

## Department of Energy

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**DEC 21 2011**

Mr. Wm. Turpin Ballard  
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U.S. Environmental Protection Agency, Region 4  
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PPPO-02-1327428-12

Mr. Todd Mullins, FFA Manager  
Kentucky Department for Environmental Protection  
Division of Waste Management  
200 Fair Oaks Lane, 2<sup>nd</sup> Floor  
Frankfort, Kentucky 40601

Dear Mr. Ballard and Mr. Mullins:

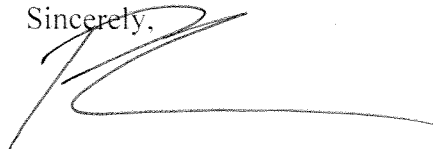
**TRANSMITTAL OF THE REVISED PROPOSED PLAN FOR THE VOLATILE ORGANIC COMPOUND CONTAMINATION AT THE C-400 CLEANING BUILDING AT THE PADUCAH GASEOUS DIFFUSION PLANT, PADUCAH, KENTUCKY, (DOE/LX/07-1263&D1)**

Enclosed for your review is the certified *Revised Proposed Plan for the Volatile Organic Compound Contamination at the C-400 Cleaning Building at the Paducah Gaseous Diffusion Plant, Paducah, Kentucky*, DOE/LX/07-1263&D1. This revised proposed plan identifies that two technologies will be utilized for the completion of the C-400 interim remedial action. Electrical resistance heating (ERH), which was used in Phase I operations and was documented in the signed 2005 record of decision (ROD), will continue to be utilized for the Phase IIa treatment of the Upper Continental Recharge System and upper Regional Gravel Aquifer (RGA) in the C-400 Southeast area. Because of lessons learned in the Phase I operations, it has been shown that ERH is unlikely to be successful in reaching target temperatures in the lower RGA; thus, the remediation of volatile organic contamination will not be achieved. For Phase IIb, which will treat the lower RGA in the C-400 Southeast area, this revised proposed plan proposes to implement Staged Implementation of Baseline/Rebound Analysis and *In Situ* Chemical Treatment, which is a combination of pumping and *ex situ* treatment and/or an initial low-dose *in situ* chemical treatment (Stage 1) followed by *in situ* chemical treatment to remove volatile organics in the lower RGA (Stage 2). Staged Implementation of Baseline/Rebound Analysis and *In Situ* Chemical Treatment, Alternative 5, has its details documented in the *Evaluation of the Technologies and Alternatives for C-400 Phase IIb, Regional Gravel Aquifer, at the Paducah Gaseous Diffusion Plant, Paducah, Kentucky*, which is included as an appendix to this revised proposed plan.

In order to accommodate our project schedules, please provide your comments no later than January 20, 2012. A ROD Amendment also will be made available for your review once the revised proposed plan is approved and available for public comment.

If you have any questions or require additional information, please contact David Dollins at (270) 441-6819.

Sincerely,



Reinhard Knerr  
Paducah Site Lead  
Portsmouth/Paducah Project Office

Enclosures:

1. Certification Page
2. Revised Proposed Plan for Volatile Organic Compound Contamination at C-400 Cleaning Building

e-copy w/enclosures:

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CERTIFICATION

DOCUMENT IDENTIFICATION: *Revised Proposed Plan for the Volatile Organic Compound Contamination at the C-400 Cleaning Building at the Paducah Gaseous Diffusion Plant, Paducah, Kentucky, DOE/LX/07-1263&D1*

I certify under penalty of law that this document and all attachments were prepared under my direction or supervision in accordance with a system designed to ensure that qualified personnel properly gather and evaluate the information submitted. Based on my inquiry of the person or persons directly responsible for gathering the information, the information submitted is, to the best of my knowledge and belief, true, accurate, and complete. I am aware that there are significant penalties for submitting false information, including the possibility of fine and imprisonment for knowing violations.

LATA Environmental Services of Kentucky, LLC



Mark J. Duff, Paducah Project Manager

12-21-11  
Date Signed

I certify under penalty of law that this document and all attachments were prepared under my direction or supervision in accordance with a system designed to ensure that qualified personnel properly gather and evaluate the information submitted. Based on my inquiry of the person or persons directly responsible for gathering the information, the information submitted is to the best of my knowledge and belief, true, accurate, and complete. I am aware that there are significant penalties for submitting false information, including the possibility of fine and imprisonment for knowing violations.

U.S. Department of Energy (DOE)



William E. Murphie, Manager  
Portsmouth/Paducah Project Office

12/21/11  
Date Signed

**DOE/LX/07-1263&D1  
Primary Document**

**Revised Proposed Plan  
for the Volatile Organic Compound Contamination  
at the C-400 Cleaning Building  
at the Paducah Gaseous Diffusion Plant,  
Paducah, Kentucky**



**CLEARED FOR PUBLIC RELEASE**



**Revised Proposed Plan  
for the Volatile Organic Compound Contamination at the C-400 Cleaning  
Building at the Paducah Gaseous Diffusion Plant, Paducah, Kentucky  
December 2011**



## INTRODUCTION

The U.S. Department of Energy (DOE) is conducting cleanup activities at the Paducah Gaseous Diffusion Plant (PGDP), Paducah, Kentucky, to address contamination resulting from past waste-handling and disposal practices at the plant. As part of these cleanup activities, DOE, the U.S. Environmental Protection Agency (EPA), and the Commonwealth of Kentucky's Energy and Environment Cabinet (KEEC) request public review and comment on this Revised Proposed Plan (PP) for the Volatile Organic Compound Contamination at the C-400 Cleaning Building. DOE is the lead agency for conducting this action, and EPA and KEEC are supporting regulatory agencies providing oversight. This Revised PP was developed consistent with the PGDP Federal Facility Agreement.

