controls to prevent future use of the groundwater resource, but cannot monitor future conditions.

Because the extent of Plume B appears to be stable or shrinking, passive bioremediation currently appears to be occurring throughout the shallow plume, TCE concentrations in monitoring wells at the Crow Creek intercept are below MCLs, no unacceptable risk has been identified, and concentrations of TCE will be reduced over long periods of time, MNA (Option 3B-INT) would provide protection of human health and the environment through implementation and enforcement of both the LTM program and institutional controls. However, the time to achieve RAOs would be longer than Option 4B-INT. $KMnO_4$ and MNA (Option 4B-INT) would achieve RAOs (i.e., protection of human health and the environment) in the shortest time period through injection of $KMnO_4$ solution into the intermediate zone, enforcement of the LTM program, and institutional controls.

Therefore, Options 3B-INT and 4B-INT would be protective of human health and the environment in both the short- and long-term (Table 6-8). However, Options 1B-INT and 2B-INT cannot provide long-term protectiveness with any certainty and do not meet this threshold criterion.

6.3.8.2 Compliance with ARARs

The No Action option (Option 1B-INT) would not comply with ARARs. The Institutional Controls option (Option 2B-INT) would comply with potential action- and location-specific ARARs, but not with the potential chemical-specific groundwater ARAR of the federal MCL for TCE of 5 µg/L or with ARARs requiring monitoring of releases. Because these first two options do not meet this threshold criterion, they are not carried through the remainder of the comparative analysis (Table 6-8).

Options 3B-INT and 4B-INT would comply with potential action and location specific ARARs and with ARARs requiring monitoring of releases (i.e., 40 CFR Part 264). Option 3B-INT would comply with the potential chemical-specific groundwater ARAR set at the federal MCL for TCE of 5 µg/L by the end of a 110-year LTM period; and Option 4B-INT after a combined 35-year *in situ* treatment and LTM period (Table 6-8).

6.3.8.3 Long-Term Effectiveness and Permanence

Option 4B-INT would reduce the highest concentrations from greater than 53 µg/L TCE to 5 µg/L in six months, leaving other areas of concentrations below 10 µg/L for an additional 35 years (Figure 6-8). This option would provide a higher degree of long-term effectiveness and

permanence than Option 3B-INT because Option 3B-INT would leave TCE concentrations in groundwater at Plume B until near the end of the 110-year LTM period (Figure 6-6; Table 6-8).

6.3.8.4 Reduction of Toxicity, Mobility, and Volume Through Treatment

Option 3B-INT, MNA, would not provide active treatment for the contaminated groundwater, but over time (110 years) the plume would be expected to attenuate through natural processes that would reduce the toxicity and volume of contamination. Option 4B-INT would combine chemical oxidation to actively treat the highest concentrations in groundwater for six months, followed by natural attenuation to ARARs in 35 years. Thus, the use of treatment in Option 4B-INT would reduce the total time for remediation of the intermediate zone by 70 percent over a 110-year MNA period (Table 6-8).

6.3.8.5 Short-Term Effectiveness

Option 3B-INT would not include an active remediation component, so there would be no additive short-term exposure to the community, but LTM workers would be monitored to prevent exposure. The Option 4B-INT chemical oxidation/MNA system would have no additive short-term exposure to the community, but chemical oxidation treatment and LTM workers would be monitored to prevent exposure. However, Option 3B-INT requires 110 years to achieve RAOs and Option 4B-INT 35 years. Therefore, Option 4B-INT would provide better short-term effectiveness than Option 3B-INT (Table 6-8).

6.3.8.6 Implementability

Option 3B-INT would be easy to implement technically due to its need only for additional monitoring wells, but perhaps more difficult administratively. Option 4B-INT would be more difficult to implement technically than Option 3B-INT, but perhaps less difficult administratively due to its rapid reduction of the highest contaminant concentrations. Therefore, Option 3B-INT would be the simpler to implement technically, and Option 4B-INT may be more easily implemented administratively (Table 6-8).

6.3.8.7 Cost

For quantitative cost comparisons, refer to Table 6-6; for qualitative comparisons, refer to Table 6-8. Option 3B-INT has the lower present value cost and Option 4B-INT has the higher of the two intermediate-zone groundwater options.

This section consists of the development, detailed analysis, and comparison of the alternatives selected for Plume C.

7.1 DEVELOPMENT OF ALTERNATIVES

The following alternatives have been developed for Plume C. The "C" designation for each of these alternatives refers to Plume C.

- Alternative 1C – No Action
- Alternative 2C – Institutional Controls
- Alternative 3C – Groundwater Extraction, *Ex situ* Treatment, and MNA
- Alternative 4C – Chemical Oxidation at Plume Head, Localized Chemical Oxidation, PRB, and MNA
- Alternative 5C – ERH, Localized Chemical Oxidation, PRB, and MNA
- Alternative 6C – Groundwater Extraction and *Ex situ* Treatment, Localized Chemical Oxidation, and MNA

All of the alternatives presented would result in concentrations on site above health-based levels, therefore, site review would be required no less frequent than every five years. Additionally, all of the alternatives would be subject to institutional controls, including stipulations to evaluate potential risk if future buildings are to be constructed overlying higher concentration areas of the groundwater plumes, and none of the alternatives would result in off-site discharge. As such, substantive permit requirements would be met, but actual permits would not be required. A remedial alternatives summary is included in Table 7-6.

With limited options for the intermediate zone, the FS alternatives have been structured and developed to focus on addressing contaminants in the shallow groundwater where most of the contaminant mass exists and hydraulic properties are not as much of a limiting factor. Following discussion of the shallow zone remedial alternatives in subsequent sections, natural attenuation time frames and simulations of active treatment for the intermediate zone are presented for the respective plumes. Remediation of the intermediate zone is focused on MNA and $KMnO_4$ injection. This approach has been taken with the understanding that a selected alternative for the shallow zone would also incorporate one of the options for the intermediate zone. These options would include:

- No Action (possibly with monitoring)
- Institutional Controls
- MNA
- Chemical Oxidation ($KMnO_4$)

For all of the alternatives, the proposed monitoring approaches are regarded as baseline assumptions for the purposes of scoping monitoring needs and to provide a basis for FS cost estimates. Actual monitoring needs would be evaluated as the design of the selected alternative progresses.

Waste streams generated during implementation of the alternatives include soil from drill cuttings and trench excavation, water from monitoring well development and purging, and spent carbon from liquid-phase treatment of extracted, vacuum-stripped groundwater. In general, these wastes would be managed consistent with current USEPA-approved waste management practices at FEW.

7.1.1 Alternative 1C – No Action

The No Action Alternative assumes no further action would be taken regarding contaminants in groundwater. No institutional controls, such as legal/management control or LTM would be implemented. This alternative is required by the NCP for baseline comparison purposes. Under this alternative, the simulated concentration in Crow Creek under worst-case conditions, as described in Volume II of the FS, will meet the surface water standard of 2.7 µg/L in 55 years.

7.1.2 Alternative 2C – Institutional Controls

This alternative would consist of physical and/or institutional controls to limit access and future development of groundwater and assess risk from indoor air if buildings are planned to be constructed overlying higher concentration areas of the groundwater plumes. Access to the groundwater would be controlled and activities inconsistent with the prescribed usage of the groundwater would be prohibited. Because this alternative does not allow unrestricted use and unlimited exposure, this alternative would be subject to review not less than every five years. Under this alternative, the simulated concentration in Crow Creek under worst-case conditions, as described in Volume II of the FS, will meet the surface water standard of 2.7 µg/L in 55 years.

Refer to Section 4.1.2 for discussions of the Process Description, Rationale, Conceptual Design, and Performance Monitoring associated with Institutional Controls.

7.1.3 Alternative 3C – Groundwater Extraction, *Ex situ* Treatment and Monitored Natural Attenuation

This alternative provides the USEPA "presumptive remedy" for chlorinated VOC contamination in groundwater for Zone D TCE Plume C. Because Plume C has not been demonstrated to be stable or shrinking, no "MNA only" alternative was considered. All MNA at Plume C is associated with another passive or active treatment method technology in order to stabilize or control the migration of plume contaminants prior to the application of MNA. The following sections provide a process description, rationale for selection, conceptual design, and process monitoring plan of the groundwater extraction and treatment method plus MNA alternative. This alternative would also be subject to institutional controls, as described in Section 7.1.2, to limit access and future development of groundwater.

7.1.3.1 Process Description

The proposed process for Plume C would be the same as that discussed for Plume A in Section 4.1.2.2 and includes two-phase extraction, treatment of extracted vapors in a bioreactor and groundwater with GAC, then discharge to a surface stream. A more detailed discussion is included in Section 4.1.4.1. Refer to Section 4.1.3.1 for the process description of MNA.

7.1.3.2 Rationale for Alternative

The rationale for Plume C would be the same as that discussed for Plume A in Section 4.1.2.2.

7.1.3.3 Conceptual Design

A groundwater extraction and treatment system would be implemented to remove TCE-contaminated groundwater from the portions of Plume C that exceed the MCL of 5 µg/L. The following assumptions were made for purposes of preparing a conceptual design of the system (based on 2001 data):

- The dimensions of the TCE plume exceeding 5 µg/L are approximately 3,600 feet long, up to 1,600 feet wide, and up to 50 feet bgs.
- The maximum TCE concentration is 6,870 µg/L in a temporary well located near the head of the plume.
- Approximately 190 kg of dissolved TCE are present.
- The Zone D groundwater model was used to estimate the number and placement of extraction wells (Figure 7-1), well pumping rates, and time required to reduce TCE concentrations to 5 µg/L throughout the entire plume (Figure 7-2).

Operational Goals

The goals for operating a groundwater extraction and treatment system at Plume C would be the same as those for Plume A in Section 4.1.4.3.

Conceptual Design Approach

A configuration of 67 extraction wells was selected to provide an extraction system capable of pumping a majority of Plume C in a reasonable time but still be implementable and effective (Figure 7-1). This configuration of wells was selected through an iterative modeling process involving comparison of results for various scenarios where different numbers and placements of wells were evaluated.

Groundwater modeling results indicate that it would not be feasible to extract and treat the entire plume. An extraction system consisting of up to 67 wells could feasibly be operated in the shallow plume. The layout of this system was optimized to provide hydraulic containment, as well as extraction, of the downgradient toe of the plume in order to minimize containment discharge to Crow Creek. In addition, the extraction wells were located to minimize their radius of influence in order to prevent reducing surface water flow in the creek. As can be seen in Figure 7-1, the wells nearest Crow Creek would be set back from creek, but still aligned to intercept downgradient migration from all of the Plume C (excluding Plume E to the southeast of SS-002, which is discussed in Section 8.1).

Groundwater modeling simulations of more than 67 wells would results in large areas of very thin to partially dry saturated thickness due to aquifer dewatering (Volume II). In the three-dimensional transport model, MT3D, the areas of very low saturated thickness were converted to inactive cells. Therefore, the contaminated groundwater could not be transported to the

extraction wells in these areas. These results suggest that some portions of the plume are dominated by lower permeability aquifer materials, including the southern and southwestern parts of the plume, and conditions, therefore, are not suitable for implementing extraction and treatment. Therefore, model simulations using more than 67 wells indicated no added benefit and were not feasible.

The assumptions to evaluate this alternative using the Zone D groundwater model are the same as those assumed for Plume A in Section 4.1.4.1. The extraction and treatment method system would operate for 20 years, and MNA would occur for an additional 10 years for the shallow zone (Figure 7-2). Under this alternative, the simulated concentration in Crow Creek under worst-case conditions (no dilution from surface water runoff and no volatilization) will meet the surface water standard of 2.7 μg/L in one year. Due to uncertainties described in Volume II of the FS, the effective time frame to achieve the surface water RAO is estimated to be less than five years.

Extraction System

The extraction system would consist of 67 new, 4-inch wells screened from static groundwater level to the bottom of the shallow zone at depths ranging from 25 to 35 feet bgs.

Based on groundwater modeling, the 67 extraction wells were anticipated to have a combined pumping rate of approximately 53 gpm. The wells would be two-phase wells as described in Section 4.1.4.1.

Aboveground Treatment System

The anticipated influent flow rate at any one time would be approximately 53 gpm, and the treatment system would be designed to treat up to 60 gpm. The treatment plant would be designed to treat the extracted groundwater to meet the RAO and substantive requirements of an NPDES permit as discussed in Section 4.1.4.3. Following treatment, effluent would be released to surface discharge at a maximum discharge rate of 60 gpm.

Treatment and discharge components are summarized in Table 7-1. A conceptual design layout for the groundwater extraction and treatment system is included as Figure 7-1.

Monitored Natural Attenuation

An LTM program would be developed for the 20-year pump-and-treat and 10-year MNA period. The LTM program would be reviewed and modified accordingly as new data are obtained during the 30-year total remediation period. The design for MNA would be similar to that for Plume A in Section 4.1.3.4.

7.1.3.4 Performance Monitoring

A performance monitoring plan would be a required component of the groundwater extraction and treatment method alternative/MNA and should be considered for planning and budgeting purposes. The performance monitoring plan would describe a groundwater monitoring program for the groundwater extraction system extending over a 20-year period, and a monitoring program for MNA extending over a 10-year period after extraction would be discontinued. The

performance monitoring plan should be reviewed and modified accordingly as new data are obtained during and after operation of the extraction system.

Performance Monitoring Goals

The goals for the performance monitoring program at Plume C would be the same as those for Plume A described in Section 4.1.4.1. However, instead of assessing the degree to which potential receptors in Diamond Creek were being protected from contamination, the protection of Crow Creek would be required. Performance monitoring would consist of both groundwater and surface water monitoring, as discussed in the following paragraphs.

Groundwater Monitoring

The monitoring network would be adjusted and located according to the most appropriate design to measure the effectiveness of each of the chosen alternatives. The monitoring well network would tentatively consist of 12 selected wells in the following locations (Plate 1):

- In-plume—MW-111, MW-113, MW-022, MW-070, MW-177B, MW-178
- Crossgradient— MW-089, MW-180, MW-072
- Creek intercept—MW-038S, MW-1020, MW-1021

Monitoring of the shallow zone at Plume C would occur until established groundwater standards are met in the shallow plume. Samples would be collected according to the monitoring plan developed for each alternative during the design phase.

Surface Water Monitoring

Groundwater sampling and modeling results indicate that TCE concentrations in groundwater will be attenuated to below 5 µg/L before reaching Crow Creek. Based on modeling, the TCE concentrations at MW-1021 may currently exceed MCLs (Figure 7-2), but the hydraulic control of the plume by the pumping system and dilution in Crow Creek would prevent exceedances of the 2.7 µg/L RAO for surface water before Year 10 at station C5.2. In order to monitor the accuracy of the modeling, however, a surface water monitoring network is proposed that would include the following locations:

- Plume intercept—C5.2
- Upstream
- Downstream

The plume intercept monitoring point would document any exceedance of the 2.7 µg/L RAO for surface water. An upstream location would serve as a reference point to establish whether any reported concentrations in surface water at the plume intercept are in fact attributable to the plume and not an upstream source. The downstream location would help to define the extent of the TCE-plume intercept, as well as potentially documenting the attenuation of the TCE in surface water. For purposes of the FS, it is assumed that existing surface water stations would be used and no new locations established.

Analytical Protocol

All groundwater monitoring points would be sampled and analyzed for those analytes listed in Table 4-2 to evaluate the effectiveness of groundwater extraction and treatment at achieving the RAOs. The list includes parameters that may relate to potential precipitates or discharge requirements. In addition to laboratory analyses, groundwater elevations and water quality parameters would also be measured, and surface water monitoring points would be analyzed for the parameters listed in Table 4-1.

Sampling Frequency and Duration of Monitoring

It is anticipated that the full-plume groundwater extraction and treatment system would remediate a majority of groundwater in approximately 20 years, and the remaining TCE plume would attenuate to 5 μg/L within 10 years after extraction is discontinued. Therefore, the performance monitoring program sampling frequency and duration would be based on a 30-year monitoring period. The sampling frequency would be consistent with that presented in Section 4.1.3.4.

7.1.4 Alternative 4C – Chemical Oxidation at Plume Head, Localized Chemical Oxidation, Permeable Reactive Barrier at Creek Intercept and Monitored Natural Attenuation

This alternative would provide chemical oxidation treatment using Fenton's Reagent injected into the chlorinated VOC contamination in groundwater at the head of Plume C, localized chemical oxidation with $KMnO_4$ in selected "hot spots" within the plume, a PRB to protect surface water in Crow Creek, and MNA for the remainder of the plume. Because Plume C has not been demonstrated to be stable or shrinking, no "MNA only" alternative was considered. All MNA at Plume C is associated with another passive or active treatment method technology in order to stabilize or control the migration of plume contaminants prior to the application of MNA. The following sections provide a process description, rationale for selection, conceptual design, and process monitoring plan of the alternative. This alternative would be also subject to institutional controls, as described in Section 7.1.2, to limit access and future development of groundwater.

7.1.4.1 Process Description

The proposed process for the plume head is the same as that discussed for Alternative 6S in SS7 and would include chemical oxidation using Fenton's Reagent injection into the groundwater. More detailed discussion is included in Section 5.1.6.1.

The proposed process for "hot spot" treatment is the same as the chemical oxidation using $KMnO_4$ discussed for SS7 in Section 5.1.6.1.

The proposed process for the PRB at Plume C is the same as those for SS7 in Section 5.1.4.1.

The proposed process for MNA at Plume C is the same as those for Plume A in Section 4.1.3.1.

7.1.4.2 Rationale for Alternative

The rationale for the chemical oxidation using Fenton's Reagent at the head of Plume C is the same as that discussed for SS7 in Section 5.1.6.2.

The rationale for chemical oxidation using $KMnO_4$ at Plume C is the same as that for SS7 in Section 5.1.6.2.

The rationale for the PRB at Plume C is the same as those for SS7 in Section 5.1.2.2.

The rationale for MNA at Plume C is the same as those for Plume A in Section 4.1.3.2.

7.1.4.3 Conceptual Design

This alternative includes conceptual designs/layouts for chemical oxidation using Fenton's Reagent at the head of Plume C, localized chemical oxidation in selected "hot spots" within the plume, and PRB to protect surface water in Crow Creek, and MNA for the remainder of the plume (Figure 7-3). The following describes the Alternative 4C goals, monitoring network, and analytical protocol.

Plume Head. Chemical oxidation using Fenton's Reagent injection would be implemented to remediate TCE-contaminated groundwater at the head of Plume C (Figure 7-3). The following assumptions were made for purposes of preparing a conceptual design of the system (based on 2001 data):

- The dimensions of the area to be remediated by chemical oxidation using Fenton's Reagent is approximately 0.4 acre and 7 to 30 feet bgs.
- The maximum TCE concentration was 6,870 µg/L in a temporary well located near the head of the plume.
- The Zone D groundwater model was used to estimate the number and placement of extraction wells, well pumping rates, and time required to reduce TCE concentrations to 5 µg/L at the plume head.
- A treatment system consisting of up to 50 wells and injection points would be utilized.

"Hot spots" within the plume. An *in situ* chemical oxidation injection system using $KMnO_4$ would be implemented to treat TCE-contaminated groundwater in selected "hot spots" with TCE concentrations greater than 300 µg/L within Plume C (Figure 7-3). The following assumptions were made for purposes of preparing a conceptual design of the system (based on 2001 data):

- The area to be remediated by $KMnO_4$ injection covers approximately 1.7 acres, with injection depths extending to 25 feet bgs.
- The Zone D groundwater model was used to estimate the number and placement of injection wells, injection rates, and time required to reduce TCE concentrations to 5 µg/L in the hot spots.
- An injection system consisting of up to 90 points would be utilized.

Creek Intercept. An *in situ* PRB using granular ZVI would be implemented to treat TCE-contaminated groundwater at the intercept of Plume C with Crow Creek in order to minimize

TCE concentrations in groundwater reaching the creek (Figure 7-3). The following assumptions were made for purposes of preparing a conceptual design of the system (based on 2001 data):

- The zone to be remediated by the PRB covers a length of approximately 800 feet at the downgradient toe of Plume C.
- There would be no replacement of PRB due to migration and distribution of the contamination following Year 30.
- The 0.25-foot-thick ZVI section would extend throughout the 20 feet of saturated thickness of the shallow aquifer zone.
- The depth of the PRB was chosen based on depth to water measurements obtained from two existing wells in the area.
- The Zone D groundwater model was used to estimate the size and placement of the PRB and the time required to reduce TCE concentrations to 5 µg/L in the area downgradient of the iron.
- A total of 1,000 cubic feet or 100 tons of ZVI would be utilized.
- The PRB would not be replaced at the end of its 30-year life based on the model (Figure 7-4), which indicates that contaminated groundwater would no longer be present in the vicinity of the PRB at Year 30.

Remainder of Plume. MNA would be utilized to remediate the portions of Plume C that were not remediated by one of the other technologies (Figure 7-4).

This alternative produces a clean up time of 50 years. The simulated concentration in Crow Creek under worst-case conditions (no dilution from surface water runoff and no volatilization) would meet the surface water standard of 2.7 µg/L in one year. Due to uncertainties described in Volume II of the FS, the effective time frame to achieve the surface water RAO is estimated to be less than five years.

The large areal extent of Plume C prompted the application of a chemical oxidant, $KMnO_4$, over a relatively large treatment zone. This treatment was used in conjunction with a treatment technology at the head of the plume (e.g., ERH) and a PRB at the creek intercept. A detailed evaluation of the hydrogeology revealed a relatively lower hydraulic conductivity distribution along the northwestern margin of the plume. This inhibits the ability for the contaminant plume flowing through this region to disperse and attenuate. Thus, a larger $KMnO_4$ application zone of approximately 15 acres, focusing upon the northwestern margin of the plume where contaminant concentrations are greater than 50 µg/L, was evaluated. This also produced an estimated cleanup time of 50 years for the shallow zone with no improvement over the "hot spot" treatment.

Phytoremediation was also evaluated as an alternative technology of PRB at the creek intercept in Alternatives 4C, 5C, and 6C. Assuming a total of 1,650 trees at 9-foot spacing along Crow Creek at the intercept of Plume C, an evapotranspiration rate of 0.33 inches/day was simulated. The cleanup times remained the same at 50 years for the shallow zone, but the PRB was deemed a more suitable technology based on ease of implementability (Volume II).

Operational Goals

The goals for chemical oxidation using Fenton's Reagent at Plume C are the same as those for SS7 in Section 5.1.6.3.

The goals for chemical oxidation using $KMnO_4$ at Plume C are the same as those for SS7 in Section 5.1.6.3.

The goals for the PRB at Plume C are the same as those for SS7 in Section 5.1.4.3.

The goals for MNA at Plume C are the same as those for Plume A in Section 4.1.3.3.

Conceptual Design Approach

This alternative would include conceptual designs/layouts for ERH at the head of Plume C, localized chemical oxidation in selected "hot spots" within the plume, and PRB to protect surface water in Crow Creek, and MNA for the remainder of the plume (Figure 7-3). These are described in the following sections.

Plume Head. A configuration of 50 injection wells and points on a 20-foot-grid spacing was selected to provide a chemical oxidation using Fenton's Reagent system capable of treating the head of Plume C in a reasonable amount of time and cost-effective manner (Figure 7-3). This configuration of injection wells/points was selected through an iterative modeling process involving comparison of results for various scenarios where different numbers and placements of wells were evaluated. The assumptions made to evaluate this alternative using the Zone D groundwater model are the same as those assumed for SS7 in Section 5.1.6.3.

The treatment would consist of injecting 200 gallons of Fenton's Reagent in each well/point from static groundwater level to the bottom of the shallow zone at depths ranging from 7 to 30 feet bgs. The assumptions made to evaluate this alternative using the Zone D groundwater model are the same as those assumed for SS7 in Section 5.2.6.3. The chemical oxidation treatment would be completed in six months. Treatment components are summarized in Table 7-2.

"Hot spots" within the plume. A configuration of 90 *in situ* chemical oxidation injection wells for $KMnO_4$ would treat the hot spots greater than 300 μg/L, located outside the head of Plume C, in a reasonable amount of time and cost-effective manner (Figure 7-3). As discussed above, this configuration of injection wells/points was selected through an iterative modeling process involving comparison of results for various scenarios where different numbers and placements of wells were evaluated.

The assumptions made to evaluate this alternative using the Zone D groundwater model are the same as those assumed for SS7 in Section 5.2.6.3. The chemical oxidation treatment would be completed in six months. Treatment components are summarized in Table 7-2.

Creek Intercept. An *in situ* PRB using granular ZVI would be implemented to treat TCE-contaminated groundwater at the intercept of Plume C with Crow Creek (Figure 7-3). This PRB would be 800 feet long and 0.25 foot thick, with ZVI placed from 8 to 13 feet bgs. This configuration was selected through an iterative modeling process involving comparison of results for various scenarios where different placements of PRBs were evaluated.

The assumptions made to evaluate this alternative using the Zone D groundwater model are the same as those assumed for SS7 in Section 5.2.4.3. The PRB treatment would be completed in 30 years (Figure 7-4).

Remainder of Plume. An LTM program would be developed for the 50-year PRB treatment method/MNA period (Figure 7-4). The LTM program would be reviewed and modified accordingly as new data are obtained during the 50-year monitoring period. The design for MNA at Plume C would be similar to that for Plume A in Section 4.1.3.2.

7.1.4.4 Performance Monitoring

A performance monitoring plan would be a required component of the full-plume groundwater extraction and treatment alternative and should be considered for planning and budgeting purposes. The performance monitoring plan would describe a groundwater monitoring program for Alternative 4C extending over a 50-year period. The performance monitoring plan should be reviewed and modified accordingly as new data are obtained during and after operation of the extraction system.

Performance Monitoring Goals

The goals for the performance monitoring program at Plume C are the same as those for Plume A described in Section 4.2.3.3. However, instead of assessing the degree to which potential receptors in Diamond Creek are being protected from contamination, the protection of Crow Creek would be required.

Performance monitoring would consist of both groundwater and surface water monitoring, as discussed in the following paragraphs.

Groundwater Monitoring

The monitoring network would be adjusted and located according to the most appropriate design to measure the effectiveness of each of the chosen alternatives. The monitoring well network would tentatively consist of 12 selected wells in the following locations (Plate 1):

- In-plume—MW-111, MW-113, MW-022, MW-070, MW-177B, MW-178
- Crossgradient— MW-089, MW-180, MW-072
- Creek intercept—MW-038S, MW-1020, MW-1021

Monitoring of the shallow zone at Plume C would occur until established groundwater standards are met in the shallow plume. Samples would be collected according to the monitoring plan developed for each alternative during the design phase.

Surface Water Monitoring

Groundwater sampling and modeling results indicate that TCE concentrations in groundwater will be attenuated to below 5 µg/L before reaching Crow Creek. Based on modeling, the TCE concentrations at MW-1021 may exceed MCLs during the MNA period (Figure 7-4), but the passive treatment method of the groundwater with the PRB and dilution in Crow Creek would

prevent exceedances of the 2.7 µg/L RAO for surface water. In order to monitor the accuracy of the modeling, however, a surface water monitoring network is proposed that would include the following locations:

- Plume intercept—C5.2
- Upstream
- Downstream

The plume intercept monitoring point would document any exceedance of the 2.7 µg/L RAO for surface water.

An upstream location would serve as a reference point to establish whether any reported concentrations in surface water at the plume intercept are in fact attributable to the plume and not an upstream source. The downstream location would help to define the extent of the TCE-plume intercept, as well as potentially documenting the attenuation of the TCE in surface water. For purposes of the FS, it is assumed that existing surface water stations would be used and no new locations established.

Analytical Protocol

All groundwater and surface water monitoring points would be sampled and analyzed for those analytes listed in Table 4-1. Refer to Section 4.1.3.4 for additional details concerning the analytical protocol.

Sampling Frequency and Duration of Monitoring

It is anticipated that Alternative 4C would remediate the most highly contaminated groundwater in approximately five years, and the remaining TCE plume would attenuate to 5 µg/L within 45 years after active treatment using two-phase extraction and $KMnO_4$ are discontinued. Therefore, the performance monitoring program sampling frequency and duration is based on a 50-year monitoring period. The sampling frequency would be consistent with that presented in Section 4.1.3.4.

7.1.5 Alternative 5C – Electrical Resistance Heating at Plume Head, Localized Chemical Oxidation, Permeable Reactive Barrier at Creek Intercept and Monitored Natural Attenuation

This alternative provides ERH for the chlorinated VOC contamination in groundwater at the head of Plume C, localized chemical oxidation in selected "hot spots" within the plume, and PRB to protect surface water in Crow Creek, and MNA for the remainder of the plume. The hot spot, PRB, and MNA technologies are identical to Alternative 4C. Because Plume C has not been demonstrated to be stable or shrinking, no "MNA only" alternative was considered. All MNA at Plume C is associated with another passive or active treatment method technology in order to stabilize or control the migration of plume contaminants prior to the application of MNA. The following sections provide a process description, rationale for selection, conceptual design, and process monitoring plan of the alternative. This alternative would also be subject to

institutional controls, as described in Section 7.1.2, to limit access and future development of groundwater.

7.1.5.1 Process Description

The proposed process for the plume head is the same as that discussed for Alternative 6S in SS7 and includes six-phase heating, extraction, and treatment of extracted vapors with GAC, and discharge to the atmosphere. A more detailed discussion is included in Section 5.1.6.1.

The proposed process for "hot spot" treatment is the same as the chemical oxidation using $KMnO_4$ discussed for SS7 in Section 5.1.6.1.

The proposed process for the PRB at Plume C is the same as those for SS7 in Section 5.1.4.1.

The proposed process for MNA at Plume C is the same as those for Plume A in Section 4.1.3.1.

7.1.5.2 Rationale for Alternative

The rationale for the ERH at the head of Plume C is the same as that discussed for SS7 in Section 5.1.6.2.

The rationale for chemical oxidation using $KMnO_4$ at Plume C is the same as that for SS7 in Section 5.1.6.2.

The rationale for the PRB at Plume C is the same as those for SS7 in Section 5.1.4.2.

The rationale for MNA at Plume C is the same as those for Plume A in Section 4.1.3.2.

7.1.5.3 Conceptual Design

This alternative would include conceptual designs/layouts for ERH at the head of Plume C, localized chemical oxidation in selected "hot spots" within the plume, and PRB to protect surface water in Crow Creek, and MNA for the remainder of the plume (Figure 7-5 and Table 7-3). The following describes the Alternative 5C goals, monitoring network, and analytical protocol.

Plume Head. An ERH system would be implemented to remove TCE-contaminated groundwater from the head of Plume C (Figure 7-5). The following assumptions were made for purposes of preparing a conceptual design of the system (based on 2001 data):

- The dimensions of the area to be remediated by extraction and treatment are approximately 0.5 acre, and 7 to 30 feet bgs.
- The maximum TCE concentration has 6,870 μg/L in a temporary well located near the head of the plume.
- The Zone D groundwater model was used to estimate the number and placement of extraction wells, well pumping rates, and time required to reduce TCE concentrations to 5 μg/L at the plume head.
- A treatment system consisting of up to eight 50-foot-diameter hexagonal electrical grids could feasibly be operated.

"Hot spots" within the plume. See Section 7.1.4.3 and Figure 7-5.

Creek Intercept. See Section 7.1.4.3 and Figure 7-5.

Remainder of Plume. MNA would be utilized to remediate the portions of Plume C that were not remediated by one of the other technologies (Figure 7-6).

This alternative produces a cleanup time of 50 years. The simulated concentration in Crow Creek under worst-case conditions (no dilution from surface water runoff and no volatilization) will meet the surface water standard of 2.7 µg/L in one year. Due to uncertainties described in Volume II of the FS, the effective time frame to achieve the surface water RAO is estimated to be less than five years.

Operational Goals

The goals for operating a groundwater extraction and treatment system at Plume C are the same as those for SS7 in Section 5.1.6.3.

The goals for chemical oxidation using $KMnO_4$ at Plume C are the same as those for SS7 in Section 5.1.6.3.

The goals for the PRB at Plume C are the same as those for SS7 in Section 5.1.4.3.

The goals for MNA at Plume C are the same as those for Plume A in Section 4.1.3.3.

Conceptual Design Approach

This alternative would include conceptual designs/layouts for ERH at the head of Plume C, localized chemical oxidation in selected "hot spots" within the plume, and PRB to protect surface water in Crow Creek, and MNA for the remainder of the plume (Figure 7-5). These are described in the following sections.

Plume Head. A configuration of eight 50-foot-diameter hexagonal grids was selected to provide a heating system capable of treating the head of Plume C in a reasonable amount of time and cost-effective manner (Figure 7-5). This configuration of the grids was selected through an iterative modeling process involving comparison of results for various scenarios where different numbers and placements of wells were evaluated. The assumptions made to evaluate this alternative using the Zone D groundwater model are the same as those assumed for SS7 in Section 5.2.6.3. The ERH system would be constructed, operate, and be dismantled within six months. Treatment components are summarized in Table 7-3.

"Hot spots" within the plume. See Section 7.1.4.3 and Figure 7-5.

Creek Intercept. See Section 7.1.4.3 and Figure 7-5.

Remainder of Plume. MNA would be utilized to remediate the portions of Plume C that were not remediated by one of the other technologies (Figure 7-6). An LTM program would be developed for the 50-year MNA period. The LTM program would be reviewed and modified accordingly as new data are obtained during the 50-year monitoring period

7.1.5.4 Performance Monitoring

A performance monitoring plan would be a required component of the full-plume groundwater extraction and treatment alternative and should be considered for planning and budgeting purposes. The performance monitoring plan would describe a groundwater monitoring program for Alternative 5C extending over a 50-year period. The performance monitoring plan should be reviewed and modified accordingly as new data are obtained during and after operation of the extraction system.

Performance Monitoring Goals

The goals for the performance monitoring program at Plume C are the same as those for Plume A, exclusive of SS7, described in Section 4.2.3.3. However, instead of assessing the degree to which potential receptors in Diamond Creek are being protected from contamination, the protection of Crow Creek would be required. Performance monitoring would consist of both groundwater and surface water monitoring, as discussed in the following paragraphs.

Groundwater Monitoring

The monitoring network would be adjusted and located according to the most appropriate design to measure the effectiveness of each of the chosen treatment alternatives. The monitoring well network would tentatively consist of 12 selected wells in the following locations (Plate 1):

- In-plume—MW-111, MW-113, MW-022, MW-070, MW-177B, MW-178
- Crossgradient— MW-089, MW-180, MW-072
- Creek intercept—MW-038S, MW-1020, MW-1021

Monitoring of the shallow zone at Plume C would occur until established groundwater standards are met in the shallow plume. Samples would be collected according to the monitoring plan developed for each alternative during the design phase.

Surface Water Monitoring

Groundwater sampling and modeling results indicate that TCE concentrations in groundwater will be attenuated to below 5 µg/L before reaching Crow Creek. Based on modeling, the TCE concentrations at MW-1021 may exceed MCLs during the MNA period (Figure 7-6), but the passive treatment method of the groundwater with the PRB and dilution in Crow Creek would prevent exceedances of the 2.7 µg/L RAO for surface water. In order to monitor the accuracy of the modeling, however, a surface water monitoring network is proposed that would include the following locations:

- Plume intercept—C5.2
- Upstream
- Downstream

The plume intercept monitoring point would document any exceedance of the 2.7 µg/L RAO for surface water. An upstream location would serve as a reference point to establish whether any

reported concentrations in surface water at the plume intercept are in fact attributable to the plume and not an upstream source. The downstream location would help to define the extent of the TCE-plume intercept, as well as potentially documenting the attenuation of the TCE in surface water. For purposes of the FS, it is assumed that existing surface water stations would be used and no new locations established.

Analytical Protocol

All groundwater and surface water monitoring points would be sampled and analyzed for those analytes listed in Table 4-1. Refer to Section 4.1.3.4 for additional details concerning the analytical protocol.

Sampling Frequency and Duration of Monitoring

It is anticipated that Alternative 5C would remediate the most highly contaminated groundwater in approximately five years, and the remaining TCE plume would attenuate to 5 µg/L within 45 years after active treatment using two-phase extraction and $KMnO_4$ are discontinued. Therefore, the performance monitoring program sampling frequency and duration is based on a 50-year monitoring period. The sampling frequency would be consistent with that presented in Section 4.1.3.4.

7.1.6 Alternative 6C – Groundwater Extraction and *Ex situ* Treatment at Plume Head, Localized Chemical Oxidation, Permeable Reactive Barrier at Creek Intercept and Monitored Natural Attenuation

This alternative provides the USEPA "presumptive remedy" for the chlorinated VOC contamination in groundwater at the head of Plume C, localized chemical oxidation in selected "hot spots" within the plume, and PRB to protect surface water in Crow Creek, and MNA for the remainder of the plume. The hot spot, PRB, and MNA technologies are identical to Alternative 4C. Because Plume C has not been demonstrated to be stable or shrinking, no "MNA only" alternative was considered. All MNA at Plume C is associated with a passive or active treatment method technology in order to stabilize or control the migration of plume contaminants prior to the application of MNA. The following sections provide a process description, rationale for selection, conceptual design, and process monitoring plan of the alternative. This alternative would also be subject to institutional controls, as described in Section 7.1.2, to limit access and future development of groundwater.

7.1.6.1 Process Description

The proposed process for the plume head would be the same as that discussed for Plume A in Section 4.1.2.2 and includes two-phase extraction, treatment of extracted vapors in a bioreactor and groundwater within GAC , and discharge to a surface stream. A more detailed discussion is included in Section 4.1.4.1.

The proposed process for "hot spot" treatment is the same as the chemical oxidation using $KMnO_4$ discussed for SS7 in Section 5.1.6.1.

The proposed process for the PRB at Plume C is the same as those for SS7 in Section 5.1.4.1.

The proposed process for MNA at Plume C is the same as those for Plume A in Section 4.1.3.1.

7.1.6.2 Rationale for Alternative

The rationale for the extraction and treatment system at the head of Plume C is the same as that discussed for Plume A in Section 4.1.4.2.

The rationale for chemical oxidation using $KMnO_4$ at Plume C is the same as that for SS7 in Section 5.1.6.2.

The rationale for the PRB at Plume C is the same as those for SS7 in Section 5.1.4.2.

The rationale for MNA at Plume C is the same as those for Plume A in Section 4.1.3.2.

7.1.6.3 Conceptual Design

This alternative would include conceptual designs/layouts for groundwater extraction and treatment method at the head of Plume C, localized chemical oxidation in selected "hot spots" within the plume, and PRB to protect surface water in Crow Creek, and MNA for the remainder of the plume (Figure 7-7 and Table 7-4). The following describes the Alternative 6C goals, monitoring network, and analytical protocol.

Plume Head. A groundwater extraction and treatment system would be implemented to remove TCE-contaminated groundwater from the head of Plume C (Figure 7-7). The following assumptions were made for purposes of preparing a conceptual design of the system (based on 2001 data):

- The dimensions of the area to be remediated by extraction and treatment are approximately 250 feet long, up to 150 feet wide, and 7 to 30 feet bgs.
- The maximum TCE concentration was 6,870 µg/L in a temporary well located near the head of the plume.
- The Zone D groundwater model was used to estimate the number and placement of extraction wells, well pumping rates, and time required to reduce TCE concentrations to 5 µg/L at the plume head.
- An extraction system consisting of up to six wells could feasibly be operated.

"Hot spots" within the plume. See Section 7.1.4.3 and Figure 7-7.

Creek Intercept. See Section 7.1.4.3 and Figure 7-7.

Remainder of Plume. MNA would be utilized to remediate the portions of Plume C that were not remediated by one of the other technologies (Figure 7-8).

This alternative produces a cleanup time of 50 years. The simulated concentration in Crow Creek under worst-case conditions (no dilution from surface water runoff and no volatilization) will meet the surface water standard of 2.7 µg/L in one year. Due to uncertainties described in Volume II of the FS, the effective time frame to achieve the surface water RAO is estimated to be less than five years.

Operational Goals

The goals for operating a groundwater extraction and treatment system at Plume C are the same as those for Plume A in Section 4.1.4.3.

The goals for chemical oxidation using $KMnO_4$ at Plume C are the same as those for SS7 in Section 5.1.6.3.

The goals for the PRB at Plume C are the same as those for SS7 in Section 5.1.4.3.

The goals for MNA at Plume C are the same as those for Plume A in Section 4.1.3.3.

Conceptual Design Approach

This alternative would include conceptual designs/layouts for groundwater extraction and treatment method at the head of Plume C, localized chemical oxidation in selected "hot spots" within the plume, and PRB to protect surface water in Crow Creek, and MNA for the remainder of the plume (Figure 7-7). These are described in the following sections.

Plume Head. A configuration of six extraction wells was selected to provide an extraction system capable of pumping the head of Plume C in a reasonable amount of time and cost-effective manner (Figure 7-7). This configuration of wells was selected through an iterative modeling process involving comparison of results for various scenarios where different numbers and placements of wells were evaluated. The assumptions made to evaluate this alternative using the Zone D groundwater model are the same as those assumed for Plume A in Section 4.2.3.3.

The extraction system would consist of six new, 4-inch wells screened from static groundwater level to the bottom of the shallow zone at depths ranging from 7 to 30 feet bgs. The wells would be two-phase wells as described in Section 4.2.3.3. Based on groundwater modeling, the six extraction wells would be anticipated to have a combined pumping rate of approximately 13 gpm, and the treatment system would be designed to treat up to 15 gpm.

The treatment plant would be designed to treat the extracted groundwater to meet the RAO and substantive requirements of an NPDES permit as discussed in Section 4.2.3.3. Following treatment, effluent would be released to surface discharge at a maximum discharge rate of 15 gpm. The extraction and treatment system would operate for five years. Treatment and discharge components are summarized in Table 7-4.

"Hot spots" within the plume. See Section 7.1.4.3 and Figure 7-7.

Creek Intercept. See Section 7.1.4.3 and Figure 7-7.

Remainder of Plume. MNA would be utilized to remediate the portions of Plume C that were not remediated by one of the other technologies (Figure 7-8). An LTM program would be developed for the 50-year MNA period. The LTM program would be reviewed and modified accordingly as new data are obtained during the 50-year monitoring period

7.1.6.4 Performance Monitoring

A performance monitoring plan would be a required component of the full plume groundwater extraction and treatment alternative and should be considered for planning and budgeting

purposes. The performance monitoring plan would describe a groundwater monitoring program for Alternative 6C extending over a 50-year period. The performance monitoring plan should be reviewed and modified accordingly as new data are obtained during and after operation of the extraction system.

Performance Monitoring Goals

The goals for the performance monitoring program at Plume C are the same as those for Plume A, exclusive of SS7, described in Section 4.2.3.3. However, instead of assessing the degree to which potential receptors in Diamond Creek are being protected from contamination, the protection of Crow Creek would be required. Performance monitoring would consist of both groundwater and surface water monitoring, as discussed in the following paragraphs.

Groundwater Monitoring

The monitoring network would be adjusted and located according to the most appropriate design to measure the effectiveness of each of the chosen alternatives. The monitoring well network would tentatively consist of 12 selected wells in the following locations (Plate 1):

- In-plume—MW-111, MW-113, MW-022, MW-070, MW-177B, MW-178
- Crossgradient— MW-089, MW-180, MW-072
- Creek intercept—MW-038S, MW-1020, MW-1021

Monitoring of the shallow zone at Plume C would occur until established groundwater standards are met in the shallow plume. Samples would be collected according to the monitoring plan developed for each alternative during the design phase.

Surface Water Monitoring

Groundwater sampling and modeling results indicate that TCE concentrations in groundwater will be attenuated to below 5 µg/L before reaching Crow Creek. Based on modeling, the TCE concentrations at MW-1021 may currently exceed MCLs (Figure 7-8), but the passive treatment of the groundwater with the PRB and dilution in Crow Creek would prevent exceedances of the 2.7 µg/L RAO for surface water before Year 10 at station C5.2. In order to monitor the accuracy of the model, however, a surface water monitoring network is proposed that would include the following locations:

- Plume intercept—C5.2
- Upstream
- Downstream

The plume intercept monitoring point would document any exceedance of the 2.7 µg/L RAO for surface water. An upstream location would serve as a reference point to establish whether any reported concentrations in surface water at the plume intercept are in fact attributable to the plume and not an upstream source. The downstream location would help to define the extent of the TCE-plume intercept, as well as potentially documenting the attenuation of the TCE in

surface water. For purposes of the FS, it is assumed that existing surface water stations would be used and no new locations established.

Analytical Protocol

All performance monitoring points would be sampled and analyzed for those analytes listed in Table 4-2 to evaluate the effectiveness of groundwater extraction and treatment at achieving the RAOs for Plume C. The list includes parameters that may relate to potential precipitates or discharge requirements. In addition to laboratory analyses, groundwater elevations and water quality parameters would also be measured, and surface water monitoring points would be analyzed for the parameters listed in Table 4-1.

Sampling Frequency and Duration of Monitoring

It is anticipated that Alternative 6C would remediate the most highly groundwater in approximately five years, and the remaining TCE plume would attenuate to 5 μg/L within 45 years after active treatment using two-phase extraction and $KMnO_4$ are discontinued. Therefore, the performance monitoring program sampling frequency and duration is based on a 50-year monitoring period. The sampling frequency would be consistent with that presented in Section 4.1.3.4.

7.1.7 Intermediate Zone Options

This section discusses the following options developed for the intermediate-depth portion of Plume C:

- Option 1C-INT – No Action
- Option 2C-INT – Institutional Controls
- Option 3C-INT – MNA
- Option 4C-INT – Localized Chemical Oxidation and MNA

The first two options—Option 1C-INT, No Action, and Option 2C-INT, Institutional Controls, for the intermediate zone of Plume C are identical in name and description to Alternative 1C, No Action, and Alternative 2C, Institutional Controls, for the shallow zone of Plume C. Therefore, the development of those intermediate zone options assumes that all of the discussion in Sections 4.1.1 and 4.1.2 applies and will not be repeated in this section.

For the purposes of cost estimating, the value associated with the most conservative intermediate MNA option is presented. Due to variations in length of the different shallow zone alternatives, the institutional controls and 5-Year Reviews associated with the intermediate MNA costs differ. For a complete list of costs associated with each, individual intermediate option, refer to Volume III.

7.1.7.1 Option 3C-INT – Monitored Natural Attenuation

According to USEPA guidance (USEPA 1999), the most important considerations regarding the suitability of MNA as a remedy include:

- Whether the contaminants are likely to be effectively addressed by natural attenuation processes;
- Stability of the groundwater contaminant plume and its potential for migration; and
- Potential for unacceptable risks to human health or environmental resources by the contamination.

Groundwater sampling data and numerical modeling results suggest that the intermediate zone at Plume C is relatively stable and is shrinking in size and contaminant mass (Volume II). Based on these results, MNA is identified as a viable alternative. This alternative would also be subject to institutional controls, as described in Section 7.1.2, to limit access and future development of groundwater.

Process Description

Refer to Section 4.1.3.1 for the process description of natural attenuation.

Based on results of MNA groundwater modeling presented in Volume II, the time for TCE concentrations throughout the entire plume to be naturally attenuated to 5 µg/L from present conditions is estimated to be approximately 100 years. Modeled results for Option 3C-INT (MNA) are shown on Figure 7-9.

Conceptual Design

Refer to Section 4.1.6.2 for conceptual design of MNA.

Performance Monitoring

Performance monitoring would consist of groundwater monitoring, as discussed in the following paragraphs.

Groundwater Monitoring. The LTM monitoring well network would be similar to that for the shallow zone of Plume C. Monitoring of the intermediate zone would occur until established groundwater standards are met in the zone, and four intermediate-depth monitoring wells are assumed.

Surface Water Monitoring. Surface water sampling would not be required for the intermediate zone because there are no surface water effects from intermediate zone contamination.

Analytical Protocol. All performance monitoring points would be sampled and analyzed for those analytes listed in Table 4-1. For further discussion, see Section 7.1.3.

Sampling Frequency and Duration of Monitoring. Results of MNA groundwater modeling (Volume II) suggest that TCE concentrations in groundwater will attenuate to 5 µg/L from present conditions in approximately 100 years. Therefore, the proposed LTM program sampling duration is based on a 100-year monitoring period. For additional details, see Section 4.1.6.1.

7.1.7.2 Option 4C-INT – Localized Chemical Oxidation and MNA

This option would provide chemical oxidation using $KMnO_4$, followed by MNA, to treat the low-concentration groundwater found in the intermediate zone of Plume C. The following sections provide a process description, rationale for selection, conceptual design, and process monitoring plan of this intermediate zone option. This alternative would also be subject to institutional controls, as described in Section 7.1.2, to limit access and future development of groundwater.

Process Description

For a process description of $KMnO_4$, for intermediate zone groundwater, see Section 4.1.6.2. For details of MNA, see Section 4.1.3.

Rationale for Alternative

For the rationale for using $KMnO_4$ and MNA for intermediate zone groundwater, see Section 4.1.6.2. The proposed treatment area of 0.7 acre for this zone was an optimization of the area in an attempt to treat the area of highest observed TCE concentrations in the intermediate zone and remove the most contaminant mass. Thus, the cleanup time for the intermediate layer of Plume C was estimated as 60 years (Table 7-5).

Conceptual Design

The concept of the designs for injected $KMnO_4$ and MNA for the intermediate zone are discussed in the following paragraphs.

Potassium Permanganate. Plume C encompasses a relatively large area; therefore, only the higher concentration portion of the plume would be treated with $KMnO_4$ to remove contaminant mass and accelerate MNA. The treatment area is approximately 2.1 acres and is displayed on Figure 7-10. The depth of the treatment area is estimated to be 40 to 50 feet bgs in the intermediate aquifer, and an estimated 90 injection points are planned. For additional details, see Section 4.1.6.2.

In situ chemical treatment and MNA modeling results are shown in Figure 7-11. The modeling assumptions made to evaluate the effectiveness of this technology using the Zone D groundwater model are provided in Volume II.

Monitored Natural Attenuation. The LTM program goals for the intermediate zone at Plume C in Section 4.1.3 are identical to those for the shallow zone with the exception of surface water. Because the intermediate groundwater does not impact surface water, a surface water-related goal would not be included.

Performance Monitoring

Performance monitoring would consist of groundwater monitoring, as discussed in the following paragraphs.

Groundwater Monitoring. The LTM monitoring well network would be similar to that for the shallow zone of Plume C. Monitoring of the intermediate zone would occur until established groundwater standards are met in the zone, and four intermediate-depth monitoring wells are assumed.

Surface Water Monitoring. Surface water sampling would not be required for the intermediate zone because there are no surface water effects from intermediate zone contamination.

Analytical Protocol. All performance monitoring points would be sampled and analyzed for those analytes listed in Table 4-1. For further discussion, see Section 7.1.3.

Sampling Frequency and Duration of Monitoring. Results of MNA groundwater modeling (Volume II) suggest that TCE concentrations in groundwater would attenuate to 5 µg/L from present conditions in approximately 60 years. Therefore, the proposed LTM program sampling duration is based on a 60-year monitoring period. For additional details, see Section 4.1.6.1.

7.2 DETAILED ANALYSIS OF ALTERNATIVES

This section presents the individual analysis and assessment of each Plume C groundwater remedial alternative with respect to the nine evaluation criteria. The first two (Overall Protection and Compliance with ARARs) are threshold criteria. Alternatives are evaluated for whether they provide protectiveness or comply with ARARs. Alternatives must be both protective and comply with ARARs to be considered for a remedy. The next five are balancing criteria, where the relative tradeoffs among the criteria are evaluated. These first seven criteria are further described in Table 4-3. The final two are modifying criteria, in which the state and the community express whether they support or oppose the alternatives, which are evaluated by the end of the public comment period. Following the individual analysis is a comparative analysis among the groundwater alternatives. The comparative analysis will assess the relative performance of each groundwater alternative with respect to each criterion.

The Institutional Controls Alternative will be incorporated into all of the alternatives. Costs associated with institutional controls have been added to the costs associated with each alternative. Table 7-7 contains a summary of detailed analysis for the alternatives.

7.2.1 Alternative 1C – No Action

The No Action Alternative assumes no further action would be taken for groundwater at Zone D. This alternative is required by the NCP and selected for detailed analysis so that it may be used as a baseline for comparative analysis of the risk and cost associated with other alternatives. Although there would be no capital cost involved with this alternative, the future costs and liabilities associated with exposure risks are unknown. The No Action Alternative would not take into account natural attenuation of the groundwater plume through time.

7.2.1.1 Overall Protection of Human Health and the Environment

Although the BRA identified no unacceptable threat to human health or the environment under current groundwater conditions, this alternative would not include a means to monitor or assess protection of human health or the environment. Therefore, the No Action Alternative would not be protective of human health and the environment.

7.2.1.2 Compliance with ARARs

The No Action Alternative would not comply with ARARs.

7.2.1.3 Long-Term Effectiveness

The potential risk of exposure to groundwater would continue to exist with this alternative, and untreated TCE contamination would remain in groundwater. Therefore, the No Action Alternative would not provide long-term effectiveness.

7.2.1.4 Reduction of Toxicity, Mobility, and Volume

Since no active treatment of groundwater would be undertaken, there would not be an active reduction of toxicity, mobility, or volume. However, over time, the groundwater plume would be expected to naturally attenuate.

7.2.1.5 Short-Term Effectiveness

Because no action for groundwater would be taken, there would be no additive short-term exposure to the community or workers.

7.2.1.6 Implementability

There would be no implementation concerns associated with the No Action Alternative for groundwater.

7.2.1.7 Cost

The No Action Alternative for groundwater would incur no cost. The cost associated with long-term liability would be unknown.

7.2.2 Alternative 2C – Institutional Controls

The Institutional Controls Alternative assumes that legal and/or physical controls would be implemented for groundwater at Zone D. This alternative has limited capital cost, but the future costs and liabilities associated with exposure risks can only be estimated. The Institutional Controls Alternative would not take into account natural attenuation of the groundwater plume through time.

7.2.2.1 Overall Protection of Human Health and the Environment

The Institutional Controls Alternative would protect human health and the environment through implementation and enforcement of administrative controls described in Section 7.1.2. No unacceptable short-term or cross-media impacts would be expected.

7.2.2.2 Compliance with ARARs

The Institutional Controls Alternative would comply with potential action- and location-specific ARARs. It would not comply with the potential chemical-specific ARAR of the federal MCL for TCE of 5 µg/L. This alternative would not comply with ARARs requiring monitoring of releases (i.e., 40 CFR Part 264).

7.2.2.3 Long-Term Effectiveness and Permanence

The untreated TCE contamination in groundwater would continue to exist at Zone D. This alternative would offer a level of protection through the regulation of groundwater use as discussed in Section 7.1.2. Controls would be implemented to limit or exclude use of the groundwater and thus reduce the potential for exposure. These controls would be contained in the General Plan and would be a long-term and reliable management control, enforced by USAF within the installation boundaries. The groundwater plume would be expected to naturally attenuate over time.

7.2.2.4 Reduction of Toxicity, Mobility and Volume

The contaminated groundwater would not be treated to reduce the toxicity, mobility, or volume. However, over time, the groundwater plume would be expected to naturally attenuate.

7.2.2.5 Short-Term Effectiveness

This alternative would not include a remediation component, so there would be no additive short-term exposure to the community or workers.

7.2.2.6 Implementability

This alternative would be easy to implement technically and administratively. Documentation in the General Plan and coordination with installation personnel, as discussed in Section 7.1.2, would be a reliable management control that would be easy to implement.

7.2.2.7 Cost

Costs for this alternative include a capital cost of $18,484, plus annual costs of $2,387 for updates. These costs are outputs of RACER™ and reflected in present value dollars in Volume III.

7.2.3 Alternative 3C – Groundwater Extraction, *Ex situ* Treatment, and Monitored Natural Attenuation

Alternative 3C assumes that groundwater extraction and treatment would reduce TCE concentrations to a threshold concentration, then long-term groundwater monitoring, and legal and/or physical institutional controls (Alternative 2C) would be used to complete the remediation of groundwater in Plume C. The future O&M costs, LTM costs, and potential liabilities associated with exposure risks can only be estimated. Based on groundwater modeling, this

alternative would require 20 years of extraction and treatment, followed by 10 years of natural attenuation of the groundwater plume to complete remediation.

7.2.3.1 Overall Protection of Human Health and the Environment

Alternative 3C would protect human health and the environment by removing and treating the contaminated groundwater, enforcement of the LTM program, and the administrative controls described in Section 7.1.2.

The human health BRA results indicate that TCE contamination in the groundwater at Zone D would not pose an unacceptable threat to human health under current conditions. An unacceptable risk may be posed if residences were built on the site and used the groundwater for drinking, washing, and other domestic uses; but this is considered unlikely because municipal supplies are available. Or, unacceptable risk may be encountered with the construction of new buildings over moderate to high concentrations of TCE in groundwater. However, this risk can be mitigated through design additions such as a sub slab depressurization system.

By comparing historical and current site data, TCE concentrations currently exceed MCLs at the furthest downgradient monitoring wells. The groundwater extraction and treatment alternative would be designed to remove contaminant concentrations exceeding MCLs through groundwater extraction. The contaminants present in the extracted groundwater would be removed by phase separation and then destroyed by a bioreactor, providing long-term protection. Treated groundwater discharge would be monitored to demonstrate compliance with effluent goals that protect water quality.

No unacceptable short-term or cross-media impacts would be expected.

7.2.3.2 Compliance with ARARs

Alternative 3C would comply with potential action- and location-specific ARARs and with the potential chemical-specific ARAR of the federal MCL for TCE of 5 µg/L at the end of the 30-year LTM period. This alternative complies with the USEPA preference for treatment and ARARs requiring monitoring of releases (i.e., 40 CFR Part 264), and this alternative would meet substantive NPDES discharge requirements.

7.2.3.3 Long-Term Effectiveness

The extraction and treatment alternative would rely on the effectiveness of groundwater extraction and hydraulic control to reduce contaminant concentrations and minimize contaminant migration over time. Modeling indicates that TCE concentrations within the high concentration area would decrease to 50 µg/L within 20 years with 67 extraction wells pumping at a combined rate of approximately 53 gpm, leaving small areas of concentrations below 50 µg/L for the additional 10 years of the MNA period (Figure 7-2). Natural attenuation of the plume would reduce TCE concentrations to 5 µg/L during this additional 10-year period.

This alternative would offer a level of protection through the treatment and monitoring of groundwater contaminant concentration and flow, as discussed in Section 7.1.3, and by regulation of groundwater use, as discussed in Section 7.1.2.

7.2.3.4 Reduction of Toxicity, Mobility, and Volume

Alternative 3C would reduce contaminant concentrations and minimize contaminant migration over time through groundwater extraction and hydraulic control. The contaminated groundwater would be actively treated for 20 years to reduce the toxicity and volume. After active treatment, the groundwater plume would be expected to naturally attenuate to ARARs in an additional 10 years, for a combined time frame of 30 years.

7.2.3.5 Short-Term Effectiveness

The estimated time to meet RAOs for this alternative is 30 years, although it is likely that RAOs in some areas would be met sooner. Adsorption- and diffusion-limited conditions may be achieved quickly, and pulsing of the extraction system may be needed.

This alternative would include a remediation component, but there would be no additive short-term exposure to the community. However, treatment system O&M and LTM workers would use protective measures such as on-site monitoring and appropriate PPE while conducting intrusive, construction, or disposal activities within the plume area. Therefore, minimal potential would exist for exposure to contaminants.

Soil spoils from drilling and construction will be placed in soil containers, covered or sealed, and transported to a Class C landfill. Because the soil will be contained, the community does not incur incremental risk associated with disposal, but could incur a slight incremental risk due to increased traffic.

7.2.3.6 Implementability

Technology approval by federal, state, and local agencies would be anticipated due to the "presumptive remedy" nature of Alternative 3C. Construction and O&M of a groundwater extraction and treatment system and installation of monitoring wells at the site is technically feasible and could easily be implemented. The groundwater extraction and treatment alternative would require well installation, treatment system construction, discharge to a tributary of Crow Creek, O&M of the treatment system, and groundwater and treatment system monitoring. The equipment and personnel for performing these tasks are widely available. Management of the O&M and monitoring programs would be required to allow proper and effective system operation. Periodic site reviews would be conducted to confirm the completeness of data and to verify the effectiveness of the alternative.

An O&M Plan would be prepared for the two-phase extraction system and the bioreactor treatment system as discussed in Section 7.1.3, an LTM Plan would be prepared for the 30-year LTM period, and documentation would be provided in the General Plan as discussed in Section 7.1.2.

7.2.3.7 Cost

Costs of Alternative 3C would include capital costs for the extraction and treatment system design and construction, preparation of the LTM Plan, changes to the General Plan, community and educational programs, reporting, and management and administrative efforts. Capital costs associated with this alternative are estimated to be $2.1 million. Total O&M costs that include

extraction and treatment system O&M, LTM data collection, analysis, evaluation, and reporting costs are estimated to be about $11.1 million over the 30-year life of the alternative. Present value cost is $8.2 million. A summary of the costs is provided in Table 7-2. The detailed cost estimate is provided in Volume III.

7.2.4 Alternative 4C – Chemical Oxidation at Plume Head, Localized Chemical Oxidation, Permeable Reactive Barrier, and Monitored Natural Attenuation

Alternative 4C assumes that chemical oxidation using Fenton's Reagent at the head of the plume and $KMnO_4$ in the areas of greater than 300 µg/L TCE would reduce TCE concentrations to a threshold concentration. Downgradient treatment by flow through a PRB at the toe of the plume, long-term groundwater monitoring, and legal and/or physical institutional controls (Alternative 2C) would be used to complete the remediation of groundwater in Plume C. The future O&M costs, LTM costs, and potential liabilities associated with exposure risks can only be estimated. Based on groundwater modeling, this alternative would require six months of chemical oxidation, followed by 40 years of PRB treatment to protect Crow Creek water quality, and an additional 10 years of natural attenuation of the groundwater plume to complete remediation in a 50-year time period.

7.2.4.1 Overall Protection of Human Health and the Environment

Alternative 4C would protect human health and the environment by *in situ* treatment of the contaminated groundwater with chemical oxidizers and a PRB, enforcement of the LTM program, and the administrative controls described in Section 7.1.2.

The human health BRA results indicate that TCE contamination in the groundwater at Zone D would not pose an unacceptable threat to human health under current conditions. An unacceptable risk may be posed if residences were built on the site and used the groundwater for drinking, washing, and other domestic uses; but this is considered unlikely because municipal supplies are available. Or, unacceptable risk may be encountered with the construction of new buildings over moderate to high concentrations of TCE in groundwater. However, this risk can be mitigated through design additions such as a sub slab depressurization system.

By comparing historical and current site data, TCE concentrations currently exceed MCLs at the furthest downgradient monitoring wells. The chemical oxidation/PRB alternative would be designed to destroy contaminant concentrations exceeding MCLs through *in situ* groundwater treatment. No unacceptable short-term or cross-media impacts would be expected.

7.2.4.2 Compliance with ARARs

Alternative 4C would comply with potential action- and location-specific ARARs and with the potential chemical-specific ARAR of the federal MCL for TCE of 5 µg/L at the end of the 50-year LTM period. This alternative complies with the USEPA preference for treatment and ARARs requiring monitoring of releases (i.e., 40 CFR Part 264).

7.2.4.3 Long-Term Effectiveness

The chemical oxidation/PRB alternative would rely on the effectiveness of *in situ* groundwater treatment and hydraulic control to reduce contaminant concentrations and minimize contaminant migration over time. Modeling indicates that TCE concentrations within the high concentration area would decrease within six months to less than 10 µg/L in the treated areas by using 50 Fenton's Reagent and 90 $KMnO_4$ injection points, but would leave small areas of concentrations below 400 µg/L (Figure 7-3).

Continued *in situ* treatment by flow through the downgradient PRB and natural attenuation of the plume would reduce the highest TCE concentrations to near 100 µg/L during the first 10 years of the PRB/MNA period, to less than 50 µg/L during an additional 20 years, and to 5 µg/L by Year 50 (Figure 7-4).

This alternative would offer a level of protection through the *in situ* treatment and monitoring of groundwater contaminant concentration and flow, as discussed in Section 7.1.3, and by regulation of groundwater use, as discussed in Section 7.1.2.

7.2.4.4 Reduction of Toxicity, Mobility, and Volume

Alternative 4C would reduce contaminant concentrations and minimize contaminant migration over time through *in situ* treatment. The contaminated groundwater would be treated for six months with chemical oxidation to reduce the toxicity and volume of the groundwater contamination to a threshold level above the MCL, then treated by flow through a PRB for 40 years. After treatment, the groundwater plume would be expected to naturally attenuate to ARARs in an additional 10 years.

7.2.4.5 Short-Term Effectiveness

The estimated time to meet RAOs for Alternative 4C is 50 years, although it is likely that RAOs in many areas treated by chemical oxidation would be met within six months. This alternative would include a remediation component, but there would be no additive short-term exposure to the community. However, chemical oxidation injection workers, PRB construction workers, and LTM workers would use protective measures such as on-site monitoring and appropriate PPE while conducting intrusive and construction activities within the plume area. Therefore, minimal potential would exist for exposure to contaminants.

Soil spoils from drilling and construction will be placed in soil containers, covered or sealed, and transported to a Class C landfill. Because the soil will be contained, the community does not incur incremental risk associated with disposal, but could incur a slight incremental risk due to increased traffic.

7.2.4.6 Implementability

Technology approval of Alternative 4C by federal, state, and local agencies would be anticipated due to the successful use of both chemical oxidation and PRBs in pilot tests and IRAs in Zone D. Injection of chemical oxidizers, construction of a PRB, and installation of monitoring wells at the site are technically feasible and could be implemented with some difficulty. The equipment and

personnel for performing these tasks are available in the Rocky Mountain Region. Periodic site reviews would be conducted to verify the effectiveness of the alternative.

An injection system and PRB design would be prepared as discussed in Section 7.1.4, an LTM Plan would be prepared for the 50-year LTM period, and documentation would be provided in the General Plan as discussed in Section 7.1.2.

7.2.4.7 Cost

Costs of this alternative would include capital costs for chemical oxidation and PRB design and implementation, preparation of the LTM Plan, changes to the General Plan, community and educational programs, reporting, and management and administrative efforts. Capital costs associated with this alternative are estimated to be $3.4 million and do not include replacement costs for a PRB since no replacement is planned. Total O&M costs that include LTM data collection, analysis, evaluation, and reporting costs; five-year review costs; and administrative costs for the institutional controls are estimated to be about $3.8 million over the 50-year life of the alternative. Present value cost is approximately $4.9 million. The detailed cost estimate is provided in Volume III.

7.2.5 Alternative 5C – Electrical Resistance Heating at Plume Head, Localized Chemical Oxidation, Permeable Reactive Barrier, and Monitored Natural Attenuation

Alternative 5C assumes that ERH in the highest concentration upgradient head of the plume and chemical oxidation using Fenton's Reagent and $KMnO_4$ in the areas in the hot spots would reduce TCE concentrations to MCLs within the treated zone. A PRB to protect the plume intercept with Crow Creek, LTM for the residual groundwater contamination after treatment and the untreated fringes of the plume, and legal and/or physical institutional controls (Alternative 2C) would be used to complete the remediation of groundwater in Plume C. The future O&M costs, LTM costs, and potential liabilities associated with exposure risks can only be estimated. Based on groundwater modeling, this alternative would require six months of ERH and chemical oxidation to reduce central plume concentrations below 10 µg/L, followed by 50 years of natural attenuation of the groundwater plume to complete remediation in a 50-year time period.

7.2.5.1 Overall Protection of Human Health and the Environment

Alternative 5C would protect human health and the environment by *in situ* treatment of the contaminated groundwater with ERH, chemical oxidizers, enforcement of the LTM program, and the administrative controls described in Section 7.1.2.

The human health BRA results indicate that TCE contamination in the groundwater at Zone D would not pose an unacceptable threat to human health under current conditions. An unacceptable risk may be posed if residences were built on the site and used the groundwater for drinking, washing, and other domestic uses; but this is considered unlikely because municipal supplies are available. Or, unacceptable risk may be encountered with the construction of new buildings over moderate to high concentrations of TCE in groundwater. However, this risk can be mitigated through design additions such as a sub slab depressurization system.

By comparing historical and current site data, TCE concentrations currently exceed MCLs at the furthest downgradient monitoring wells. The ERH/chemical oxidation/MNA alternative would

be designed to destroy contaminant concentrations exceeding MCLs through *in situ* groundwater treatment.

No unacceptable short-term or cross-media impacts would be expected.

7.2.5.2 Compliance with ARARs

Alternative 5C would comply with potential action- and location-specific ARARs and with the potential chemical-specific ARAR of the federal MCL for TCE of 5 µg/L at the end of the 50-year LTM period. This alternative would comply with the USEPA preference for treatment and ARARs requiring monitoring of releases (i.e., 40 CFR Part 264).

7.2.5.3 Long-Term Effectiveness

The ERH/chemical oxidation/PRB/MNA alternative would rely on the effectiveness of *in situ* groundwater treatment to reduce contaminant concentrations and minimize contaminant migration over time. Modeling indicates that TCE concentrations within the high concentration area would decrease within six months to less than 10 µg/L in the treated areas by using one large-diameter ERH hexagonal grid, 50 Fenton's Reagent injection points, and 90 $KMnO_4$ injection points, but would leave areas of concentrations below 150 µg/L outside the treated zone (Figure 7-5).

Continued contaminant reduction by natural attenuation of the plume would reduce the highest TCE concentrations to around 100 µg/L during the first 10 years of the MNA period, to less than 100 µg/L during an additional 10 years, and to 5 µg/L by Year 50 (Figure 7-6). However, the presence of the PRB would protect Crow Creek from TCE concentrations greater than 5 µg/L prior to Year 10.

This alternative would offer a level of protection through the *in situ* treatment and monitoring of groundwater contaminant concentration and flow, as discussed in Section 7.1.6, and by regulation of groundwater use, as discussed in Section 7.1.2.

7.2.5.4 Reduction of Toxicity, Mobility and Volume

Alternative 5C would reduce contaminant concentrations and minimize contaminant migration over time through *in situ* treatment. The contaminated groundwater would be treated for six months with ERH and chemical oxidation to reduce the toxicity and volume of the groundwater contamination to a threshold level above the MCL. After treatment, the groundwater plume would be expected to naturally attenuate to ARARs in 50 years. However, the presence of the PRB would protect Crow Creek from TCE prior to Year 10.

7.2.5.5 Short-Term Effectiveness

The estimated time to meet RAOs for Alternative 5C is 50 years, although it is likely that RAOs in many areas treated by chemical oxidation would be met within six months. This alternative would include a remediation component, but there would be no additive short-term exposure to the community. However, ERH, chemical oxidation, and PRB construction/ injection workers, and LTM workers would use protective measures such as on-site monitoring and appropriate

PPE while conducting intrusive activities within the plume area. Therefore, minimal potential would exist for exposure to contaminants.

Soil spoils from drilling and construction will be placed in soil containers, covered or sealed, and transported to a Class C landfill. Because the soil will be contained, the community does not incur incremental risk associated with disposal, but could incur a slight incremental risk due to increased traffic.

7.2.5.6 Implementability

Administrative approval of Alternative 5C by federal, state, and local agencies would be anticipated due to the successful use of chemical oxidation in pilot test at Plume C. However, the success of ERH has not been demonstrated at FEW, although it has been used successfully at other DoD sites. Injection of chemical oxidizers, construction of an ERH/SVE system and a PRB, and installation of monitoring wells at the site are technically feasible and could be implemented with some difficulty. The equipment and personnel for performing the injection, SVE, and PRB construction tasks are available in the Rocky Mountain Region. However, ERH, including SPH, and Fenton's Reagent injection require national specialty subcontractors who are not available locally. Periodic site reviews would be conducted to verify the effectiveness of the alternative.

An injection system and PRB design would be prepared as discussed in Section 7.1.6, an LTM Plan would be prepared for the 50-year LTM period, and documentation would be provided in the General Plan as discussed in Section 7.1.2.

7.2.5.7 Cost

Costs of this alternative would include capital costs for chemical oxidation, ERH/SVE, PRB design and implementation, preparation of the LTM Plan, changes to the General Plan, community and educational programs, reporting, and management and administrative efforts. Capital costs associated with this alternative are estimated to be $6.0 million and do not include replacement costs for a PRB since no replacement is planned. Total O&M costs that include LTM data collection, analysis, evaluation, and reporting costs are estimated to be about $3.9 million over the 50-year life of the alternative. Present value cost is $7.3 million. The detailed cost estimate is provided in Volume III.

7.2.6 Alternative 6C – Groundwater Extraction and *Ex situ* Treatment at Plume Head, Localized Chemical Oxidation, Permeable Reactive Barrier, and Monitored Natural Attenuation

Alternative 6C assumes that groundwater extraction and treatment at the head of the plume and chemical oxidation using $KMnO_4$ in the areas of greater than 300 µg/L TCE would reduce TCE concentrations to MCLs within the treated zone. Downgradient treatment by flow through a PRB at the toe of the plume, long-term groundwater monitoring, and legal and/or physical institutional controls would be used to complete the remediation of groundwater in Plume C. The future O&M costs, LTM costs, and potential liabilities associated with exposure risks can only be estimated. Based on groundwater modeling, this alternative would require six months of chemical oxidation, five years of extraction and treatment, 40 years of treatment with the

downgradient PRB, then an additional five years of natural attenuation of the groundwater plume to complete remediation in a 50-year period.

7.2.6.1 Overall Protection of Human Health and the Environment

Alternative 6C would protect human health and the environment by removing and treating the contaminated groundwater at the head of the plume, *in situ* treatment of "hot spots" with chemical oxidizers, downgradient treatment of the creek intercept with a PRB, enforcement of the LTM program, and the administrative controls described in Section 7.1.2.

The human health BRA results indicate that TCE contamination in the groundwater at Zone D would not pose an unacceptable threat to human health under current conditions. An unacceptable risk may be posed if residences were built on the site and used the groundwater for drinking, washing, and other domestic uses; but this is considered unlikely because municipal supplies are available. Or, unacceptable risk may be encountered with the construction of new buildings over moderate to high concentrations of TCE in groundwater. However, this risk can be mitigated through design additions such as a sub slab depressurization system.

By comparing historical and current site data, TCE concentrations currently exceed MCLs at the furthest downgradient monitoring wells. This alternative would be designed to remove contaminant concentrations exceeding MCLs through groundwater extraction, *in situ* chemical oxidation, and a PRB. The contaminants present in the extracted groundwater would be removed by phase separation and then destroyed by a bioreactor, by chemical oxidation with $KMnO_4$, and by flow through a ZVI PRB to provide long-term protection. Treated groundwater discharge would be monitored to demonstrate compliance with effluent goals that protect water quality.

No unacceptable short-term or cross-media impacts would be expected.

7.2.6.2 Compliance with ARARs

Alternative 6C would comply with potential action- and location-specific ARARs and with the potential chemical-specific ARAR of the federal MCL for TCE of 5 µg/L at the end of the 50-year LTM period. This alternative would comply with the USEPA preference for treatment and ARARs requiring monitoring of releases (i.e., 40 CFR Part 264), and this alternative would meet substantive NPDES discharge requirements.

7.2.6.3 Long-Term Effectiveness

The extraction and treatment/chemical oxidation/PRB alternative would rely on the effectiveness of groundwater extraction and hydraulic control, *in situ* chemical oxidation, and flow through a ZVI PRB to reduce contaminant concentrations and minimize contaminant migration over time. Modeling indicates that TCE concentrations within the area treated with $KMnO_4$ would decrease to MCLs in six months, with the extraction and treatment system to 10 µg/L within five years with six extraction wells pumping at a combined rate of approximately 13 gpm, leaving small areas of concentrations below 200 µg/L for the additional 35 years of the treatment period by flow through the PRB (Figure 7-8). Natural attenuation the plume would reduce TCE concentrations to 5 µg/L during the 10-year period after the end of design-life of the PRB.

This alternative would offer a level of protection through the treatment and monitoring of groundwater contaminant concentration and flow, as discussed in Section 7.1.6, and by regulation of groundwater use, as discussed in Section 7.1.2.

7.2.6.4 Reduction of Toxicity, Mobility, and Volume

Alternative 6C would reduce contaminant concentrations and minimize contaminant migration over time through *in situ* treatment, groundwater extraction, and hydraulic control. The contaminated groundwater would be treated for six months with $KMnO_4$, five years with extraction and treatment, and 40 years with a PRB to reduce the toxicity and volume of the groundwater contamination. After treatment, the groundwater plume would be expected to naturally attenuate to ARARs in an additional 10 years.

7.2.6.5 Short-Term Effectiveness

The estimated time to meet RAOs for this alternative is 50 years, although it is likely that RAOs in some areas would be met sooner. Adsorption- and diffusion-limited conditions may be achieved quickly, and pulsing of the extraction system may be needed.

This alternative would include a remediation component, but there would be no additive short-term exposure to the community. However, injection system installation workers, PRB construction workers, treatment system construction and O&M workers, and LTM workers would use protective measures such as on-site monitoring and appropriate PPE while conducting intrusive, construction, or disposal activities within the plume area. Therefore, minimal potential would exist for exposure to contaminants.

Soil spoils from drilling and construction will be placed in soil containers, covered or sealed, and transported to a Class C landfill. Because the soil will be contained, the community does not incur incremental risk associated with disposal, but could incur a slight incremental risk due to increased traffic.

7.2.6.6 Implementability

Technology approval by federal, state, and local agencies would be anticipated due to the "presumptive remedy" nature of Alternative 6C and the successful use of two-phase extraction, bioreactor treatment, chemical oxidation, and PRBs in pilot tests and IRAs at Plume C and SS7 (Figure 7-7). Construction of a groundwater extraction and treatment system and PRB and injection of $KMnO_4$ are technically feasible and could be implemented with some difficulty. This alternative would require PRB and extraction well installation, $KMnO_4$ injection, treatment system construction, discharge to a tributary of Crow Creek, O&M of the treatment system, and LTM. The equipment and personnel for performing these tasks are available in the Rocky Mountain Region. Management of the O&M and monitoring programs would be required to allow proper and effective system operation. Periodic site reviews would be conducted to confirm the completeness of data and to verify the effectiveness of the alternative.

Designs for the $KMnO_4$ injection, PRB, and extraction/treatment system and an O&M Plan for the two-phase extraction system and the bioreactor treatment system would be prepared as discussed in Section 7.1.6, an LTM Plan would be prepared for the 50-year LTM period, and documentation would be provided in the General Plan as discussed in Section 7.1.2.

7.2.6.7 Cost

Costs of Alternative 6C would include capital costs for the extraction and treatment system and PRB design and construction, injection of the $KMnO_4$, preparation of the LTM Plan, changes to the General Plan, community and educational programs, reporting, and management and administrative efforts. Capital costs associated with this alternative are estimated to be $3.5 million and do not include replacement costs for a PRB since no replacement is planned. Total O&M costs that include extraction and treatment system O&M, LTM data collection, analysis, evaluation, and reporting costs are estimated to be about $5.6 million over the 50-year life of the alternative. Present value cost is $6.4 million. The detailed cost estimate is provided in Volume III.

7.2.7 Intermediate Zone Options

This section presents the individual analysis and assessment of each intermediate zone option with respect to the seven evaluation criteria, as described above. For a summary of this analysis, see Table 7-8.

For detailed analysis of Option 1C-INT, No Action, and Option 2C-INT, Institutional Controls, see Sections 7.2.1 and 7.2.2.

7.2.7.1 Option 3C-INT – Monitored Natural Attenuation

Option 3C-INT assumes that LTM of natural attenuation processes that reduce TCE concentrations over time would be implemented for groundwater in the intermediate zone at Plume C. Institutional controls would be included in the alternative to prevent the use of groundwater for human consumption prior to the end of the MNA period.

Overall Protection of Human Health and the Environment

With institutional controls, MNA in the intermediate zone would protect human health and the environment under current conditions through natural attenuation processes. No unacceptable short-term or cross-media impacts would be expected.

Compliance with ARARs

With institutional controls, the use of MNA in the intermediate zone would comply with all potential action- and location-specific ARARs, but would not comply with the potential chemical-specific ARAR of the federal MCL for TCE of 5 µg/L until near the end of the 100-year monitoring period. MNA would comply with ARARs requiring monitoring of releases.

Long-Term Effectiveness

Natural processes will reduce contaminant levels in groundwater to RAOs over time. Continued monitoring would provide a reliable means to assess the residual concentrations and manage the risk posed by the residual. Institutional controls would limit or prevent use of the intermediate zone groundwater, and this process would produce no residual contamination. Minimal O&M of wells and groundwater sampling would be required.

Reduction of Toxicity, Mobility, and Volume

Toxicity, mobility, and volume of TCE would be reduced over time from natural attenuation of contaminants in groundwater, and TCE levels would be reduced to RAOs in intermediate zone groundwater in approximately 100 years. No residuals would be present in groundwater at completion, and attenuation would be irreversible.

Short-Term Effectiveness

No additional risk to site workers and the environment would occur because there is no construction of a treatment system. There would also be no increased risk to workers, the community, or the environment during implementation. Time to achieve RAOs within the intermediate zone at Plume C was estimated to be approximately 100 years.

Soil spoils from drilling will be placed in soil containers, covered or sealed, and transported to a Class C landfill. Because the soil will be contained, the community does not incur incremental risk associated with disposal, but could incur a slight incremental risk due to increased traffic.

Implementability

This option would be easy to implement and should not create schedule delays. Passive methods such as MNA do not require removal, aboveground treatment method, or TSD services. Monitoring the effectiveness would be simple, and administrative requirements to accommodate this option would include modifying the General Plan.

Cost

Costs of this option would include an LTM Plan, changes to the General Plan, community and educational programs, reporting, and management and administrative efforts. There are no capital costs associated with this alternative due to the availability of numerous existing monitoring wells. Total O&M costs that include LTM data collection, analysis, evaluation, and reporting costs are estimated to be about $3.2 million over the 100-year life of the alternative. Present value cost is $0.7 million. The detailed cost estimate is provided in Volume III.

7.2.7.2 Option 4C-INT – Localized Chemical Oxidation and MNA

Option 4C-INT assumes that a combination of chemical oxidation, long-term groundwater monitoring, and legal and/or physical institutional controls would be implemented for intermediate zone groundwater in Plume C. The future O&M costs, LTM costs, and potential liabilities associated with exposure risks can only be estimated.

Overall Protection of Human Health and the Environment

Comparing historical and current site data, TCE concentrations currently exceed RAOs in some intermediate-zone monitoring wells. This chemical oxidation/MNA option would protect human health and the environment by *in situ* treatment of the contaminated groundwater with chemical oxidizers, application of an LTM program, and enforcement of institutional controls. The option would be designed to destroy contaminant concentrations exceeding RAOs through a

combination of *in situ* groundwater treatment and MNA. No unacceptable short-term or cross-media impacts would be expected.

Compliance with ARARs

This option would comply with potential action- and location-specific ARARs and with the potential chemical-specific ARAR of the federal MCL for TCE of 5 µg/L at the end of the LTM period. It would also comply with the USEPA preference for treatment of contaminated groundwater (i.e., 40 CFR Part 264). No discharge permits would be required for this option.

Long-Term Effectiveness and Permanence

Active treatment would reduce the TCE concentrations in the intermediate zone groundwater to 50 µg/L in approximately six months, and natural processes would reduce the TCE concentration in groundwater to the RAOs approximately 60 years after completion of active treatment. Continued monitoring would provide a reliable means to assess the treatment effectiveness, and institutional controls would limit or prevent use of groundwater. Greater O&M than the MNA option would occur only during the six-month treatment method period.