The C-400 Interim Remedial Action (IRA,) as documented in the original 2005 Record of Decision (ROD), is for treatment of volatile organic compound (VOC) sources in soils and groundwater in the Upper Continental Recharge System (UCRS) and the Regional Gravel Aquifer (RGA), which is contaminated with trichloroethene (TCE), a VOC that is believed to be the source of the larger groundwater contamination area identified as the Northwest Plume. The C-400 IRA now is known as Phase I and Phase IIa. This Revised PP is for Phase IIb that addresses a revised remedy for a specific

subset of the C-400 VOC sources located southeast of the building. This Revised PP presents the preferred alternative for remediation of VOC sources found in the lower RGA subsurface soils and groundwater.

The basis for this decision is documented in the "Evaluation of the Technologies and Alternatives for C-400 Phase IIb, Regional Gravel Aquifer, at the Paducah Gaseous Diffusion Plant, Paducah, Kentucky" (hereafter referred to as the Technical Evaluation), which is included as an appendix to this Revised PP; and the "Record of Decision for Interim Remedial Action for the Groundwater Operable Unit for the Volatile Organic Compound Contamination at the C-400 Cleaning Building at the Paducah Gaseous Diffusion Plant, Paducah, Kentucky," DOE/OR/07-2150&D2/R2, U.S. Department of Energy, Paducah, KY, July 2005 (ROD).

DOE considered a range of remedial actions for the IRA for the VOC contamination at C-400. The 2005 ROD documented the decision to implement direct heating, also known as electrical resistance heating (ERH). During the design of the ERH system, DOE decided to divide the treatment system into two phases, Phase I and Phase II. Phase I was implemented in the source areas that are east and southwest of the C-400 Building. Phase I implementation was completed in December 2010 and results were evaluated. Based on the evaluation and the lessons learned from

Phase I, it was determined that the ERH base design was successful in reaching target temperatures in the subsurface and removing contaminants in the UCRS and upper RGA. The evaluation of Phase I also indicated that target temperatures were not achieved in the lower RGA, which has resulted in splitting the Phase II IRA for the southeast source areas into two separate actions:

- (1) UCRS and Upper RGA action (Phase IIa) and
- (2) Lower RGA action (Phase IIb).

Phase IIa includes continuing to treat the VOC sources in the UCRS and the upper RGA with ERH and enhancements learned from Phase I activities. The Phase IIb IRA proposed in this Revised PP is to implement a Staged Implementation of Baseline/Rebound Analysis and In Situ Chemical Treatment instead. This revised interim action will involve the following:

- (1) Establishing baseline and rebound conditions in the target treatment volume and
- (2) Implementing in situ chemical treatment.

This plan fulfills the public participation requirements of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980; the Resource Conservation and Recovery Act (RCRA) of 1976; Kentucky Revised Statute 224.46-530(1); and the National Environmental Policy Act (NEPA) of 1969 by summarizing the revised proposed action and requesting public comments.

DOE, EPA, and the Kentucky Department for Environmental Protection (KDEP) encourage public review and comment on the revised proposed alternative to address the VOC contamination at C-400. This plan has been prepared to provide information to the public and to solicit comments from the public on the preferred alternative, as well as on the other alternatives considered. This Revised PP provides a summary of the information presented in the appendix to this document. The preferred alternative represents a recommendation by DOE, subject to public comment. The Administrative Record file for this action is available for review at the DOE Environmental Information Center

(see page 20) or at the Web site, <http://www.paducaheic.com>.

Since the Groundwater Operable Unit (GWOU) is extensive, multiple actions either have been identified or are planned for the future. The GWOU strategy includes a phased approach consisting of the following steps: (1) prevention of human exposure; (2) reduction, control, or minimization of major groundwater contaminant source areas contributing to off-site contamination; and (3) evaluation and selection of long-term solutions for the off-site dissolved-phase groundwater plumes and remaining groundwater contaminant sources. Early actions already have been implemented to prevent exposure and to reduce further off-site migration of contaminant plumes, including implementation of the DOE Water Policy and construction of ongoing groundwater treatment systems for the Northwest and Northeast Plumes. The short-term goal of the GWOU is to accelerate the reduction of contaminant source areas that contribute to groundwater contamination [i.e., C-400 and the Southwest Plume source(s)]. This Revised PP focuses on the reduction of VOC sources in the lower RGA at C-400. This area is located within the secured area of PGDP (Figure 1).