Reduction of Toxicity, Mobility and Volume

Toxicity, mobility, and volume of TCE would be reduced over time from active treatment of groundwater and natural processes. TCE concentrations in groundwater would be reduced to RAOs in intermediate zone groundwater in approximately 60 years, and the treatment process would be irreversible.

Short-Term Effectiveness

There would be minimal additional risk to site workers and the environment during the construction phase involving drilling and injection of chemicals. Soil spoils from drilling will be placed in soil containers, covered or sealed, and transported to a Class C landfill. Because the soil will be contained, the community does not incur incremental risk associated with disposal, but could incur a slight incremental risk due to increased traffic. There would be no increased risk to workers, the community, or the environment during the implementation phase, which would involve only groundwater sampling. The time to achieve RAOs is estimated to be approximately 60 years.

Implementability

This option would be easy to implement and chemical oxidation is a proven and reliable technology. The chemical oxidation compound ($KMnO_4$) is readily available, as are the conventional well drilling and installation techniques that would be used. Schedule delays should not be expected due to lack of availability since multiple drilling contractors and $KMnO_4$ suppliers are available. Competitive bids can be obtained and monitoring the effectiveness is simple. Administrative requirements would include preparation of a treatment system design, an LTM Plan, and modifying the General Plan.

Cost

Costs of this alternative would include capital costs for chemical oxidation design and implementation, preparation of the LTM Plan, changes to the General Plan, community and educational programs, reporting, and management and administrative efforts. Capital costs associated with this alternative are estimated to be $1.8 million. Total O&M costs that include LTM data collection, analysis, evaluation, and reporting costs are estimated to be about $1.5 million over the 60-year life of the alternative. Present value cost is approximately $2.3 million. This cost may be reduced slightly if this option is utilized in combination with Alternatives 4C, 5C, or 6C due to reduced chem-ox mobilization costs. A summary of the costs is provided in Table 7-8. The detailed cost estimate is provided in Volume III.

7.3 COMPARATIVE ANALYSIS

The first seven sections compare these alternatives for the shallow Plume C groundwater:

- Alternative 1C – No Action
- Alternative 2C – Institutional Controls
- Alternative 3C – Groundwater Extraction, *Ex situ* Treatment, and MNA
- Alternative 4C – Chemical Oxidation, PRB, and MNA
- Alternative 5C – ERH, Localized Chemical Oxidation, PRB, and MNA
- Alternative 6C – Groundwater Extraction, *Ex situ* Treatment, Localized Chemical Oxidation, PRB, and MNA

One section also compares the following options for intermediate zone groundwater at Plume C:

- Option 1C-INT – No Action
- Option 2C-INT – Institutional Controls
- Option 3C-INT – MNA
- Option 4C-INT – Localized Chemical Oxidation and MNA

Tables 7-9 and 7-10 present a comparison among the criteria for each alternative/option comparison for the shallow zone and intermediate zone groundwater of Plume C, respectively. The tables are for the shallow groundwater zone or the intermediate groundwater zone of each plume, but do not combine the two. Because the comparisons are relative to the other alternatives for this plume, they should not be used for comparison to other plumes or even to the shallow versus intermediate groundwater in Plume C.

7.3.1 Overall Protection of Human Health and the Environment

No Action (Alternative 1C) would be protective of human health and the environment under current conditions because no current unacceptable risk has been identified. However, because this alternative would provide no means to monitor future contamination, it would not be protective over the long term. Institutional Controls (Alternative 2C) would provide

implementation and enforcement of administrative controls to prevent future use of the groundwater resource, but cannot monitor future conditions.

Because MNA alone was not considered for Plume C due to continuing high TCE concentrations at the plume head/source zone, the extraction, treatment method, and MNA alternative (Alternative 3C) would provide protection of human health and the environment through implementation of a plume-wide, two-phase, groundwater extraction and treatment method system, enforcement of the LTM program, and institutional controls.

The only differences in Alternatives 4C, 5C, and 6C are the technologies used to remediate the plume head; but none of these technologies would significantly improve the total time for remediation of the shallow zone over the others. All three alternatives would involve treatment of the "hot spot" with chemical oxidation, treatment of the creek intercept with a PRB, establishing an LTM program, and enforcement of institutional controls. In addition, the chemical oxidation/PRB/MNA alternative (Alternative 4C) would protect human health and the environment through implementation of chemical oxidation at the plume head. The ERH/chemical oxidation/PRB/MNA alternative (Alternative 5C) would implement ERH at the plume head, and the extraction/treatment/chemical oxidation/PRB/MNA alternative (Alternative 6C) would implement a groundwater extraction and treatment system at the plume head.

Therefore, Alternatives 3C, 4C, 5C, and 6C would be protective of human health and the environment in both the short- and long-term (Table 7-9). However, Alternatives 1C and 2C cannot provide long-term protectiveness with any certainty and do not meet this threshold criterion.

7.3.2 Compliance with ARARs

The No Action Alternative would not comply with ARARs. The Institutional Controls Alternative would comply with potential action- and location-specific ARARs, but not with the potential chemical-specific groundwater ARAR of the federal MCL for TCE of 5 µg/L or with ARARs requiring monitoring of releases. Because these first two alternatives do not meet this threshold criterion, they are not carried through the remainder of the comparative analysis.

Alternatives 3C, 4C, 5C, and 6C would comply with potential action and location specific ARARs and with ARARs requiring monitoring of releases (i.e., 40 CFR Part 264). Alternative 3C would comply with substantive NPDES discharge requirements. Alternative 3C would also comply with the potential chemical-specific groundwater ARAR set at the federal MCL for TCE of 5 µg/L near the end of a 30-year full-plume extraction, treatment method, and MNA period; Alternative 4C would comply after a 50-year *in situ* chemical oxidation/PRB/MNA period; Alternative 5C after a 40-year *in situ* ERH/chemical oxidation/PRB/MNA period; and Alternative 6C after a 50-year limited-area extraction/treatment method/chemical oxidation/PRB/MNA. Therefore, based on total time to comply with ARARs, Alternatives 3C, 4C, 5C, and 6C would be very similar (Table 7-9).

7.3.3 Long-Term Effectiveness and Permanence

In Alternative 3C, full-plume extraction and treatment would reduce the highest concentrations from greater than 7,000 µg/L TCE to 50 µg/L in 20 years, leaving small areas of concentrations below 50 µg/L for the additional 10 years of the MNA period (Figure 7-2, Table 7-9). However,

pump-and-treat systems may not be able to remove all sorbed contamination from some low hydraulic conductivity lithologies. Alternative 4C, chemical oxidation/PRB/MNA, would reduce the highest concentrations from greater than 7,000 µg/L TCE to less than 10 µg/L in six months in the treated areas, with continuing treatment by the PRB for an additional 40 years, leaving small areas of concentrations below 50 µg/L for the last 10 years of the MNA period (Figure 7-4).

Alternative 5C, ERH/chemical oxidation/PRB/MNA, would reduce concentrations in the same time frames as Alternative 4C, but would provide the highest degree of long-term effectiveness and permanence because virtually all of the highest concentration contaminants would be quickly and permanently removed from the aquifer through a SPH treatment method technology that boils the groundwater, even in low-permeability clays and silts, and can remove sorbed TCE and LNAPLs from the aquifer (Figure 7-6). Alternative 6C would combine extraction/treatment method/chemical oxidation and a PRB with MNA to reduce the highest concentrations from greater than 7,000 µg/L to less than 10 µg/L in five years through extraction/treatment method at the plume head. The other portions of the plume would be treated in the same time periods as Alternatives 4C and 5C (Figure 7-8). Therefore, all four alternatives would be effective and permanent.

7.3.4 Reduction of Toxicity, Mobility, and Volume Through Treatment

Alternative 3C would treat large volumes of contaminated groundwater for 20 years to reduce their toxicity and volume, then rely on 10 years of MNA to complete the remediation. Alternative 4C would use chemical oxidation/PRB/MNA to reduce the toxicity and volume of the highest concentration portions of the plume in six months, followed by groundwater treatment by the PRB for an additional 40 years. Alternative 5C, the ERH/chemical oxidation/ PRB/MNA alternative, would treat the contaminated groundwater for six months to reduce the toxicity and volume of the groundwater contamination, then 40 years for the PRB. The active treatment period for "hot spots" using Alternative 6C, extraction and treatment would last for five years, including six-months of chemical oxidation, then an additional 35 years for the PRB. After PRB treatment, the remainder of the groundwater plume for Alternatives 4C, 5C, and 6C would be expected to naturally attenuate to ARARs in the last 10 years of the MNA period. Therefore, although all four alternatives would provide reductions, Alternative 4C and 5C would provide much faster reductions in the highest concentration portions of the shallow zone of Plume C than Alternatives 3C and 6C (Table 7-9).

7.3.5 Short-Term Effectiveness

Alternative 3C would have no additive short-term exposure to the community, but construction workers, treatment system O&M workers, and LTM workers must be monitored to prevent short-term exposure. Alternative 4C would have no additive short-term exposure to the community, but construction workers for the PRB, chemical oxidation injection workers, and LTM workers must be monitored to prevent short-term exposure. Alternative 5C would have no additive short-term exposure to the community, but construction workers for the ERH system and PRB, chemical oxidation injection workers, treatment system O&M workers, and LTM workers must be monitored to prevent short-term exposure. Alternative 6C would have no additive short-term exposure to the community, but construction workers, treatment system

O&M workers, and LTM workers must be monitored to prevent short-term exposure. Therefore, Alternative 4C would provide the least exposure followed by Alternative 6C, then Alternatives 3C and 5C.

Alternative 3C achieves RAOs in 30 years, Alternative 4C in 50 years, Alternative 5C in 40 years, and Alternative 6C in 50 years. Therefore, Alternative 3C has the shortest remediation time, followed by Alternative 5C, then Alternatives 4C and 6C. However, all of these remediation times are reasonably similar when compared to the other plumes.

"Averaging" the three sub-criteria (community protection, worker protection, and time to achieve RAOs) shows that Alternative 5C has greater short-term effectiveness than Alternatives 3C and 4C, followed by Alternative 6C (Table 7-9).

7.3.6 Implementability

Alternative 3C would be a relatively simple alternative and the least difficult to implement technically because only a single technology—pump-and-treat—would be employed and experienced contractors are available locally. It should also be administratively acceptable because it would incorporate the USEPA presumptive remedy for contaminated groundwater. Alternative 4C would be the next least difficult treatment alternative to implement technically only because a national contractor would be required to inject Fenton's Reagent, but may also be relatively easily implementable administratively due to the success of chemical oxidation in FEW treatability studies. Alternative 5C would be the most difficult alternative to implement technically and administratively, as few contractors have had experience with ERH, as have few regulatory agencies. Alternative 6C would be the second most difficult alternative to implement technically, although experienced contractors are available locally, because both a pump-and-treat system and a PRB must be constructed and oxidation chemicals injected. However, all of these Alternative 6C technologies are familiar to the agencies and may be moderately implementable administratively.

Therefore, Alternative 3C would be the simplest to implement technically followed by Alternative 4C, then Alternatives 5C and 6C. Administratively, Alternative 3C may be easiest to implement, followed by Alternative 4C, then Alternatives 5C and 6C (Table 7-9).

7.3.7 Cost

For cost comparisons, refer to Table 7-7; for qualitative comparisons, refer to Table 7-9. Alternative 4C has the lowest present value cost of the shallow-zone groundwater alternatives, Alternative 6C has the second lowest, Alternative 5C has the second highest, and Alternative 3C has the highest.

7.3.8 Intermediate Zone Options

The following subsections compare these options for intermediate zone groundwater at Plume C:

- Option 1C-INT – No Action
- Option 2C-INT – Institutional Controls
- Option 3C-INT – MNA

- Option 4C-INT – Localized Chemical Oxidation and MNA

7.3.8.1 Overall Protection of Human Health and the Environment

No Action (Option 1C-INT) would be protective of human health and the environment under current conditions because no current unacceptable risk has been identified (Table 7-10). However, because this alternative would provide no means to monitor future contamination, it is not protective over the long-term. Institutional Controls (Option 2C-INT) would provide implementation and enforcement of administrative controls to prevent future use of the groundwater resource, but cannot monitor future conditions.

Because Crow Creek is a Class 2AB stream and concentrations of TCE in the intermediate zone will attenuate naturally over long periods of time, MNA (Option 3C-INT) would provide protection of human health and the environment through implementation and enforcement of both the LTM program and institutional controls. However, the time to achieve RAOs would be longer than Option 4C-INT. $KMnO_4$ and MNA (Option 4C-INT) would achieve RAOs (i.e., protection of human health and the environment) in the shortest time period through injection of $KMnO_4$ solution into the intermediate zone, enforcement of the LTM program, and institutional controls.

Therefore, Options 3C-INT and 4C-INT would be protective of human health and the environment in both the short- and long-term (Table 7-10). However, Options 1C-INT and 2C-INT cannot provide long-term protectiveness with any certainty and do not meet this threshold criterion.

7.3.8.2 Compliance with ARARs

The No Action option (Option 1C-INT) would not comply with ARARs. The Institutional Controls option (Option 2C-INT) would comply with potential action- and location-specific ARARs, but not with the potential chemical-specific groundwater ARAR of the federal MCL for TCE of 5 µg/L or with ARARs requiring monitoring of releases. Because these first two options do not meet this threshold criterion, they are not carried through the remainder of the comparative analysis (Table 7-10).

Options 3C-INT and 4C-INT would comply with potential action- and location-specific ARARs and with ARARs requiring monitoring of releases (i.e., 40 CFR Part 264). Option 3C-INT would comply with the potential chemical-specific groundwater ARAR set at the federal MCL for TCE of 5 µg/L near the end of a 100-year LTM period, and Option 4C-INT after a combined 60-year *in situ* treatment and LTM period (Table 7-10).

7.3.8.3 Long-Term Effectiveness and Permanence

Option 4C-INT would reduce the highest concentrations from greater than 50 µg/L TCE to 5 µg/L in six months, leaving small areas of concentrations below 10 µg/L for an additional 60 years (Figure 7-11). This option would provide a higher degree of long-term effectiveness and permanence than Option 3C-INT because Option 3C-INT would leave TCE concentrations in groundwater at Plume C until near the end of the 100-year LTM period (Figure 7-9; Table 7-10).

7.3.8.4 Reduction of Toxicity, Mobility, and Volume Through Treatment

Option 3C-INT would not provide active treatment for the contaminated groundwater, but over time (100 years) the plume would be expected to attenuate through natural processes that reduce the toxicity and volume of contamination. Option 4C-INT would combine chemical oxidation to actively treat the highest concentrations in groundwater for six months, followed by natural attenuation to ARARs in 60 years. Thus, the use of treatment in Option 4C-INT would reduce the total time for remediation of the intermediate zone at Plume C by only 40 percent of the 100-year MNA-only period (Figures 7-9 and 7-11; Table 7-10).

7.3.8.5 Short-Term Effectiveness

Option 3C-INT, MNA, would not include an active remediation component, so there would be no additive short-term exposure to the community, but LTM workers would be monitored to prevent exposure. The Option 4C-INT would have no additive short-term exposure to the community, but chemical oxidation treatment and LTM workers would be monitored to prevent exposure. Option 3C-INT requires 100 years to achieve RAOs and Option 4C-INT requires 60 years. Therefore, Option 4C-INT would provide better short-term effectiveness than Option 3C-INT (Table 7-10).

7.3.8.6 Implementability

Option 3C-INT would be easy to implement technically due to its need only for additional monitoring wells, but perhaps more difficult administratively. Option 4C-INT would be more difficult to implement technically than Option 3C-INT, but perhaps less difficult administratively due to its rapid reduction of the highest contaminant concentrations. Therefore, Option 3C-INT would be the simpler to implement technically and Option 4C-INT may be more easily implemented administratively (Table 7-10).

7.3.8.7 Cost

For quantitative cost comparisons, refer to Table 7-8; for qualitative comparisons, refer to Table 7-10. Option 3C-INT has the lower present value cost and Option 4C-INT has the higher of the two intermediate-zone groundwater options.

This section consists of the development, detailed analysis, and comparison of the alternatives selected for Plume E.

8.1 DEVELOPMENT OF ALTERNATIVES

The following alternatives have been developed for Plume E. The "E" designation for each of these alternatives refers to Plume E.

- Alternative 1E – No Action
- Alternative 2E – Institutional Controls
- Alternative 3E –MNA and Existing PRB
- Alternative 4E – Groundwater Extraction, *Ex situ* Treatment, Existing PRB, and MNA
- Alternative 5E – Existing PRB, Localized Bioaugmentation, and MNA
- Alternative 6E – Localized Chemical Oxidation and MNA (disregard existing PRB)

All of the alternatives presented would result in concentrations on site above health-based levels, therefore, a site review would be required no less frequent than every five years. Additionally, all of the alternatives would be subject to institutional controls, including stipulations to evaluate potential risk if future buildings are to be constructed overlying higher concentration areas of the groundwater plumes. Finally, none of the alternatives would result in off-site discharge. As such, substantive permit requirements would be met, but actual permits are not required. A summary of the alternatives is in Table 8-5, and Table 8-6 contains a detailed analysis summary of the alternatives.

There is no surface water treatment option included for Plume E. Plume E contributes to Crow Creek, a Class 2AB creek, which has a current regulatory limit of 2.7 µg/L. Modeling demonstrates that the contaminant load to Crow Creek from Plume E is not significant enough to require surface water treatment.

With limited options for the intermediate zone, the FS alternatives have been structured and developed to focus on addressing contaminants in the shallow groundwater where most of the contaminant mass exists and hydraulic properties are not as much of a limiting factor. Following discussion of the shallow zone remedial alternatives in subsequent sections, natural attenuation time frames and simulations of active treatment for the intermediate zone are presented for the respective plumes. Remediation of the intermediate zone is focused on MNA and $KMnO_4$ injection. This approach has been taken with the understanding that a selected alternative for the shallow zone would also incorporate one of the options for the intermediate zone. These options would include:

- No Action (possibly with monitoring)
- Institutional Controls
- MNA
- Chemical Oxidation ($KMnO_4$)

For all of the alternatives, the proposed monitoring approaches are regarded as baseline assumptions for the purposes of scoping monitoring needs and to provide a basis for FS cost estimates. Actual monitoring needs would be evaluated as the design of the selected alternative progresses.

Waste streams generated during implementation of the alternatives include soil from drill cuttings and trench excavation, water from monitoring well development and purging, and spent carbon from liquid-phase treatment of extracted, vacuum-stripped groundwater. In general, these wastes would be managed consistent with current USEPA-approved waste management practices at FEW.

8.1.1 Alternative 1E – No Action

The No Action Alternative assumes no further action would be taken regarding contaminants in groundwater. No institutional controls, such as legal/management control or LTM would be implemented. This alternative is required by the NCP for baseline comparison purposes.

8.1.2 Alternative 2E – Institutional Controls

This alternative would consist of physical and/or institutional controls to limit access and future development of groundwater and assess risk from indoor air if buildings are planned to be constructed overlying higher concentration areas of the groundwater plumes. Access to the groundwater would be controlled and activities inconsistent with the prescribed usage of the groundwater would be prohibited. Because this alternative would not allow unrestricted use and unlimited exposure, this alternative would be subject to review not less than every five years.

Refer to Section 4.1.2 for discussions of the Process Description, Rationale, Conceptual Design, and Performance Monitoring associated with Institutional Controls.

8.1.3 Alternative 3E – Monitored Natural Attenuation and Existing Permeable Reactive Barrier

As with Plume A (Section 4.1.3), groundwater sampling data and numerical modeling results suggest that Plume E is relatively stable and shrinking in size and contaminant mass (Volume II and Sections 4.1.3.4, 5.4.4, and Figure 5-21 of the Zone D Groundwater RI [USAF 2003a]). Modeled results for Alternative 3E (MNA) are shown on Figure 8-1.

Based on these results, MNA would be considered a viable alternative. This alternative would also be subject to institutional controls, as described in Section 8.1.2, to limit access and future development of groundwater.

8.1.3.1 Process Description

The following sections describe the combination of MNA and the existing PRB at Plume E.

Monitored Natural Attenuation

For a detailed discussion of the process of natural attenuation, refer to Section 4.1.3.1. For a detailed discussion of natural attenuation in Plume E since 1989, refer to Sections 4.1.3.4 and

5.4.4 of the Zone D Groundwater RI (USAF 2003a). These RI sections indicate that TCE concentrations in nine monitoring wells along the length of Plume E, including source area well DRMO-003, have dropped an average of 78 percent since 1989, including source area well DRMO-003, with a 98 percent reduction, and creek intercept well MW-269, with an 82 percent reduction. The half-life of TCE in this plume calculated from eight of these nine wells is five years. Only in wells MW-075, near the center of the plume, and MW-076 and MW-089 at SS-02 have the TCE concentrations remained static during the past 15 years.

Permeable Reactive Barrier

In addition to data indicating the existence of natural attenuation in Plume E, groundwater contaminant data collected during the injected PRB treatability study suggest that shallow zone groundwater immediately downgradient of the MW-75 well cluster is being passively treated by this PRB (see Section 1.3.3.5). MW-075, the shallow well in the cluster, had the highest TCE concentrations of any well in Plume E, 450 µg/L. This TCE concentration has been reduced by as much as 60 to 100 percent in wells immediately downgradient of the iron. Although short, the PRB is destroying contaminant mass in the highest concentration portion of the shallow plume.

However, the PRB is discontinuous along its length and may not be as thick as designed at the intermediate depths due to installation problems. Therefore, the reductions in TCE concentrations at those depths are not as high. The intermediate depth TCE concentrations in MW-075M are, however, only 10 percent of those in the shallow zone. Therefore, the overall impact of the PRB is to reduce contaminant mass in both shallow and intermediate zone groundwater downgradient of the PRB to TCE concentrations between 30 and 100 µg/L.

8.1.3.2 Rationale for Alternative

Groundwater sampling data indicate that TCE concentrations are decreasing throughout most of Plume E, which suggests that natural attenuation, migration, and dilution are occurring in some areas of the site. TCE concentrations in groundwater samples collected as part of the Zone D RI (USAF 2003), and MNA groundwater modeling for the Zone D FS (Volume II) suggest that:

- The leading edge of the plume has remained constant in the shallow zone of the aquifer and, according to the model, will remain below RAOs until Year 20 (Figure 8-1).
- After that interval, concentrations will increase to levels between 10 and 50 µg/L for at least 30 years (Figure 8-1).
- TCE concentrations are decreasing throughout most of the plume, especially in the original source area, although the higher-concentration center of the plume appears to be moving downgradient (Figure 8-1 and Section 4.1.3.4 of the Zone D RI [USAF 2003a]).

Based on results of additional groundwater sampling and MNA groundwater modeling presented in Volume II, the time for TCE concentrations throughout the shallow zone of the plume to be naturally attenuated to 5 µg/L from present conditions is estimated to be approximately 70 years. Currently no exceedances of the surface water standard of 2.7 µg/L have been measured in Crow Creek. Under this alternative, mass loading calculations indicate that there would be no future exceedances.

The model shows the core of the plume migrating downgradient through time, rather than the leading edge being stable. The TCE concentrations appear to increase to levels between 10 and 50 µg/L at some time between Year 10 and Year 20 of the 70-year MNA period and will remain at those levels until some time between Year 50 and Year 70. By comparing historical and current site data and interpreting groundwater modeling results, TCE concentrations are not expected to exceed the current concentration of slightly more than 5 µg/L at the furthest downgradient monitoring well (i.e., MW-269) until Year 20. Based on the model, during the period from Year 20 to Year 60 or so, the concentration in MW-269 may increase to between 10 and 50 µg/L, but not exceed the concentration that it had in 1989 (34 µg/L), having dropped 82 percent to the present time due to MNA in the intervening 15 years. While modeling and mass loading calculations do not indicate future exceedances of the 2.7 µg/L surface water RAO, LTM would allow for continued evaluation of contaminant migration and the effectiveness of this alternative. If not effective at the fourth Five-Year Review (Year 20), other technologies could be added to the alternative at that time to reduce the TCE levels at the creek intercept.

8.1.3.3 Conceptual Design

The actual design for the existing Plume E PRB is described below.

Permeable Reactive Barrier

The existing PRB extends to a depth of 50 feet below the water table along a length of 28 feet in the center of the plume. It currently has a network of 12 monitoring wells located upgradient and downgradient of the iron. Groundwater modeling results have shown that the time frame for flow through the existing PRB and MNA, to remediate the plume to MCLs is 70 years. The model shows that contaminated groundwater in this area would flow through the existing PRB during the first 20 years of the remediation period, but that the existing PRB should not be replaced after its 30-year life-expectancy because the contamination would have migrated downgradient beyond the PRB by that time (Figure 8-1). Replacement of the PRB after the initial 30 years would not be an effective treatment as the remaining contamination would not be in an area that would reach the PRB location.

8.1.3.4 Performance Monitoring

Performance monitoring would apply to the shallow groundwater zone and existing surface water stations, as discussed in the following paragraphs.

Groundwater Monitoring

The monitoring network would be adjusted and located according to the most appropriate design to measure the effectiveness of each of the chosen alternatives. The monitoring well network would tentatively consist of 12 selected wells in the following locations (Plate 1):

- In-plume—DRMO-003 cluster (three wells), MW-075 cluster (three wells), MW-025, MW-125R, MW-076
- Crossgradient

- Downgradient (creek intercept)—MW-269, MW-1006, MW-079

Monitoring at Plume E would occur until established groundwater standards are met in the shallow plume. Samples would be collected according to the monitoring plan developed for each alternative during the design phase, and no new monitoring wells were assumed.

Surface Water Monitoring

Groundwater sampling and modeling results indicate that TCE concentrations in groundwater would be attenuated to below 5 µg/L before reaching Crow Creek. However, for conservative FS estimating purposes, a surface water monitoring network is proposed that would include the following locations:

- Plume intercept
- Upstream
- Downstream

The plume intercept monitoring point would document any exceedance of the state surface water standards. An upstream location would serve as a reference point to establish whether any reported concentrations in surface water at the plume intercept are in fact attributable to the plume and not an upstream source. The downstream location would help to define the extent of the TCE-plume intercept, as well as potentially documenting the attenuation of the TCE in surface water. For purposes of the FS, it is assumed that existing surface water stations would be used and no new locations established.

Analytical Protocol

All performance monitoring points would be sampled and analyzed for those analytes listed in Table 4-1. Refer to Section 4.1.3.4 for additional details concerning the analytical protocol.

Sampling Frequency and Duration of Monitoring

Results of MNA groundwater modeling (Volume II and Figure 8-1) suggest that TCE concentrations in groundwater would attenuate to 5 µg/L from present conditions in approximately 70 years. Therefore, the proposed LTM program sampling frequency and duration is based on a 70-year monitoring period.

The sampling frequency would be consistent with that presented in Section 4.1.3.4.

8.1.4 Alternative 4E – Groundwater Extraction, *Ex situ* Treatment and Monitored Natural Attenuation

This alternative provides the USEPA "presumptive remedy" for chlorinated VOC contamination in groundwater for Zone D TCE Plume E. The following sections provide a process description, rationale for selection, conceptual design, and process monitoring plan of the groundwater extraction and treatment alternative. This alternative is also subject to institutional controls, as described in Section 8.1.2 to limit access and future development of groundwater.

8.1.4.1 Process Description

The proposed process is the same as that discussed for Plume A and includes two-phase extraction, treatment of extracted vapors and groundwater in a bioreactor, and discharge to a surface stream. More detailed discussion is included in Section 4.1.4.1.

8.1.4.2 Rationale for Alternative

The rationale for Plume E is the same as that discussed for Plume A in Section 4.1.4.2.

8.1.4.3 Conceptual Design

A groundwater extraction and treatment system would be implemented to remove TCE-contaminated groundwater from the portions of Plume E that exceed the MCL of 5 µg/L. The following assumptions were made for purposes of preparing a conceptual design of the system (based on 2001 data):

- The dimensions of the TCE plume exceeding 5 µg/L are approximately 5,200 feet long, up to 960 feet wide, and up to 40 feet bgs.
- The maximum TCE concentration was 450 µg/L in monitoring well MW-075 located in the center of the plume.
- Approximately 105 kg of dissolved TCE are present.
- The Zone D groundwater model was used to estimate the number and placement of extraction wells (Figure 8-2), well pumping rates, and time required to reduce TCE concentrations to 5 µg/L throughout the entire plume (Figure 8-3).

Groundwater modeling results indicate that it would not be feasible to extract and treat the entire plume. An extraction system consisting of up to 30 wells could feasibly be operated; however, a small portion of the plume within the intermediate/deep aquifer of Plume E cannot be extracted and would be remediated using MNA.

Groundwater modeling simulations of more than 30 wells resulted in large areas of very thin to partially dry saturated thickness due to aquifer dewatering. In the three-dimensional transport model, MT3D, the areas of very low saturated thickness were converted to inactive cells. Therefore, the contaminated groundwater could not be transported to the extraction wells in these areas. These results suggest that the downgradient portion of the plume is dominated by low permeability aquifer materials and conditions are not suitable for implementing extraction and treatment. Therefore, model simulations using more than 30 wells indicated no added benefit and were not feasible.

Operational Goals

The goals for operating a groundwater extraction and treatment system at Plume E are the same as those for Plume A in Section 4.1.4.3.

Conceptual Design Approach

A configuration of 30 extraction wells was selected to provide an extraction system capable of pumping a majority of Plume E in a reasonable amount of time but still be implementable and effective (Figure 8-2). This configuration of wells was selected through an iterative modeling process involving comparison of results for various scenarios where different numbers and placements of wells were evaluated.

The assumptions were made to evaluate this alternative using the Zone D groundwater model are the same as those assumed for Plume A in Section 4.2.1.3. The extraction and treatment system would operate for 10 years. MNA would occur for an additional 30 years for the shallow zone until cleanup is achieved (Figure 8-3). Currently no exceedances of the surface water standard of 2.7 µg/L have been measured in Crow Creek. Under this alternative, mass loading calculations indicate that there will be no future exceedances.

Extraction System

The extraction system would consist of 30 new, 4-inch wells screened from static groundwater level to the bottom of the shallow zone at depths ranging from 25 to 35 feet bgs.

Based on groundwater modeling, the 30 extraction wells would be anticipated to have a combined pumping rate of approximately 42 gpm. The wells would be two-phase wells, as described in Section 4.2.3.3.

Above-ground Treatment System

The anticipated influent flow rate at any one time would be approximately 42 gpm and the treatment system would be designed to treat up to 50 gpm. The treatment plant would be designed to treat the extracted groundwater to meet the RAO and substantive requirements of an NPDES permit as discussed in Section 4.2.3.3. Following treatment, effluent would be released to surface discharge at a maximum discharge rate of 50 gpm. Treatment and discharge components are summarized in Table 8-1.

Monitored Natural Attenuation

MNA would be utilized to remediate the portions of Plume E that were not remediated by one of the other technologies. An LTM program would be developed for the 40-year MNA period. The LTM program would be reviewed and modified accordingly as new data are obtained during the 40-year monitoring period

8.1.4.4 Performance Monitoring

A performance monitoring plan is a required component of the full plume groundwater extraction and treatment alternative and should be considered for planning and budgeting purposes. The performance monitoring plan would describe a groundwater monitoring program for the groundwater extraction system extending over a 10-year period, and a monitoring program for MNA extending over a 30-year period after extraction is discontinued. The performance monitoring plan should be reviewed and modified accordingly as new data are obtained during and after operation of the extraction system.

Performance Monitoring Goals

The goals for the performance monitoring program at Plume E would be the same as those for Plume A, exclusive of SS7, described in Section 4.2.3.3. However, instead of assessing the degree to which potential receptors in Diamond Creek are being protected from contamination, the protection of Crow Creek would be required. Performance monitoring would consist of both groundwater and surface water monitoring, as discussed in the following paragraphs.

Groundwater Monitoring

The monitoring network will be adjusted and located according to the most appropriate design to measure the effectiveness of each of the chosen alternatives. The monitoring well network would tentatively consist of 12 selected wells in the following locations (Plate 1):

- In-plume—DRMO-003 cluster (three wells), MW-075 cluster (three wells), MW-025, MW-125R, MW-076
- Creek intercept—MW-269, MW-1006, MW-079

Monitoring of the shallow zone at Plume E will occur until established groundwater standards are met in the shallow plume. Samples will be collected according to the monitoring plan developed for each alternative during the design phase.

Surface Water Monitoring

Groundwater sampling and modeling results indicate that TCE concentrations in groundwater would be attenuated to below 5 µg/L before reaching Crow Creek. However, for conservative FS estimating purposes, a surface water monitoring network is proposed that would include the following locations:

- Plume intercept
- Upstream
- Downstream

The plume intercept monitoring point would document any exceedance of the state surface water standards. An upstream location would serve as a reference point to establish whether any reported concentrations in surface water at the plume intercept are in fact attributable to the plume and not an upstream source. The downstream location would help to define the extent of the TCE-plume intercept, as well as potentially documenting the attenuation of the TCE in surface water. For purposes of the FS, it is assumed that existing surface water stations would be used and no new locations established.

Analytical Protocol

All performance monitoring points would be sampled and analyzed for those analytes listed in Table 4-2 to evaluate the effectiveness of groundwater extraction and treatment at achieving the RAOs for Plume E. The list includes parameters that may relate to potential precipitates or discharge requirements. In addition to laboratory analyses, groundwater elevations and water quality parameters would also be measured.

Sampling Frequency and Duration of Monitoring

It is anticipated that the shallow plume groundwater extraction and treatment system would remediate a majority of groundwater in approximately 10 years, and the remaining shallow plume would attenuate to 5 µg/L within 30 years after extraction is discontinued. Therefore, the performance monitoring program sampling frequency and duration would be based on a 40-year monitoring period. The sampling frequency would be consistent with that presented in Section 4.1.3.2.

8.1.5 Alternative 5E – Existing Permeable Reactive Barrier, Localized Bioaugmentation and Monitored Natural Attenuation

This alternative provides a combination of bioaugmentation and MNA, with a minor contribution from the existing PRB, to treat the chlorinated VOC contamination in groundwater in the upgradient plume at Plume E and to protect the surface water interface of Plume E. The following sections provide a process description, rationale for selection, conceptual design, and process monitoring plan of this groundwater treatment alternative. This alternative would also be subject to institutional controls, as described in Section 8.1.2, to limit access and future development of groundwater.

8.1.5.1 Process Description

The following sections discuss the rationale for the combination of the existing PRB, bioaugmentation, and MNA at Plume E.

Permeable Reactive Barrier

Refer to Section 5.1.3.1 for the process description of PRBs. A PRB has already been constructed as a pilot test for injected iron using jet grouting technology in Plume E near MW-075.

Bioaugmentation

Refer to Section 4.1.5.2 for the process description of bioaugmentation.

Monitored Natural Attenuation

Refer to Section 4.1.3.1 for the process description of natural attenuation. Following active treatment of portions of the plume, the remainder of the contaminants would be allowed to naturally attenuate.

8.1.5.2 Rationale for Alternative

Groundwater sampling data indicate that TCE concentrations are decreasing in some areas of Plume E, which suggests that natural attenuation and minor PRB treatment is occurring at the site. The groundwater modeling for the Zone D FS (Volume II) suggests that TCE concentrations are decreasing downgradient of the PRB, but at a slow rate in the remainder of the plume.

By comparing historical and current site data and interpreting groundwater modeling results, TCE concentrations will be expected to exceed the MCL at the furthest downgradient monitoring well until year 100 without the use of another technology. The use of bioaugmentation will reduce this period to 40 years (Figure 8-5). LTM will allow for continued evaluation of contaminant migration and effectiveness of this alternative.

Permeable Reactive Barrier

The existing PRB extends to a depth of 50 feet below the water table along a length of 28 feet in the center of the plume. Groundwater modeling results have shown that the time frame for the existing PRB, together with bioaugmentation and MNA, to remediate the plume to MCLs is 40 years. The model shows that contaminated groundwater in this area would flow through the existing PRB during the first 10 years of the remediation period, but that the existing PRB should not be replaced after its 30-year life-expectancy because the contamination near MW-075 would have been remediated by that time (Figure 8-5). Replacement of the PRB after the initial 30 years would not be an effective treatment as the remaining contamination will not be in an area that would reach the PRB location.

Monitored Natural Attenuation

The rationale for MNA at Plume E is similar to that discussed for Plume A in Section 4.1.3.2.

8.1.5.3 Conceptual Design

The following sections describe the design of the proposed alternative.

Permeable Reactive Barrier

The existing PRB was installed in 2002 as part of the Zone D Treatability Study. Because this alternative assumes that no modifications will be made to this system and that a performance monitoring network has already been established, no additional design is required. It currently has a network of 12 existing monitoring wells located upgradient and downgradient of the iron.

Bioaugmentation

Refer to Section 4.1.5.3 for the conceptual design of bioaugmentation.

Proposed bioaugmentation treatment areas are displayed on Figure 8-4. This area is approximately 21 acres. The depth of the treatment area is estimated to be 20 to 40 feet bgs.

Bioaugmentation modeling results for Plume E are shown on Figure 8-5. The modeling indicates that 40 years will be required to remediate Plume E using this alternative. Currently no exceedances of the surface water standard of 2.7 µg/L have been measured in Crow Creek. Under this alternative, mass loading calculations indicate that there will be no future exceedances. The assumptions that were made to evaluate the effectiveness of this technology using the Zone D groundwater model are provided in Volume II.

Monitored Natural Attenuation

MNA would be utilized to remediate the portions of Plume E that were not remediated by one of the other technologies. An LTM program would be developed for the 40-year MNA period. The LTM program would be reviewed and modified accordingly as new data are obtained during the 40-year monitoring period

8.1.5.4 Performance Monitoring

A performance monitoring plan would be a required component of the bioaugmentation/MNA alternative and should be considered for planning and budgeting purposes. The performance monitoring plan would describe a groundwater monitoring program for the bioremediation period and the MNA period, which together extend over a 40-year period. The performance monitoring plan should be reviewed and modified accordingly as new data are obtained during and after operation of the extraction system.

Performance Monitoring Goals

The goals for the performance monitoring program at Plume E would be the same as those for Plume A, exclusive of SS7, described in Section 4.2.3.3. However, instead of assessing the degree to which potential receptors in Diamond Creek are being protected from contamination, the protection of Crow Creek would be required. Performance monitoring will consist of both groundwater and surface water monitoring, as discussed in the following paragraphs.

Groundwater Monitoring

The monitoring network will be adjusted and located according to the most appropriate design to measure the effectiveness of each of the chosen treatment alternatives. The monitoring well network would tentatively consist of 12 selected wells in the following locations (Plate 1):

- In-plume—DRMO-003 cluster (three wells), MW-075 cluster (three wells), MW-025, MW-125R, MW-076
- Creek intercept—MW-269, MW-1006, MW-079

Monitoring of the shallow zone at Plume E will occur until established groundwater standards are met in the shallow plume. Samples will be collected according to the monitoring plan developed for each alternative during the design phase.

Surface Water Monitoring

Groundwater sampling and modeling results indicate that TCE concentrations in groundwater would be attenuated to below 5 µg/L before reaching Crow Creek. However, for conservative FS estimating purposes, a surface water monitoring network is proposed that would include the following locations:

- Plume intercept
- Upstream
- Downstream

The plume intercept monitoring point would document any exceedance of the state surface water standards. An upstream location would serve as a reference point to establish whether any reported concentrations in surface water at the plume intercept are in fact attributable to the plume and not an upstream source. The downstream location would help to define the extent of the TCE-plume intercept, as well as potentially documenting the attenuation of the TCE in surface water. For purposes of the FS, it is assumed that existing surface water stations would be used and no new locations established.

Analytical Protocol

All performance monitoring points would be sampled and analyzed for those analytes listed in Table 4-1. Refer to Section 4.1.3.4 for additional details concerning the analytical protocol.

Sampling Frequency and Duration of Monitoring

Results of bioaugmentation/MNA groundwater modeling (Volume II) suggest that TCE concentrations in groundwater would attenuate to 5 μg/L from present conditions in approximately 40 years. Therefore, the proposed LTM program sampling duration would be based on a 40-year monitoring period. The sampling frequency would be consistent with that presented in Section 4.1.3.4.

8.1.6 Alternative 6E – Chemical Oxidation and Monitored Natural Attenuation

In situ chemical oxidation is based on the delivery of a chemical oxidant to contaminated media to destroy the contaminants or to convert them to innocuous compounds commonly found in nature. $KMnO_4$ is an effective oxidant typically applied to treat compounds such as PCE. $KMnO_4$ attacks the carbon-carbon bonds in chlorinated organic compounds. The following sections present a process description, rationale for selection, and conceptual design for the *in situ* chemical oxidation and monitoring alternative for Plume E. This alternative would also be subject to institutional controls, as described in Section 8.1.2, to limit access and future development of groundwater.

8.1.6.1 Process Description

The process for this alternative would consist of chemical oxidation and groundwater monitoring, as discussed in the following paragraphs.

Chemical Oxidation

Refer to Section 4.1.6.2 for the process description of $KMnO_4$.

Monitored Natural Attenuation

Refer to Section 4.1.3.1 for the process description of natural attenuation.

8.1.6.2 Rationale for Alternative

The rationale for both chemical oxidation and MNA are discussed in the following sections.

Chemical Oxidation

From the Zone D Plume C $KMnO_4$ Treatability Study observation, it was assumed that the injection technique using small volumes and low concentration of $KMnO_4$ is successful in avoiding permeability loss due to MnO_2 precipitation. Using the results from the Zone D Plume C Treatability Study, a preliminary plan and conceptual design for a chemical oxidation and monitoring alternative were developed. The $KMnO_4$ Treatability Study conducted in Plume C is applicable to Plume E for the following reasons.