The remedial action selected in the upcoming ROD Amendment may be different from the preferred alternative presented in this document, depending upon public comments. The public comment period for this Revised PP is scheduled from TBD, 2012, through TBD, 2012. The "Responsiveness Summary" section of the upcoming ROD Amendment will address significant public comments received on this Revised PP.

Additional information regarding the public participation process and the public meeting can be found in the "Community Participation" section of this Revised PP.

## SITE BACKGROUND

PGDP is located in McCracken County in western Kentucky, about 3.5 miles south of the Ohio River and approximately 10 miles west of the city of Paducah. It is an operating uranium enrichment facility owned by DOE. DOE leases the plant

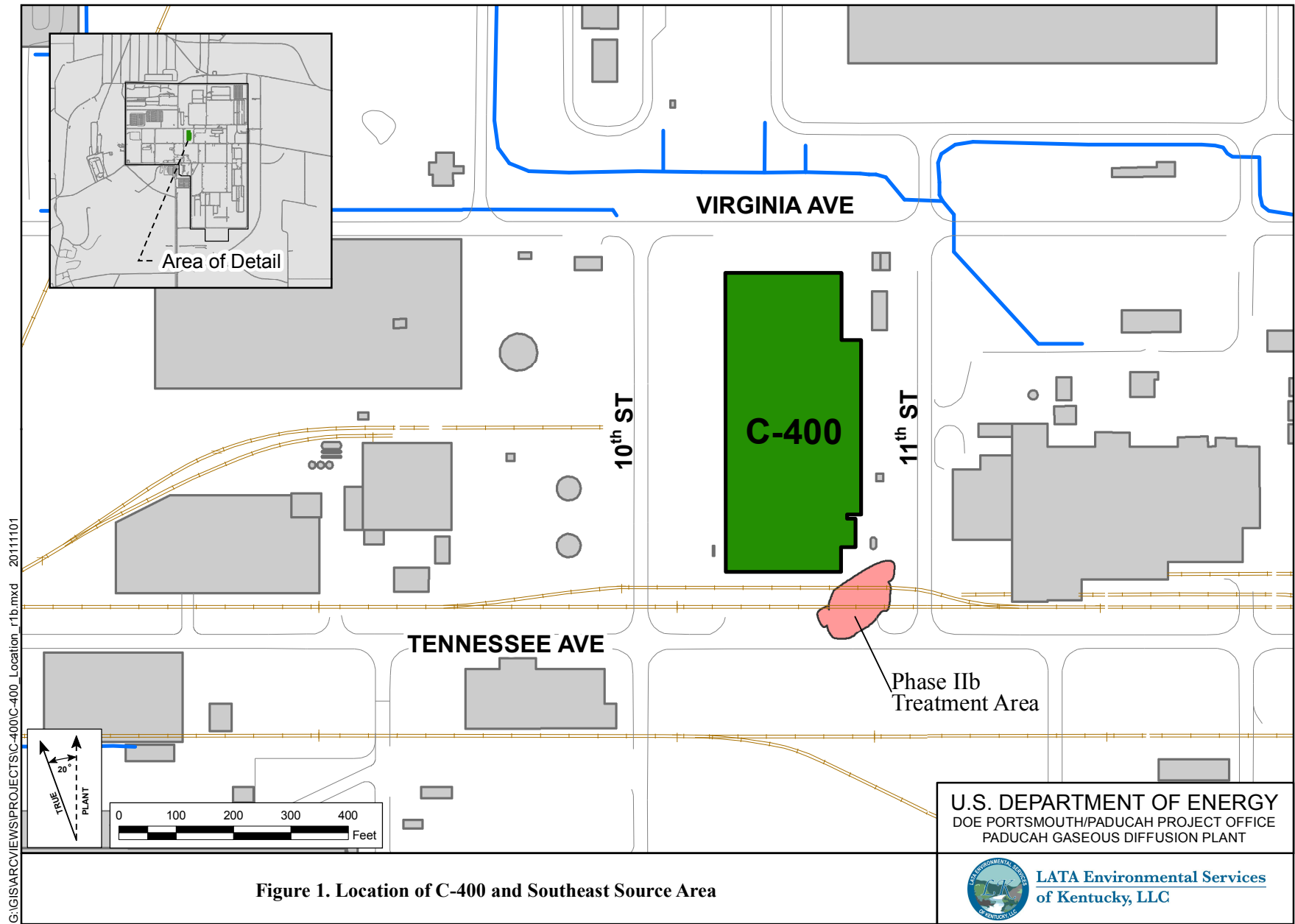


Figure 1. Location of C-400 and Southeast Source Area

U.S. DEPARTMENT OF ENERGY  
DOE PORTSMOUTH/PADUCAH PROJECT OFFICE  
PADUCAH GASEOUS DIFFUSION PLANT



LATA Environmental Services  
of Kentucky, LLC



production operation facilities to the United States Enrichment Corporation.

The C-400 Cleaning Building is located inside the plant secured area, near the center of the industrial section of PGDP. The building is bound by 10<sup>th</sup> and 11<sup>th</sup> Streets to the west and east, respectively, and by Virginia and Tennessee Avenues to the north and south, respectively. Figure 1 shows the location of C-400.