- Plume E and Plume C, where the $KMnO_4$ Treatability Study was conducted, are both within Zone D.
- The geology at the Treatability Study site is very similar to that observed in the proposed injection area at Plume E.
- Findings of the Zone D Plume C $KMnO_4$ Treatability Study indicate that this technology is effective in reducing TCE concentrations of 357 µg/L to nondetect. The highest TCE concentration recently observed in Plume E was 449 µg/L (MW-075, January 2003), which is approximately one-third the highest concentration observed at the Plume C Treatability Study site.

In addition to the results of the $KMnO_4$ Treatability Study conducted in Plume C, contaminant concentrations within Plume E are low enough so that the majority of the contamination present is expected to be in the dissolved-phase rather than the sorbed-phase, making the plume area conducive to treatment with $KMnO_4$.

Monitored Natural Attenuation

The rationale for MNA at Plume E is similar to that discussed for Plume A in Section 41.3.2.

8.1.6.3 Conceptual Design

Refer to Section 5.1.6.3 for conceptual design of the $KMnO_4$ injection and Section 4.1.3.2 for MNA.

Plume E encompasses a relatively large area; therefore, only the higher concentration portion of the plume will be treated with $KMnO_4$ to remove contaminant mass and accelerate MNA. The treatment area is approximately 20 acres, with points on 20-foot by 40-foot centers, as displayed on Figure 8-6. The depth of the treatment area is estimated to be 20 to 40 feet bgs in the shallow aquifer. Existing monitoring wells that are located in the vicinity of the injection area and are screened across both the shallow and intermediate aquifer zones may require installation of a packer within the well casing to deter loss of injected $KMnO_4$ through migration up the casing and into the shallow aquifer zone (Table 8-3).

In situ chemical treatment and MNA modeling results are shown on Figure 8-7. This alternative produced an estimated cleanup time of 50 years. The modeling assumptions that were made to evaluate the effectiveness of this technology using the Zone D groundwater model are provided in Volume II. Currently no exceedances of the surface water standard of 2.7 µg/L have been measured in Crow Creek. Under this alternative, mass loading calculations indicate that there would be no future exceedances.

Plume B and Plume E exhibit a similar elongate geometry. Based on the rationale and results in Alternative 5B, in which a smaller, localized area of application yielded similar cleanup times to a larger area of application, a simulation was performed to evaluate the remedial effectiveness of $KMnO_4$ on a smaller area in Plume E (Figure 8-5). Bioaugmentation would be applied within the area that encompasses shallow groundwater concentrations equal to or greater than 100 µg/L. The area of application is 10 acres. While implementability would be increased by applying bioaugmentation over a smaller area, the groundwater RAO time frame would be approximately 20 years greater (Table 3-5).

8.1.6.4 Performance Monitoring

A performance monitoring plan would be a required component of the chemical oxidation/MNA alternative and should be considered for planning and budgeting purposes. The performance monitoring plan would describe a groundwater monitoring program for the bioremediation period and the MNA period, which together extend over a 40-year period. The performance monitoring plan should be reviewed and modified accordingly as new data are obtained during and after operation of the extraction system.

Performance Monitoring Goals

The goals for the performance monitoring program at Plume E would be the same as those for Plume A, exclusive of SS7, described in Section 4.2.3.3. However, instead of assessing the degree to which potential receptors in Diamond Creek are being protected from contamination, the protection of Crow Creek would be required. Performance monitoring would consist of both groundwater and surface water monitoring, as discussed in the following paragraphs.

Groundwater Monitoring

The monitoring network would be adjusted and located according to the most appropriate design to measure the effectiveness of each of the chosen alternatives. The monitoring well network would tentatively consist of 12 selected wells in the following locations (Plate 1):

- In-plume—DRMO-003 cluster (three wells), MW-075 cluster (three wells), MW-025, MW-125R, MW-076
- Creek intercept—MW-269, MW-1006, MW-079

Monitoring of the shallow zone at Plume E would occur until established groundwater standards are met in the shallow plume. Samples would be collected according to the monitoring plan developed for each alternative during the design phase.

Surface Water Monitoring

Groundwater sampling and modeling results indicate that TCE concentrations in groundwater would be attenuated to below 5 µg/L before reaching Crow Creek. However, for conservative FS estimating purposes, a surface water monitoring network would be proposed that will include the following locations:

- Plume intercept

- Upstream
- Downstream

The plume intercept monitoring point would document any exceedance of the state surface water standards. An upstream location would serve as a reference point to establish whether any reported concentrations in surface water at the plume intercept are in fact attributable to the plume and not an upstream source. The downstream location would help to define the extent of the TCE-plume intercept, as well as potentially documenting the attenuation of the TCE in surface water. For purposes of the FS, it is assumed that existing surface water stations would be used and no new locations established.

Analytical Protocol

All performance monitoring points would be sampled and analyzed for those analytes listed in Table 4-1. Refer to Section 4.1.3.4 for additional details concerning the analytical protocol.

Sampling Frequency and Duration of Monitoring

Results of MNA groundwater modeling (Volume II) suggest that TCE concentrations in groundwater would attenuate to 5 µg/L from present conditions in approximately 40 years. Therefore, the proposed LTM program sampling duration would be based on a 40-year monitoring period. The sampling frequency would be consistent with that presented in Section 4.1.3.4.

8.1.7 Intermediate Zone Options

This section discusses the following options developed for the intermediate-depth portion of Plume E:

- Option 1E-INT – No Action
- Option 2E-INT – Institutional Controls
- Option 3E-INT – MNA
- Option 4E-INT – Localized Chemical Oxidation and MNA

The first two options—Option 1E-INT, No Action and Option 2E-INT, Institutional Controls—for the intermediate zone of Plume E are identical in name and description to Alternative 1E, No Action and Alternative 2E, Institutional Controls for the shallow zone of Plume E. Therefore, the development of those intermediate-zone options assumes that all of the discussion in Sections 4.1.1 and 4.1.2 applies and will not be repeated in this section.

For the purposes of cost estimating, the value associated with the most conservative intermediate MNA option is presented. Due to variations in length of the different shallow zone alternatives, the institutional controls and 5-year Reviews associated with the intermediate MNA costs differ. For a complete list of costs associated with each, individual intermediate option, refer to Volume III.

8.1.7.1 Option 3E-INT – Monitored Natural Attenuation

According to USEPA guidance (USEPA 1999), the most important considerations regarding the suitability of MNA as a remedy include:

- Whether the contaminants are likely to be effectively addressed by natural attenuation processes;
- Stability of the groundwater contaminant plume and its potential for migration; and
- Potential for unacceptable risks to human health or environmental resources by the contamination.

Groundwater sampling data and numerical modeling results suggest that the intermediate zone at Plume E is relatively stable and is shrinking in size and contaminant mass (Volume II). Based on these results, MNA is identified as a viable alternative. This alternative would also be subject to institutional controls, as described in Section 8.1.2, to limit access and future development of groundwater.

Process Description

Natural attenuation is comprised of biological, chemical, and physical processes that reduce contaminant mass, toxicity, mobility, volume, and/or concentration without the application of actively engineered remediation techniques. For details, see Section 4.1.3.

Conceptual Design

Refer to Section 4.1.6.2 for conceptual design of MNA.

Performance Monitoring

The monitoring network, analytical protocol, sampling frequency, and duration of monitoring are discussed in the following paragraphs.

Monitoring Network. The LTM monitoring well network would be similar to that for the shallow zone of Plume E. Monitoring of the intermediate zone would occur until established groundwater standards are met in the zone. Four intermediate-depth monitoring wells were assumed. Surface water sampling would not be required for the intermediate zone because there are no surface water effects from intermediate zone contamination.

Analytical Protocol. All performance monitoring points would be sampled and analyzed for those analytes listed in Table 4-1. For further discussion, see Section 4.1.3.

Sampling Frequency and Duration of Monitoring. Results of MNA groundwater modeling (Volume II) suggest that TCE concentrations in groundwater would attenuate to 5 μg/L from present conditions in approximately 130 years. Therefore, the proposed LTM program sampling duration is based on a 130-year monitoring period. For details, see Section 4.1.6.2.

8.1.7.2 Option 4E-INT – Localized Chemical Oxidation and MNA

This option provides chemical oxidation using $KMnO_4$, followed by MNA, to treat the low-concentration groundwater found in the intermediate zone of Plume E. The following sections provide a process description, rationale for selection, conceptual design, and process monitoring plan of this intermediate-zone option. This alternative would also be subject to institutional controls, as described in Section 8.1.2 to limit access and future development of groundwater.

Process Description

For a process description of $KMnO_4$ for intermediate zone groundwater, see Section 4.1.6.2. For details of MNA, see Section 4.1.3.1.

Rationale for Alternative

For the rationale for using $KMnO_4$ and MNA for intermediate zone groundwater, see Section 4.1.6.2. The proposed treatment area of 6.8 acres for this zone was an optimization of the area in an attempt to treat the area of the highest observed TCE concentrations in the intermediate zone and remove the most contaminant mass. Thus, the cleanup time for the intermediate layer of Plume E was 35 years (Table 8-5).

Conceptual Design

The concept of the designs for injected $KMnO_4$ and MNA for the intermediate zone are discussed in the following paragraphs. Table 8-4 describes the system components for this option.

Potassium Permanganate. Plume E encompasses a relatively large area; therefore, only the higher concentration portion of the plume would be treated with $KMnO_4$ to remove contaminant mass and accelerate MNA. The treatment area is approximately 9.3 acres and is displayed on Figure 8-9. The depth of the treatment area is estimated to be 50 to 70 feet bgs in the intermediate aquifer. For additional details, see Section 4.1.6.2 and Table 8-4.

In situ chemical treatment and MNA modeling results are shown in Figure 8-10. The modeling assumptions made to evaluate the effectiveness of this technology using the Zone D groundwater model are provided in Volume II.

Monitored Natural Attenuation. The LTM program goals for the intermediate zone at Plume E in Section 4.1.3 are identical to those for the shallow zone with the exception of surface water. Because the intermediate groundwater does not impact surface water, a surface water-related goal is not included.

Performance Monitoring

The monitoring network, analytical protocol, sampling frequency, and duration of monitoring are discussed in the following paragraphs.

Monitoring Network. The LTM monitoring well network would be similar to that for the shallow zone of Plume E. Monitoring of the intermediate zone would occur until established

groundwater standards are met in the zone. Four intermediate-depth monitoring wells were assumed. Surface water sampling would not be required for the intermediate zone because there are no surface water effects from intermediate zone contamination.

Analytical Protocol. All performance monitoring points would be sampled and analyzed for those analytes listed in Table 4-1. For further discussion, see Section 4.1.3.

Sampling Frequency and Duration of Monitoring. Results of MNA groundwater modeling (Volume II) suggest that TCE concentrations in groundwater would attenuate to 5 µg/L from present conditions in approximately 35 years with the addition of $KMnO_4$. Therefore, the proposed LTM program sampling duration would be based on a 35-year monitoring period. For details, see Section 4.1.6.2.

8.2 DETAILED ANALYSIS OF ALTERNATIVES

This section presents the individual analysis and assessment of each Plume E groundwater remedial alternative with respect to the nine evaluation criteria. The first two (Overall Protection and Compliance with ARARs) are threshold criteria. Alternatives are evaluated for whether they provide protectiveness or comply with ARARs. Alternatives must be both protective and comply with ARARs to be considered for a remedy. The next five are balancing criteria, where the relative tradeoffs among the criteria are evaluated. These first seven criteria are further described in Table 4-3. The final two are modifying criteria, in which the state and the community express whether they support or oppose the alternatives, which are evaluated by the end of the public comment period. Following the individual analysis is a comparative analysis among the groundwater alternatives. The comparative analysis will assess the relative performance of each groundwater alternative with respect to each criterion.

The Institutional Controls Alternative would be incorporated into all of the alternatives. Costs associated with institutional controls have been added to the costs associated with each alternative. Table 8-6 contains a summary of the detailed analysis for the alternatives.

8.2.1 Alternative 1E – No Action

The No Action Alternative assumes no further action would be taken for groundwater at Zone D. This alternative is required by the NCP and selected for detailed analysis so that it may be used as a baseline for comparative analysis of the risk and cost associated with other alternatives. Although there is no capital cost involved with this alternative, the future costs and liabilities associated with exposure risks are unknown. Although expected, the No Action Alternative would not take into account natural attenuation of the groundwater plume through time.

8.2.1.1 Overall Protection of Human Health and the Environment

Although the BRA identified no unacceptable threat to human health or the environment under current groundwater conditions, this alternative would not include a means to monitor or assess protection of human health or the environment. Therefore, the No Action Alternative is not protective of human health and the environment.

8.2.1.2 Compliance with ARARs

The No Action Alternative would not comply with ARARs.

8.2.1.3 Long-Term Effectiveness

The potential risk of exposure to groundwater would continue to exist with this alternative, and untreated TCE contamination would remain in groundwater. Therefore, the No Action Alternative would not provide long-term effectiveness.

8.2.1.4 Reduction of Toxicity, Mobility, and Volume

Since no active treatment of groundwater would be undertaken, there would not be an active reduction of toxicity, mobility, or volume. However, over time the groundwater plume would be expected to naturally attenuate.

8.2.1.5 Short-Term Effectiveness

Because no action for groundwater would be taken, there would be no additive short-term exposure to the community or workers.

8.2.1.6 Implementability

There would be no implementation concerns associated with the No Action Alternative for groundwater.

8.2.1.7 Cost

The No Action Alternative for groundwater would incur no cost. The cost associated with long-term liability would be unknown.

8.2.2 Alternative 2E – Institutional Controls

The Institutional Controls Alternative assumes that legal and/or physical controls would be implemented for groundwater at Zone D. This alternative has limited capital cost, but the future costs and liabilities associated with exposure risks can only be estimated. Although expected, the Institutional Controls Alternative would not take into account natural attenuation of the groundwater plume through time.

8.2.2.1 Overall Protection of Human Health and the Environment

The Institutional Controls Alternative would protect human health and the environment through implementation and enforcement of administrative controls described in Section 8.1.2. No unacceptable short-term or cross-media impacts would be expected.

8.2.2.2 Compliance with ARARs

The Institutional Controls Alternative would comply with potential action- and location-specific ARARs. It would not comply with the potential chemical-specific ARAR of the federal MCL for TCE of 5 µg/L. This alternative would not comply with ARARs requiring monitoring of releases (i.e., 40 CFR Part 264).

8.2.2.3 Long-Term Effectiveness and Permanence

The untreated TCE contamination in groundwater would continue to exist at Zone D. This alternative would offer a level of protection through the regulation of groundwater use as discussed in Section 8.1.2. Controls would be implemented to limit or exclude use of the groundwater and thus reduce the potential for exposure. These controls would be contained in the General Plan and are a long-term and reliable management control, enforced by the USAF within the installation boundaries. The groundwater plume would be expected to naturally attenuate over time.

8.2.2.4 Reduction of Toxicity, Mobility and Volume

The contaminated groundwater would not be treated to reduce the toxicity, mobility, or volume. However, over time, the groundwater plume would be expected to naturally attenuate.

8.2.2.5 Short-Term Effectiveness

This alternative would not include a remediation component, so there would be no additive short-term exposure to the community or workers.

8.2.2.6 Implementability

This alternative would be easy to implement technically and administratively. Documentation in the General Plan and coordination with installation personnel as discussed in Section 8.1.2 would be a reliable management control that would be easy to implement.

8.2.2.7 Costs

Costs for this alternative include a capital cost of $18,484, plus annual costs of $2,387 for updates. These costs are outputs of RACER™ and reflected in present value dollars in Volume III.

8.2.3 Alternative 3E – Monitored Natural Attenuation and Existing Permeable Reactive Barrier

Alternative 3E assumes that the existing injected pilot PRB, long-term groundwater monitoring, and institutional controls would be utilized for groundwater in Plume E. Unlike Alternative 2E, however, the MNA alternative takes into account natural attenuation of the groundwater plume through time. The future LTM costs and potential liabilities associated with exposure risks can only be estimated. In addition, the life of the existing PRB is only 30 to 35 years, or half the predicted 70-year MNA period for Plume E, so the PRB is assumed to have a 35-year life with no replacement.

8.2.3.1 Overall Protection of Human Health and the Environment

The PRB/MNA alternative would protect human health and the environment through treatment in the existing pilot PRB, implementation and enforcement of the LTM program described in Section 8.1.1, and the administrative controls described in Section 8.1.2. No unacceptable short-term or cross-media impacts would be expected.

8.2.3.2 Compliance with ARARs

The PRB/MNA alternative would comply with potential action and location specific ARARs. It would not comply with the potential chemical-specific ARAR of the federal MCL for TCE of 5 µg/L until near the end of the 70-year LTM period. This alternative would comply with ARARs requiring monitoring of releases (i.e., 40 CFR Part 264).

8.2.3.3 Long-Term Effectiveness

The untreated TCE contamination in groundwater would continue to exist at Plume E until the end of the 70-year LTM period (Figure 8-1). However, the highest concentration location (MW-75) within the plume would continue to be treated for as long as 30 years by the existing injected pilot PRB. This alternative would offer a level of protection through localized treatment by the PRB, monitoring of groundwater contaminant concentration and flow, as discussed in Section 8.1.3, and regulation of groundwater use, as discussed in Section 8.1.2. LTM and institutional controls would be implemented to monitor, limit, and/or exclude use of the groundwater and thus reduce the potential for exposure.

8.2.3.4 Reduction of Toxicity, Mobility, and Volume

Small volumes of contaminated groundwater would be treated by the existing pilot PRB to reduce the toxicity and volume at one location of Plume E. However, the remainder of the groundwater plume would be expected to naturally attenuate in 70 years.

8.2.3.5 Short-Term Effectiveness

This alternative would include an existing, very local remediation component so there would be no additive short-term exposure to the community. However, LTM workers would be monitored to prevent exposure.

Soil spoils from drilling will be placed in soil containers, covered or sealed, and transported to a Class C landfill. Because the soil will be contained, the community does not incur incremental risk associated with disposal, but could incur a slight incremental risk due to increased traffic.

8.2.3.6 Implementability

This alternative would be easy to implement technically because the PRB and the monitoring wells already exist, but more difficult administratively due to the existence of the General Plan. An LTM Plan would be prepared for the 70-year LTM period, as discussed in Section 8.1.3, and documentation would be provided in the General Plan, as discussed in Section 8.1.2.

8.2.3.7 Cost

Costs of this alternative would include an LTM Plan, changes to the General Plan, community and educational programs, reporting, and management and administrative efforts. The capital costs for the existing pilot PRB have already been spent, so are not included in this estimate and no replacement of the PRB is included. Total O&M costs that include LTM data collection, analysis, evaluation, and reporting costs are estimated to be about $4.7 million over the 70-year life of the alternative. Present value cost is $1.6 million. A summary of the costs is provided in Table 8-2. The detailed cost estimate is provided in Volume III.

8.2.4 Alternative 4E – Groundwater Extraction, *Ex situ* Treatment and Monitored Natural Attenuation

Alternative 4E assumes that a combination of groundwater extraction and treatment method, long-term groundwater monitoring (Alternative 3E), and institutional controls would be implemented for groundwater in Plume E. The future O&M costs, LTM costs, and potential liabilities associated with exposure risks can only be estimated. Based on groundwater modeling, this alternative would require 10 years of extraction and treatment, followed by 30 years of natural attenuation of the groundwater plume to complete remediation.

8.2.4.1 Overall Protection of Human Health and the Environment

Alternative 4E would protect human health and the environment through implementation of the groundwater extraction and treatment system described in Section 8.1.4, enforcement of the LTM program described in Section 8.1.3, and the administrative controls described in Section 8.1.2. No unacceptable short-term or cross-media impacts would be expected.

8.2.4.2 Compliance with ARARs

Alternative 4E would comply with potential action- and location-specific ARARs and with the potential chemical-specific ARAR of the federal MCL for TCE of 5 µg/L at the end of the 40-year LTM period. This alternative would comply with the USEPA preference for treatment and ARARs requiring monitoring of releases (i.e., 40 CFR Part 264) and this alternative would meet substantive NPDES discharge requirements.

8.2.4.3 Long-Term Effectiveness and Permanence

The untreated TCE contamination in groundwater would continue to exist at Plume E until the end of the 40-year LTM period (Figure 8-3). However, the extraction and treatment system would reduce the highest concentrations from greater than 500 µg/L TCE to 50 µg/L in 10 years, leaving small areas of concentrations below 50 µg/L for an additional 30 years of the MNA period. This alternative would offer a level of protection through the treatment and monitoring of groundwater contaminant concentration and flow, as discussed in Section 8.1.4 and by regulation of groundwater use, as discussed in Section 8.1.2.

8.2.4.4 Reduction of Toxicity, Mobility and Volume

The contaminated groundwater would be treated for 10 years to reduce the toxicity and volume of the groundwater contamination. After treatment, the groundwater plume would be expected to naturally attenuate to ARARs in an additional 30 years.

8.2.4.5 Short-Term Effectiveness

This alternative would include a remediation component, but there would be no additive short-term exposure to the community. However, treatment system O&M and LTM workers would be monitored to prevent exposure.

Soil spoils from drilling and construction will be placed in soil containers, covered or sealed, and transported to a Class C landfill. Because the soil will be contained, the community does not incur incremental risk associated with disposal, but could incur a slight incremental risk due to increased traffic.

8.2.4.6 Implementability

This alternative would be the most difficult alternative to implement technically, but relatively easy administratively due to its status as USEPAs "presumptive remedy." An O&M Plan would be prepared for the two-phase extraction system and the bioreactor treatment system, as discussed in Section 8.1.4, an LTM Plan would be prepared for the 40-year LTM period, as discussed in Section 8.1.3, and documentation would be provided in the General Plan, as discussed in Section 8.1.2.

8.2.4.7 Cost

Costs of this alternative would include capital costs for the extraction and treatment system design and construction, preparation of the LTM Plan, changes to the General Plan, community and educational programs, reporting, and management and administrative efforts. Capital costs associated with this alternative are estimated to be $1.4 million. Total O&M costs that include extraction and treatment system O&M, LTM data collection, analysis, evaluation, and reporting costs are estimated to be about $7.1 million over the 40-year life of the alternative. Present value cost is $5.6 million. A summary of the costs is provided in Table 8-2. The detailed cost estimate is provided in Volume III.

8.2.5 Alternative 5E – Existing Permeable Reactive Barrier, Localized Bioaugmentation and Monitored Natural Attenuation

Alternative 5E assumes that a combination of bioaugmentation, long-term groundwater monitoring (Alternative 3E), and institutional controls would be implemented for groundwater in Plume E. The future O&M costs, LTM costs, and potential liabilities associated with exposure risks can only be estimated. Based on groundwater modeling, this alternative would require six months to establish reducing conditions and add microbes, followed by 10 years of bioactivity to reduce concentrations to MCLs in the treated zone, then natural attenuation of the groundwater plume for 30 additional years to complete remediation.

8.2.5.1 Overall Protection of Human Health and the Environment

The PRB, bioaugmentation, and MNA alternative (Alternative 5E) would protect human health and the environment through implementation of treatment of the "hot spot" with the existing PRB, bioaugmentation of the central plume, as described in Section 8.1.5, enforcement of the LTM program described in Section 8.1.3, and institutional controls described in Section 8.1.2. No unacceptable short-term or cross-media impacts would be expected.

8.2.5.2 Compliance with ARARs

The PRB, bioaugmentation, and MNA alternative would comply with potential action- and location-specific ARARs and with the potential chemical-specific ARAR of the federal MCL for TCE of 5 µg/L at the end of the 40-year LTM period. This alternative would comply with the USEPA preference for treatment and ARARs requiring monitoring of releases (i.e., 40 CFR Part 264).

8.2.5.3 Long-Term Effectiveness

Some untreated TCE contamination in groundwater would continue to exist at Plume E until the end of the 40-year LTM period. However, the PRB, bioaugmentation, and MNA alternative would reduce the highest concentrations from greater than 500 µg/L TCE to 20 µg/L in 10 years, leaving small areas of concentrations below 20 µg/L for an additional 30 years of the MNA period (Figure 8-5). This alternative would offer a level of protection through the treatment and monitoring of groundwater contaminant concentration and flow, as discussed in Section 8.1.5 and by regulation of groundwater use, as discussed in Section 8.1.2.

8.2.5.4 Reduction of Toxicity, Mobility, and Volume

The PRB, bioaugmentation, and MNA alternative would treat the contaminated groundwater for 10 years to reduce the toxicity and volume of the groundwater contamination. After treatment, the groundwater plume would be expected to naturally attenuate to ARARs in 30 additional years.

8.2.5.5 Short-Term Effectiveness

The PRB, bioaugmentation, and MNA alternative would include a remediation component, but there would be no additive short-term exposure to the community. However, bioaugmentation treatment and LTM workers would be monitored to prevent exposure.

Soil spoils from drilling will be placed in soil containers, covered or sealed, and transported to a Class C landfill. Because the soil will be contained, the community does not incur incremental risk associated with disposal, but could incur a slight incremental risk due to increased traffic.

8.2.5.6 Implementability

The PRB, bioaugmentation, and MNA alternative would be the least difficult active treatment alternative to implement technically, but more difficult administratively due to its lack of an FEW treatability study. A bioaugmentation treatment system design would be prepared as discussed in Section 8.1.5, an LTM Plan would be prepared for the 40-year LTM period as

discussed in Section 8.1.3, and documentation would be provided in the General Plan as discussed in Section 8.1.2.

8.2.5.7 Cost

Costs of this alternative would include capital costs for bioaugmentation design and implementation, preparation of the LTM Plan, changes to the General Plan, community and educational programs, reporting, and management and administrative efforts. Capital costs associated with this alternative are estimated to be $9.0 million and do not include replacement costs for a PRB since no replacement is planned. Total O&M costs that include LTM data collection, analysis, evaluation, and reporting costs are estimated to be about $3.7 million over the 40-year life of the alternative. Present value cost is $10.1 million. A summary of the costs is provided in Table 8-2. The detailed cost estimate is provided in Volume III.

8.2.6 Alternative 6E – Localized Chemical Oxidation and Monitored Natural Attenuation

Alternative 6E assumes that a combination of chemical oxidation, long-term groundwater monitoring (Alternative 3E), and institutional controls will be implemented for groundwater in Plume E. The future O&M costs, LTM costs, and potential liabilities associated with exposure risks can only be estimated. Based on groundwater modeling, this alternative would require six months of chemical oxidation, followed by 40 years of natural attenuation of the groundwater plume to complete remediation.

8.2.6.1 Overall Protection of Human Health and the Environment

Alternative 6E would protect human health and the environment through implementation of the chemical oxidation system described in Section 8.1.6, enforcement of the LTM program described in Section 8.1.3, and the administrative controls described in Section 8.1.2. No unacceptable short-term or cross-media impacts would be expected.

8.2.6.2 Compliance with ARARs

Alternative 6E would comply with potential action- and location-specific ARARs and with the potential chemical-specific ARAR of the federal MCL for TCE of 5 µg/L at the end of the 40-year LTM period. This alternative would comply with the USEPA preference for treatment and ARARs requiring monitoring of releases (i.e., 40 CFR Part 264).

8.2.6.3 Long-Term Effectiveness and Permanence

The untreated TCE contamination in groundwater would continue to exist at Plume E until the end of the 40-year LTM period. However, the chemical oxidation system would reduce the highest concentrations from greater than 500 µg/L TCE to 50 µg/L in 6 months, leaving small areas of concentrations below 50 µg/L for the additional 40 years of the MNA period (Figure 8-7). This alternative would offer a level of protection through the treatment and monitoring of groundwater contaminant concentration and flow, as discussed in Section 8.1.6 and by regulation of groundwater use, as discussed in Section 8.1.2.

8.2.6.4 Reduction of Toxicity, Mobility and Volume

The contaminated groundwater would be treated for six months to reduce the toxicity and volume of the groundwater contamination. After treatment, the groundwater plume would be expected to naturally attenuate to ARARs in 40 years.

8.2.6.5 Short-Term Effectiveness

This alternative would include a remediation component, but there would be no additive short-term exposure to the community. However, chemical oxidation treatment and LTM workers would be monitored to prevent exposure.

Soil spoils from drilling will be placed in soil containers, covered or sealed, and transported to a Class C landfill. Because the soil will be contained, the community does not incur incremental risk associated with disposal, but could incur a slight incremental risk due to increased traffic.

8.2.6.6 Implementability

This alternative would be the least difficult active treatment alternative to implement technically and only slightly difficult administratively. A chemical oxidation treatment system design would be prepared as discussed in Section 8.1.6, an LTM Plan would be prepared for the 40-year LTM period as discussed in Section 8.1.3, and documentation would be provided in the General Plan as discussed in Section 8.1.2.

8.2.6.7 Cost

Costs of this alternative would include capital costs for chemical oxidation design and implementation, preparation of the LTM Plan, changes to the General Plan, community and educational programs, reporting, and management and administrative efforts. Capital costs associated with this alternative are estimated to be $6.5 million. Total O&M costs that include LTM data collection, analysis, evaluation, and reporting costs are estimated to be about $3.5 million over the 40-year life of the alternative. Present value cost is $7.7 million. A summary of the costs is provided in Table 8-2. The detailed cost estimate is provided in Volume III.

8.2.7 Intermediate Zone Options

This section presents the individual analysis and assessment of each intermediate zone option with respect to the seven evaluation criteria, as described above. For a summary of this analysis, see Table 8-7.

For detailed analysis of Option 1E-INT, No Action and Option 2E-INT, Institutional Controls, see Section 8.2.1 and 8.2.2.

8.2.7.1 Option 3E-INT – Monitored Natural Attenuation

Option 3E-INT assumes that LTM of natural attenuation processes that reduce TCE concentrations over time would be implemented for groundwater in the intermediate zone at Plume E. Institutional controls would be included in the alternative to prevent the use of groundwater for human consumption prior to the end of the MNA period.

Overall Protection of Human Health and the Environment

With institutional controls, MNA in the intermediate zone would protect human health and the environment under current conditions through natural attenuation processes. No unacceptable short-term or cross-media impacts would be expected.

Compliance with ARARs

With institutional controls, the use of MNA in the intermediate zone would comply with all potential action- and location-specific ARARs, but would not comply with the potential chemical-specific ARAR of the federal MCL for TCE of 5 µg/L until near the end of the 130-year monitoring period. MNA would comply with ARARs requiring monitoring of releases. There would be no discharge, so there would be no substantive requirements for NPDES discharge.

Long-Term Effectiveness

Natural processes will reduce contaminant levels in groundwater to MCLs over time. Continued monitoring would provide a reliable means to assess the residual concentrations and manage the risk posed by the residual. Institutional controls would limit or prevent use of the intermediate zone groundwater, no untreated residual contamination would be produced by this treatment process. Minimal O&M of wells and groundwater sampling would be required.

Reduction of Toxicity, Mobility, and Volume

Toxicity, mobility, and volume of TCE would be reduced over time from natural attenuation of contaminants in groundwater. TCE levels would be reduced to RAOs in intermediate zone groundwater in approximately 130 years, no residuals would be present in groundwater at completion. The attenuation would be irreversible.

Short-Term Effectiveness

No additional risk to site workers and the environment would occur because there is no construction of a treatment system. There would also be no increased risk to workers, the community, or the environment during implementation. Time to achieve RAOs within the intermediate zone at Plume E was estimated to be approximately 130 years.

Implementability

This option would be easy to implement and should not create schedule delays. Passive methods such as MNA do not require removal, aboveground treatment method, or TSD services. Monitoring the effectiveness would be simple and administrative requirements to accommodate this option would include modifying the General Plan.

Cost

Costs of this option would include an LTM Plan, changes to the General Plan, community and educational programs, reporting, and management and administrative efforts. There would be no

capital costs associated with this alternative due to the availability of numerous existing monitoring wells. Total O&M costs that include LTM data collection, analysis, evaluation, and reporting costs are estimated to be about $4.6 million over the 130-year life of the alternative. Present value cost is nearly $0.7 million. A summary of the costs is provided in Table 8-6. The detailed cost estimate is provided in Volume III.

8.2.7.2 Option 4E-INT – Localized Chemical Oxidation and MNA

Option 4E-INT assumes that a combination of chemical oxidation, long-term groundwater monitoring, and institutional controls would be implemented for intermediate zone groundwater in Plume E. The future O&M costs, LTM costs, and potential liabilities associated with exposure risks can only be estimated.

Overall Protection of Human Health and the Environment

Comparing historical and current site data, TCE concentrations currently exceed RAOs in some intermediate-zone monitoring wells. This chemical oxidation/MNA option would protect human health and the environment by *in situ* treatment of the contaminated groundwater with chemical oxidizers, application of an LTM program, and enforcement of institutional controls. The option would be designed to destroy contaminant concentrations exceeding RAOs through a combination of *in situ* groundwater treatment and MNA. No unacceptable short-term or cross-media impacts would be expected.

Compliance with ARARs

This option would comply with potential action- and location-specific ARARs and with the potential chemical-specific ARAR of the federal MCL for TCE of 5 µg/L at the end of the LTM period. It would also comply with the USEPA preference for treatment of contaminated groundwater (i.e., 40 CFR Part 264). No discharge permits would be required for this option.

Long-Term Effectiveness and Permanence

Active treatment would reduce the TCE concentrations in the intermediate zone groundwater to 50 µg/L in approximately six months. Natural processes would reduce the TCE concentration in groundwater to the RAO approximately 35 years after completion of active treatment. Continued monitoring would provide a reliable means to assess the treatment effectiveness. Institutional controls would limit or prevent use of groundwater. Greater O&M than the MNA option would occur only during the six-month treatment period.

Reduction of Toxicity, Mobility and Volume

Toxicity, mobility, and volume of TCE would be reduced over time from active treatment of groundwater and natural processes. TCE concentrations in groundwater would be reduced to RAOs in intermediate zone groundwater in approximately 35 years, and the treatment process would be irreversible.

Short-Term Effectiveness

There would be minimal additional risk to site workers and the environment during "construction" phase involving drilling and injection of chemicals. Soil spoils from drilling would be placed in soil containers, covered or sealed, and transported to a Class C landfill. Because the soil will be contained, the community does not incur incremental risk associated with disposal, but could incur a slight incremental risk due to increased traffic. There would be no increased risk to workers, the community, or the environment during the implementation phase, which would involve only groundwater sampling. The time to achieve RAOs is estimated to be approximately 35 years.

Implementability

This option would be easy to implement and chemical oxidation is a proven and reliable technology. The chemical oxidation compound ($KMnO_4$) is readily available, as are the conventional well drilling and installation techniques that would be used. Schedule delays should not be expected due to lack of availability since multiple drilling contractors and $KMnO_4$ suppliers are available. Competitive bids can be obtained and monitoring the effectiveness would be simple. Administrative requirements would include preparation of a treatment system design, an LTM Plan, and modifying the General Plan.

Cost

Costs of this alternative would include capital costs for chemical oxidation design and implementation, preparation of the LTM Plan, changes to the General Plan, community and educational programs, reporting, and management and administrative efforts. Capital costs associated with this alternative are estimated to be $6.7 million. Total O&M costs that include LTM data collection, analysis, evaluation, and reporting costs are estimated to be about $1.3 million over the 35-year life of the alternative. Present value cost is $6.9 million. This cost may be reduced slightly if this option is utilized in combination with Alternative 6E due to reduced chem-ox mobilization costs. A summary of the costs is provided in Table 8-6. The detailed cost estimate is provided in Volume III.

8.3 COMPARATIVE ANALYSIS

The first seven sections compare these alternatives for the shallow Plume E groundwater:

- Alternative 1E – No Action
- Alternative 2E – Institutional Controls
- Alternative 3E – MNA and Existing PRB
- Alternative 4E – Groundwater Extraction, *Ex situ* Treatment, and MNA
- Alternative 5E – Existing PRB, Localized Bioaugmentation, and MNA
- Alternative 6E – Localized Chemical Oxidation and MNA

One section also compares the following options for intermediate zone groundwater at Plume E:

- Option 1E-INT – No Action
- Option 2E-INT – Institutional Controls
- Option 3E-INT – MNA
- Option 4E-INT – Localized Chemical Oxidation and MNA

Tables 8-8 and 8-9 present a comparison among the criteria for each alternative/option comparison for the shallow zone and intermediate zone groundwater of Plume E, respectively. The tables are for the shallow groundwater zone or the intermediate groundwater zone of each plume, but do not combine the two. Because the comparisons are relative to the other alternatives for this plume, they should not be used for comparison to other plumes or even to the shallow vs. intermediate groundwater in Plume E.

8.3.1 Overall Protection of Human Health and the Environment

No Action (Alternative 1E) would be protective of human health and the environment under current conditions because no current unacceptable risk has been identified. However, because this alternative would provide no means to monitor future contamination, it is not protective over the long term. Alternative 2E would provide implementation and enforcement of administrative controls to prevent future use of the groundwater resource, but cannot monitor future conditions. Because the source of Plume E has been removed, the maximum extent of the shallow zone plume appears stable or shrinking, passive bioremediation currently appears to be occurring in parts of the shallow plume, TCE concentrations in monitoring wells at the Crow Creek intercept are very near MCLs, no unacceptable risk has been identified, and concentrations of TCE would be reduced over long periods of time through natural attenuation and the existing PRB, MNA and the existing PRB (Alternative 3E) would provide protection of human health and the environment through treatment by an existing PRB and implementation and enforcement of both the LTM program and institutional controls.

Extraction, treatment method, and MNA (Alternative 4E) would also provide protection of human health and the environment through a combination of *ex situ* groundwater extraction and treatment method, MNA, and institutional controls. This alternative would achieve complete remediation of the surface groundwater zone in the same total time (40 years) as Alternatives 5E and 6E. Bioaugmentation/ MNA (Alternative 5E) would provide significant protection of human health and the environment through implementation of treatment method of the "hot spot" with the existing PRB, bioaugmentation of the central plume, enforcement of the LTM program, and institutional controls. The chemical oxidation/ MNA alternative (Alternative 6E) would disregard the existing PRB, but would not significantly improve the time for remediation of the shallow zone over Alternatives 4E and 5E. However, it would provide the greatest protection of human health and the environment through treatment of the high concentration area with chemical oxidation, enforcement of the LTM program, and institutional controls.

Therefore, Alternatives 3E, 4E, 5E, and 6E would be protective of human health and the environment in both the short- and long-term (Table 8-8). However, Alternatives 1E and 2E cannot provide long-term protectiveness with any certainty and do not meet this threshold criterion.

8.3.2 Compliance with ARARs

The No Action Alternative would not comply with ARARs. The Institutional Controls Alternative would comply with potential action- and location-specific ARARs, but not with the potential chemical-specific groundwater ARAR of the federal MCL for TCE of 5 µg/L or with ARARs requiring monitoring of releases. Because these first two alternatives do not meet this threshold criterion, they are not carried through the remainder of the comparative analysis.

Alternatives 3E, 4E, 5E, and 6E would comply with potential action- and location-specific ARARs and with ARARs requiring monitoring of releases (i.e., 40 CFR Part 264). Alternative 4E would comply with substantive NPDES discharge requirements. Alternative 3E would comply with the potential chemical-specific groundwater ARAR set at the federal MCL for TCE of 5 µg/L near the end of a 70-year LTM period; Alternative 4E after a 40-year *ex situ* extraction, treatment method, and MNA period; Alternative 5E after a 40-year *in situ* bioaugmentation and MNA period; and Alternative 6E after treatment method with *in situ* chemical oxidation, then 40 years of MNA. Therefore, based on total time to comply with ARARs, Alternative 4E, 5E, and 6E would be identical and all three are nearly twice as fast as Alternative 3E (Table 8-8).

8.3.3 Long-Term Effectiveness and Permanence

Alternative 4E would provide a high degree of long-term effectiveness and permanence because the contaminants are permanently removed from the aquifer through a 40-year groundwater removal and treatment method/MNA period (Figure 8-3; Table 8-8). However, pump-and-treat systems may not be able to remove all sorbed contamination from some low hydraulic conductivity lithologies. Alternative 5E would also provide a high degree of long-term effectiveness and permanence because the highest concentration contaminants are permanently removed from the aquifer through 40 years of biological treatment method/MNA that can remove even sorbed TCE from the aquifer (Figure 8-5). Alternative 6E would provide the highest degree of long-term effectiveness and permanence because the highest concentration contaminants are permanently removed from the aquifer through chemical oxidation treatment method technologies in a six-month period, then MNA will remove the remainder over 40 years (Figure 8-7). Alternative 3E would have the longest remediation period (70 years), but would also remove the sorbed contaminants during this period and may currently be providing some remediation of the TCE contamination in the shallow Plume E aquifer (Figure 8-1). Therefore, all four alternatives would be effective and permanent.

8.3.4 Reduction of Toxicity, Mobility, and Volume Through Treatment

Alternative 3E would not provide active treatment for the contaminated groundwater, but over time the groundwater contamination can be expected to attenuate through natural processes that are already at work reducing the toxicity of at least some portion of the shallow Plume E groundwater. Alternative 4E would combine extraction and *ex situ* treatment to reduce the toxicity and volume of the plume in 10 years, then MNA for an additional 30 years to remove the lower concentration plume. Alternative 5E would combine bioaugmentation to treat the contaminated groundwater for 10 years to significantly reduce the toxicity of the groundwater contamination, with the existing PRB/MNA for 20 additional years, and a final 10 years by MNA alone. The active treatment method period for "hot spots" using Alternative 6E, chemical oxidation/MNA, would last only six months but, after treatment, the remainder of the low-

concentration plume would naturally attenuate to ARARs in 40 years. Therefore, all four alternatives would provide contaminant reductions. Alternative 6E would provide a much faster reduction in the highest concentrations than Alternatives 4E and 5E, but Alternatives 4E, 5E, and 6E would be twice as fast as Alternative 3E in reaching RAOs (Table 8-8).

8.3.5 Short-Term Effectiveness

Alternative 3E would involve no construction as the PRB already exists and would not include an active remediation component, so there would be no additive short-term impacts to the community or the environment, although LTM workers would be monitored to prevent exposure. Alternative 4E would have no additive short-term exposure to the community, but both construction workers and treatment system O&M workers must be monitored to prevent short-term exposure. Alternative 5E and Alternative 6E would include no additive short-term exposure to the community, but both treatment methods and LTM workers would be monitored to prevent exposure. Therefore, Alternative 3E would provide the least exposure followed by Alternative 5E and 6E, then Alternative 4E.

Alternative 3E achieves RAOs in 70 years, Alternative 4E in 40 years, and Alternative 5E in 40 years, and Alternative 6E in 40 years. Therefore, Alternatives 4E, 5E, and 6E have the same remediation times, followed by Alternative 3E.

"Averaging" the three sub-criteria (community protection, worker protection, and time to achieve RAOs) shows that Alternative 5E has greater short-term effectiveness than Alternative 6E, followed by Alternatives 3E and 4E (Table 8-8).

8.3.6 Implementability

The MNA/PRB alternative (Alternative 3E) would be easy to implement technically, potentially requiring only new monitoring wells, but perhaps be more difficult administratively due to its passive attenuation of the contaminated groundwater. However, due to the stability of the contamination in Plume E and the evidence for current bioremediation, administrative implementability may be slightly better than some other Zone D plumes. The extraction and treatment method alternative/MNA (Alternative 4E) would be the most difficult alternative to implement technically, but relatively easy administratively as it is a USEPA presumptive remedy for contaminated groundwater. The bioaugmentation/PRB/MNA alternative (Alternative 5E) would be less difficult to implement technically than Alternative 4E, but may be more difficult administratively due to its lack of an FEW treatability study. The chemical oxidation/MNA alternative (Alternative 6E) would be less difficult to implement technically than Alternatives 4E and 5E and likely less difficult administratively due to its success in FEW treatability studies.

Therefore, Alternative 3E would be the simplest to implement technically followed by Alternative 6E, then Alternatives 5E and 4E. Administratively, Alternative 6E may be easiest to implement, followed by Alternative 4E and 5E, then Alternative 3E (Table 8-8).

8.3.7 Cost

For cost comparisons, refer to Table 8-6; for qualitative comparisons, refer to Table 8-8. Alternative 3E has the lowest present value cost of the shallow-zone groundwater alternatives,

Alternative 4E has the second lowest, Alternative 6E has the second highest, and Alternative 5E has the highest.

8.3.8 Intermediate Zone Options

The following subsections compare these options for intermediate zone groundwater at Plume E:

- Option 1E-INT – No Action
- Option 2E-INT – Institutional Controls
- Option 3E-INT – MNA
- Option 4E-INT – Localized Chemical Oxidation and MNA

8.3.8.1 Overall Protection of Human Health and the Environment

No Action (Option 1E-INT) would be protective of human health and the environment under current conditions because no current unacceptable risk has been identified (Table 8-9). However, because this alternative would provide no means to monitor future contamination, it would not be protective over the long term. Institutional Controls (Option 2E-INT) would provide implementation and enforcement of administrative controls to prevent future use of the groundwater resource, but cannot monitor future conditions.

Because the source of Plume E has been removed, the extent of the intermediate zone plume appears stable or shrinking, passive bioremediation currently appears to be occurring in parts of the overlying shallow plume, TCE concentrations in monitoring wells in the intermediate zone at the Crow Creek intercept are below MCLs, no unacceptable risk has been identified, and concentrations of TCE would be reduced over long periods of time through natural attenuation and the existing PRB. MNA (Option 3E-INT) would provide protection of human health and the environment through implementation and enforcement of both the LTM program and institutional controls. However, the time to achieve RAOs would be longer than Option 4E-INT. $KMnO_4$ and MNA (Option 4E-INT) would achieve RAOs (i.e., protection of human health and the environment) in the shortest time period through injection of $KMnO_4$ solution into the intermediate zone, enforcement of the LTM program, and institutional controls.

Therefore, Options 3E-INT and 4E-INT would be protective of human health and the environment in both the short- and long-term (Table 8-9). However, Options 1E-INT and 2E-INT cannot provide long-term protectiveness with any certainty and do not meet this threshold criterion.

8.3.8.2 Compliance with ARARs

The No Action option (Option 1E-INT) would not comply with ARARs. The Institutional Controls option (Option 2E-INT) would comply with potential action- and location-specific ARARs, but not with the potential chemical-specific groundwater ARAR of the federal MCL for TCE of 5 µg/L or with ARARs requiring monitoring of releases. Because these first two options do not meet this threshold criterion, they are not carried through the remainder of the comparative analysis (Table 8-9).

Options 3E-INT and 4E-INT would comply with potential action and location specific ARARs and with ARARs requiring monitoring of releases (i.e., 40 CFR Part 264). Option 3E-INT would comply with the potential chemical-specific groundwater ARAR set at the federal MCL for TCE of 5 µg/L by the end of a 130-year LTM period and Option 4E-INT after a combined 35-year *in situ* treatment and LTM period (Table 8-9).

8.3.8.3 Long-Term Effectiveness and Permanence

Option 4E-INT would reduce the highest concentrations from greater than 100 µg/L TCE to 5 µg/L in six months, leaving other areas of concentrations below 10 µg/L for an additional 35 years (Figure 8-10). This option would provide a higher degree of long-term effectiveness and permanence than Option 3E-INT because Option 3E-INT would leave TCE concentrations in groundwater at Plume E until near the end of the 130-year LTM period (Figure 8-8; Table 8-9).

8.3.8.4 Reduction of Toxicity, Mobility, and Volume Through Treatment

Option 3E-INT would not provide active treatment method for the contaminated groundwater, but over time (130 years) the plume would be expected to attenuate through natural processes that reduce the toxicity and volume of contamination. Option 4E-INT would combine chemical oxidation to actively treat the highest concentrations in groundwater for 6 months, followed by natural attenuation to ARARs in 35 years. Thus, the use of active treatment methods in Option 4E-INT would reduce the total time for remediation of the intermediate zone of Plume E by more than 75 percent of the 130-year MNA-only period.

8.3.8.5 Short-Term Effectiveness

Option 3E-INT would not include an active remediation component, so there would be no additive short-term exposure to the community, but LTM workers would be monitored to prevent exposure. The Option 4E-INT system would have no additive short-term exposure to the community, but chemical oxidation treatment method and LTM workers would be monitored to prevent exposure. However, Option 3E-INT requires 130 years to achieve RAOs and Option 4E-INT requires 35 years. Therefore, Option 4E-INT would provide better short-term effectiveness than Option 3E-INT (Table 8-9).

8.3.8.6 Implementability

Option 3E-INT would be easy to implement technically due to its need only for additional monitoring wells, but perhaps more difficult administratively. Option 4E-INT would be more difficult to implement technically than Option 3E-INT, but perhaps less difficult administratively due to its rapid reduction of the highest contaminant concentrations. Therefore, Option 3E-INT would be the simpler to implement technically, and Option 4E-INT may be more easily implemented administratively (Table 8-9).

8.3.8.7 Cost

For cost comparisons, refer to Table 8-7; for qualitative comparisons, refer to Table 8-9. Option 3E-INT has the lower present value cost and Option 4E-INT has the higher of the two intermediate-zone groundwater options.

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Appendix A

Technical Memorandum: Bioaugmentation Treatability Study - Preliminary Results

TECHNICAL MEMORANDUM:

BIOAUGMENTATION TREATABILITY STUDY PRELIMINARY RESULTS

F. E. Warren Air Force Base, Wyoming

Prepared for:

90 SW/EM
F. E. Warren Air Force Base, Wyoming

and

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February 2004

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This bioaugmentation study was conducted in association with the Zone D Groundwater Feasibility Study. The purpose of this investigation is to gain information to better evaluate the indigenous microbial community and supporting environmental conditions in the groundwater systems within Zone D. This information will be used to (1) aid in the selection of a final remedy for Zone D groundwater, and (2) aid in implementation of the selected remedy by gaining site-specific data. A flow diagram representing the process followed to evaluate bioaugmentation as a potential treatment technology for Zone D is display on Figure A-1.

The implementability and effectiveness of bioaugmentation depends on the nature of the groundwater system to receive treatment. Data collected during this investigation may be used to optimize a bioaugmentation remedial treatment design for bench- or field-scale testing.

1.1 GROUNDWATER SAMPLING PARAMETERS

Groundwater samples were collected from 10 groundwater monitoring wells in the area of Spill Site 7 (SS7) and Plume A as displayed on Figure A-2. The wells were selected based on their spatial distribution, depth, and TCE concentration (USAF 2002). Six wells were selected within SS7 and four were selected within Plume A. The well locations are well distributed across both of the contaminated areas to provide comprehensive data that is representative of SS7 and Plume A as a whole. Samples were collected from wells that are screened at shallow depths (approximately 35 feet) and with historical concentrations of TCE ranging from approximately 13,170 to 0.67 µg/L within SS7, and 80 to 2.25 µg/L within Plume A (USAF 2002). Laboratory analysis and field measurements were performed to collect data for the following parameters:

- *Dehalococcoides* percent intensity
- Dissolved ethene
- Trichloroethene (TCE) and degradation products
- Ferrous iron
- Dissolved oxygen (DO) and oxidation-reduction potential (ORP)

Results of testing and analysis are included in Table A-1. The rationale for each analysis or test is provided in the sub-sections that follow.

1.1.1 Dehalococcoides

The SiREM Gene-Trac™ *Dehalococcoides* Test was used to determine the presence or absence of *Dehalococcoides* microorganisms in groundwater. The anaerobic bacterium *Dehalococcoides ethenogenes* is currently the only known organism that can completely dechlorinate tetrachloroethene (PCE) and TCE to ethene via dehalorespiration (Magnuson et al. 2000; Maymó-Gatell et al. 1997; Damborsky 1999; Duhamel et al. 2002). The presence of an effective *Dehalococcoides* strain has been correlated with complete dechlorination at contaminated sites in North America and Europe (Hendrickson E.R. 2002). At sites where *Dehalococcoides ethenogenes* is absent or if an ineffective strain is present, PCE and TCE dechlorination typically stalls at *cis*-1,2-dichloroethene (DCE) despite ample nutrient (electron donors such as hydrogen) availability (SiREM 2003).

The results of *Dehalococcoides* testing can provide information about the nature of the microbial community at the site and the redox conditions of the aquifer. Strong detections of the bacteria could indicate that reducing conditions are prevalent and able to support a dominant anaerobic community. Weak detections could indicate that reducing conditions are not ideal and that small, isolated anaerobic zones may exist throughout a generally aerobic aquifer. In other words, the bacteria exist, but under unfavorable growth conditions.

When the results of *Dehalococcoides* testing are nondetect or low, indicating the bacteria are present but poorly distributed and/or exist at very low population densities, bioaugmentation with *Dehalococcoides* should be considered to promote the desired rate and extent of microbial dechlorination or increase the density and distribution of the microorganisms to achieve cleanup goals within the desired timeframe (SiREM 2003).

1.1.2 Ethene

The detection of ethene as a dissolved gas in groundwater can be used as evidence for the presence of *Dehalococcoides*, since ethene is the end result of complete TCE dechlorination. Concentrations of ethene in groundwater can indicate that anaerobic contaminant degradation has occurred within the plume. However, it is possible that abiotic dechlorination can produce ethene concentrations in groundwater. In addition, ethene produced at an upgradient location could be transported downgradient while no active conversion of TCE is occurring in the downgradient location. Although, ethene concentrations combined with the detection of microorganisms belonging to the *Dehalococcoides* species presents a strong case that anaerobic reductive dechlorination is occurring at a site.

1.1.3 TCE and Degradation Products

Anaerobic bacteria degrade TCE through the reductive dehalogenation process. In a complete process, TCE is converted to DCE isomers, then to vinyl chloride, and then further to ethene. An incomplete reductive dehalogenation process results in a “stall” or a build up of *cis*-1,2-DCE. This stall can occur if *Dehalococcoides* is absent, weak, or if a less effective strain is present. Groundwater samples were collected and analyzed for VOCs to investigate if the reductive dehalogenation process is occurring, and whether it is complete or appears to stall at *cis*-1,2-DCE.

1.1.4 Ferrous Iron

The reduction of ferric iron (Fe^{3+}) through iron reducing microbial metabolic processes results in the production of ferrous iron (Fe^{2+}). Elevated concentrations of ferrous iron can be found in anaerobic groundwater systems; therefore, if microbial iron reduction is occurring, ferrous iron concentrations may be elevated above background concentrations. During the investigation, a field test kit was used to measure Fe^{2+} concentrations in groundwater.

1.1.5 Dissolved Oxygen and Oxidation-Reduction Potential

DO is representative of redox conditions in the aquifer. Similarly, ORP is a measure of the tendency of a solution to donate or accept elections. DO concentrations and ORP measurements indicative of anaerobic conditions are typically less than 1.0 milligram per liter (mg/L) and less than -100 millivolts (mV), respectively. During the investigation, both parameters were measured in the well using a bladder pump equipped with a down-hole water quality meter.

The results and a discussion of the data collected are included in the sections that follow.

2.1 DEHALOCOCCOIDES

Dehalococcoides bacterial deoxyribo nucleic acid (DNA) was detected in 9 of the 10 samples collected (Table A-1). The highest percent intensity (101%) was detected in the sample collected from MW-186, which is located directly downgradient and adjacent to the SS7 permeable reactive barrier (PRB). The high percent intensity indicates that reducing conditions created by the PRB favor the growth of anaerobic microorganisms such as *Dehalococcoides*. The percent intensity in the other samples with positive detections ranged from 4 to 40%, indicating that generally low or poorly distributed levels of a strain of *Dehalococcoides* is present.

The near site-wide presence of this bacteria indicates that weak anaerobic conditions, although significant to support some anaerobic microbial growth, exist across the SS7 and Plume A area of Zone D. In order for these microorganisms to thrive, anaerobic conditions must be enhanced. Such enhancement would stimulate the indigenous dechlorinating microbes as well as establish the reducing conditions necessary for bioaugmentation. Stimulating the indigenous microorganisms alone may not result in achieving treatment goals since less effective strains of *Dehalococcoides* may be present, which would require more time to degrade TCE or initiate incomplete degradation. The evidence of small areas exhibiting anaerobic conditions indicates that establishing reducing conditions for bioaugmentation could be easier to implement than if the aquifer was purely aerobic.

2.2 ETHENE

Dissolved ethene was detected in 2 of the 10 groundwater samples collected (Table A-1). The two locations where ethene was detected were MW-186 and MW-173B, both of which are adjacent to and downgradient of the PRB. Considering the ethene and the *Dehalococcoides* data collected from these two wells, it is suspected that the PRB has created reducing conditions necessary for *Dehalococcoides* to thrive and degrade TCE to ethene. However, this effect is more apparent in MW-186 than in MW-173B since *Dehalococcoides* and ethene detections in samples from MW-186 were significantly higher than in samples from MW-173B.

2.3 TCE AND DEGRADATION PRODUCTS

Concentrations of *cis*-1,2-DCE were detected in the 10 groundwater samples along with some minor detections of the 1,1-DCE and *trans*-1,2-DCE isomers, indicating that an incomplete reductive dehalogenation process resulting in the production and persistence of DCE may be occurring (Table A-1).

Vinyl chloride was detected in 2 of the 10 groundwater samples collected. The two locations where vinyl chloride was detected were MW-186 and MW-173B, both of which are adjacent to and downgradient of the PRB. Considering this detection as well as the ethene and *Dehalococcoides* data collected from these two wells, it is further suspected that the PRB has created reducing conditions necessary for *Dehalococcoides* to thrive and degrade TCE through the complete reductive pathway of TCE to DCE to vinyl chloride to ethene. Because the degradation of vinyl chloride to ethene through anaerobic processes is rate limiting, levels of

vinyl chloride may persist before the final reduction to ethene (Freedman 1989). Recent microbial research has isolated a strain of *Dehalococcoides* (BAV1) that readily reduces vinyl chloride to ethene (He 2003). Using this strain in an anaerobic microbial consortia could eliminate the persistence of vinyl chloride.

2.4 FERROUS IRON

Ferrous iron was not detected in the 10 samples indicating that iron reducing bacteria are not present, or that the anaerobic conditions required to support microbial iron reduction do not currently exist within SS7 and Plume A.

2.5 DISSOLVED OXYGEN AND OXIDATION-REDUCTION POTENTIAL

Because accurate DO and ORP measurements are difficult to collect due to sample aeration, a bladder pump equipped with an in-well water quality meter was used for groundwater sampling. DO and ORP measurements clearly indicative of reducing conditions were observed in MW-186 and MW-173B. At the other sampling locations, DO and ORP measurements indicated predominantly aerobic conditions. However, due to the detections of *Dehalococcoides*, it appears that in addition to the generally aerobic environment, sporadic anaerobic conditions significant enough to support anaerobic microbial growth may be present in portions of the aquifer (e.g. lower permeability soils).

DO and ORP groundwater measurements collected in the area of SS7 and Plume A in Zone D indicate that redox conditions appear to be predominantly aerobic with the exception of the area immediately adjacent to and downgradient of the PRB, where significant reducing conditions were observed. The lack of ferrous iron in groundwater also suggests that anaerobic processes are not prevalent.

The detection of native *Dehalococcoides* in 9 out of 10 samples collected across the investigation area suggests that weak or poorly distributed areas of anaerobic conditions also exist. Significant evidence of existing small-scale anaerobic environments was observed in the wells adjacent to the PRB. It is speculated that once reducing conditions were established by the PRB, the native anaerobic community was able to grow and degrade TCE completely to ethene. Therefore, if bioaugmentation were selected as a remedial treatment option, reducing conditions would have to be established before microbial augmentation.

Based on the data received during this investigation, conditions in the SS7 and Plume A areas of Zone D appear to be acceptable for bioaugmentation, however aquifer pretreatment to establish a reducing environment would be required. A reagent containing an oxygen scavenger, electron donor, and various nutrients should be added to condition the aquifer before foreign dechlorinators are augmented. This pre-treatment can add additional challenges, time, and expense to the bioaugmentation treatment option.

Although *Dehalococcoides* are present, the addition of laboratory-grown microbes may still be required since the anaerobic microbes are present but appear to be poorly distributed and/or exist at very low population densities. In addition, the strain present does not appear to be the most effective since a stall at *cis*-1,2-DCE may be occurring. Bioaugmentation with additional cells of a more effective strain of *Dehalococcoides* should be considered to promote the desired rate and extent of microbial dechlorination or increase the density and distribution of the microorganisms to achieve cleanup goals within a desired timeframe.

It is recommended that a bioaugmentation bench- or field-scale treatability study be designed and conducted before bioaugmentation is recorded as the selected treatment option. The results of bench-scale testing would include the appropriate mixture of reagents needed to establish reducing conditions within a specific area of Zone D. Because laboratory conditions seldom mirror field conditions, the mixture of reagents, as well as the augmentation of a *Dehalococcoides* consortia should be further tested in the field before attempting to implement full-scale bioaugmentation.

Results from bench-scale testing may not be easily extrapolated to other plumes within Zone D, including Plume C and Plume E. Although lithologic, geochemical, and contaminant conditions within these plumes are similar to those observed in Plume A, separate bench-scale tests conducted on a plume by plume basis should be considered before extensive bioaugmentation is implemented. Bench-scale tests can be small-scale and cost approximately $8,000 to $10,000.

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Table A-1
BIOAUGMENTATION INVESTIGATION DATA SUMMARY

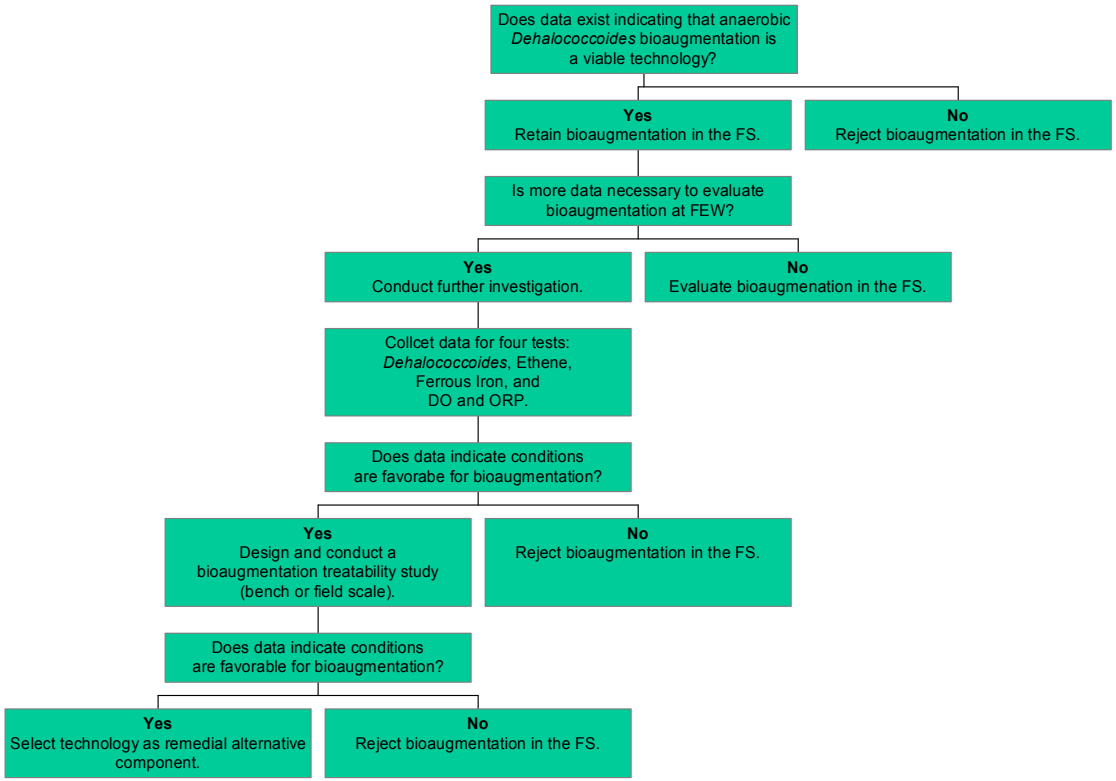
Well ID	Location	Sample Dates	Fe2+ (mg/L)	DO (mg/L)	ORP (mV)	Dehaloco-ccoides (test intensity %)	Ethene (ug/L)	Methane (ug/L)	TCE (ug/L)	cis-1,2-DCE (ug/L)	1,1-DCE (ug/L)	trans-1,2-DCE (ug/L)	vinyl chloride (ug/L)
SS7MW-35	*SS7*	5/29/2003	0	3.17	169	40	ND	ND	360	41	0.95	0.19	ND
MW-151	*SS7*	5/27/2003	0	11.3	114	35	ND	0.3	13000	230	ND	ND	ND
MW-173B	*SS7*	5/28/2003	0	0.19	-256	12	1.4	2400	32	52	ND	ND	6.5
MW-186	*SS7*	5/28/2003	0	0.85	-147	101	22	3800	89	120	4.2	1.8	70
MW-190	*SS7*	5/29/2003	0	6.28	143	20	ND	ND	500	11	0.23	0.25	ND
MW-144R	*Plume A*	5/28/2003	0	11.06	93	20	ND	4	47	0.41	2.3	ND	ND
MW-165C	*Plume A*	5/29/2003	0	3.62	115	0	ND	ND	25	0.18	1.2	ND	ND
MW-1002	*Plume A*	5/29/2003	0	4.37	101	4	ND	0.3	40	0.43	1.7	ND	ND
MW-099	*Background*	5/29/2003	0	1.71	100	7	ND	ND	4.2	0.3	ND	ND	ND
MW-321	*Background*	5/28/2003	0	6.03	78	16	ND	6.7	2.2	0.14	ND	ND	ND

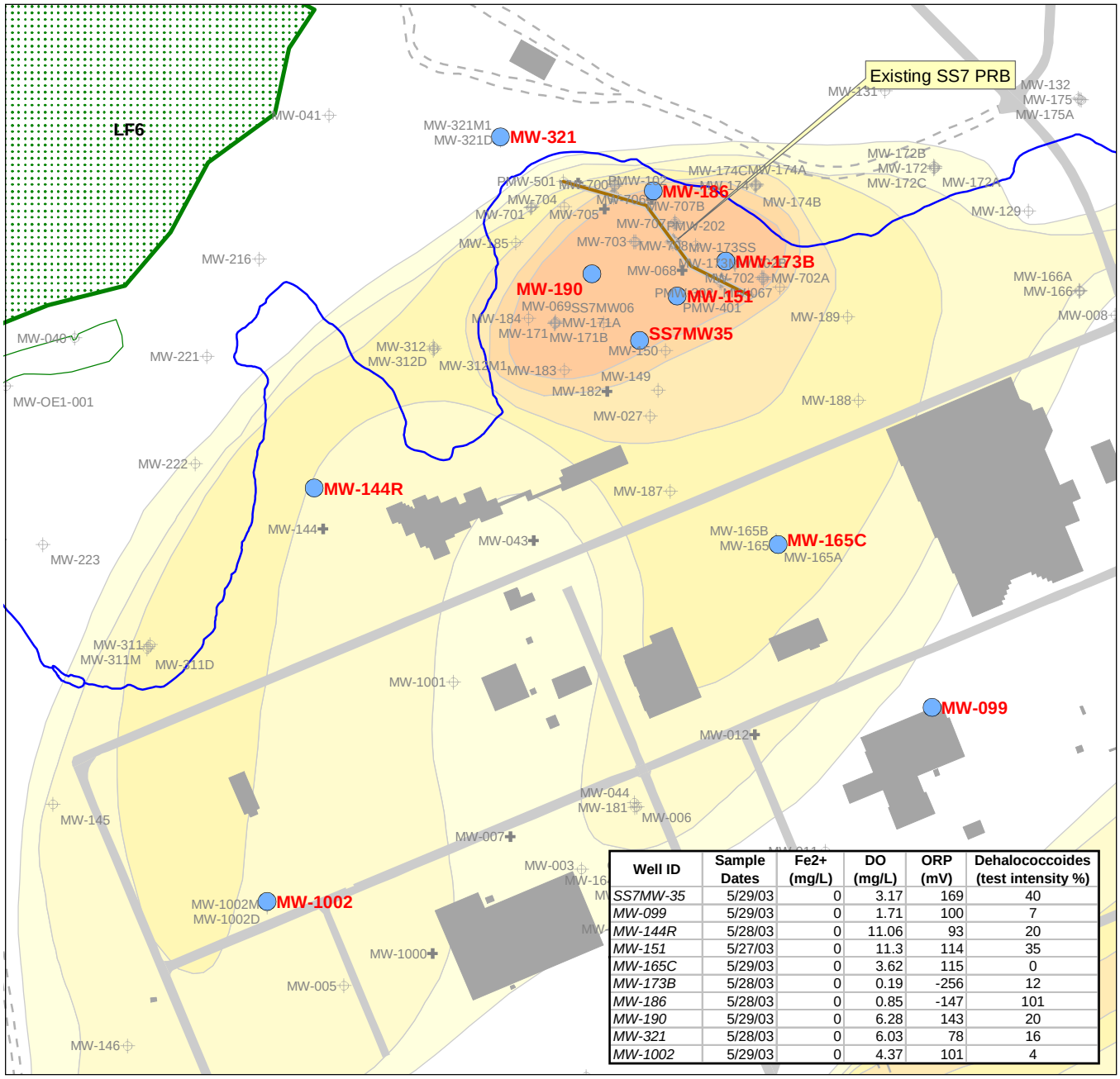
Notes:

SS7 = Spill Site 7
Fe2+ = ferrous iron
DO = dissolved oxygen
ORP = oxidation-reduction potential
TCE = trichloroethene
DCE = dichloroethene
mg/L = milligrams per liter
ug/L = micrograms per liter
mV = millivolts

Well ID	Location	Sample Dates	Fe2+ (mg/L)	DO (mg/L)	ORP (mV)	Dehalococcoides (test intensity %)	Ethene	Methane	PCE	TCE	cis-1,2-DCE	1,1-DCE	trans-1,2-DCE	vinyl chloride
SS7MW-35	*SS7*	5/29/2003	0	3.17	169	40	ND	ND	ND	360	41	0.95	0.19	ND
MW-151	*SS7*	5/27/2003	0	11.3	114	35	ND	0.3	ND	13000	230	ND	ND	ND
MW-173B	*SS7*	5/28/2003	0	0.19	-256	12	1.4	2400	ND	32	52	ND	ND	6.5
MW-186	*SS7*	5/28/2003	0	0.85	-147	101	22	3800	ND	89	120	4.2	1.8	70
MW-190	*SS7*	5/29/2003	0	6.28	143	20	ND	ND	ND	500	11	0.23	0.25	ND
MW-144R	*Plume A*	5/28/2003	0	11.06	93	20	ND	4	ND	47	0.41	2.3	ND	ND
MW-165C	*Plume A*	5/29/2003	0	3.62	115	0	ND	ND	ND	25	0.18	1.2	ND	ND
MW-1002	*Plume A*	5/29/2003	0	4.37	101	4	ND	0.3	ND	40	0.43	1.7	ND	ND
MW-099	*Background*	5/29/2003	0	1.71	100	7	ND	ND	ND	4.2	0.3	ND	ND	ND
MW-321	*Background*	5/28/2003	0	6.03	78	16	ND	6.7	0.19	2.2	0.14	ND	ND	ND

Figure A-1
Bioaugmentation Technology Evaluation





Well ID	Sample Dates	Fe2+ (mg/L)	DO (mg/L)	ORP (mV)	Dehalococcoides (test intensity %)
SS7MW-35	5/29/03	0	3.17	169	40
MW-099	5/29/03	0	1.71	100	7
MW-144R	5/28/03	0	11.06	93	20
MW-151	5/27/03	0	11.3	114	35
MW-165C	5/29/03	0	3.62	115	0
MW-173B	5/28/03	0	0.19	-256	12
MW-186	5/28/03	0	0.85	-147	101
MW-190	5/29/03	0	6.28	143	20
MW-321	5/28/03	0	6.03	78	16
MW-1002	5/29/03	0	4.37	101	4

EXPLANATION

- Shallow Groundwater Monitoring Well Proposed Bioaugmentation Location
- Groundwater Monitoring Well
- Abandoned Well
- IRP Site
- Excavated (fully/partially)
- Buildings
- Paved Road
- Unpaved Road

Interpreted TCE Concentrations of 2001 (µg/L)

- 5-10
- 10-50
- 50-100
- 100-400
- 400-1000
- >1000

N W E S

0 200 400 800 Feet

NOTES:
1. Horizontal Datum: Wyoming State Plane, East Zone, NAD83, Feet
2. Vertical Datum: NAVD88, Feet

Bioaugmentation Treatability Study Monitoring Wells

FILE NAME	LAST REVISION DATE	DR BY
Bioaug_wells.mxd	August 2003	JLC

Figure A-2

Appendix B

Response to Agency Comments on the Draft Zone D Groundwater Feasibility Study

RESPONSE TO EPA COMMENTS
DRAFT FINAL ZONE D GROUNDWATER FEASIBILITY STUDY (3 VOLUMES)
F. E. Warren Air Force Base, Wyoming
February 2004

Review of the Draft-Final Feasibility Study is in the form of a Response Evaluation. In this case, the original EPA comment is identified, followed by an evaluation of the response. Only those comments for which additional follow through or effort is needed are identified. Revisions and responses to comments are otherwise accepted.

GENERAL COMMENTS

1. EPA General Comment 5. The EPA previously commented that the Draft FS refers to monitored natural attenuation (MNA) as treatment and requested that references to MNA as treatment be removed from the document. The response to comments indicates that EPA has described MNA as a "treatment method" in *A Citizen's Guide to Monitored Natural Attenuation* (dated October 1996) and the *Treatment Technologies Toolkit* (EPA 2002), and therefore the description of MNA as a treatment will be continued in the this FS.

   However, EPA does not view MNA as "treatment". EPA indicates that the term monitored natural attenuation refers to the reliance on natural attenuation processes (within the context of a carefully controlled and monitored site cleanup approach) to achieve site-specific remediation objectives within a time frame that is reasonable compared to that offered by other more active methods. The fact sheet referenced in the response to comments was revised in April 2001 and the referenced statement was removed. The majority of EPA's literature (including the OSWER directive on MNA [EPA 1999]) refers to MNA as an option, method, or process, not treatment. In fact, the OSWER directive, reserves use of the term "treatment," to describe specific actions, not including MNA.

   Response: *The EPA "Toolkit," updated in September 2002—the most recent document mentioned in the comment, uses the term "treatment method" in reference to MNA. However, the FS text has been revised to indicate MNA as an option, method, or process, and not as "treatment" .*

2. EPA General Comment 9. EPA previously commented that in some cases consideration should be given to combining the treatment technologies from the shallow and intermediate zones of the same plume because of economies of scale. The response to comments indicates that the overall cost would only be nominally improved by combining the alternatives because the same amount of potassium permanganate would be needed for injection and the same number of monitoring points would be required. While this is true and maintaining separate alternatives is acceptable, it should be noted (Perhaps as a qualifier in Section 3.2?) that the costs of mobilization and demobilization (which can be significant in some cases) would be decreased by combination of the alternatives which would provide an economy of scale.

Response: *As the only intermediate-zone technology selected for any of the five plumes is chemical oxidation, the only economy-of-scale would be where chemical oxidation is also a shallow-zone alternative. For those alternatives (6S, 5B, 4C-6C, and 6E), some economies might be realized, although mob/demob cost differences would be minimal. This incremental cost difference is small because only HSA drill rigs are capable of chem-ox injection in the intermediate zone, while both HSA and Geoprobe are planned for the shallow zone. There are, therefore, 2 mob/demob events already incorporated into shallow-zone chem-ox, and a third mob for an HSA rig is not a large additional expense. A comment to this effect has been added to Section 3.2 and Sections 5.2.7.2, 6.2.6.2, 7.2.7.2, and 8.2.7.2.*

3. In the Comparative Analysis of Alternatives, elaboration is needed in the discussion for "Short-Term Effectiveness". Explicitly use the estimated time frames for achieving cleanup (i.e., final RAOs) in ranking the alternatives. If this changes the relative rankings, the corresponding table may also need to be modified. Discussing the time frames in other criteria (mainly "Compliance with ARARs") does not explicitly describe for the reader the tradeoffs in time frames.

   Response: *The time frames to reach RAOs have been incorporated into the "Short-Term Effectiveness" subsections of the "Comparative Analysis of Alternatives" sections.*

SPECIFIC COMMENTS

1. Some of the responses to EPA's comments on the Draft FS are accepted yet were not incorporated into the document. Follow-through to incorporate the changes is still needed for Specific Comments 28, 35, 66, 69 (regarding threshold levels), 106, 107, 129, 134. For example, the response to comment 28 indicates that the general response action title would be changed from mobilization to flushing, however, this was not done. Incorporate the responses to comments.

   Response: *The previous comment responses have been incorporated as recommended by EPA.*

2. For Specific Comment 26, the text was modified to indicate that nutrient enhancement was an established technology; however, not all of the tables reflect this change. For example Table 3-2, indicates in the description of the effectiveness of anaerobic biostimulation with nutrient enhancement that the technology is innovative. Update the tables to reflect the changes made in the text

   Response: *The tables, including Table 3-2, have been updated to reflect the modifications in the text.*

3. EPA Specific Comment 154. EPA previously commented that Section 8.2.7.2, which describes the short-term effectiveness of localized chemical oxidation and MNA, is the first place which discusses soil spoils and their disposal. However, this discussion is appropriate for many alternatives. The response to comment does not address this comment; nor is the discrepancy corrected in the document. The intent of the comment was to have any alternative-specific waste streams and their handling addressed, which is still needed.

Response: *The previous identical statements in Sections 4.2.6.2, 5.2.7.2, 6.2.6.2, 7.2.7.2, and 8.2.7.2 were incorrect for handling of soil spoils at FEW and have therefore been corrected. Alternative-specific waste streams and their handling have now been addressed in the Detailed Analysis section for each alternative and option.*

OTHER RECOMMENDATIONS

1. Recommendation: Section 3.12.1, Page 3-27. This section discusses the reinjection and indicates that reinjection is preferred by the State Engineer's Office. However, the administrative implementability is rated as low. If this is the preferred method, it is unclear why the administrative implementability is considered low. Provide additional rationale for reinjection's low administrative implementability. Given the relatively low permeabilities, fluid injection might require many injection wells or galleries, making the technical implementability low. EPA acknowledges this results in no net change to the implementability of injection; however the ranking should more accurately portray the rationale.

Response: *This section has been rewritten with additional rationale provided for the technical and administrative implementability.*

REFERENCES

U.S. Environmental Protection Agency (EPA). 1999. *OSWER Directive 9200.4-17P -- Use of Monitored Natural Attenuation at SUPERFUND, RCRA Corrective Action, and Underground Storage Tank Sites*. EPA-540-R-99-009 April 21.

EPA. 2001. *A Citizen's Guide to Monitored Natural Attenuation*. EPA-542-F-01-004. http://www.epa.gov/tio/download/citizens/mna.pdf. April.

Response: *The references above have been added to, or edited in, Section 9 of the FS.*

EDITORIAL COMMENTS

Sec. 5.1, Development of Alternatives, 3rd paragraph of Section (Page 5-1), 4th sentence. This can be broken into two sentences or modified as "... Zone D plumes, **which** limits ...".

Response: *The change was made.*

Sec. 5.1, Development of Alternatives, 4th paragraph of Section (Page 5-1), 2nd sentence. Either delete "which" in the second sentence or combine the first and second sentences.

Response: *The sentence was split into two sentences and ", which has" was replaced with "with".*

Sec. 5.1.8, Option 1S Channel Drop Structures, 3rd paragraph, last sentence. Change "are frozen" to "is frozen".

Response: *The change was made.*

Table 3-8, Sheet 3 of 4, Phytoremediation row, Creek Intercept Column. 3rd bulletin: Delete "has". 4th bulletin: The end word or phrase is missing.

Response: *"Has" was deleted and "technologies" added to 4th bulletin.*

Table 4-11, Sheet 1 of 1, Row for Long-term effectiveness and permanence. Alternative 3A-INT is listed twice and 4A-INT is not in the row. Typo?

Response: *This typo has been corrected by changing "Option 3A-INT" in column 3 to "Option 4A-INT".*

RESPONSE TO EPA COMMENTS ON
DRAFT ZONE D GROUNDWATER FEASIBILITY STUDY (3 VOLUMES)
F. E. Warren Air Force Base, Wyoming
October 2003

EPA Comments are structured into General Comments and Specific Comments. General Comments are used to identify an overall issue or concern, or may summarize issues. Specific Comments are keyed to text in the document by the Section, paragraph, page, figure, table or similar feature. Specific Comments pertain to particular issues or concerns.

GENERAL COMMENTS

1. There are numerous inconsistencies throughout the document. For example, Section 1.2.3, which describes the nature and extent of contamination, indicates on page 1-14 that the downgradient edge of Plume B does not extend to Crow Creek; however, Plate 1 shows the plume intercepting the creek and the document evaluates alternatives for remediation of the creek intercept of Plume B. Another example can be found in Section 4, which describes Alternative 4A for Plume A shallow groundwater consisting of groundwater extraction, treatment with a liquid-vapor phase bioreactor, and discharge. However, Table 4-8 which summarizes the detailed analysis of alternatives describes treatment with activated carbon. An additional example can be seen on page 7-4, in Section 7.1.3.3 which should contain the conceptual design for the Plume C alternative encompassing extraction, treatment and monitored natural attenuation (MNA); the section describing MNA discusses Plume B. These examples are only a few of many major inconsistencies found throughout the document. These inconsistencies hamper understanding of the technologies and the alternatives, and cast doubt on the data and conclusions presented in the document.

   Response: *An effort has been made to address inconsistencies within the Draft document. With respect to the specific examples cited in the comment, the referenced text has been reviewed and revised accordingly as described below.*

   Concerning Plume B and the intercept with Crow Creek, there is no current empirical data to support the discharge of the TCE-plume into Crow Creek. However, based on transport modeling in Volume II, the potential for discharge exists and as a result the text in Section 1 has been revised to indicate that this potential for discharge of TCE-contaminated groundwater to the creek exists. These statements are consistent with how remediation of the creek intercept is addressed in subsequent sections.

   Concerning Alternative 4A and treatment with a liquid-vapor phase bioreactor versus activated carbon, changes have been made to both the text and tables. In brief, the intended approach for the two-phase extraction and treatment technology is to treat the low-concentration aqueous phase (i.e., groundwater) that has been "stripped" by two-phase extraction with activated carbon and to treat the high-concentration vapor phase using a bioreactor; therefore both technologies are proposed. Similar changes to those for Alternative 4A have been made to the other plume alternatives that also include extraction and treatment as a technology.

In the discussion of the Plume C alternative that includes MNA, the reference to Plume B has been removed.

2. Three RAOs have been developed for the site: 1) restore groundwater to beneficial use, by reducing trichloroethene (TCE) and its degradation byproducts below their respective maximum contaminant levels (MCLs); 2) prevent concentrations of TCE and its degradation products in surface water from exceeding class specific standards; and 3) prevent volatile organic compound (VOC) vapors from groundwater plumes from accumulating to unacceptable risk levels in the indoor air of future buildings (page 2-1). The surface water and indoor air RAOs are not consistently addressed throughout the text. Frequently when the ability to meet the RAOs is discussed, only the groundwater RAO is addressed. The document should be modified to address all RAOs.

   Response: *Discussions regarding the surface water and indoor air RAOs have been incorporated into the appropriate sections. In particular the following text updates concerning indoor air have been added to subsections 2.4.1, 4.1, 4.2, and the corresponding subsections for other plumes.*

   For example, in many of the discussions regarding protection of human health and the environment, the document indicates that "The human health BRA [baseline risk assessment] indicates that TCE contamination in the groundwater at Zone D would not pose an unacceptable threat to human health under current conditions. An unacceptable risk may only be posed if residences were built on the site and used the groundwater for drinking, washing and other domestic uses; but this is considered unlikely because municipal supplies are available." These sections as well as others in the document do not consider the risk to surface water and indoor air quality addressed by the second and third RAOs.