Historically, some of the primary activities associated with C-400 are cleaning machinery parts, disassembling and testing uranium enrichment cascade components, and laundering plant clothes. The building also has housed various other activities, including recovery of precious metals and treatment of radiological waste streams.

Suspected sources of leaks and spills at C-400 include (1) degreaser and cleaning tank pits, (2) drains and sewers, (3) the east side plenum/fan room basement, (4) tanks and sumps outside the building, and (5) various first-floor C-400 processes. These sources have resulted in contamination of soil and groundwater by VOCs (primarily TCE and its breakdown products), semivolatile organic compounds, and various metals and radionuclides.

The two most significant sources of leaks and spills of VOCs that have been identified are located at the southeast corner of the building. This is where a drain line from the degreaser sump was connected to a storm sewer and also where transfer pumps and piping delivered solvents to and from storage to processes in the building.

In June 1986, a routine construction excavation along the 11<sup>th</sup> Street storm sewer unearthed TCE soil contamination. The cause of the contamination was determined to be a leak in a drain line from the building's basement sump to the storm sewer. After the discovery of the TCE leak in June 1986, some of the soils were excavated in an attempt to reduce the contamination in the area. Excavation was halted to prevent structural damage to the adjacent TCE storage tank and to 11<sup>th</sup> Street. Approximately 310 ft<sup>3</sup> of TCE-contaminated soil was drummed for treatment and off-site disposal. The excavation was backfilled with clean soil and the area was capped with a layer of clay. The area of

contamination became known as the C-400 Trichloroethene Leak Site and was given the designation of Solid Waste Management Unit (SWMU) 11. After the initial discovery of contamination, four borings were installed to define the extent of the soil contamination. SWMU 11 and the C-400 area have been the subjects of several investigations since then.

Two environmental investigations in 1991 and 1992 included the C-400 area. The investigations included installing soil borings and groundwater monitoring wells. These investigations confirmed that TCE contamination at the southeast corner of C-400 extended from the ground surface to the base of the RGA at 92 ft bgs. These investigation results are documented in *Results of the Site Investigation, Phase I, at the Paducah Gaseous Diffusion Plant*, KY/ER-4, CH2M HILL Southeast, Inc., Oak Ridge, TN, March 1991, and *Results of the Site Investigation, Phase II, Paducah Gaseous Diffusion Plant, Paducah, Kentucky*. KY/Sub/13B-97777C P03/1991/1, CH2M HILL Southeast, Inc., Oak Ridge, TN, April 1992.

In 1995, another environmental investigation demonstrated that the C-400 area was a major source of TCE contamination for the Northwest Plume. This investigation is documented in *Work Plan for Phase I of the Waste Area Grouping 6 Remedial Investigation Industrial Hydrogeologic Study at Paducah Gaseous Diffusion Plant, Paducah, Kentucky*, DOE/OR/07-1406&D2, U.S. Department of Energy, Paducah, Kentucky, October 1995. Also in 1995, a review of C-400 activities was completed and documented in *C-400 Process and Structure Review*, KY/ERWM-38.

In 1997, another environmental investigation focused on the C-400 area, further delineating contamination at SWMU 11. This investigation identified the TCE transfer system at the southeast corner of the building as a significant source of soil and groundwater contamination. The area of contamination became known as the "Trichloroethene Spill Site from Historical TCE Unloading Operations at C-400" and was given the designation of SWMU 533. An additional area of VOC soil contamination was identified near the southwest corner of the building, associated with a storm sewer. The results of the investigation are documented in the *Remedial Investigation Report for Waste Area Grouping 6 at the Paducah*

*Gaseous Diffusion Plant*, DOE/OR/07-1777/V1&D2.

Four treatability studies have been conducted to investigate methods for reducing or remediating the VOC contamination in the C-400 area. The first, using a chemical cosolvent, was conducted in 1994 at the southeast corner of the C-400 area using the existing monitoring wells. The results are reported in *The In situ Decontamination of Sand and Gravel Aquifers by Chemically Enhanced Solubilization of Multiple-Component DNAPLs with Surfactant Solutions*, submitted by Intera Inc., in January 1995. The next two studies were bench scale studies conducted as part of the 1995 environmental investigation. One looked at other surfactants and cosolvents, while the other evaluated chemical oxidation. The results of these studies are documented in *Surfactant Enhanced Subsurface Remediation Treatability Study Report for Waste Area Grouping 6 at the Paducah Gaseous Diffusion Plant, Paducah, Kentucky*, DOE/OR/07-1787&D2, and in *Bench Scale In Situ Chemical Oxidation Studies of Trichloroethene in Waste Area Grouping 6 at the Paducah Gaseous Diffusion Plant, Paducah, Kentucky*, DOE/OR/07-1788&D2.