   Response: *Sections pertaining to the protection of human health and the environment have been revised, as appropriate, to include surface water and indoor air. Concerning the comments about "risk" to surface water, the Surface Water Risk Assessment (USAF 2002b) did not identify any unacceptable risk from TCE to surface water at FEW.*

   In addition, Section 2.1 indicates that based on uncertainties associated with the modeling of VOCs from groundwater to indoor air, that actions related to future construction will be assessed on a case-by case basis. It is unclear how this will be accomplished; institutional controls for the alternatives only describe limiting access to groundwater. The ability to provide protection from exposure to potentially affected indoor air must be addressed as part of this document.

   Response: *Sections that discuss institutional controls have been revised to include references to indoor air.*

3. The logic behind the technology and process options screening rankings of low to high used to judge effectiveness, implementability, and costs is not always clear. Low administrative feasibility is often attributed to the technology not being proven or lack of regulatory agency awareness. However, the basis for these assumptions is not obvious. For example, phytoremediation with poplar trees is assessed as having low administrative feasibility because of potential lack of regulatory agency awareness (this is also considered a limitation of the technology). However, the reasoning behind this assumption regarding regulatory agencies is not clear. In addition, lack of familiarity is not necessarily a detriment to a technology. In addition, the document ranks Hydrogen Release Compound (HRC) as possessing a high operation and maintenance (O&M) cost even though the text states on page 3-3 that the technology dramatically reduces O&M costs because mechanical O&M is eliminated and there are fewer long-term monitoring costs.

   Response: *The text and tables have been subjected to revisions and refinements in an effort to clarify the logic used for the screening rankings.*

   The logic behind the retention and rejection of technologies is not always clear. For example, anaerobic biostimulation through nutrient enhancement is moderately effective, moderately technically implementable and is considered to have a low capital cost. However, it is considered to have low administrative implementability, because it is not a proven technology (even though it is stated on page 2-8 that it has been used effectively to degrade TCE), and it is considered to have high O&M costs. The technology is rejected "due to the availability of other anaerobic technologies that work more rapidly or provide greater effectiveness, such as HRC." However, HRC is not recommended based on bench scale results as described in Section 1.3.2, page 1-18, and although initially retained, is later rejected at each plume and site. In addition, technologies with similar or lesser ratings were retained. For example, zero valence iron (ZVI) by injection, which has limited information regarding effectiveness, low technical and administrative feasibility, and high capital costs, was retained even though this technology was not recommended based on the results of the treatability test. Give additional thought and discussion to the technology screening criteria ratings and the subsequent retention and rejection of technologies.

   Response: *The text and tables have been subjected to revisions and refinements in an effort to clarify the logic used for retaining and rejecting technologies.*

4. The results and conclusions of the treatability studies have not been consistently included in the text. For example, Section 3.1 through 3.10, which describe technology screening, indicate that several technologies will be retained pending the results of the current pilot studies. In addition, Section 3.2.2 retains the use of HRC, even though it is not recommended based on bench scale results described in Section 1.3.2, page 1-18. Later in the chapter, after the initial retention of these technologies, they are rejected for every plume and site based on the pilot test results and other rationale as seen in Tables 3-3 through 3-8. The treatability studies have been completed and the results should be incorporated into Sections 3.1 through 3.10. Base the technologies' effectiveness

rankings on the treatability study results. If a technology is ineffective based on treatability studies, the technology should be removed in the initial screening in the chapter.

Response: *The treatability studies results have been updated (except for the electrical barrier for which result are not yet available). As suggested, if the results indicated low effectiveness for site conditions of FEW the technology was rejected (Table 3-2).*

5. The document frequently refers to treatment by MNA, and indicates how "the toxicity, mobility and volume of TCE are reduced over time by natural attenuation." MNA is not an active treatment process. Remove all references indicating such. The text should be clear that while the toxicity, mobility, and volume of TCE are reduced via natural attenuation processes, it is not attributable to active treatment.

   Response: *In the first paragraph of "A Citizen's Guide to National Attenuation" (EPA 542-F-96-015 dated Oct. 1996), EPA stated that "Natural attenuation – also referred to as intrinsic remediation, bioattenuation, or intrinsic bioremediation – is an in situ treatment method." This same sentence is repeated in EPA's "Treatment Technologies Toolkit" (Sept. 2002). The Air Force agrees that MNA or "intrinsic remediation" is not active treatment, but is one of many passive treatment methods currently in use. If the criterion were "reduction in toxicity, mobility, and volume through <u>active</u> treatment," all passive treatment systems—PRBs, bioaugmentation, HRC, etc.—would be eliminated from use at a CERCLA site.*

6. In the "Conceptual Design" discussion of alternatives which include ground water extraction and treatment (pump and treat), there is some discussion placed in the shallow zone alternatives which actually belongs with the intermediate/deep alternatives. Specifically, references are frequently made about extraction feasibility and dewatering (inactive cells). This can cause confusion, because the alternative nonetheless goes on to develop an alternative (for shallow ground water). Separate the discussions.

   Response: *The discussion regarding extraction feasibility and dewatering (inactive cells) is placed in the correct location, contrary to the inference provided in the above comment. Due to the relatively low calibrated hydraulic conductivity (see Figure 2-2, Volume II) within the Plume A/SS7 area of the model domain, pumping wells in the shallow zone at rates less than 3 gpm results in "drying out" of model cells. These relatively low hydraulic conductivities are comparable to the values obtained during slug test analyses, also shown in Figure 2-2, Volume II.*

7. It is unclear how the treatment technologies combined under some alternatives were selected. For example, Alternative 6S combines electrical resistance heating with soil vapor extraction and chemical oxidation with potassium permanganate and Fenton's reagent for the plume at Spill Site 7 (SS7). The rationale for this alternative is described in Section 5.1.6.2; however, the rationale provides the same general descriptions of the technologies as presented in Section 2. The document does not indicate why these technologies were combined or selected for specific areas of the SS7 plume. Additional

information should be provided in the rationale for the alternative, which explains why the technologies were specifically selected based on-site conditions.

Response: *More detail has been added to the "Rationale" sections of each alternative to clarify these combinations. More references to the modeling of "Other Simulated Remedial Alternatives" in Volume II have also been added. However, the text in Volume I must be read in combination with Volume II and Volume III, which are not appendices, but an integral part of the FS.*

8. As part of the comparative analysis, a comparative ranking is performed for each of the alternatives with regard to the criteria. The comparative ranking uses a numerical score that defines the alternatives from best to worst. This ranking is subjective, and the results are questionable. For example, the no action alternative is ranked as "best" for implementability (page 4-38) because it is easily implementable. However, this judgement does not take into account administrative implementability. Do not use a numerical ranking system. Ranking systems such as those in the Landfill 4 and Landfill 7 RI/FS documents will provide appropriate ranking with fewer opportunities for misunderstanding and mis-use.

   Response: *The numerical ranking has been deleted and a ranking system similar to that used in the Landfill 4 RI/FS has been added.*

9. In general, different treatment technologies are proposed for the shallow and intermediate zones of the same plume. In some cases this approach is warranted, in other cases treatment of both of these zones could be combined. Consideration should be given to this option as appropriate (such as overlying or overlapping plume-cores or hot spots) because it will provide an economy of scale.

   Response: *For alternatives that use a common technology in both the shallow and intermediate zones the current structure of the alternatives allows the shallow and intermediate to be readily combined. For example, Alternative 4B may be combined with Alternative 4B-INT as both alternatives involve injection $KMnO_4$ over approximately the same aerial extent. Injection of $KMnO_4$ into both the shallow and intermediate zones may be conducted into common injection points that penetrate both hydrologic zones. This is also true to a limited extent for alternatives involving Plumes C, E, and SS7 as their are areas in which $KMnO_4$ is injected in the shallow and intermediate zones, but not necessarily in overlapping locations. While treatment of both the shallow and intermediate zone may be achieved with a single injection location, this would neither reduce the amount of $KMnO_4$ that would be needed for injection nor would it reduce the amount of monitoring points in the alternative. Combining these alternatives would result in a nominal difference in overall cost and therefore not improve the economy of scale. While some overlap in the application of technologies in the shallow and intermediate layers is warranted, these were maintained as separate entities for the purposes of alternative development and cost estimation.*

10. Two technologies are rejected which may warrant additional consideration. Anaerobic biostimulation with nutrient enhancement is rejected during the initial technology screening. However, the use of electron donor amendments, such as sodium lactate or molasses, in conjunction with MNA has been used to successfully to stimulate anaerobic reductive dechlorination of TCE in plumes. In addition, phytoremediation with poplar trees is rejected at all of the creek intercept sites; however, it may be a reasonable option for protection of surface water. While the site presents unique challenges for these technologies, these techniques may be worth evaluating further.

Response: *The use of electron donor amendments such as sodium lactate or molasses can stimulate a wide variety of indigenous anaerobic microorganisms. Approximately 15 such microorganisms from different metabolic groups (e.g., halorespirators, acetogens, methanogens, and facultative anaerobes) are able to metabolize TCE. Different organisms dehalogenate contaminants to different end products. Some strains convert TCE to DCE only; others convert TCE to DCE to vinyl chloride, which is considered to be partial or incomplete dechlorination; and still others convert TCE to ethene, considered to be complete dechlorination. Results of the HRC® study conducted by Earth Tech (USAF 2003f) indicated that a stall at cis-1,2-DCE did indeed occur. (HRC® is an electron donor that initiates the same microbial degradation process as lactate or molasses.) Therefore a contaminant conversion from TCE to cis-1,2-DCE is not an effective treatment.*

In light of rationale for rejection of phytoremeditation as presented in Tables 3-4 through 3-9, it was originally retained and evaluated during the initial stages of alternative development. It was applied at the creek intercepts of Plumes A and C, where groundwater levels are shallow enough to warrant application. Model simulations showed that the use of phyoremediation can lead to dewatering of the creeks, particularly in the case of Diamond Creek where surface water flow is generally sparse. Other reasons for not considering phyoremediation for further evaluation were its relatively high cost and the potential difficulty in field implementation due to the dense brush that currently exists along the creek. In addition, phytoremediation in Plume A did not exhibit a noticeable decrease in mass-loading to the creeks when compared to other alternatives that employed other technologies. Details of this simulation are described in Sections 4.3 of Volume II. In Plume C, phytoremediation was considered as an alternative to the PRB at the creek intercept. Simulations did not improve cleanup times and exhibited no marked improvement in the reduction of mass-loading to Crow Creek. These observations, in addition to constraints due to implementation and cost, led to the PRB being deemed a more suitable technology.

11. In describing alternatives, also identify waste streams which will need to be managed during construction (in most cases this would be soil spoils from drilling and excavation) and how the wastes are intended to be managed. Waste management will also need to be addressed within the context of the NCP criteria (Overall Protection ..., Compliance with ARARs, etc).

Response: *The following paragraph has been added as the last paragraph of Sections 4.1, 5.1, 6.1, 7.1, and 8.1, Development of Alternatives, to identify waste streams that would need to be managed during construction:*

"Waste streams generated during implementation of the alternatives include soil from drill cuttings and trench excavation, water from monitoring well development and purging, and spent carbon from liquid-phase treatment of extracted, vacuum-stripped groundwater. In general, these wastes would be managed consistent with current EPA-approved waste management practices at FEW."

FEW waste management practices should not affect the ability of any alternative to satisfy the NCP criteria. Therefore, waste management is not discussed in Sections 4.3, 5.3, 6.3, 7.3, or 8.3, Comparison of Alternatives.

12. Thoroughly edit the document. Some of the comments offered indicate misunderstanding which may be due to propagation of errors by "cut and paste". In some cases, verbs or articles are missing. These features would not be identified by "Spell Check".

    Response: *The document has been subjected to further editorial reviews.*

13. Specific Comments are not directed to the Executive Summary to minimize repetition. Accordingly carry through changes to the Executive Summary.

    Response: *The Executive Summary has been revised accordingly.*

SPECIFIC COMMENTS

14. Section 1.2.1.1, Zone D Removal Actions (Page 1-6), 1st para., 2nd sentence. Clarify under what action decision document (Action Memorandum or Record of Decision [ROD]) the soils at Spill Site 4 (SS4) were excavated.

    Response: *The Spill Site 4 soils were excavated in 1984. The OU1 ROD (USEPA 1996b) makes reference to this action but there is no decision document cited.*

15. Section 1.2.1.1, Gain/Loss Analysis (Page 1-9). Because subsequent discussion describes gain/loss relative to surface water sampling points, refer the reader to Plate 1 (or similarly usable figure).

    Response: *There are earlier references to some of these locations within Section 1.2.2.1, Surface Water Hydrology. Therefore, the following sentence has been added to the first paragraph in Section 1.2.2.1: "Crow Creek, Diamond Creek, and the surface water locations on these creeks referenced in the following subsections are identified on Plate 1."*

16. Section 1.2.2.2, Geology. Describe the thickness distribution of the alluvium (i.e., thickens near the creeks, in particular Crow Creek).

Response: *The second sentence of Section 1.2.2.2 has been revised as follows: "These Quaternary deposits are thickest along present day creeks, and generally are less than 25 feet in depth (USAF 1991)."*

17. Section 1.2.2.4, Hydrogeology. Describe expected ranges of permeability (or based on available slug tests) of the alluvium where it thickens near Crow Creek and is effectively the shallow aquifer zone.

Response: *The hydraulic conductivity of the alluvium along the floodplain of Crow Creek is generally higher than that of the Tertiary deposits. The generalization that hydraulic conductivities of the alluvium are higher is based on the observed flatter hydraulic gradient of approximately 0.006 foot/foot along the floodplain compared to a gradient of 0.03 foot/foot south of Crow Creek).*

18. Section 1.2.2.4, Hydrogeology (Page 1-12), last paragraph of Section 1.2.2.4. Slug test data did not identify the relatively dominant low-permeability in the Zone C (LF3) plume. This was identified by pumping tests which provided a more accurate measure of aquifer response. Also, there were changes in the units (uppermost units eroded farther down gradient). In the discussion here, describe how this was assessed and addressed for the purpose of this feasibility study (FS), and whether specific assumptions were used in the ground water model.

Response: *Section 1.2.2.4 is intended to give a general hydrogeologic description of the FEW area. Hydraulic conductivities stated in the last paragraph of that section are intended to provide a general range of values based on available data. Results of the Zone C pumping test and integration of that data into the Zone D groundwater model is described thoroughly in Section 2.2 of Volume II of the FS. That section describes uncertainties in the available hydraulic conductivity data, results of the Zones B and C pumping tests, and resulting improvements of the groundwater model since its initial development for the RI. The sentence "Volume II of the FS provides a detailed analysis of these hydraulic conductivity data and the methodology for incorporation of these data into the groundwater flow and transport model" has been added to the last paragraph of Section 1.2.2.4 to refer the reader to the analysis of these data.*

In addition, erosion of the uppermost geologic units in the downgradient areas as observed in Zone C, does not affect the Zone D FS as this geologic condition has not been identified in Zone D and is therefore not addressed.

Furthermore, review of the paragraph in question has revealed some inconsistencies in the presented hydraulic conductivity data. The range of hydraulic conductivity should read "0.003 to 179 feet/day", not "0.03 to 107.7 feet/day". The number of slug tests evaluated to produce this range of values is 184, not 34 as stated in Section 1.2.2.4. The text has been updated accordingly. This data is provided in the Zone D RI, Volume IV and is also restated in Volume II of the FS.

19. Section 1.2.4, Contaminant Fate and Transport, last paragraph on Page 1-16. The second bulletin refers to "substantially" decreasing concentrations in Plumes A, B, and E. Define "substantially" by describing actual changes in concentrations and overall mass.

Response: *The adjective "substantially" has been removed. Decreases in concentrations within Plumes A, B, and E have been described quantitatively using changes in concentration.*

20. Section 1.3.3.3, Pump-and-Treat, Dual-Phase, and Two-Phase Extraction. The first sentence refers to a treatability study at the head of Plume C (USAF, 1996b). However, the reference is for a remedial investigation/feasibility study (RI/FS) document pertaining to Fire Protection Area 1 (FPTA1), rather than a treatability report. Correct and/or clarify in the discussion.

Response: *The reference has been corrected to (USAF 1996d).*

21. Section 1.3.3.5, Feasibility Study-Specific Treatability Studies, Chemical Oxidant Injection, Page 1-20. Zero concentration is not measurable, there is always a limit of detectability, generally the reporting limit. Change all discussions of "zero" to "non-detectable".

Response: *The discussions have been revised to state "non-detectable."*

22. Section 2.2, ARARs, Action-Specific ARARs, 2nd paragraph on Page 2-3. This approach is generally inappropriate to the screening and identification of ARARs within a feasibility study. At this stage of the response action, ARARs which may apply or be relevant and appropriate to one alternative may not be other alternatives. It would be appropriate to describe the administrative infeasibility of discharge to the POTW based on past experience, where the Cheyenne Board of Public Utilities has allowed only short-duration limited volume discharges, but does not have the capacity for larger, long-term discharges to the POTW. Release of radioactives, ammonia, or bacteriological agents may also be an appropriate assumption. The hazardous waste identification and storage would be alternative-specific and must be included in the tables; similarly for air emissions. Analyze these as ARARs for the alternatives.

Response: *Section 2 has nothing to do with alternatives, but with technologies.*

23. Section 2.4, Identification of Technology Types and Process Options. Good summaries of treatment technology types. Include a similar discussion for Institutional Controls, particularly as they would be used at FEW.

Response: *The following paragraph has been inserted into Section 2.4.1 to summarize Institutional Controls at FEW.*

"The use of institutional controls allows for both legal and managerial control of a specific area, including resources such as groundwater. Examples of such controls at FEW would be extended land use restrictions (including required review by 90 SW/EM for potential conflict with implementation of groundwater cleanup activities), and/or control of groundwater access. Additionally, all new construction over or adjacent to groundwater plumes would require sub-slab vapor venting systems to limit risk from indoor air potentially caused by volatilization of VOCs in groundwater. This approach does not address treatment of contamination, however restricts exposure to the contamination and development of the affected area until contamination concentrations are within acceptable levels."

24. Section 2.4, General Comment. Most of the descriptions of technologies focus on process and effectiveness to meet remedial goals (which is needed). Where there is a potential depth limitation, describe this also for all of the technologies. This will help clarify where more than one approach is used in a geographic area. For example, it is unclear from these descriptions whether the e-barrier is depth limited due to construction constraints or whether there is a typical depth to which the poplar species roots will grow.

    Response: *The limitations have been expanded to include depth limitations for applicable technologies.*

25. Section 2.4.1, Monitored Natural Attenuation, last paragraph of Section 2.4.1. This paragraph belongs in a discussion of Institutional Controls.

    Response: *Section 2.4.1 has been changed to Section 2.4.2. A new Section 2.4.1, Institutional Controls has been created. The subject paragraph has been restructured and moved to the new Section 2.4.1.*

    The second sentence needs to be rephrased to the effect of "Thus, extended monitoring and land-use restrictions must be used whenever unlimited use and unrestricted exposure do not result from the alternative". The sentence implies (with "should") such restrictions are optional when they are not. Clarify the intent: This sentence also perhaps incorrectly implies there is a cost trigger as to whether such restrictions are part of an alternative. There is an associated O&M cost, which will be significant for long-term remedies.

    Response: *The paragraph (which is now the 2nd paragraph of the new Section 2.4.1) has been rewritten as follows: Longer timeframes may be required to achieve RAOs. Because the site may not be available for reuse, extended monitoring and land use restrictions must be used whenever unlimited use and unrestricted exposure do not result from any alternative.*

26. Section 2.4.2.1, Page 2-7, Anaerobic Biostimulation using Nutrient Enhancement, 3rd paragraph, last sentence. Nutrient enhancement is an established, rather than "innovative" technology unless the nutrient itself is untried and presents better performance for similar cost or similar performance for lower cost.

Response: *The word "innovative" has been replaced with "established." Note: Section 2.4.2 is now 2.4.3.*

27. Section 2.4.2.1, Page 2-8, Anaerobic Biostimulation using Nutrient Enhancement, last paragraph of the section. The results at two USAF bases are very different. What would be useful here for screening purposes is to identify any significant differences in the treatment processes and/or site conditions (ground water flow and/or chemical or biological conditions). Clarify whether either were in an aquifer dominated by fines, such as at FEW.

Response: *Despite limited available data on the two USEPA sites (not USAF sites as stated in the comment), additional text further describing differences between the two studies has been added to the last portion of Section 2.4.2.1. Note: Section 2.4.2 is now 2.4.3.*

28. Section 2.4.7, Contaminant Mobilization. Add that contaminant mobilization is also known as in-situ flushing. Rationale: Easing research for an interested person since many web sites (including ITRC and EPA) and papers use this name for the technology. In discussing surfactant and solvent use, clarify if there are potential limitations due to the lithology (clay minerals) or permeability (delivery).

Response: *The General Response Action title was changed from "Mobilization" to "Flushing." Lithology and permeability were added to the "Limitations." Note: Section 2.4.7 is now 2.4.8.*

29. Section 2.4.7.2, Page 2-27. The section describes the use of solvents for contaminant mobilization; however, most of the discussion appears to focus on *ex situ* soil washing. Also describe the use of solvents for in-situ contaminant mobilization.

Response: *Only in-situ solvent extraction was discussed in the revised document. Ex-situ soil treatment technologies have not been included in this groundwater FS. Lithology and permeability were added to the "Limitations." Note: Section 2.4.7 is now 2.4.8.*

30. Section 2.4.8.1, Pumping, 2nd paragraph, 2nd bulletin. The phrasing may give the reader the incorrect impression all of the TCE occurrences on FEW are in DNAPL form. This may be correct in the vicinity of SS7, but is not likely elsewhere. Dissolved TCE is generally pumpable (although the subsequent discussion for desorption is relevant). Residual DNAPL TCE is generally not pumpable. Clarify the difference.

Response: *The bulletin was changed to state "... and, when undissolved, tends to exist in pools along the bottom of an aquifer or sorbed to soil particles within the aquifer. Note: There is no documented presence of TCE DNAPL at FEW, although residual DNAPL is suspected in localized areas of SS7." Note: Section 2.4.8 is now 2.4.9.*

31. Section 2.4.8.1, Pumping, 2nd paragraph, 4th bulletin (on Page 2-29). Describe uncertainties. In fact, uncertainties with all technologies must be described, not just for pump and treat.

    Response: *Uncertainty discussion was added to this section and, where known, to the discussion of other technologies. Note: Section 2.4.8 is now 2.4.9.*

32. Section 2.4.8.1, Pumping, last paragraph of section. This discusses order of magnitude costs. Add similar discussions for all technologies in Section 2.4, or delete it here. Rationale: Consistency of presentation.

    Response: *The discussion was deleted. Note: Section 2.4.8 is now 2.4.9.*

33. Section 2.4.8.3, Two-Phase Extraction (Page 2-30). 1st paragraph, last sentence: Bioventing is generally venting to the subsurface to allow greater aeration (i.e., it is not forced). It is a form of biostimulation. Forced air injection/extraction rely more on the physical in-situ stripping of VOCs.

    Response: *The comment describes only "passive" bioventing. Historically, "active" bioventing has been more commonly used. At low pressures, active biovent air is injected into the vadose zone just as it is injected at low pressures into the saturated zone in biosparging systems. These low-pressure injection systems do not physically strip VOCs, but provide oxygen for biostimulation (see Hinchee, Miller, and Johnson, In Situ Aeration: Air Sparging, Bioventing, and Related Remedial Processes, Battelle Press, 1995). As stated in the USACE Soil Vapor Extraction and Bioventing engineering design manual (EM1110-1-4001, 1995, section 1-4), "BV airflow rates need to be sufficient to provide oxygen to the micro-organisms, which are usually oxygen-limited, but slow enough to allow sufficient contaminant residence time in the subsurface and minimize volatilization losses to areas outside the treatment zone." Note: Section 2.4.8 is now 2.4.9.*

    2nd paragraph, 1st bulletin: Delete "expensive" unless costs will be consistently described to provide a valid comparison.

    Response: *"Expensive" was deleted. Note: Section 2.4.8 is now 2.4.9.*

34. Section 2.4.8.3, Two-Phase Extraction, last paragraph (Page 2-31). In discussing the system used at Plume C, give the write up a similar degree of detail as for the more recent treatability studies.

Response: *The paragraph was modified by adding "(See Section 1.3.3.3)" to the first sentence. Note: Section 2.4.8 is now 2.4.9.*

35. Section 2.4.9, Ex-situ treatment, Page 2-34. Add that EPA has identified air stripping, carbon adsorption, and UV oxidation as presumptive treatment technologies for TCE and other VOCs because of their recognized effectiveness and which are also usually cost-effective. Bio-reactors are conventional technologies used at wastewater treatment plants.

    Response: *The effectiveness and cost statements were added to Section 2.4.9 immediately after the list of technologies. Note: Section 2.4.9 is now 2.4.10.*

36. Section 2.4.9.4, Liquid/Vapor-Phase Bioreactor. Explain in general what a bioreactor is, and how it works. This discussion goes directly into a comparison of vendors products without the explanation.

    Response: *A vapor-phase bioreactor would be used to treat vapors and, since the groundwater has theoretically been stripped of most of its contaminants, a liquid-phase granular activated carbon unit would be used to treat the water. That would allow the water to be discharged by any disposal method chosen without concern for residual contaminants.*

    The following text was added to Section 2.4.10.4.

    "Biofiltration is the process of treating a contaminated gas stream in a biologically active packed bed. Biofilters or bioreactors have been used to treat malodorous gases at wastewater treatment plants since the early 1950s and are now being used to treat a wide range of waste gases, including volatile organic compounds (VOCs). Bioreactors are first 'seeded' with the appropriate microorganism for degrading the target contamination such as TCE. This stage typically lasts between one and three weeks, depending upon the species of microorganism. Once the microorganisms reach an acceptable concentration, the waste stream is passed through the packed bed reactor. As long as contaminate concentrations remain fairly stable, little maintenance is required to sustain the vapor-phase treatment. However, on occasion when the system has to be shutdown for routine maintenance, the microorganisms must be fed an alternative diet (typically monosodium glutomate [MSG], or similar nutrient), or they will die and produce sludge within the reactor. In this case, the system must be cleaned and 're-seeded.' "

37. Section 2.4.10.1, Reinjection, 1st paragraph, 2nd sentence. Change "requirement for an Underground Injection Control (UIC) Permit" to "substantive requirements for Underground Injection Control (UIC) or requirements to obtain the permit for off-site actions". Delete the cost comment unless costs will also be consistently compared. Later discussion appropriately notes numerous wells or infiltration galleries may be needed, particularly in low-permeability aquifer materials.

    Response: *The changes have been incorporated to Section 2.4.11.1.*

1st paragraph, last sentence. Reinjection wells have also been used to drive contaminants down gradient towards extraction wells.

Response: *The sentence has been revised as follows: "Reinjection wells have been used to create a hydraulic mound that either can drive contaminants downgradient towards extraction wells or if injected at the leading edge of a plume can reduce on reverse the gradient in that area and in effect create a hydraulic barrier."*

There are several locations where "costly" is used, where "labor intensive" might be more appropriate. Rationale: The intent of the initial description of technologies is to identify mainly technical feasibility. Cost issues come into play once technologies are screened (the high/medium/low comparison), and assembled alternatives compared (now with cost estimates based on conceptual design).

Response: *The change from "costly" to "labor intensive" was changed where appropriate.*

38. Section 2.4.10.2, Surface Streams. Rephrase this for the discharge to meet "substantive NPDES requirements" for on-site discharge and actually obtaining a permit for off-site discharge.

Response: *The references to NPDES permits have been revised accordingly in Section 2.4.11.2.*

39. Section 2.4.10.3, Publicly Owned Treatment Works. The City of Cheyenne has allowed smaller quantity discharges. They have refused large quantity, continuous discharges because of capacity limitations(?).

Response: *The following sentence has been added to Section 2.4.11.3: "The City of Cheyenne has allowed only short-duration, limited-volume discharges, but does not have the capacity for larger, long-term discharges to the POTW."*

40. Section 2.4.11, Pages 2-40 and 2-41. This section describes the application for technologies and process options, and low, moderate and high concentrations of TCE in various plumes. The concentration ranges associated with low, moderate and high concentrations are not provided. Define the ranges.

Response: *Section 2.4.11 has been moved to create a new Section 3.1. In the second paragraph of Section 3.1, the following text has been added: "The references to low, moderate and high TCE concentrations as they apply to Zone D groundwater are relative but in general correspond to concentration ranges of less than 100 µg/L, 100 to 500 µg/L, and greater than 500 µg/L, respectively."*

41. Section 2.4.11, Application of the Technologies and Process Options to the Zone D Plumes. All of this discussion (and apparently Table 2-6) is relevant to screening technologies for FEW, and thus belongs in Section 3. Table 2-6 belongs in Section 3 if the dots, dashes, and other symbols are used to identify technologies retained or not (include an explanation of the symbols on the Table).

Response: *Section 2.4.11 has been moved to create a new Section 3.1 and Table 2-6 has been relabeled as Table 3-1.*

42. Section 3, General Comments to Technology Descriptions.

Standardize units and unitize costs in discussion wherever practicable. This had to have been done to do cost estimates. For example, stating the cost per pound of HRC does not allow the reader to compare to other in-situ methods where the cost is described as a function of the gallons treated. In some cases, the gallons treated are not comparable (i.e., 1,000 gallons in one place, 1,500 gallons in another).

Response: *Costs have been normalized/standardized whenever practicable. A new Section 3.2, General Costing of Technologies, has been added and it describes why not all costs can be standardized.*

Some of these technologies would be suitable to the intermediate depths, and some not due to lower hydraulic conductivity. Where this distinction exists, explicitly state it so the reader can understand to which zone the technology may be applied or for which it is rejected.

Response: *Refer to Table 3-1 which illustrates the areas of applicability for technologies in each plume.*

43. Section 3.1, Monitored Natural Attenuation. For effectiveness, describe that EPA policy restricts MNA to plumes which are stable or shrinking. Clarify why the administrative implementability is considered low. Neither EPA nor WDEQ disagree with MNA where it is stable or shrinking, and performs well under the remedial alternative evaluation criteria of the NCP.

Response: *A quote from EPA's OSWER Directive 9200.4-17P (Use of Monitored Natural Attenuation at Superfund, RCRA Corrective Action, and Underground Storage Tank Sites, 1999, p. 18) has been added to Section 3.3 (formerly 3.1) that states " sites where the contaminant plumes are no longer increasing in extent, or are shrinking, would be the most appropriate candidates for MNA remedies." Although Plume A, exclusive of SS7, is apparently no longer increasing in extent (see Figure 4-1), the specific sources (WSA and SS4) have been mitigated, and VOC measurements in the ephemeral surface waters of Class 3B Diamond Creek at location D2.8 have been at trace levels (as discussed in the Zone D RI, 2003, Section 5.5 and Figure 5-22), obtaining WDEQ approval for an MNA alternative may "lower" administrative implementability."*

44. Section 3.2.1, Anaerobic Biostimulation ... Enhancement, 1st two paragraphs. Nutrient addition as a general process is a conventional rather than innovative technology in general. Use of alternative nutrients may make the technology innovative. Correct and/or clarify.

Response: *In Section 3.4.1 (formerly Section 3.2.1), the term "innovative" has been replaced with "increasingly conventional."*

45. Section 3.2.2, Hydrogen Release Compound, last paragraph of implementability. In the last sentence, change "only" to "one" or "only one".

Response: *In Section 3.4.2 (formerly Section 3.2.2), the word "one" has been added to read "only one."*

46. Section 3.2.5, Anaerobic Biostimulation using iSOC/iMOX, last paragraph of the section (Page 3-6). Since the study is now complete, the technology discussion and the "pending" status needs to be updated.

Response: *The "pending" status has been removed in Section 3.4.5 (formerly Section 3.2.5) and the text updated. In addition, the text in the discussion has been modified based on results of the Zone D Treatability Study and the technology has been rejected.*

47. Section 3.3.1, Potassium Permanganate, Effectiveness, 2nd paragraph. Because measurement ability does not allow verification of "100 percent", rephrase the results to reduction to "non-detect" levels.

Response: *Text in Section 3.5.1 (formerly 3.3.1) has been revised to indicate a contaminant reduction to "non-detect levels."*

48. Section 3.3.1, Potassium Permanganate, Implementability, 3rd paragraph. Correct and/or clarify: The limitation of injection close to surface water is the toxicity to aquatic organisms, not because the solution has a purple color. The color is useful as an indicator of the presence of KMnO4, where visually observed color is also presumed to indicate the reaction is continuing.

Response: *The following text in Section 3.5.1 (formerly Section 3.3.1) has been added: "The potential for toxicity to organisms from a $KMnO_4$ solution limits the location of an injection site to areas at FEW at least an estimated 200 feet upgradient from any surface water bodies. This is because of the potential surface water expression within nearby creeks". Text regarding color has been modified and moved to the discussion on effectiveness.*

49. Section 3.3.1, Potassium Permanganate, Cost, last paragraph. Since the study is now complete, the technology discussion and the "pending" status needs to be updated.

Response: *The text in Section 3.5.1 (formerly Section 3.3.1) has been updated accordingly.*

50. Section 3.3.4, Air/Ozone Sparging with C-Sparger System. Since the study is now complete, the technology discussion and the "pending" status needs to be updated.

    Response: *The text in Section 3.5.4 (formerly Section 3.3.4) has been updated and based on results of the Zone D Treatability Study, the technology has been rejected.*

51. Section 3.4.1, Additional ZVI by trenching, Implementability, 2nd sentence. The PRB at FEW is nowhere near a property boundary. Correct and/or clarify.

    Response: *The reference to the "property boundary" is a typo. This sentence has been rephrased in Section 3.6.1 (formerly Section 3.4.1) to say "Previous applications of a ZVI PRB at FEW SS7 have successfully reduced concentrations of TCE and associated daughter products to below the MCL."*

52. Section 3.4.3, Additional ZVI by Deep Soil Mixing. The potential effectiveness of ZVI by DSM is also dependent on the lithology of the earth materials with which the iron is mixed. In relatively permeable sandy/gravelly aquifers, the flow through ability is likely to be retained. In clayey/fines lithologies, the permeability after mixing would be questionable. Evaluate/screen this technology in light of site conditions.

    Response: *In low conductivity lithologies, the higher conductivity zones created by adding iron and sand to the fines during DSM have been shown to "focus" the flow, analogous to the focusing by a lens, by diverting flowpaths through the DSM zone. Therefore, enhanced flow should occur in the DSM zone compared to the surrounding low-conductivity zones and in situ treatment may occur in a larger area than that of the DSM.*

53. Section 3.4.4, Electrical Barrier. Since the study is now complete or nearly so, the technology discussion and the "pending" status needs to be updated.

    Response: *The treatability study being conducted by Colorado State University is still underway and the preliminary results have not been made available. The text in Section 3.6.4 (formerly Section 3.4.4) has not been changed.*

54. Section 3.8.2, Page 3-20. This section discusses dual-phase extraction and indicates that dual-phase extraction is ". . . 25 percent more expensive than pumping alone. . . ." The last paragraph of the sections states that "This technology is rejected because it costs three times that of pumping alone. . . ." These figures regarding the cost appear inconsistent and should be corrected or clarified.

Response: *Dual-Phase extraction is typically three times the cost of pumping alone, depending upon the size of the system. This correction was made in Section 3.10.2 (formerly Section 3.8.2).*

55. Section 3.8.2, Dual-Phase Extraction, Implementability, 1st partial paragraph on Page 3-20. Revise the last sentence. If the discharge/emission is on-site, the substantive requirements must be met, but a permit is not required.

Response: *The sentence in Section 3.10.2 (formerly 3.8.2) has been revised to state: "Dual-phase extraction does not require permits for both groundwater disposal and vapor emissions on-site, but substantive permit requirements would have to be met."*

56. Section 3.8.3, Two-Phase Extraction, Effectiveness. Clarify what is mean by "twice as effective". Is this effectiveness in extraction rate? In hydraulic control (i.e., radius of influence)? In contaminant reduction?

Response: *Two-phase extraction is twice as effective in contaminant reduction (in pounds removed per day) as pump-and-treat and dual-phase extraction, based on the 1995 treatability study of these three technologies at the head of Plume C (USAF 1996d). Similar text has been added to Section 3.10.3 (formerly 3.8.3).*

57. Section 3.8.4, Air Sparging with SVE, Effectiveness. Effectiveness also depends on the ability of the sparged air to move through the aquifer, which is poor in fines-dominated systems.

Response: *The following sentence has been added to Section 3.10.4 (formerly 3.8.4): "Effectiveness also depends on the ability of the sparged air to move through the aquifer, which is poor in the fines-dominated systems characteristic of FEW."*

58. Section 3.9.2, Page 3-23. This section describes carbon adsorption and indicates that liquid phase carbon adsorption is effective for ". . . removing high concentrations of contaminants from water at low flow rates (typically 0.5 to 1 gpm [gallon per minute])." This flow rate seems particularly low since units can be sized to address flow rate; a reference should be provided or the statement removed.

Response: *The text citing flow rates was removed in Section 3.11.2 (formerly 3.9.2).*

59. Section 3.10.1, Reinjection, Implementability. A permit is not required. The appropriate discussion is the substantive requirements of the underground injection control (UIC) program must be met.

Response: *The sentence in Section 3.12.1 (formerly 3.10.1) has been revised as follows: "This technology is preferred by the State Engineers Office and must meet the substantive permit requirements of the UIC program prior to reinjection into the Ogallala Aquifer."*

60. Section 3.10.2, Surface Streams, Implementability. A permit is not required. Substantive requirements of the NPDES program must be met.

Response: *The sentence has been revised to state: "... and substantive requirements of an NPDES permit would be required to discharge treated water."*

61. Section 3.11, Application of Retained Technologies ... Plumes, last paragraph on Page 3-27. Either the nomenclature or USAF intent must be clarified. To begin with, no technical impracticability argument was presented in the initial stages of this FS. Any such must appear in the document.

Technical impracticability vs. implementability. Technical impracticability is an argument based on chemical-specific, technology-specific, and geology-specific properties. The significance of technical impracticability (TI) is that it may serve as the basis for waiving one or more ARARs consistent with the NCP. A waiver of an ARAR does not obviate other actions, such as engineering controls. A TI argument is a formal process by which all aspects of a particular situation are summarized in a report for which there is guidance. This is then formally evaluated by an EPA committee. There has been no such report submitted to EPA. What the Zone C FS demonstrated is low implementability for pumping the intermediate depths, at least for Zone C. It was not a technical impracticability demonstration. This does not by itself obviate any other area, any other technology, or addressing the intermediate depths by other means. Provided there is a distinct comparison provided here between lithologies and properties of the intermediate depths at Zone C and within each plume area, this argument may extend to the larger plumes in Zone D, although this would be best as site-specific modeling. Unless USAF intends to go through the formal TI process, restrict the nomenclature to "implementability."

Response: *The terminology has been changed in Section 3.13 (formerly Section 3.11) from "impracticability" to "implementability" and other minor revisions to the last paragraph to indicate that the technical challenges are with respect to implementability.*

An additional cautionary note to extending these results: The pumping ability at Zone C was from the perspective of restoring the plume as a whole. This does not necessarily obviate the use of intermediate depth pumping as a means of hydraulic control such as an intercept where maximum pumping rates may not be needed.

Response: *Acknowledged.*

Delete the last sentence. While MNA and KMnO4 may be retained technologies for the intermediate depths, they would not be the only retained technologies (at the screening level) for Zone D. What this paragraph does is attempt to minimize technology screening efforts for the intermediate depths. Some of the technologies screened could also be practicable for the intermediate zone. Expand the screening for the intermediate zone (and subsequent development of alternatives for the plumes).

Response: *The last sentence was deleted. Tables 3-3 through 3-9 have been modified and now provide a more comprehensive screening of technologies for the intermediate zone.*

62. General Comments on Section 4. (1) Since alternatives are developed to address primarily the shallow zone, EPA comments will be similarly focused. This is because EPA expects the draft final document to have a more thorough treatment of the intermediate zone.

(a) The Institutional Controls (ICs), also described as Land Use Controls (LUCs), need to address potential restrictions or design additions on construction to address the indoor air RAO. Include in the IC Alternative the corresponding elements to the other alternatives: Process Description, Rationale, Conceptual Design, and Performance Monitoring. EPA acknowledges the ultimate structure of this alternative may be subject to the resolution of an ongoing national level dispute regarding the use, function, enforceability, and monitoring of the controls. EPA nonetheless expects these elements to be addressed.

Response: *The corresponding elements have been added to the Development of Alternatives sections.*

(b) Extraction and Treatment (Pump and Treat, or P&T) is a presumptive strategy, rather than a presumptive remedy. Rephrase where "remedy" is used. The difference is that P&T is as much a process as a technology, which can apply to different contaminants, at different sites, and to different degrees (such as an intercept vs. pumping the entire plume and hybrids between the two). Presumptive remedies are usually both contaminant- and media-specific, such as air stripping or GAC for VOCs in water or SVE for VOC-contaminated soils.

Response: *EPA stated in OSWER Directive 9355.0-047FS that "pump & treat" is a "presumptive remedy" for "contaminated groundwater" (EPA540-F-93-047, September 1993, pg. 3, Table 1).*

(c) Cost Discussions sometimes include as Capital costs cost for occasional updates. While these may seem capital in nature, updating the system is a periodic O&M cost. Revise discussions of total costs to present a single capital cost, then O&M (which can include "periodic" as well as annual O&M), and present worth (net present value).