The fourth treatability study was a test of ERH, the six-phase heating (SPH) technology, at the southeast corner of the C-400 area, conducted in 2003. During the SPH study, it is estimated that over 22,000 lb of TCE (approximately 1,825 gal) was removed from the subsurface in the southeast corner of the C-400 area. The SPH treatability study tested the effectiveness of full-scale deployment of ERH technology in the area adjacent to the southeast corner of the C-400 Building at PGDP, and it was considered successful. The treatability study included the installation and operation of one SPH treatment array, using ERH, and a vapor recovery system. The SPH treatability study began on February 14, 2003, and was discontinued on September 6, 2003. The primary objective, as outlined in the *Treatability Study Work Plan for Six-Phase Heating, Groundwater Operable Unit, at the Paducah Gaseous Diffusion Plant, Paducah, Kentucky*, DOE/OR/07-1889&D2/R1, was to demonstrate the implementability of the ERH technology in the unsaturated and saturated soils of the UCRS and in the groundwater of the underlying RGA. During the SPH, the removal of TCE in the groundwater of the RGA was assessed

by comparing the pretreatment groundwater sample results to posttreatment groundwater sampling results. The posttreatment groundwater sample results indicated a 99.1% reduction in TCE concentration in groundwater that met the removal efficiency criteria outlined in *Six-Phase Heating Technology Assessment*, written by GEO Consultants in 2003.

The success of the SPH project led to a 2005 ROD to implement ERH to remove additional volatile organics from the UCRS and RGA and, as discussed above, to implement it in two phases, Phase I and Phase II. The Phase I ERH system consisted of a network of inground electrodes and vapor extraction wells distributed throughout the east and southwest zones of contamination. The east and southwest areas were selected for Phase I because they were the smaller of the source areas near C-400 and had contaminants only in the UCRS. Phase I also included an objective to evaluate the heating performance of the ERH base design through the RGA down to the McNairy Formation interface in the southwest treatment area. Phase II was to follow Phase I to treat the southeast area, which is expected to contain the larger amount of source contamination in both the UCRS and the RGA. Phase I's lessons learned were utilized in planning and implementing the Phase II ERH.

ERH consisted of heating soil in the saturated and unsaturated zones by passing current between electrodes buried in the soil, with simultaneous injection of water through the electrodes to maintain conductivity and to transfer heat by convection. The coupling of ERH with heat transfer via convection greatly enhances the efficiency and uniformity of heating by ERH technology. Volatilization of contaminants was achieved by heating subsurface soils to at least the TCE boiling point. Simultaneous vapor extraction removed the contaminants from the subsurface. The vapor produced from Phase I ERH operations was a mixture of air, water vapor, and high levels of VOCs (primarily TCE). The organic vapors extracted during the Phase I ERH operations were condensed and liquid TCE was collected. The water vapor was discharged to the atmosphere. Approximately 7,000 lb of TCE (or approximately 580 gal) was removed from the subsurface during Phase I.

An important objective of Phase I was to evaluate

the heating performance of the base ERH design through the RGA down to the McNairy Formation interface in the southwest treatment area. During Phase I, temperature goals were not attained in the lower RGA in the southwest treatment area (particularly in the deep lower RGA below 70 ft bgs).

Because of the inability of ERH to reach target temperatures, a recommendation to change the method of removing TCE from lower RGA soils is being made for the Phase IIb part of the C-400 IRA project.

The revised response action proposed in this report will continue reducing the TCE concentrations and other VOCs in the lower RGA in the C-400 Cleaning Building area, and it meets the threshold criteria of CERCLA Section 121 and the National Contingency Plan (NCP) at 40 *CFR* § 300 (see “How Does DOE choose a Cleanup Plan?” on page 18). The revised response action recommended in this report will continue to be protective of human health and the environment and will comply with applicable or relevant and appropriate requirements (ARARs) that were identified in the ROD signed in 2005. A copy of this Revised PP has been placed in the Administrative Record file, as stipulated by 40 *CFR* § 300.825(a)(2), and the DOE Environmental Repository along with the supporting document, *Record of Decision for Interim Remedial Action for the Groundwater Operable Unit for the Volatile Organic Compound Contamination at the C-400 Cleaning Building at the Paducah Gaseous Diffusion Plant*, DOE/OR/07-2150&D2/R2.

## **SITE CHARACTERISTICS**

In the area of C-400, the topography is relatively flat, with elevations ranging from approximately 370 to 376 ft above mean sea level. Thick concrete aprons cover the heavy traffic areas immediately north and south of the building, while gravel or asphalt covers the areas on the east and west sides of the building. Various utility lines are buried on all sides of the building. An active railroad track serves the south side of the building. Aboveground steam lines run along the west side of the building. Most of the storm water from the C-400 area flows to storm drain inlets around the building and discharges via the storm sewer on the south side of

the building to Outfall 008, then to Bayou Creek on the west side of the plant. Runoff from the north side of C-400 flows into the North-South Diversion Ditch then is pumped to the C-616 Lagoons and released through Outfall 001 to Bayou Creek.