Response: *The text was modified to exclude annual updates from capital costs.*

63. Section 4.1.4, Alternative 4A, Groundwater Extraction and Ex-situ Treatment. The alternative is described as having no MNA as a component (Section 4.1.4.1). The conceptual design describes implementation to remove TCE-contaminated ground water from the portion of the plume which exceeds the 5 µg/l MCL. Figure 4-2, which illustrates the conceptual design, shows a configuration keyed to the core of the plume and which does not extend to the 5 µg/l limits of the plume. Figure 4-2 also illustrates

large areas of Plume A, such as surrounding Spill Site 4/Building 1250, which have no form of extraction control. The statements are inconsistent with the figure. If the figure and modeling are the basis for the alternative, then MNA appears to be intended as a component for the fringes of the plume and the aforementioned area without extraction systems. Reconcile.

Response: *The statements are consistent with the modeling results shown in Figure 4-3, on which the locations of the extraction wells were based. These figure numbers have been reversed to clarify the conceptual design.*

64. Section 4.1.4.3, Conceptual Design (Alt. 4A). Correct the references in the "Extraction System" and "Aboveground Treatment System" sections. Both sections refer to Table 4-1 to list components of the system. The treatment system discussion refers to a process flow diagram on Figure 4-2, which is the time-series modeling results for the alternative.

Response: *The reference for Table 4-1 has been changed to Table 4-4. The reference a "process flow diagram" has been changed to a "conceptual design."*

65. Section 4.1.4.3, Conceptual Design (Alt. 4A). The last sentence makes a comparison to MNA. Clarify if this is the MNA for Alternative 3A (in which case the statement needs revision) or is MNA presumed for the parts of the plume in which wells are not indicated in the figure (in which case the statement at the end of section 4.1.4.1 needs revision).

Response: *The last sentence makes a comparison to MNA as stated in Alternative 3A, but is incorrect. Therefore, the sentence "MNA of the shallow aquifer would reach the TCE MCL at the same time as the extraction and treatment system" has been removed to alleviate confusion.*

66. Section 4.1.5.4, Performance Monitoring (Alt. 5A). The second sentence refers to a ground water extraction system for a bioaugmentation and MNA alternative. Correct and/or clarify. ["Cut and Paste" error?].

Response: *The "cut and paste" error has been corrected by removing the references to the groundwater extraction system.*

67. Section 4.2.3.3, Long-Term Effectiveness (Alt. 3A), second paragraph (on Page 4-25). Rather than describing the source has been "Removed" (as in having taken a formal response action), describe it has been investigated under a separate remedial action. It would be more accurate to describe no clear remaining source was found and is presumed to have been exhausted and will no longer contribute contaminants to ground water.

Response: *The description of the source has been revised as suggested and a reference to the Zone D Sources RI added (USAF 2002a).*

68. Section 4.2.3.4, Reduction of Toxicity, Mobility, and Volume. This criterion is Reduction of Toxicity, Mobility, and Volume (TMV) through Treatment. The discussion does not address treatment. Discuss/recognize MNA does constitute treatment (man-made). Briefly describe the presumed "half lives" of the contaminants.

Response: *See response to General Comment #5. The criterion does not state "man-made" treatment any more than "active" treatment. The discussion of presumed half-lives is found in Volume II.*

69. Section 4.2.4, Alternative 4A - Groundwater Extraction and Ex-situ Treatment. The description of the alternative has changed from Section 4.1.4.3. Section 4.1.4.3 describes pump and treat until MCLs are achieved. Section 4.2.4 describes pumping and treating to a threshold level, then what is effectively MNA. Reconcile the apparent discrepancy. If the latter is intended, this must (1) be consistent in the descriptions; include MNA in the title; and (3) identify the threshold concentration under consideration.

Response: *The plume would be pumped until TCE levels are below 5 µg/l, as shown in Figure 4-3. "Threshold levels" and "MNA" were removed from the discussion.*

70. Section 4.2.4.6, Implementability. Use "strategy" rather than "remedy".

Response: *EPA states that pump & treat is a presumptive remedy for contaminated ground water. See Specific Comment #62.*

71. Section 4.2.6.2, Option 3A-INT (MNA), Reduction of TMV. This criterion is Reduction of Toxicity, Mobility, and Volume (TMV) through Treatment. The discussion does not address treatment. Discuss/recognize MNA does constitute treatment (man-made). Briefly describe the presumed "half lives" of the contaminants.

Response: *See response to General Comment #5.*

72. Section 4.3, Comparative Analysis. Overall Protection of Human Health and the Environment and Compliance with ARARs are threshold criteria. Even in the comparative analysis, the discussion must identify *how* the alternative is protective (or not). However, alternatives are not relatively ranked as they are the balancing criteria. Revise discussions so that one alternative is not described as "more protective" or "less protective" than others. In many cases, this will be a short word fix (delete "greater" or "better"). *This is a general comment applicable throughout any discussion of the detailed analysis of alternatives for all plumes.*

Response: *Text has been deleted (e.g., "the greatest") such that the one alternative is not described as "more protective" or "less protective" than others.*

73. Section 4.3, Comparative Analysis. In the balancing criteria discussion, explicitly rank the retained alternatives comparatively to each other. The discussion appears to describe the (sub)criteria by which ranking can be done, but the relative ranking is not explicit. For example, Section 4.3.4, Reduction of TMV, both pump and treat and bioaugmentation with MNA recognize treatment occurs, but it is not clear if the difference in time frames would rank pump and treat over bioaugmentation with MNA. *This is a general comment applicable throughout any discussion of the detailed analysis of alternatives for all plumes.*

Response: *Section 4.3 has been rewritten to compare the alternatives in a relative, qualitative ranking. Section 4.3.9 – Comparative Ranking – has been deleted and Table 4-10 has been revised as stated in the response to Specific Comment #171.*

74. Section 4.3.6, Implementability. The extraction and treatment alternative is again described as extraction and treatment/MNA. Reconcile for consistency.

Response: *"MNA" has been removed from this description.*

75. Section 4.3.7, Cost. Rephrase. MNA is not <u>treatment</u>. Costs of alternatives are compared irrespective of whether treatment is used.

Response: *EPA says natural attenuation is "an in situ treatment method." See response to General Comment #5.*

76. Section 4.3.9, Comparative Ranking. Most of the discussion is useful and appropriate. Although the discussion clearly identifies the "numbers" are qualitative, the simple use of numbers has led to issues on other sites because it's almost inevitable the qualifiers about the use of the "numbers" will be missed or ignored. Use a non-numerical system of tabulating the relative rankings.

Response: *A non-numerical system has been adopted and Section 4.9 has been deleted. See response to General Comment #8.*

Last sentence: The rankings appear to be in Tables 4-10 and 4-11, rather than as described in Tables 4-7 and 4-8.

Response: *The table references have been corrected in Section 4.3 to Tables 4-10 and 4-11.*

77. Section 5.1, Development of Alternatives. It does not appear the prior discussion has established the SS7 ground water plume as stable or shrinking. These are pre-requisites to the use of MNA. Establish the stability or re-structure the alternatives (3S, 4S, and 5S). Explain why extensions to the PRB are for selected areas (or more accurately, why are there gaps left?). Explain why pump and treat was not considered for the shallow

zone, either for restoration, or for containment (i.e., an intercept line between the source and Diamond Creek).

Response: *Because SS7 has not been demonstrated to be stable or shrinking, no "MNA only" alternative was considered. All MNA at SS7 is associated with another passive or active treatment technology in order to stabilize or control the migration of plume contaminants prior to the application of MNA.*

Application of a PRB in select areas was based on iterative model simulations and analysis of groundwater flow patterns in the SS7 area. Extending the PRB as a continuous structure does not improve the remedial effectiveness of the alternative in achieving the groundwater RAO. Because Diamond Creek is a class 3B stream and is not subject to the surface water RAO, the extension of the PRB to the east and the addition of the PRB to the west were implemented in areas that would treat the largest amounts of contaminant mass based on the present flow regime. This has been clarified in the text of Section 5.1.3.

A pump-and-treat system <u>was constructed and operated</u> at SS7 for a year and was unsuccessful at restoring even part of the plume. Pump-and-treat was originally considered in local areas as a possible alternative as an intercept line between the source area and Diamond Creek, in part because pump-and-treat is EPA's presumptive remedy for contaminated groundwater. However, the pumping model in the immediate vicinity of the creek, as shown in Figure 5-12 of Volume II, but long-term operational cost is greater, but more importantly, added to significant benefit to the alternative when using a PRB. This is discussed in Section 5.3 of Volume II, "Other Simulated Alternatives."

Other factors that influenced the omission of pump-and-treat at SS7 include hydraulic conductivity and the success of the existing PRB. The low overall hydraulic conductivity of the SS7 area, lower than in other Zone D plume, limit the use of pump-and-treat as an effective technology to remediate this area. And, because the existing PRB is successfully remediating a portion of the plume and because a pumping system could reverse the groundwater gradient through the PRB, a pumping system was not proposed in any SS7 alternative.

78. Section 5.1.3.1, Monitored Natural Attenuation (SS7). If stability/shrinking is demonstrated, identify specifically the zones/areas for which MNA is considered here. Some flows of SS7 ground water upgradient of the PRB are not intercepted by the PRB. This could also apply to areas down gradient of the PRB.

    Response: *These zones have been identified and discussed with conclusions from the RI in Section 5.1.3.2 (Rationale for Alternative).*

79. Section 5.1.3.2, Rationale for Alternative, 1st sentence. The word "rati5ionale" should be "rationale".

    Response: *"Rati5ionale" has been replaced with "rationale."*

80. Section 5.1.4, Pages 5-5 through 5-8. This section discusses Alternative 4S, extension of the existing permeable reactive barrier (PRB), creation of a western PRB and MNA for the SS7 area. Recent long-term monitoring shows bypass of the PRB on the western edge. However, this bypass is not discussed in this section. The western bypass of contaminated ground water and extension of the existing PRB to control this bypass should be addressed and considered in this section.

Response: *The PRB locations were optimized during modeling to maximize interception of groundwater flow intercepting Class 3B Diamond Creek. Although by-pass of the existing PRB has recently been documented, there is no evidence from the model that this by-pass will increase the impact to the creek (see Figure 5-3, Year 10 and Year 20).*

81. Section 5.1.4.2, Rationale for Alternative, Permeable Reactive Barrier, 3rd bulletin of 2nd full paragraph on Page 5-6. This statement uses cost as a criterion for the structure of the alternative. This is improper as it makes cost a threshold criterion before the alternative is even analyzed against the nine criteria, where cost is a balancing criterion. Revise to a technical/implementability justification. The NCP requires ground water alternatives to evaluate remedies for different time frames. If there is little difference in time frame, then there is little or no justification for a greater degree or extent of treatment.

Response: *The term "installation expense" has been replaced by "use" in this bulletin. PRBs have practical minimum thicknesses, therefore are not implementable for very low concentration plumes.*

82. Section 5.1.4.3, Permeable Reactive Barrier, 4th paragraph, 2nd bulletin. Clarify if "bgs" was intended to be "below ground water". A total depth of 8 to 13 feet may not reach ground water, and the trencher machine is described as able to reach about 25 feet in depth.

Response: *The "bgs" is below ground surface. The proposed West PRB depth within SS7 is 30 feet bgs. The text has been corrected.*

83. Section 5.1.5.2, last paragraph of 'Bioaugmentation' (Alt. 5S), (Page 5-10). This statement uses cost as a criterion for the structure of the alternative. This is improper as it makes cost a threshold criterion before the alternative is even analyzed against the nine criteria, where cost is a balancing criterion. Revise to a technical/implementability justification. The NCP requires ground water alternatives to evaluate remedies for different time frames. If there is little difference in time frame, then there is little or no justification for a greater degree or extent of treatment.

Response: *The paragraph will be changed by deleting "final costs and" from the first sentence and changing the last sentence to read "Estimated cleanup times for the smaller area scenarios were greater than 60 years (Volume II)."*

84. Section 5.1.6.2, last paragraph of subsection 'Potassium Permanganate'(Page 5-15). This statement uses cost as a criterion for the structure of the alternative. This is improper as it makes cost a threshold criterion before the alternative is even analyzed against the nine criteria, where cost is a balancing criterion. Revise to a technical/implementability justification. The NCP requires ground water alternatives to evaluate remedies for different time frames. If there is little difference in time frame, then there is little or no justification for a greater degree or extent of treatment.

Response: *The paragraph has been changed by deleting "remedial costs" from the first sentence and adding "the cleanup time."*

85. Section 5.1.6.3, Conceptual Design, Potassium Permanganate subsection, 2nd paragraph on Page 5-18. The second sentence refers to using logs from Plume B. Plume A is more proximal and likelier to provide more useful information. Typo?

Response: *Plume A logs are more appropriate. The text has been changed accordingly from "Plume B" to "Plume A."*

86. Section 5.1.8, Surface Water Treatment Options for Diamond Creek. Address surface water treatment options within the screening of technologies. In the description of the alternatives for each plume, add a sentence identifying (1) whether a surface water treatment option is necessary or not, and, (2) if so, which option was used for the purpose of cost estimates. The following are comments to the existing text. Incorporate the corresponding changes in the revision:

Response: *Section 3.12 was inserted into the document to address the surface water treatment options within the screening of technologies. Text was added into the description of the alternatives for each plume to identify applicable surface water technologies.*

Section 5.1.8, Surface Water Treatment Options for Diamond Creek, 1st paragraph, 4th sentence. There is no Figure 1-12 as referenced. Typo? Should be Figure 1-2.

Response: *The typo has been corrected from "1-12" to "1-2."*

Section 5.1.8, Surface Water Treatment Options for Diamond Creek, 1st paragraph. Clarify why a more complete range of surface water options were not addressed in the screening of technologies. Streamlining, (and sometimes skipping) the screening is appropriate where the available technologies are limited, or where other constraints (such as minimizing ecological damage; minimizing damage to critical habitat) limit the available options.

Response: *The following text was added to Section 5.1.8.*

> *"Due to protected vegetation and wildlife, the treatment technologies were narrowed to four options described in the following paragraphs. Ecological damage and destruction of critical habits range from minimal to no damage with these options."*

Section 5.1.8, Option 1S, Channel Drop Structures. Address the seasonal function as with the other options (i.e., freezing in winter - would the increase in velocity prevent freeze?).

Response: *Seasonal fluctuation of water flow is not an issue for the channel drop structures. The structures would be designed to increase surface area of the liquid flow by three whether the flow is 10 cfm or less than 1 cfm. Freezing is not a factor since there would be no contribution of contaminated flow into Crow Creek if Diamond Creek is frozen.*

Section 5.1.8, Option 1S, Channel Drop Structures. Delete the 1st sentence of the 4th paragraph and the 5th paragraph entirely. This appears again to use cost as if it were a threshold criterion. This is an inappropriate place in the document to recommend the technology (which should actually be in the proposed plan). A recommendation at this stage appears to be pre-selection of remedy. *This is a general comment which applies to all of the surface water options. Nearly all of the final paragraphs need to be deleted.*

Response: *Deletions have been completed.*

87. Section 5.2.5, Alternative 5S..., 1st sentence (Page 5-31). Delete the portion of the statement about the alternative having the second highest cost here. This items of discussion belongs in the comparative analysis of alternatives.

Response: *The referenced text has been deleted.*

88. Section 5.2.5.1, Overall Protection of Human Health and the Environment (Page 5-31). Delete "implementation of" for simpler phrasing.

Response: *The text "implementation of" has been deleted.*

89. Section 5.2.5.6, Implementability, 1st sentence. The word "had" should be "has".

Response: *The word "had" has been replaced with "has."*

90. Section 5.2.7.1, Compliance with ARARs (Option 3S-INT), last sentence. Delete the last sentence or rephrase it to the effect of "substantive requirements" rather than obtaining a permit.

Response: *The last sentence has been deleted.*

91. Section 5.2.7.1, Short-Term Effectiveness, last sentence. This refers to Plume A, which may be a typo or intentional because Plume A co-mingles with the plume from SS7. If typo, correct it. If intentional, clarify for the reader the modeling of the intermediate zone is combined for SS7 and Plume A.

Response: *The typo has been corrected from "Plume A" to "SS7."*

92. Section 5.3.1, Overall Protection of Human Health and the Environment (Page 5-38). Overall Protection of Human Health and the Environment (and Compliance with ARARs) are threshold criteria. Even in the comparative analysis, the discussion must identify *how* the alternative is protective (or not). However, alternatives are not relatively ranked as they are the balancing criteria. Revise discussions so that one alternative is not described as "more protective" or "less protective" than others. In many cases, this will be a short word fix (delete "greater" or "better"). *This is a general comment applicable throughout any discussion of the detailed analysis of alternatives for all plumes.*

    Response: *Text has been deleted (e.g., "the greatest") such that one alternative is not described as "more protective" or "less protective" than others.*

93. Section 5.3, Comparative Analysis. In the balancing criteria discussion, explicitly rank the retained alternatives comparatively to each other. The discussion appears to describe the (sub)criteria by which ranking can be done, but the relative ranking is not explicit. For example, Section 4.3.4, Reduction of TMV, both pump and treat and bioaugmentation with MNA recognize treatment occurs, but it is not clear if the difference in time frames would rank pump and treat over bioaugmentation with MNA. *This is a general comment applicable throughout any discussion of the detailed analysis of alternatives for all plumes.*

    Response: *See response to Specific Comment #73.*

94. Section 5.3.8.7, Cost, last sentence. Change "options" to "option". MNA is not a treatment process.

    Response: *"Options" has been changed to "option". MNA is, according to EPA, "an in situ treatment method." See General Comment #5.*

95. Section 5.3.9, Comparative Ranking. Most of the discussion is useful and appropriate. Although the discussion clearly identifies the "numbers" are qualitative, the simple use of numbers has led to issues on other sites because it's almost inevitable the qualifiers about the use of the "numbers" will be missed or ignored. Use a non-numerical system of tabulating the relative rankings.

    Response: *A non-numerical system has been adopted and the text in Section 5.3.9 has been revised accordingly. See response to General Comment #8.*

96. Section 6.1.3.2, Rationale for Alternative, 1st paragraph, 1st bulletin. Clarify "migrated slightly" for the leading edge of the plume. Has the leading edge moved down gradient (or receded)? Is this based on comparisons of historical data to current? Is this relevant to the plume as a whole, or is the truncation at LF7 consistent through time such that only

the leading edge of the small eastern lobe can be evaluated? Rationale: this statement appears inconsistent with the case for a stable or receding plume.

Response: *Section 6.1.3.2 has been revised and additional rationale has been added in the bullets in support of MNA.*

97. Section 6.1.3.2, Rationale for Alternative, 3rd paragraph. Specifically state whether the plume potentially intercepts Crow Creek (or based on the modeling, does not after a time period). Rationale: Clarify the need (or not) to address the surface water protection RAO.

Response: *There are currently no documented exceedances of the WDEQ surface water criteria for Crow Creek at the leading edge of Plume B. Modeling results presented in Volume II for this alternative indicate no future exceedances of this criteria in the future. This clarification has been added to the text in Section 6.1.3.2. This section has been extensively rewritten to address this and other inconsistencies.*

98. Section 6.1.4, Alternative 4B, 1st paragraph. Consistent with previous comments, this should be presumptive "strategy". Since "full plume" is in parentheses, explain. Based on the configuration of the alternative, this is not truly the full plume and consists mainly of a line of wells in the longitudinal core area. Will areas outside of the zone of influence of the pumping system attenuate naturally within the same or lessor time frame?

Response: *Because of the longitudinal nature of the plume, the model simulations suggest that a single line of extraction wells would be sufficient to capture the bulk of the surrounding plume and MNA in the "fringe" areas is not necessary. The wells are limited to the "core" area as indicated in the above comment to treat the zone of highest contaminant mass. As discussed in Section 6.1.4.3, the single line of wells proves most effective, as additional wells within this zone will show no significant improvement in the application of this technology. The rationale for which the line extraction wells are not continued to the down gradient portions of the plume toward LF7 are address in comment #99.*

In addition, the term "full plume" has been removed to alleviate confusion with application of the treatment alternative.

99. Section 6.1.4.3, Conceptual Design Approach (Alt. 4B). The well configuration does not appear designed to minimize the remedial time frame, addressing mainly the up gradient portions of the plume. In addition, there is not rationale provided for operating a pump and treat system for ten years, and then allowing MNA for twenty years. Extending the line of extraction wells farther to LF7 may result in a substantial difference in time frame. Explore this alternative. The existing configuration may be retained as a 'hybrid' alternative.

Response: *As in all of the alternatives that implement pump and treat technology, the arrangement and number of pumping wells was derived through an iterative process to determine the most effective design. While not discussed in the text, the "extension" of wells to the LF7 area was evaluated. As illustrated in the time series in Figures 6-1, 6-3,*

and 6-5, the area surrounding MW-086 is an area where contamination persisted in the simulations. This is attributed primarily to a calibrated low conductivity zone in the groundwater model (Figure 2-2, Volume II). This calibrated value is supported by a slug test value of approximately 1 ft/day. Simulation of this alternative within the low conductivity zone precludes the effective application of a pump and treat system in this area. Therefore, the pump and treat system was limited to the higher conductivity regions which correspond to zones of higher TCE concentrations. The remainder of the plume following the cessation of pumping after ten years would then be allowed to naturally attenuate. The rationale for this alternative was not clearly stated in the original draft in the FS and therefore, has been updated in Section 6.1.4.3 to reflect the above reasoning.

100. Section 6.1.4.3, Above Ground Treatment System (Alt. 4B), last sentence. Clarify and/or correct. Figure 6-2 as referenced is not a process flow diagram.

Response: *The sentence was corrected to describe Figure 6-2 as a conceptual design.*

101. Section 6.1.4.3, Monitored Natural Attenuation. There is no PRB described in this alternative. Correct and/or clarify.

Response: *The references to the PRB and SS7 have been deleted, and the monitoring period of 100 years has been changed to 30 years.*

102. Section 6.1.4.4, Performance Monitoring (Alt. 4B). The time frames described for pumping and MNA are inconsistent with the description in the Conceptual Design Approach. Reconcile.

Response: *The time frames have been made consistent to reflect a period of 10 years for pumping and an additional 20 years for MNA.*

103. Section 6.1.5.2, Rationale for Alternative, 3rd paragraph. Optimization at an alternative's conceptual design stage is based on implementability and effectiveness, not cost. If little is gained by the originally larger planned area, explain it in this context. It may be necessary to demonstrate some of the iterative modeling, calculations, and/or with elaboration of the explanation (with corresponding costs as a secondary consideration). This may also relate to the zone of somewhat higher permeability discussed.

Response: *The phrase "Optimization of the area was conducted in an attempt to reduce remedial costs" has been removed. The text regarding optimization of the treatment alternative based on cost has been revised to reflect optimization based on remedial effectiveness. While this comment was directed solely toward Alternative 5B, similar revisions to other alternatives have been conducted as well.*

104. Section 6.1.5.4, Sampling Frequency and Duration of Monitoring (Alt. 5B). The duration of monitoring described is longer than is necessary based on the time-series model figures and refers to MNA, rather than post-KMnO4 injection. Reconcile.

Response: *The time frame for MNA monitoring following the $KMnO_4$ injection is 35 years; the text has been revised accordingly.*

105. Section 6.1.6.2, Rationale for Alternative, 1st paragraph. Optimization at an alternative's conceptual design stage is based on implementability and effectiveness, not cost. If little is gained by the originally larger planned area, explain it in this context with the appropriate modeling or calculations to supplement (corresponding costs may be addressed in discussion as a secondary consideration, but would be best addressed in the Cost criterion where costs are the primary consideration for the criterion).

Response: *The text regarding optimization of the treatment alternative based on cost has been revised to reflect optimization based on remedial effectiveness. While this comment was directed solely toward Option 4B-INT, similar revisions to other alternatives have been conducted as well.*

106. Section 6.2.4.6, Implementability (Alt. 4B), 1st sentence. This phrasing is more appropriate for the comparative analysis. Describe the implementability rather than compare it to other alternatives here.

Response: *The first sentence was changed to "This alternative would be difficult to implement technically due to the requirement to design and install a large-scale, dual-tube, extraction well system in the shallow groundwater, to install extraction piping in a number of trenches, and to connect this extraction system to a treatment system, which must also be installed by the contractor." New second and third sentences were added that stated "However, all of this construction can be accomplished by experienced local contractors and the equipment is readily available. Administratively, this alternative may be easily implemented due its status as the EPA "presumptive remedy" for contaminated groundwater and to its success in a treatability study at the head of Plume C."*

107. Section 6.2.5.6, Implementability (Alt 5B), 1st sentence. This phrasing is more appropriate for the comparative analysis. Describe the implementability rather than compare it to other alternatives here.

Response: *The first sentence was changed to "This alternative would be relatively easy to implement technically due to the ready availability of the required chemicals and of local contractors with previous experience in injecting $KMnO_4$." A new second sentence was added that stated "This alternative should also be easy to implement administratively due to its proven effectiveness in treating shallow groundwater TCE contamination at other sites and its successful use in a treatability study in Plume C."*

108. Section 6.2.6.1, Compliance with ARARs (Option 3B-INT). Rephrase the last sentence to the effect of no need to meet substantive requirements for NPDES discharge.

Response: *The last sentence has been rephrased to state "There is no need to meet the substantive requirements of an NPDES discharge permit for this alternative."*

109. Section 6.2.6.2, Compliance with ARARs (Option 4B-INT). Rephrase the last sentence to the effect of no need to meet substantive requirements for NPDES discharge.

Response: *The last sentence has been rephrased to state "There is no need to meet the substantive requirements of an NPDES discharge permit for this alternative."*

110. Section 6.3.1, Overall Protection of Human Health and the Environment, 2nd paragraph. Overall Protection of Human Health and the Environment (Page 5-38). Overall Protection of Human Health and the Environment (and Compliance with ARARs) are threshold criteria. Even in the comparative analysis, the discussion must identify *how* the alternative is protective (or not). However, alternatives are not relatively ranked as they are the balancing criteria. Revise discussions so that one alternative is not described as "more protective" or "less protective" than others. In many cases, this will be a short word fix (delete "greater" or "better"). *This is a general comment applicable throughout any discussion of the detailed analysis of alternatives for all plumes.*

Response: *Text has been deleted (e.g., "the greatest") such that one alternative is not described as "more protective" or "less protective" than others.*

111. Sections 6.3 through 6.3.7, Comparative Analysis (Plume B). In the balancing criteria discussion, explicitly rank the retained alternatives comparatively to each other. The discussion appears to describe the (sub)criteria by which ranking can be done, but the relative ranking is not explicit for most of the criteria.

Response: *See the response to Specific Comment #73.*

112. Section 6.3.6, Implementability, 2nd paragraph, 1st sentence. Change "...presumptive remedy... to "presumptive strategy".

Response: *EPA states that pump & treat is a <u>presumptive remedy</u> for contaminated ground water. See Specific Comment #62.*

113. Section 6.3.7, Cost, 2nd sentence. Either delete "<u>treatment</u>" or rephrase, MNA is not a treatment alternative.

Response: *See the response to General Comment #5.*

114. Sections 6.3.8.3 through 6.3.8.7. In the balancing criteria discussion, explicitly rank the retained alternatives comparatively to each other. The discussion appears to describe the (sub)criteria by which ranking can be done, but the relative ranking is not explicit for most of the criteria.

Response: *See the response to Specific Comment #73.*

115. Section 6.3.9, Comparative Ranking. Most of the discussion is useful and appropriate. Although the discussion clearly identifies the "numbers" are qualitative, the simple use of numbers has led to issues on other sites because it's almost inevitable the qualifiers about the use of the "numbers" will be missed or ignored. Use a non-numerical system of tabulating the relative rankings.

Response: *A non-numerical system has been adopted and the text in Section 6.3.9 revised accordingly. See response to General Comment #8.*

116. Sections 7.1.3 through 7.1.6. Provide the basis for stability and/or shrinkage, if any, to demonstrate Plume C is stable or shrinking for the shallow zone for Plume C such that MNA is a viable alternative. Similar evaluations exist for the previously evaluated plumes. If portions are stable/shrinking and others are not, this needs to be explained.

Response: *Because Plume C has not been demonstrated to be stable or shrinking, no "MNA only" alternative was considered. All MNA at Plume C is associated with another passive or active treatment technology in order to stabilize or control the migration of plume contaminants prior to the application of MNA.*

117. Section 7. 1.3, Alternative 3C - Ground water Extraction, Ex-Situ Treatment, and Monitored Natural Attenuation. Clarify how the structure of this alternative address the RAO for surface water protection. It is not clear if the configuration of the down gradient-most wells is intended to provide a designed stream intercept or whether attenuation is presumed for the short term. This is an area of surface water where the Class 2AB standards were recently exceeded at station C5.2. Although this results may be a function of drought conditions based on prior results, it does indicate surface water effects from ground water at the stream intercept of Plume C.

Response: *Section 7.1.3.3 ("Conceptual Design Approach" has been revised to discuss the optimization of the well configuration shown in Figure 7-1 to provide hydraulic control of the plume toe as well as minimizing well influence on surface water flows.*

118. Section 7.1.3, Alternative 3C - Ground water Extraction, Ex-Situ Treatment, and Monitored Natural Attenuation. Consistent with previous comments, this should be presumptive "strategy". Since "full plume" is in parentheses, explain. Based on the configuration of the alternative, this is not truly the full plume and consists mainly of a line of wells in the longitudinal core area. Will areas outside of the zone of influence of the pumping system attenuate naturally within the same or lessor time frame?

Response: *EPA states that pump & treat is a presumptive remedy for contaminated ground water. See Specific Comment #62.*

119. Section 7.1.3.3, Conceptual Design. The well configuration does not appear designed to minimize the remedial time frame, where the areas south and southwest of Spill Site 2 and the Acid Dry Wells have no extraction points although the concentration range is similar to areas with extraction points. This also clearly is not intended to address concentrations above 5 µg/l as described in the first sentence. In addition, there is not rationale provided for operating a pump and treat system for twenty years, and then allowing MNA for ten years.

Response: *Multiple modeling scenarios were run with the objective of selecting an optimized well configuration for cleanup of the plume. The configuration presented in Figure 7-1 was chosen based upon establishing a pumping network that would be concentrated in areas of the plume that dictated the overall timeframe for plume cleanup. In other areas of the plume, for example the areas south and southwest of SS-02 and the ADW, the timeframe for attenuation would be less than that of the pumping required elsewhere in the plume. In other words, additional wells in this area would not have any affect on the overall plume cleanup timeframe. This is apparent in Year 10 of the model simulation (Figure 7-2) in which even though there are limited wells in the vicinity of SS-02/ADW, there is already a significant reduction in TCE mass. By Year 15, no contaminated groundwater is observed in the referenced areas, yet pumping is still required in other areas of the plume north and northeast of the ADW and SS-02.*

120. Section 7.1.3.3, Conceptual Design Approach, 1st paragraph. Optimization at an alternative's conceptual design stage is based on implementability and effectiveness, not cost. If little is gained by addressing larger planned area, explain it in this context with the appropriate modeling, calculations, or explanations to supplement. Is this the area where aquifer de-watering was indicated? Corresponding costs may be addressed in discussion as a secondary consideration, but would be best addressed in the Cost criterion where costs are the primary consideration for the criterion.

Response: *The text regarding optimization of the treatment alternative based on cost has been revised to reflect optimization based on remedial effectiveness. The phrase "in a reasonable amount of time and cost-effective manner" has been removed. While this comment was directed solely toward Alternative 3C, similar revisions to other alternatives have been conducted as well.*

121. Section 7.1.3.3, Above ground treatment system, last sentence of section (Page 7-4). Figure 7-1 is not a process flow diagram as indicated.

Response: *The term "process flow diagram" has been replaced by "conceptual design layout."*

122. Section 7.1.3.3, Monitored Natural Attenuation. This refers to a 50 year PRB/MNA treatment period. The time frames are inconsistent with the described alternative, as is

the sudden apparent addition of a PRB to this alternative. The reference to Plume B is confusing.

Response: *The "Monitored Natural Attenuation" subsection has been revised to state "An LTM program will be developed for the 20-year pump-and-treat period and the 10-year MNA period. The LTM program would be reviewed and modified accordingly as new data are obtained during the 30-year total treatment period. The design for MNA at Plume C would be similar to that for plume A in Section 4.1.3.4."*

123. Section 7.1.4.2, Rationale for Alternative. Optimization at an alternative's conceptual design stage is based on implementability and effectiveness, not cost. If little is gained by addressing larger planned area, explain it in this context with the appropriate modeling, calculations, or explanations to supplement.

Response: *The text regarding optimization of the treatment alternative based on cost has been revised to reflect optimization based on remedial effectiveness. The sentence "Development of alternatives 4C, 5C, and 6C went through several iterations in which the results are pertinent to arriving at an optimized list of cost-effective alternatives" has been removed. While this comment was directed solely toward Alternative 4C, similar revisions to other alternatives have been conducted as well.*

6th paragraph, last sentence: This is comparative and belongs in the comparative analysis of alternatives.

Response: *This sentence has been removed.*

7th paragraph, last sentence: Extraction wells are a common intercept technology. Evaluate a line for pumping wells with treatment for discharge as a stream intercept. [Note: this could potentially be addressed in the Screening of Alternatives].

Response: *A line of pumping wells used as a stream intercept for Plume C was not evaluated because of modeling results for a similar plume/stream configuration at SS7. Results of the SS7 simulations are considered to be representative of the Plume C area because of similar hydrogeology. They suggest that the PRB and line of pumping wells would be equally effective in preventing contamination from entering Crow Creek. However, the pump and treat system would require considerably more O&M than a PRB in this hydrogeologic setting and therefore was rejected in comparison to the PRB.*

A line of pumping wells was considered as an alternative to a PRB along the west side of the SS7 area as discussed in Section 5.3 of the Groundwater Modeling Report (Volume II). While the pump and treat technology is recognized as a presumptive remedy, the PRB was retained as a Plume C alternative due to its higher administrative implementability as demonstrated in the success of the existing PRB at SS7 (Section 3). Furthermore, the technical implementability of the PRB proposed for the Plume C alternatives is higher than that for the SS7 PRB, as it is not limited by the design constraints encountered for the existing SS7 PRB. For example, the construction "footprint" would be much smaller given that the depth of excavation would not be necessary to achieve the required depth

for construction of the PRB. Additionally, the location and orientation of the PRB is not influenced by the sensitive species habitat of the Colorado Butterfly plant, which is not present along this stretch of Crow Creek.

124. Section 7.1.4.3, Conceptual Design, Plume Head. Correct the typos in the bulletins, where a square is used instead of "u" for "micro".

Response: *The typos have been corrected.*

125. Section 7.1.4.3, Conceptual Design, Creek Intercept (Page 7-7). Clarify if the same frequency to replace the PRB is assumed. Clarify if 8 to 13 feet bgs (in the 2nd bulletin and again in "Creek Intercept" on Page 7-8) should not be 8 to 13 feet below the water table. Using "bgs", little if any shallow ground water would be intercepted. Are the approximate water depths similar to SS7?

Response: *There would be no replacement of the PRB for Alternatives 4C, 5C, or 6C. According to the model, the contamination remaining after Year 30 is not in an area where replacement of the PRB would be an effective treatment technology. This is indicated in the final bullet of the "Creek Intercept" portion of Section 7.1.4.3.*

The proposed PRB installation depth is between 8 and 13 feet bgs is incorrectly stated. The proposed PRB is projected to extend throughout the saturated thickness of the shallow aquifer zone, which is interpreted to be approximately 20 feet as simulated in the groundwater model (Volume II). The text has been updated accordingly.

126. Section 7.1.4.3, Remainder of Plume. The time frames discussed here are not consistent with the time frames for the alternatives, nor is this Plume B. Correct and/or clarify.

Response: *The time frames and plume designation have been changed.*

127. Section 7.1.5.3, Conceptual Design (Alt. 5C). The only change between Alternative 4C and Alternative 5C is ERH instead of Fenton's reagent. The other elements remain the same and can be incorporated by reference to Alternative 4C. Otherwise, the comments for Section 7.1.4.3 apply here, except on Pages 7-11 and 7-12.

Response: *These sections have been changed to reference Section 7.1.4.3.*

128. Section 7.1.6, Alternative 6C ... Attenuation (Page 7-14). Consistent with previous comments, this should be presumptive "strategy". Again, many of the elements from Alternative 4C are carried through identically and can be incorporated by reference. Otherwise, the comments for Section 7.1.4.3 apply here, except on Pages 7-16 and 7-17. Clarify why an apparently smaller part of the plume head "hot spot" is addressed compared to Fenton's Reagent and ERH.

Response: *EPA states that pump & treat is a <u>presumptive remedy</u> for contaminated ground water. See Specific Comment #62.*

129. Section 7.1.6.3, "Hot spots" within the plume, 1st paragraph. Optimization at an alternative's conceptual design stage is based on implementability and effectiveness, not cost. If little is gained by addressing larger planned area, explain it in this context with the appropriate modeling, calculations, or explanations.

Response: *The text regarding optimization of the treatment alternative based on cost has been revised to reflect optimization based on remedial effectiveness. The phrase "in a reasonable amount of time and cost-effective manner" has been removed. While this comment was directed solely toward Alternative 6C, similar revisions to other alternatives have been conducted as well.*

130. Section 7.1.7.2, Option 4C-INT, 1st paragraph. Optimization at an alternative's conceptual design stage is based on implementability and effectiveness, not cost. If little is gained by addressing larger planned area, explain it in this context with the appropriate modeling, calculations, or explanations.

Response: *The text regarding the optimization of the treatment alternative based on cost has been revised to reflect optimization based on remedial effectiveness. While this comment was directed solely toward Option 4C-INT, similar revisions to other alternatives have been conducted as well.*

131. Section 7.2.3.4, Reduction of TMV (Alt. 3C). This discussion refers to 50 years, where 30 years is indicated in other criteria.

Response: *This is a typo. The number of years has been changed to consistently indicate 30 years.*

132. Section 7.2.3.6, Implementability (Alt. 3C). Pump and treat is a presumptive strategy, rather than presumptive remedy.

Response: *EPA states that pump & treat is a presumptive remedy for contaminated ground water. See Specific Comment #62.*

133. Section 7.2.6.6, Implementability (Alt. 6C). Pump and treat is a presumptive strategy, rather than presumptive remedy.

Response: *EPA states that pump & treat is a presumptive remedy for contaminated ground water. See Specific Comment #62.*

134. Section 7.2.7.1, Compliance with ARARs (Alt. 3C-INT). Rephrase the last sentence to the effect of no need to meet substantive requirements for NPDES discharge.

Response: *The sentence has been rephrased.*

135. Section 7.3.2, Compliance with ARARs, 2nd paragraph. Add Alternative 3C would also comply with substantive NPDES discharge requirements.

Response: *The addition has been made.*

136. Sections 7.3.3 through 7.3.7, Comparative Analysis (Plume C). In the balancing criteria discussion, explicitly rank the retained alternatives comparatively to each other. The discussion appears to describe the (sub)criteria by which ranking can be done, but the relative ranking is not explicit for most of the criteria.

Response: *See the response to Specific Comment #73.*

137. Section 7.3.8.7, Cost, 2nd sentence. Either delete "treatment" or rephrase, MNA is not a treatment alternative.

Response: *See response to General Comment #5.*

138. Section 7.3.9, Comparative Ranking. Most of the discussion is useful and appropriate. Although the discussion clearly identifies the "numbers" are qualitative, the simple use of numbers has led to issues on other sites because it's almost inevitable the qualifiers about the use of the "numbers" will be missed or ignored. Use a non-numerical system of tabulating the relative rankings.

Response: *A non-numerical system has been adopted and the text in Section 7.3.9 revised accordingly. See response to General Comment #8.*

139. Section 8.1.3.1, Process Description, Permeable Reactive Barrier. Address whether the plume is stable or shrinking separately from the effects of the PRB. Then specifically address the effects of the PRB, because it is of limited extent, is discontinuous across that extent, in some places may not have been installed to the appropriate depth, and is unlikely to be replaced due to the difficulties in injection. The phrasing suggests the PRB will be significant in the remediation of Plume E, when this is not likely to be the case.

Response: *The section was reorganized and modified to address MNA as the primary technology. Text was added stating that MNA has reduced TCE concentrations by an average of 78 percent over the past 15 years in nine wells along the entire length of the plume. This includes source area well DRMO-003, with a 98 percent reduction, and creek intercept well MW269, with an 82 percent reduction. In addition, although the PRB has an overall minor effect on the plume, it continues to destroy contaminant mass in the highest concentration portion of the plume and could not, therefore, be omitted from the contaminant modeling.*

140. Section 8.1.3.2, Rationale for Alternative (Alt 3E). Additional rationale is needed to be able to justify MNA as what is effectively a singular alternative. Based on the modeling, the leading edge of Plume E will travel down gradient and intercept Crow Creek at

potentially greater concentrations than currently exist at the intercept. In addition, the core appears to be mobile down gradient, and the center of mass visually appears to also be mobile down gradient. The third paragraph mis-states "slightly more than 5 µg/l" at the down gradient most well (MW-289) when the simulated model concentrations are in the 10 to 50 µg/l range from year 20 to at least year 50. MW-289 is just up gradient of the creek intercept, suggesting this alternative will not comply with the surface water protection RAO in the future.

Response: *The section has been rewritten to indicate that the model shows the core of the plume migrating downgradient through time, rather than the leading edge being stable. The text also states that concentrations appear to increase to levels between 10 and 50 µg/L at creek intercept well MW-269 (not MW-289 as stated in the comment above) at some time between Year 10 and Year 20 of the 70-year MNA period and will remain at those levels until some time between Year 50 and Year 70. Therefore, the alternative may not comply with the surface water RAO during the latter part of the MNA period. However, it should also be pointed out that, based on the model, the concentration in MW-269 may never exceed the concentration that it had in 1989 (34 µg/L), having dropped 82% to the present time due to MNA in the intervening 15 years.*

141. Section 8.1.3.3, Conceptual Design (Alt. 3E), Permeable Reactive Barrier. Explain what is illustrated by the model which indicates the existing PRB should not be replaced after its 30-year life expectancy.