The C-400 area is underlain by a sequence of clay, silt, sand, and gravel layers deposited on limestone bedrock. The shallowest stratigraphic unit consists of fill and a layer of wind-deposited, silty clay, or loess, extending from the surface to a depth of approximately 20 ft. Beneath the loess, the upper continental deposits, a subunit of the continental deposits, consisting of discontinuous sand and gravel layers interbedded with silt and clay, extend to an average depth of 55 ft bgs. The lower continental deposits or RGA, also a subunit of the continental deposits, is a highly permeable layer of gravelly sand or chert gravel, typically extending from approximately 55 to 92 ft bgs. Below the continental deposits is the McNairy Formation, a sequence of silts, clays, and fine sands that extends from approximately 92 to 350 ft bgs.

The shallow groundwater system at the site, the UCRS, is subdivided into three hydrogeologic units (HUs)—HU1, HU2, and HU3—and consists of the loess (HU1) and the underlying upper continental deposits (HU2 and HU3). The sand and gravel lenses of HU2 are separated from the underlying RGA by a 12- to 18-ft thick silty or sandy clay interval designated the HU3 aquitard. The aquitard restricts the vertical flow of groundwater from the sands and gravels of the HU2 unit to the gravels of the RGA. In some limited areas, notably the southeast corner of C-400, the HU3 aquitard is considerably thinner and a lesser barrier to groundwater movement. The RGA, the uppermost aquifer in the C-400 area, consists of the lower continental deposits stratigraphic unit. Below the RGA is the McNairy Flow System, which corresponds to the McNairy Formation. The uppermost portion of the McNairy Flow System typically is a clay or silty clay, which acts as an aquitard restricting groundwater flow between the RGA and McNairy Flow System.

The depth to the water table within the UCRS varies considerably across PGDP. In the C-400 area, ground covers and engineered drainage limit rainfall infiltration. The shallow water table generally is approximately 40 to 50 ft bgs. Water within the UCRS tends to flow downward to the

RGA. Groundwater flow in the RGA generally is to the north, eventually discharging into the Ohio River. At the C-400 area, groundwater flow is generally to the northwest as part of the Northwest Plume, although some flow diverges to the east and to the west as part of the Northeast and Southwest Plumes, respectively.

### **Nature and Extent of Contamination**

The following section provides a brief summary of the nature and extent of the VOC contamination at C-400 that is being addressed by this action. More detailed information is included in the appendix, (“Evaluation of the Technologies and Alternatives for C-400 Phase IIb, Regional Gravel Aquifer, at the Paducah Gaseous Diffusion Plant, Paducah, Kentucky”) of this document.

Sampling conducted during the 1997 remedial investigation (RI) at the C-400 area along with post-ROD sampling indicates that the primary site-related contaminant in subsurface soil and groundwater at the unit is TCE. The highest concentrations of VOCs in the soil were found southeast and southwest of the C-400 Building. The southeast area contains SWMU 11 and the former location of the TCE transfer pumps and piping. The southwest area contained an area of soil contamination that was the subject of the C-400 Phase I treatment.

The elevated concentrations of TCE in subsurface soils and groundwater suggest that dense nonaqueous-phase liquid (DNAPL) source areas existed within the UCRS and RGA soils southeast of the C-400 Building prior to implementation of Phase I. Post-ROD sampling and analysis indicates that discrete areas of the lower UCRS and the upper RGA contain DNAPL ganglia, while the lower RGA contains ganglia or pooled DNAPL.

A DNAPL source area is that region of the subsurface containing residual and/or pooled DNAPL. A DNAPL is a liquid that is denser than water and only slightly soluble in water and exists in the subsurface as a separate fluid phase in the presence of either air or water and can both vaporize into air and slowly dissolve into flowing groundwater (Keuper, B. H. et al., *An Illustrated Handbook of DNAPL Transport and Fate in the Subsurface*, Environment Agency, 2003). Once in the ground, DNAPLs can migrate downward by

gravity through the subsurface independent of the groundwater flow in the area, with a portion being trapped in the pore spaces of the soil and the remainder continuing downward. The TCE concentrations detected in the RGA during the 1997 RI, which were a maximum of 701 mg/L in groundwater (64% of the maximum solubility of TCE in water), suggest that the DNAPL source area is in the RGA and is a secondary source of groundwater contamination.

### **SCOPE AND ROLE OF THE RESPONSE ACTION**

The GWOU is one of five operable units at PGDP being used to evaluate and implement remedial actions. Past actions to address groundwater contamination from the plant include a Water Policy action that provides municipal water service to all residences within the area that may be impacted by the contaminated groundwater. In addition, DOE has undertaken interim actions involving hydraulic containment of the high concentration cores of the Northeast and Northwest Plumes to limit further spreading of the contamination.

The revised response action recommended in this report addresses subsurface contaminant sources contributing to contamination of the GWOU. The goal of the response action is to reduce DNAPL contaminated areas near the C-400 Building in order to reduce additional contributions to off-site groundwater contamination, which is consistent with the ROD signed in 2005. The completion of the action in the 2005 ROD and this amended action will contribute to the goal of eventual groundwater remediation at PGDP.

The results of the proposed response action are expected to be treatment of contamination in the lower RGA in the vicinity of the C-400 Building. Reducing or removing TCE at C-400 will reduce the time that TCE concentrations in the off-site plumes remain above health-based levels. The proposed action includes groundwater treatment to reduce the toxicity, mobility, and volume of the DNAPL contamination at C-400.

This modified action for source reduction is an IRA. All of the remedial alternatives considered for the C-400 Building contamination require additional measures, such as land use controls

(LUCs), to protect human health. Some residual contamination is expected to remain after implementation of the modified action. These contaminated areas will be subject to continued groundwater monitoring and long-term land-use restrictions to prevent exposure under current and potential future land-use scenarios. Data will be collected to verify the accomplishment of the remedial objectives.

## SUMMARY OF SITE RISKS

The human health and ecological risks posed by contamination found at or migrating from a site determine whether a remedial action is warranted. This section of this Revised PP presents a summary of the baseline risk assessments performed for the C-400 area in the 1997 RI and the *Feasibility Study for the Groundwater Operable Unit at the Paducah Gaseous Diffusion Plant, Paducah, Kentucky*, DOE/OR/07-1857&D2 (GWOU FS), dated August 2001. This summary describes the risks posed to human health and the environment by the VOC contamination found in subsurface soil and groundwater at the C-400 area that will be addressed by the modified proposed action. This discussion is presented in two subsections: human health risks and ecological risks.

Based upon the results of the baseline risk assessment, the modified preferred alternative is necessary for protection of human health and welfare or the environment from actual or threatened releases of pollutants, contaminants, or hazardous substances, which may present imminent and substantial danger to public health or welfare.

### Human Health Risks

The baseline human health risk assessments considered both the current and potential future uses of the C-400 area and the areas to which contaminants may migrate. Currently, the C-400 area lies within the industrialized areas of PGDP. Under current plans, the C-400 area is expected to remain industrial, with groundwater use restrictions in the future. It is not reasonable, therefore, to assume that groundwater would be withdrawn from the C-400 area and used for any purpose other than monitoring for environmental parameters. However, consistent with EPA risk

assessment guidance, hypothetical baseline risks were calculated under the assumption that this water would be used by residents and industrial workers for drinking and washing. Based on this approach, risks were determined to be unacceptable.

Of greater importance is the potential for contaminants in soil and groundwater to migrate to areas where groundwater may be used in the future. To address this concern, the baseline human health risk assessments used results from fate and transport modeling to estimate the potential risks that could be posed to a hypothetical resident drawing water from a well completed in the RGA at the PGDP property boundary. This analysis determined that three VOCs—TCE, vinyl chloride, and 1,1-DCE—could present unacceptable cancer risks and hazards if groundwater contaminated by these VOCs were used in the home (for consumption and washing) of the hypothetical resident. [As noted earlier, previous actions for the GWOU (i.e., the Water Policy) prevent exposure to contaminated groundwater by current residents.] The maximum predicted concentration of these VOCs, their predicted concentrations in groundwater in the RGA at the PGDP property boundary, and maximum potential cancer risk and hazards are discussed below. (The potential cancer risks and hazards presented here were calculated using toxicity values that have been updated from those used in the 1997 RI and GWOU FS, based on guidance from EPA.)

**TCE:** The maximum predicted concentrations in groundwater in the RGA at the PGDP property boundary are 7.1 mg/L, and the maximum predicted concentrations at the C-400 area are 31.7 mg/L. The estimated potential cancer risk to a hypothetical resident exposed to 31.7 mg/L is 2 in 100. The estimated potential cancer risk to a hypothetical resident exposed to 7.1 mg/L is 2 in 2,000.

**Vinyl Chloride:** The maximum predicted concentration in groundwater in the RGA at the PGDP property boundary from sources in subsurface soil in the C-400 area is 0.0007 mg/L. The estimated potential cancer risk is 2 in 100,000. The estimated hazard index (HI) to a hypothetical resident is less than 1.

1,1-DCE: The maximum predicted concentration in groundwater in the RGA at the PGDP property boundary from sources in subsurface soil in the C-400 area is 0.0025 mg/L. The estimated potential cancer risk to a hypothetical resident is 5 in 100,000. The estimated potential HI to a hypothetical resident is less than 1.

These cancer risks and hazards indices, which are based upon reasonable maximum exposure scenarios that considered use of contaminated groundwater in the home (i.e., consumption and washing), indicate that there could be a significant potential risk to children and adults from exposure to VOCs in groundwater from sources in the C-400 area. Most notable are the estimated potential cancer risks and hazards from exposure to TCE in groundwater, which exceed the upper limit of EPA's generally acceptable risk range for site-related exposures (i.e., a cancer risk equal to  $10^{-4}$ ) and the limit used by EPA to determine when noncancer risks may be unacceptable (i.e., an HI equal to or greater than 1). (Please see the text box "What is Risk and How Is It Calculated?")