Response: *Replacement of the PRB after the initial 30 years would not be an effective treatment as the remaining contamination will have migrated downgradient beyond the PRB by year 30 (Figure 8-1).*

142. Section 8.1.4, Alternative 4E ... Attenuation. Pump and treat is a presumptive strategy, not a presumptive remedy. Presumptive remedies for VOC-contaminated water would include air stripping, GAC, and UV-Oxidation.

Response: *EPA states that pump & treat is a presumptive remedy for contaminated ground water. See Specific Comment #62.*

143. Section 8.1.4.3, Conceptual Design Approach, 1st paragraph. Optimization at an alternative's conceptual design stage is based on implementability and effectiveness, not cost. If little is gained by addressing larger planned area, explain it in this context with the appropriate modeling, calculations, or explanations.

Response: *The text regarding optimization of the treatment alternative based on cost has been revised to reflect optimization based on remedial effectiveness. The phrase "in a reasonable amount of time and cost-effective manner" has been removed. While this comment was directed solely toward Alternative 4E, similar revisions to other alternatives have been conducted as well.*

144. Section 8.1.4.4, Surface Water Monitoring. The first sentence appears accurate for current concentrations. However, modeling indicates this may not be the case by Year 20, where concentrations in ground water are greater than 5 µg/l. Has the ground water - surface water interaction been evaluated to indicate whether TCE could impact Crow Creek above 2.7 µg/l?

Response: *Yes, groundwater-surface water interaction has been evaluated and determined that there is a negligible impact on Crow Creek (i.e. surface water concentrations less than 2.7 µg/L) at year 20. Mixing calculations were performed for all plumes that illustrate the potential of impacting the surface water in Crow Creek. These calculations, as described in Volume II, were used to determine the timelines in which the surface water RAOs were achieved. While Figure 8-3, in addition to Figures 8-1, 8-5, and 8-7, show groundwater concentrations adjacent to the Creek of 5 µg/L, these concentrations are diluted by upgradient groundwater discharge into Crow Creek, precluding exceedence of the 2.7 µg/L surface water criteria.*

145. Section 8.1.5, Alternative 5E - Existing ... Attenuation. 1st sentence: Explain how the existing PRB protects the surface water interface of Plume E when it is thousands of feet away.

Response: *The existing PRB within Plume E is not directly responsible for protecting the surface water interface; therefore, the phrase "…to protect the surface water interface of Plume E" has been deleted.*

146. Section 8.1.5.1, Permeable Reactive Barrier, Bioaugmentation, Monitored Natural Attenuation, Rationale for Alternative (Alternative 5E; Page 8-8). These are technology descriptions discussions already provided in the earlier text. They have not been repeated for other plume-specific sets of alternatives and it is unclear why this discussion belongs here (repetitive). [Cut and paste error?].

Response: *This was a "cut and paste" error. Process descriptions regarding the existing PRB and bioaugmentation have been removed and replaced with references to the appropriate sections that have previous discussions of these technologies.*

147. Section 8.1.6.2, Rationale for Alternative, Chemical Oxidation. Focus the discussion to Plume E. Some of this appears to be "cut and paste" without the modifications, although some has been appropriately modified.

Response: *Text has been edited accordingly.*

148. Section 8.1.6.2, last paragraph of Chemical Oxidation (Alt. 6E; Page 8-13). This is closer to the type of discussion which should be presented for optimization, where the implementability and effectiveness are adjusted to optimize the alternative. The last sentence of this paragraph is comparative and cost-based and does not belong in the description of the alternative.

Response: *The cost reference has been deleted.*

149. Section 8.1.6.3, Conceptual Design (Alt. 6E; Page 8-13). The second paragraph indicates depths corresponding to the intermediate zone. Is the intent to combine shallow and intermediate zones for the purpose of chemical oxidation? If so, state it explicitly (and remove the chemical oxidation alternative for the intermediate zone). This approach is viable where the core treatment areas of the shallow zone and intermediate zones overlap (and would help with an economy of scale).

Response: *The reference to the intermediate zone has been deleted.*

150. Section 8.1.7.2, Rationale for Alternative (Alt. 4E-INT; Page 8-16). Optimization at an alternative's conceptual design stage is based on implementability and effectiveness, not cost. If little is gained by addressing larger planned area, explain it in this context with the appropriate modeling, calculations, or explanations.

Response: *The text regarding optimization of the treatment alternative based on cost has been revised to reflect optimization based on remedial effectiveness. While this comment was directed solely toward Alternative 4E-INT, similar revisions to other alternatives have been conducted as well.*

151. Section 8.2.4, Compliance with Potential ARARs (Alt. 4E). Delete "Potential" in the subtitle. Add a sentence to address meeting substantive requirements for NPDES discharge.

Response: *"Potential" has been deleted from the subtitle, and other subtitles where it was included. A sentence addressing meeting substantive NPDES discharge requirements has been added.*

152. Section 8.2.7.1, Compliance with ARARs (Alt 3E-INT; Page 8-25). Modify the last sentence to the effect of there is no discharge, so there are no substantive requirements for NPDES discharge.

Response: *The last sentence has been modified.*

153. Section 8.2.7.2, Compliance with Potential ARARs (Alt. 4E-INT; Page 8-27). Delete "Potential" in the subtitle. Modify the last sentence to the effect of there is no discharge, so there are no substantive requirements for NPDES discharge.

Response: *The changes have been made.*

154. Section 8.2.7.2, Short-Term Effectiveness (Option 4E-INT). This is the first place in the document noted which states "Soil spoils generated from well installation will remain onsite, therefore the community does not incur incremental risk associated with traffic

and offsite disposal." Either this statement needs to be revised, or the corresponding changes made to the description for each alternative (all Plumes) where spoils are intended to remain on site, as well as addressing the spoils within the criteria for analysis (i.e., the first seven of the nine criteria).

Response: *Text has been deleted (e.g., "the greatest") such that one alternative is not described as "more protective" or "less protective" than others.*

155. Section 8.3.1, Overall Protection ... Environment (Page 8-28). Overall Protection of Human Health and the Environment (and Compliance with ARARs) are threshold criteria. Even in the comparative analysis, the discussion must identify *how* the alternative is protective (or not). However, alternatives are not relatively ranked as they are the balancing criteria. Revise discussions so that one alternative is not described as "more protective" or "less protective" than others. In many cases, this will be a short word fix (delete "greater" or "better"). *This is a general comment applicable throughout any discussion of the detailed analysis of alternatives for all plumes.*

Response: *The discussions have been revised.*

156. Section 8.3.2, Compliance with ARARs. Address compliance with substantive requirements of NPDES for alternatives with discharge to surface water.

Response: *A sentence has been added addressing substantive NPDES discharge requirements.*

157. Sections 8.3.3 through 8.3.7; and 8.3.8.3 through 8.3.8.7, Comparative Analysis (Plume E and Plume E-INT). In the balancing criteria discussion, explicitly rank the retained alternatives comparatively to each other. The discussion appears to describe the (sub)criteria by which ranking can be done. For Plume E the relative ranking is explicitly stated for most of the criteria, but not all.

Response: *See the response to Specific Comment #73.*

158. Section 8.3.4, Reduction of TMV Through Treatment, 1st paragraph, 1st sentence. Rephrase to not indicate MNA is treatment.

Response: *See the response to General Comment #5.*

159. Section 8.3.9, Comparative Ranking. Most of the discussion is useful and appropriate. Although the discussion clearly identifies the "numbers" are qualitative, the simple use of numbers has led to issues on other sites because it's almost inevitable the qualifiers about the use of the "numbers" will be missed or ignored. Use a non-numerical system of tabulating the relative rankings.

Response: *A non-numerical system has been adopted and the text in Section 8.3.9 revised accordingly. See response to General Comment #8.*

TABLES

160. Table 2-1, Wyoming Environmental Quality Act, Article 3, W.S. 35-11-301. A brief clarification. Permits would be required for off-site actions. On-site actions must meet the substantive requirements. All alternatives evaluated in this FS are on-site actions.

Response: *The text has been revised for clarification.*

161. Table 2-4, Technology Descriptions, Anaerobic Biostimulation and Hydrogen Release Compound, Sheet 1 of 6. Explain why some nutrient enhancement compounds (such as lactate) are deemed feasible for large-scale application and HRC (which is also a lactate compound) is not. Base the rationale on implementability and effectiveness as well as cost.

Response: *This is a "cut and paste" error. HRC is feasible for large-scale application. The phrase stating HRC is not feasible for large scale application has been deleted.*

162. Table 2-4, Technology Descriptions, Sheet 2 of 6. The first three technologies listed include some form of gas diffusion in the aquifer. Address the limitations of infusing into low-permeability materials, such as at FEW. This would apply to any of the "sparging" or "diffusion" technologies on this table.

Response: *The phrase "Low permeability aquifer material may hinder subsurface distribution and limit zone of treatment" has been added to all appropriate sparging or diffusion technologies in Table 2-4.*

163. Table 2-4, Technology Descriptions, Sheet 3 of 6, Additional ZVI by injection. This needs to be updated since the test is complete. Results indicate a difficulty of installation at depths corresponding to the intermediate zone. Another limitation is the drilling effort to verify wall thickness.

Response: *The phrase "Pilot test currently underway" has been removed from the Advantages of Technology Section. The phrase "Drilling necessary to verify consistency and thickness of injected iron with depth" has been added to the Disadvantages of Technology Section.*

164. Table 2-4, Technology Descriptions, Sheet 4 of 6, Additional ZVI by Deep Soil Mixing. A potential limitation is assuring 'pass through' of the contaminated water when the iron or iron/sand is mixed with clayey materials. Fines dominate at FEW, particularly in the intermediate zone.

Response: *Higher hydraulic conductivities created by a mixing zone containing iron or sand-iron tend to distort historic contaminant flowpaths and create additional flow through the "treatment zone."*

Phytoremediation/Poplar Trees: The comment about unfamiliarity to regulators is probably no longer valid. The technology has been around long enough and is now well published. A limitation may be treatability to about 20 feet bgs, which limits the use at FEW to near stream areas. It could, however, serve as a stream intercept. [Note: If there is a safety concern which affects administrative implementability, describe it. For example: prohibited proximity to helicopter pads because birds attracted to the trees can also be a safety threat to aircraft.]

Response: *The "unfamiliarly" comment has been removed. Depth limitations have been added.*

165. Table 2-4, Technology Descriptions, Sheet 5 of 6. Surfactant Injection and Solvent Injection are also permeability-dependent for adequate circulation of surfactants to the aquifer and for subsequent recovery. FEW is dominated by fines and applicability would be at best localized.

Response: *Surfactant and solvent injection systems with recovery/extraction wells are dependent on pumping-induced groundwater flow through the saturated zone, which may be heterogeneous and locally low conductivity. Limitations have been added to the table.*

Pumping: Can also be used to provide hydraulic control of plume.

Response: *This has been added as an advantage.*

Dual-phase Extraction Limitations. Why is the potential for needing a permit addressed here, but not for Pumping and Two-Phase extraction? These, too, would require a permit for off-site discharge and meet substantive requirements for on-site discharge.

Response: *Meeting substantive requirements for on-site discharge have been added to pumping and two-phase.*

Air Sparging + SVE: Air Sparging effectiveness is severely limited in lower permeability formations (fine-grained soils).

Response: *This limitation has been added.*

166. Table 2-4, Technology Descriptions, Sheet 6 of 6. Discharge by Reinjection Limitations. A permit would be required only for off-site injection. Substantive requirements must be met for on-site injection. An additional potential limitation is the fouling of the injection well or trench.

Response: *The changes have been made.*

Discharge to Surface Stream Advantages: The "dilution of existing surface water COC concentrations" needs explanation or deletion. The surface water may dilute ground

water COCs. However, other parameters such as metals, may be more concentrated in ground water and thus increase concentrations in the discharge zone.

Response: *The phrase "Dilution of existing surface water COC concentrations" has been deleted.*

Discharge to Publicly Owned Treatment Works, Limitation. Explain why the City has refused previous requests, i.e., they have allowed limited volume discharges, but (apparently) do not have the capacity to address large volume, continuous discharges.

Response: *Explanatory text has been added.*

167. Table 2-6 *(now Table 3-1)*, Technology Application Matrix for Zone D Plumes, Sheet 1 of 2.

Groundwater and Upper Extraction: The subtitle needs to be clarified. Also, Pumping, Dual-Phase Extraction, and Two-Phase extraction have been eliminated from Spill Site 7. None of the descriptive information in Table 2-4 provides a technical basis for elimination. At this point in the screening process, applicability depends on technical Implementability.

Response: *The subtitle has been changed to "Groundwater Extraction". A pump-and-treat system <u>was constructed and operated</u> at SS7 for a year and was unsuccessful at restoring any part of the plume. Because the existing PRB is successfully remediating a portion of the plume and because a pumping system could reverse the groundwater gradient through the PRB, a pumping system was not proposed for SS7 despite pump-and-treat being EPA's presumptive remedy for contaminated groundwater. See response to Specific Comment #77.*

Air Sparging and SVE and also Groundwater Circulation Wells and Vapor Extraction have been retained in limited situations. However, it is not clear the necessary permeability and homogeneity is present at some, or most, of these locations. This has potential mainly where the shallow aquifer is dominated by the coarser-grained quaternary alluvium. Cross-sections in the RI should be checked to assure this is feasible where the applicability is indicated, otherwise correct the applicability.

Response: *Bausmith et al. (1996) suggests that for technologies that are permeability dependent (i.e. air sparging/SVE), favorable conditions are generally characterized by permeabilities on the order of 10 ft/day. Figure 2-2 of Volume II of the FS shows the calibrated hydraulic conductivity distribution of the shallow zone of the Zone D groundwater model. Slug test values are also overlain for comparison. This figure illustrates that the majority of locations in which these technologies are proposed have permeabilities that are comparable to this value and up to five times higher. While these areas are undoubtedly intermixed with some fine, lower permeability material, the bulk permeability of the aquifer material as reflected in the slug tests and model calibration suggests adequate permeability for application of these technologies for alternative development.*

168. Table 2-6 *(now Table 3-1)*, Technology Application Matrix for Zone D Plumes, Sheet 2 of 2.

Ex-Situ Treatment: UV Oxidation appears to have been omitted from the table. Most of the Ex-Situ Treatment technologies would be applicable to Spill Site 7 based on technical implementability. These should not be pre-screened out, but addressed in Table 3-1 *(now Table 3-2)*.

Response: *UV Oxidation has been added to Table 2-6 (now Table 3-3).*

Offsite Discharge to Publicly-Owned Treatment Works (POTW). If capacity is the reason the city has rejected larger, long-term discharges, this can be considered not applicable at this stage. Otherwise, this should also be kept for SS7 (technically). Table 3-1 *(now Table 3-2)* appropriately later rejects it due to other concerns.

Response: *The designation of POTW as "Rejected" is presumed to reflect the non-applicability of the technology at this stage.*

169. Table 3-1 *(now Table 3-2)*, Groundwater Treatment Technology Screening.

General Comments to Table 3-1 *(now Table 3-2)*:

Some of the "Unknowns" should now be known since the tests at FEW are complete. Update this table accordingly.

Response: *The table has been updated accordingly.*

For Monitored Natural Attenuation, add the text for Effectiveness, Implementability, and Cost. These boxes are currently blank.

Response: *The text for Effectiveness, Implementability, and Cost has been added to the table.*

Present the O&M cost consistently. Some of the technologies appear to include monitoring costs (e.g., Aerobic Biostimulation technologies), others do not (e.g., Chemical Oxidation technologies).

Response: *For purposes of consistency, the costs associated with the alternatives have been referenced to the appropriate table and/or moved to Volume III and explained accordingly.*

Soil Heating (ERH) on Sheet 2. The "Recommendation" indicates "Retain for low-permeability areas only". Low-permeability areas are common at FEW. Is the recommendation also intended only for source areas with high concentrations of VOCs?

Response: *Yes, additional text has been added.*

Onsite Discharge to Surface Stream (Sheet 4): The Administrative Implementability needs to be corrected (On-site discharges do not require an NPDES permit, however, substantive requirements must be met.

Response: *The correction has been made.*

Offsite Discharge ... POTW (Sheet 4): In the Administrative Implementability, explain the reasons for rejection (e.g., capacity).

Response: *Explanatory text has been added.*

170. Table 3-2 *(now Table 3-3)*, Application Matrix for Retained Technologies. The structure of Spill Site 7 needs revision. First, a column exists entitled "Lengthen/Deepen PRB" which does not belong. Second, SS7 is treated as if there were only one direction of ground water flow, from the source areas through the PRB. This is not true, where ground water flows towards Diamond Creek from the western portions of the plume. There is the potential here for a "Creek Intercept" which is independent of the existing PRB.

Response: *The "Lengthen/Deepen PRB" column has been replaced with "Creek Intercept" and retained technologies modified accordingly..*

171. Tables 4-10 and 4-11, 5-8 and 5-9, 6-7 and 6-8, 7-9 and 7-10, 8-8 and 8-9. These are the tables which use a numerical rank for the alternatives, and where a different ranking system should be used. In spite of the explanations, numerical systems can be easily misunderstood and/or mis-used.

Response: *A non-numerical system has been adopted and Tables 4-10, 4-11, 5-8, 5-9, 6-7, 6-8, 7-9, 7-10, 8-8, and 8-9 have been revised accordingly. See response to General Comment #8.*

FIGURES

172. Figure 4-7, Intermediate Zone Plume A, KMnO4. Because the figure is intended to demonstrate the injection points for the intermediate zone, use only the intermediate zone contours and shading. Using both makes it difficult for the reader to visually estimate the amount of the intermediate zone proposed for treatment.

Response: *Figures 4-7, 5-9, 6-7, 7-10, and 8-9 have been edited to incorporate the comment.*

173. Figures 7-1, 7-3, 7-5,7-7, and 7-10. Change the label "Acid Dry W" to "Acid Dry Wells".

Response: *The label change has been made.*

174. Figure 7-10. Illustrate the intermediate zone concentrations for TCE. The overprint of the shallow zone concentrations does not allow the reader to visualize the 'core' or 'hot spot' under discussion.

Response: *The shallow zone concentrations are overlain on all the intermediate site maps, as they have been staples in almost all site maps in previous FEW reports as a point of reference. While the shallow zone concentrations are shown in Figure 7-10, the contours of intermediate concentrations for TCE <u>are</u> illustrated in this Figure. Three primary zones of contamination are delineated in the intermediate zone of this plume outlined by the iso-concentration contours of 5 μg/L (purple), 10 μg/L (blue-green), and 50 μg/L (light green). The figure illustrates the application of the chemical oxidation technology within the approximate "footprint" of the concentrations of 50 μg/L or higher. To alleviate confusion, the shallow zone concentrations have been removed and measured TCE concentrations at the appropriate intermediate wells. Similar changes have been made to Figures 4-7, 5-9, 6-7, and 8-9.*

DRAFT ZONE D GROUNDWATER FEASIBILITY STUDY
VOLUME II OF III GROUND WATER MODELING REPORT

GENERAL COMMENTS

1. The modeling approach and the results described in the report provide a useful tool for evaluating the *relative* impacts of the various remediation alternatives on the contaminant plumes in Zone D at the site. A significant strength of the report is that it identifies and discusses the uncertainties in model input parameters and the likely effect of that uncertainty on the predicted outcomes. As pointed out in the report, the uncertainties in input parameters translate to uncertainty in the simulated cleanup times. The report suggests a factor of two in variation in predicted cleanup times, but in reality the variability may be greater. A shortcoming of the report is that there are no recommendations for further analyses or testing of those parameters to which the model is particularly sensitive. For example, considering the heterogeneity of the system and the large range in hydraulic conductivities measured with slug tests, a recommendation for multiple-well pump tests would be appropriate. If and when such tests are conducted, the model should be revisited and recalibrated if necessary.

   Response: *If an ex situ remedial scenario is selected (i.e., groundwater extraction is selected or involved in the selected scenario) a pumping test would be required prior to engineering design. Multiple well pump tests would be critical in determining if an extraction scenario is feasible or not, and be critical to appropriate engineering design. If the tests are conducted, the model will be revisited and re-calibrated if necessary. We will include such recommendation in the recommendation section.*

   At the same time, we may point out that if the selected scenario is in situ, a pumping test may not be necessary. The actual permeability of the geologic materials within the contaminated plume will affect the spreading rate of the injected solutions, so that affecting the cleanup time. However, it is not as critical as for extraction scenarios. The uncertainty of estimation of hydraulic conductivity may affect the cleanup time, but may not be of critical for implementation.

2. The uncertainty in hydraulic conductivity was extensively evaluated in the report. The model calibration process appears to rely heavily on slug tests performed in Zone D and a comparison of the geometric means of the slug tests in the various sub-areas. The report also refers to pump tests in Zone B and Zone C, but it does not appear that pump tests were performed in Zone D. Considering the heterogeneity of the system, pump tests in this area should be performed prior to remedy design for any pumping alternatives chosen.

   Response: *Actually, the model calibration in estimation of hydraulic conductivity utilized three sets of available data, rather than heavily relied on the slug tests. The three sets of available data are:*

   - *Pumping test results in Zone D Plume C area and in Zone B and Zone C areas*
   - *Estimated groundwater discharge to Diamond Creek and to Craw Creek*

- *General range and geometric mean of slug test results*

Among those, the pumping test data were considered as the most reliable source of data, and were used as the critical information for the final model calibration. Both estimated groundwater recharge and slug test results were only used for general comparisons.

Prior to the Zone B and Zone C pumping test data available, the RI model was already calibrated to a generally acceptable level. The only pumping test conducted in Zone D is at the upgradient portion of Plume C. Because of the large scale of the Zone D model and the relatively large cell size, it was not possible to simulate the Plume C pumping test in the Zone D model.

It was the pumping test data and the model simulations of the pumping tests in Zone C and Zone B that provided the relationship between the pumping-test-estimated K, model-estimated K, and the actual maximum sustainable pumping rate. Reveal of this relationship suggested that the RI model, which allowed steady state pumping at a rate of 4 to 5 gpm in the Plume C area, appeared to have overestimated the K values by a factor of two. The pumping test conducted for three months in 1995 in the Plume C area indicated that a sustainable rate could not exceed 3 gpm. Therefore, the model calibration was revised in the FS phase. With or without this revision, the calibration results are all within the range of both slug test results and the estimated groundwater discharge to the creeks. This indicated that the pumping tests provided critical information, but the slug tests and groundwater discharge estimation did not.

The pumping test results were not simply used as constraints in the model calibration. It was realized that the analytical solution to pumping test may also be not reliable, given significant horizontal and vertical heterogeneity in the pumping test sites. Instead, the pumping test processes were simulated in both Zone B and Zone C groundwater models. In the Zone D model, even though the pumping test was not rigorously simulated as a transient simulation, it was simulated under steady state condition in the model, based on the condition that the pumping test was conducted for about three months. The simulation of the steady pumping rate in the upgradient area of Plume C was the major driving force for the model calibration revision in the FS phase. However, the text needs to be revised to make this clear. The estimated groundwater recharge and general range and geometric mean of the slug test results were only used for post evaluation.

We agree with the comments, that pumping tests should be performed prior to remedy design for any pumping alternatives chosen, except for the upgradient area of Plume C where a pumping test was conducted in 1995.

3. The approach used to address groundwater/surface water interactions is reasonable and appropriate. However, considering the importance of the discharge rate in determining whether or not the remedial action goals for Crow and Diamond Creek are met, further study of the discharge rate is warranted, i.e., direct measurement of the discharge rate in various seasons. This can be done with tracer studies, such as pioneered by the USGS, which use tracer dilution and mass balance principles to calculate discharge, rather than the more problematic physical means of measuring stream flow rates.

Response: *Correct estimation of the discharge rate at Diamond and Crow Creeks is very important in understanding the processes that contribute to contaminant loading which in turn can lead to potential exceedances of the surface water RAOs. However, obtaining direct measurements of discharge during various seasons from tracer studies as recommended above should be reserved for the remedial design phase, if that degree of detail is warranted to support the design.*

SPECIFIC COMMENTS

4. Section 2.2.1.1, Page 2-3, Third Paragraph. This section of the text discusses the "significant uncertainty" in the slug test estimated hydraulic conductivities, which range from 0.003 to 179.0 feet per day. Additionally, the text states that a statistical summary of the data was used based on the calculation of a geometric mean value. Averaging results that have such a wide range of values is one parameter that introduces a degree of uncertainty in the model's predictive accuracy. In addition, the geometric mean may be sensitive to the distribution of individual data points as log normal or normal. Additional discussion of how a geometric mean was selected to best represent the hydraulic conductivity value for this model should be provided.

   Response: *There are 184 slug tests conducted in the shallow layer, covering the areas of Zone A, B, C, and D. It is believed that the wide range of the slug test results, ranging from 0.003 to 179 ft/day (five orders of magnitude), reflects the heterogeneity nature of the aquifer and the uncertainty of the slug test results. The differences (one and half order of magnitude) between the slug test results that were repeated in the same well in the SS7 area probably reflect the possible range of the uncertainty of the slug tests. This indicates that large range of the slug test values is primarily contributed from the natural heterogeneity.*

   Due to the uncertainty of each individual slug test, it is not appropriate to compare the model-estimated K values location by location to each individual slug test K value. However, based on the large sample size (184 slug tests), from a statistical point of view, the mean and variance of the slug test results can be compared to the mean and variance of model-estimated K values. The mean and variance of the slug test results are considered representative of the statistical characteristics of the aquifer hydraulic property. The uncertainty of each individual slug test can be considered as randomly distributed noise. These noises are supposed to be normally distributed, thus, not impacting the statistical characteristics of the K distributions.

   Actually the mean and variance of these tests were only be used for general comparison. The key information that was used for final decision was the pumping test results (see response to comment 2).

5. Section 2.2.1.1, Page 2-7, Third Paragraph. The text states that the K_d value was ". . . selected from available technical literature for other sites rather than calculated based on site specific organic carbon content." Include additional details for how these K_d values were selected. For instance, literature references and comparison of organic content of soils should be provided. Discussion of the similarities and heterogeneity of sedimentary

materials, comparison of mineralogy and groundwater chemistry and how many other sites were included in the evaluation and selection should be included in this section. For solvents such as TCE, the organic carbon content of the soils (K_{oc}) is a factor that must be considered to estimate the contaminant plume's migration. Evaluate K_{oc} using soil samples that are representative of those found onsite.

Response: *The third paragraph actually described how the K_d value was determined for the RI phase model, not for the FS phase model. In the RI phase model, the calculated K_d value (0.076 cm/g), based on the typical Koc value (127) for TCE and the site-specific value (0.0006) of total organic carbon content, was considered too low. Thus, a higher value of 0.252 cm/g was chosen, which was based on (1) comparison of simulated plume migration rate with the apparent observed rate, and (2) the site specific f_{oc} value is lower than the critical value of f_{oc} for TCE, indicating that adsorption depends not only on total organic carbon content but is also affected by the mineral surfaces, particularly clay minerals.*

The FS model, with reduction of hydraulic conductivity of Layer 1 by 50%, the simulated plume migration rate matched the apparent observed one, using the calculated K_d value (0.1 cm^3/g) based on site specific information. This was discussed in the third paragraph on page 2-8 of the FS Draft Report. If the model were only used to simulate the plume development phase, but not to predict the plume recession phase, the lower K_d value would have been chosen for the study.

However, considering the dual-phase property of adsorption and desorption, and the inability of the model to simulate a variable desportion rate, the higher value of K_d (0.252 cm^3/g) was chosen for prediction of the plume recession for being conservative. This appears necessary given the low TCE concentrations in the Zone A area has been persisted for many years.

DRAFT ZONE D GROUNDWATER FEASIBILITY STUDY
VOLUME III OF III, COST ESTIMATES FOR REMEDIAL ALTERNATIVES

GENERAL COMMENTS

1. The costs and assumptions underlying the cost estimates are unclear. For example, Section 4.2.4.7 and Table 4-8 indicate that capital costs associated with Alternative 4A are $7.7 million, that O&M costs are $9.9 million, and that the present value costs are $7.9 million (Section 4.2.4.7) and $7.7 million (Table 4.8). However, Volume III, Appendix C of the FS which contains the cost estimates for the Plume A alternatives indicates that the initial capital costs for Alternative 4A are approximately $2.0 million, and the site costs summary found on the data provided with the Appendix lists capital costs of $2.2 million. These costs do not appear to be consistent. Correct or clarify all cost estimates to be consistently presented.

   Response: *For consistency purposes, costs directly related to the evaluated alternatives have been referenced to the appropriate table and presented in Volume III.*

2. It is difficult to understand the cost estimates without written assumptions and descriptions which make the basis and use of the assumptions obvious. While assumptions are provided in Appendix H of Volume III of the FS, the basis and use of the assumptions are not obvious. For example, 103 wells were assumed to be installed for Alternative 4A and the average well depth was assumed to be 30 feet. If it is assumed that each of the wells is 30 feet (as described in appendix H of Volume III) then 3090 liner feet of 4-inch PVC well casing and screen would be required. The 2-Phase Element Technology Cost Detail Report, provided on CD, lists 3512 linear feet of well casing and screen are required. This may be due to well stickups but it is not clear why this difference exists. Provide additional information to make the assumptions more obvious. Provide tables which summarize costs in an easily understandable manner.

   Response: *The output reports from RACER™ not only reflect the inputs as listed in Appendix H of Volume III, but also include built-in conservative equations that are under patent and unavailable for the common user to view.*

   For example, the piping equation, as described by the RACER™ Technical Support Staff, is as follows:

   PVC Pipe (feet) = (Well drill depth [feet] + 3 feet) x Number of wells

   Therefore, even though it appears that the inputs do not match the RACER™ output reports, this is not the case. It is not possible to obtain each equation used behind the RACER™ database for the purposes of the FS report; however, given that RACER™ is the accepted costing software, perhaps a conservative error associated with these idiosyncrasies will be appropriate.

SPECIFIC COMMENTS

3. Section 3.0, Cost Assumptions and Presentation by Alternative, Page 3-1. Explain why a 5% discount factor is used. [EPA's default discount factor is 7%; however this applies to Fund-financed and PRP-financed actions. Federal Facilities such as FEW are to key their discount rate to index Treasury securities. Since there has been little variability in those securities, the project managers agreed to a 5% discount rate as typical within the small range of fluctuation. There have been no fluctuations which would significantly change this discount rate.

   Response: *A 5% discount factor was used for the cost estimation of present values associated with the various alternatives. Project Managers agreed to a 5% discount rate for Federal Facilities such as FEW to key the rate to index Treasury securities. Since there has been little variability in those securities, the rate of 5% was maintained for this project.*

4. Section 3.0, last bulletin of the 1st paragraph (on Page 3-2). Explain what "Silt/silty clay" has to do with cost assumptions.

   Response: *RACER™ requires the entry of soil conditions from a pull-down menu for certain technologies. The silt/silty clay description best fit the site, according to our geochemist. RACER™ uses this input to estimate drilling times, in-situ installations, contingency, etc.*

REFERENCES

U.S. Environmental Protection Agency (EPA). 2000. *A Guide to Developing and Documenting Cost Estimates During the Feasibility Study.* Office of Emergency and Remedial Response. EPA 540-R-00-002. July.

U.S. Environmental Protection Agency (EPA). 1988. *Guidance for Conducting Remedial Investigations and Feasibility Studies under CERCLA.* Office of Emergency and Remedial Response. EPA/540/G-89-004. October.

EPA. 2001. *EPA Region III Risk-based Concentration Table.* Online at http://www.epa.gov/reg3hwmd/risk. September 25.

RESPONSE TO WDEQ/GROUNDWATER POLLUTION CONTROL PROGRAM REVIEW COMMENTS ON DRAFT ZONE D GROUNDWATER FEASIBILITY STUDY

Three Volumes F.E. Warren Air Force Base, Wyoming
October 2003

SPECIFIC COMMENTS

1. Page 1-12, second to last paragraph. TCE is identified as the principal contaminant. What is meant by "principal" contaminant? Is TCE the most widespread contaminant? If so, describe TCE as the most widespread contaminant. Are there other contaminants not as prevalent as TCE? If so, briefly summarize these.

   Response: *TCE is described as being widespread and DCE and vinyl chloride are introduced as other "less widespread and lower concentration" contaminants.*

2. Page 1-15, third paragraph. This paragraph discusses exceedances of surface water quality standards. The first sentence states surface water standards were exceeded only for TCE (2.7 µg/l) in Crow Creek. Does "2.7" refer to the water quality standard or is this the level measured? Please provide both the standard and the level at which TCE was detected in Crow Creek for comparison and greater comprehensibility. We suggest deleting "only" in the first sentence, and, "can" in the last sentence. The word "only" implies a judgment on extent of contamination. Judgments should be left out of this report. Provide an explanation for why the two sites correlate for TCE concentrations.

   Response: *The standard and level have been provided. The word "only" was retained to indicate that there are not other contaminants exceeding the state standards. The word "can" has been deleted. The word "fluctuating" was added to give insight to the nature of the correlation.*

3. Page 1-17, Section 1.3.1 Interim Remedial Actions. Add dates interim efforts were undertaken to the bullets. Some of these dates are provided on Plate 1 but would also be useful if presented in the text. For example, for the final bullet, add date as follows, "Removing a grease trap and impacted soil at the SS7 source area (August 2003)" if that is the correct date for the interim effort.

   Response: *Dates have been added.*

4. Page 2-1, first paragraph following bullets. Replace "the only TCE plume" with "one TCE plume". The word "only" implies a judgment on extent of contamination. Judgments should be left out of this report. If exceedences were more prevalent prior to this RI, include a statement to this effect.

   Response: *The word "only" was retained to indicate that the RI reported no other exceedances of surface water standards..*

5. Page 2-27, second paragraph *(page 2-26, last paragraph)*. There appears to be a typo in the last sentence. We suggest replacing, "contaminant by increasing effluents" with "contaminants by increasing effluent".

   Response: *The text has been replaced.*

6. Table 2-4 *(now Table 2-4b)*. Notes should be provided at the end of the table spelling out abbreviations used in the table. Also, HRC and ORC are described as being utilized at over 7,500 soil and groundwater projects in the U.S. We suggest a more generic statement similar to the statements for other technologies, e.g. "biosparging is a widely used and accepted technology".

   Response: *The abbreviations are defined within the text of the table after their first occurrence. The referenced number has been generalized.*

7. Table 2-4 *(now Table 2-4b)*, sheet 3 of 6, shows technology, "Chemical Reduction" preceding "Air/Ozone Sparging". In the text these are reversed in order. We suggest reversing the order in either the text or the table for consistency.

   Response: *The switch has been made in the table.*

8. Table 2-4, sheet 4 of 6, shows technology, "Electrical Resistance Heating with SVE", however in the text this is titled as "Soil Heating". We suggest changing one or the other to be consistent. In general, it is easier to follow the text on technologies if Section titles match the technology column titles in Table 2-4.

   Response: *The change has been made to "Electrical Resistance Heating".*

9. Table 2-4, sheet 4 of 6, is titled "Poplar Trees", however the corresponding text is "Phytoremediation". We suggest changing one to the other to be consistent.

   Response: *"Phytoremediation" is used.*

10. Table 2-6 *(now Table 3-1)* shows columns and rows with dots and dashes. It is unclear what the dots and dashes signify. Please clarify at the end of sheet 2 on the table what is meant by the dots and dashes. (This comment also applies to Table 3-2)

    Response: *Legend notes have been added.*

11. Page 2-15, third paragraph, last sentence, states high carbonate/bicarbonate conditions are not expected at FEW. The Ogallala formation is known to have calcite cemented zones. Would these qualify as carbonate conditions? If so, would this preclude the technology, Fenton's reagent?

Response: *The high carbonate/bicarbonate conditions that typically would be significant enough to preclude Fenton's reagent are limestone aquifers or soils. Based on historical IRPIMS groundwater data, the geology, including the cemented zones, at FEW does not produce abnormally high alkalinity concentrations in groundwater or soil.*

12. Page 2-26 *(first paragraph)*. Third paragraph. It is unclear what this paragraph is meant to say. We suggest breaking down and/or re-writing the first sentence to clarify.

    Response: *The sentence has been broken down and rewritten.*

13. Page 2-26, Section 2.4.7.1 *(now 2.4.8.1)*, Surfactants. This section describes two processes, in situ and ex situ. Does the ex situ discussion apply as a proposed technology? If not, delete the ex situ discussion.

    Response: *It does not apply as a "proposed" technology, but rather it is "identified" as a potential technology.*

14. Page 2-27, fifth paragraph, last sentence, references SS7, however this section applies to all of Zone D, not just SS7. We suggest adding, "or at Plumes A, B, C, and E" to SS7.

    Response: *The text "at SS7" was deleted.*

15. Page 2-28, third bullet references SS7, however this section applies to all of Zone D, not just SS7. We suggest adding, "or at Plumes A, B, C, and E" to SS7.

    Response: *The text "in SS7" was deleted.*

16. Page 2-40 *(now Page 3-1)*, third bullet under Spill Site 7 is "Lengthen/deepen PRB", but, is described as an Area of Concern. Is this a typo? Please clarify.

    Response: *The typo has been deleted.*

17. Page 3-2, fifth paragraph *(page 3-4, third paragraph)*. There appears to be a typo in the second sentence. We suggest replacing "are may be" with "may be".

    Response: *The word "are" has been deleted.*

18. Table 3-4, Sheet 4 of 6, both rejected and selected technologies are shaded on this sheet. Is this a typo? If so, remove shading from the rejected technologies.

    Response: *Shading has been removed from the rejected technologies.*

19. Page 3-18, last paragraph of the Section, Solvents, states the technology is rejected. No rationale was provided for rejection. For consistency with other technology screening, provide rationale for rejection/retention. This comment also applies to the sections, Air Sparging with SVE, Groundwater Recirculation Wells with SVE, Carbon Adsorption, Air Stripping, Reinjection, Surface Streams, and Publicly Owned Treatment Works.

Response: *The appropriate rationale for rejection or retention of the technologies mentioned above has been added to the text.*

20. Section 4, Development and Analysis of Alternatives. In this section Institutional Controls are not developed in enough detail. Please refer to the April 9, 2003 ECOS Memorandum of Understanding on Long-Term Stewardship at Federal Facilities. In particular, detail what restrictions will be instituted, how they will be instituted, and how they will be enforced to protect public health and the environment. Also provide detail on how these will span the full lifetime of the contamination problem. Provide detail on how local governments and the public will be involved in the institutional controls. Provide information on how representatives of federal, state, and local agencies will be involved.

Response: *Section 4.1.2 and the corresponding text in subsequent sections has been updated to include Institutional Control for information regarding Process Description, Rationale, Conceptual Design, and Performance Monitoring.*

21. Page 4-3, third from last paragraph, first bullet. Define "slightly" and "significantly". How many feet horizontally have the plumes advanced and receded?

Response: *Generic qualifiers such as "slightly" and "significantly" have been removed from the bullet to alleviate confusion in the magnitude of advancement or recession of the plume.*

The interpretation that the shallow plume has migrated and the plume in the intermediate/deep zone has receded is based on temporal changes in TCE concentrations. These changes do not facilitate an accurate distinction in the number of feet a plume may have migrated. This uncertainty is compounded by the fact that monitoring wells are space several hundred feet apart. Thus, the distance of migration or recession of the plume cannot be quantified with a high degree of certainty. The statement regarding the migration or recession of Plume A is intended to describe the dynamics of the plume in the broadest sense.

22. Page 5-3, first sentence, there appears to be a typo in this sentence. Replace "rat5ionale" with "rationale".

Response: *The text has been replaced.*

23. Page 5-5, Section Permeable Reactive Barrier appears to contain a typo. Replace "be known" with "are known".

Response: *The text in this section has been replaced and revised.*

24. Page 5-6, second paragraph. This paragraph discussing the configurations of the existing PRB and the two proposed segments. The west proposed segment is described as 300 feet in length and 13 feet deep. The east proposed segment is described as 300 feet in length but no depth is provided. Provide a depth for the east segment of the PRB.

    Response: *The depth of 13 feet is incorrectly stated. The PRB is intended to extend throughout the entire depth of the shallow saturated zone, which is interpreted to be approximately 20 feet thick. The east proposed segment is intended to extend to approximately the same depth. This has been clarified in the text.*

25. Page 5-13, last sentence is confusing. Replace "velocity and contaminant removal" with "velocity, and, contaminant removal".

    Response: *The text has been modified.*

26. Page 7-14, third paragraph, first sentence, appears to have a typo. We suggest replacing "most highly groundwater" with "most highly contaminated groundwater".

    Response: *The text has been replaced.*

27. Table 7-6 uses the abbreviation "Ck" but it is not explained in the notes for the table. Please add a note for Ck.

    Response: *"CK" has been defined as "Creek" in the legend.*

28. Table 7-6 shows Intermediate Options, C-INT MNA and C-INT-Chemox. However text on page 7-36 shows Options 1C-INT, 2C-INT, 3C-INT, and 4C-INT. Please resolve this inconsistency.

    Response: *The tables of Intermediate Options have been revised to identify four options as described in the text.*

29. Page 8-5, first bullet describes the TCE plume exceeding 5 µg/l as 5,200 feet long and 9,600 feet wide, however, Figure 8-1 shows a much narrower plume. Please resolve this inconsistency.

    Response: *The width was changed to 960 feet.*

30. Page 8-8, first paragraph, second to last sentence. There appears to be a typo in this sentence. We suggest replacing "be known" with "are known".

    Response: *This section has been replaced.*

31. Table 8-5 shows Intermediate Options, E-INT MNA and E-INT-Chemox. However text on page 8-25 shows Options 1C-INT, 2C-INT, 3C-INT, and 4C-INT. Please resolve this inconsistency.

Response: *See the response to comment 28.*

32. Page 8-25, third paragraph refers to Table 8.6 for information on Intermediate Zone Options. However, Table 8-7 contains information on Intermediate Zone Options. Please resolve this discrepancy.

Response: *The correct table in 8-7.*

33. Page 8-28, first paragraph, second to last sentence. There appears to be a typo in this sentence. Replace “Table 8-7" with “Table 8-6".

Response: *Table 8-6 is the correct reference.*