The potential cancer risks for vinyl chloride and 1,1-DCE fall within EPA's acceptable risk range. They were estimated to exceed the lower limit of EPA's generally acceptable risk range for site-related exposures (i.e., a cancer risk equal to  $10^{-6}$ ), but neither VOC has a maximum predicted concentration that exceeds its maximum contaminant level (MCL) under the Safe Drinking Water Act. The MCLs for vinyl chloride and 1,1-DCE are 0.002 and 0.007 mg/L, respectively, versus maximum concentrations at the DOE plant boundary predicted from fate and transport modeling of 0.0007 and 0.0025 mg/L, respectively. The maximum concentration at the DOE plant boundary predicted for TCE (31.7 mg/L) does exceed its MCL (0.005 mg/L) by a significant margin, making TCE the contaminant of concern (COC) to be addressed by the proposed action.

### **Ecological Risks**

A screening ecological risk assessment indicated a small potential for significant ecological impacts to occur from exposure to the contamination considered in the Revised PP. This was based upon the location of the contamination being addressed (i.e., in the subsurface) and the industrial nature of the contaminated area.

Generally, the assessment concluded that there was little potential for significant exposure of wildlife to this contamination under current conditions; therefore, ecological risks were estimated to be below levels of concern.

### **REMEDIAL ACTION OBJECTIVES**

The remedial action objectives (RAOs) describe what the proposed site cleanup is expected to accomplish. The modification of the remedy by this proposed ROD Amendment will not change the RAOs as originally applied to this interim remedial action in the 2005 ROD. The RAOs for the C-400 area are the following:

- Prevent exposure to contaminated groundwater by on-site industrial workers through institutional controls (e.g., excavation/penetration permit program);
- Reduce VOC contamination (primarily TCE and its breakdown products) in UCRS soil at the C-400 Cleaning Building area to minimize the migration of these contaminants to RGA groundwater and to off-site points of exposure (POEs); and
- Reduce the extent and mass of the VOC source (primarily TCE and its breakdown products) in the RGA in the C-400 Cleaning Building area to reduce the migration of the VOC contaminants to off-site POEs.

The revised response action recommended in this report is expected to achieve the RAOs by removing VOC mass and by continuing to implement institutional controls. The Phase IIa action applies the RAO contained in the second bullet, while the Phase IIb action will apply the RAO contained in bullet 3. Continuing the existing institutional controls (bullet 1) will reduce risk to levels below concern by preventing exposure. Implementing an action to remove VOC mass will result in less groundwater contaminant migration to off-site areas and will be a step toward meeting the overall goals of GWOU remediation at PGDP (see Scope and Role of the Response Action).

### **Basis for the ROD Amendment**

During remedial design report development, it was determined the ERH IRA would be performed in

two phases. The east and southwest areas were selected for treatment in Phase I because they were the smaller source areas near C-400 and had contaminants only in the UCRS. Phase I also included an objective to evaluate the heating performance of the ERH base design through the RGA down to the McNairy Formation interface in the Southwest treatment area. Phase I's lessons learned would support planning and implementing the Phase II ERH treatment of the RGA in the southeast area. Phase I ERH data indicated that the remedial goals for the east and southwest treatment areas (UCRS) had been achieved. Temperature goals generally were not achieved in the RGA in the southwest treatment area (particularly in the deep RGA below 70 ft bgs) during Phase I operations, with the electrodes installed according to the base design (see appendix).

Because target temperatures were not achieved in the RGA, it was determined that the base design would not be successful in the RGA. Based on the lessons learned in Phase I, a numerical simulation evaluated the use of ERH to heat the RGA to target temperature. The results of the numerical simulation confirmed that a major redesign of the ERH system would be needed for application in the RGA. An independent technical review team evaluated the application of a redesigned ERH and determined that ERH is an inappropriate technology for the RGA conditions. The team recommended identification and implementation of a more appropriate technology for treating the TCE sources located in the RGA to be addressed by the Phase IIb IRA. (*Independent Technical Review of the C-400 Interim Remedial Project Phase I Results, Paducah, Kentucky*, SRNL-STI-2010-00681).

DOE reviewed available technologies and developed alternatives for detailed analysis consistent with CERCLA criteria. The results of this evaluation are documented in the appendix to this document, the *Evaluation of the Technologies and Alternatives for C-400 Phase IIB, Regional Gravel Aquifer, at the Paducah Gaseous Diffusion Plant, Paducah, Kentucky*. DOE, as lead agency, and EPA and KDEP, as supporting agencies, have selected *Staged Implementation of Baseline/Rebound Analysis and In Situ Chemical Treatment*, instead of ERH for the lower RGA as the Phase IIb IRA. The change in the method of accomplishment for the RGA necessitates the

development and issuance of this Revised PP. ERH will continue to be utilized for treatment of the Phase IIa source area.

## SUMMARY OF ALTERNATIVES

The following sections provide detailed information concerning the components and implementation approach for the selected remedial alternative in the 2005 ROD and the recommended 2011 alternative for application in the VOC source areas of the lower RGA at C-400.

### 2005 ROD Alternative—ERH (Direct Heating)

The 2005 ROD Alternative consists of ERH supplemented with the enhancements identified in the lessons learned from the Phase I IRA. The 2005 ERH alternative consists of the following:

- Installation of an ERH electrode array designed to minimize the chance of heating failures encountered with the Phase I design;
- Withdrawal of TCE and other VOCs by vacuum extraction;

ERH was the specified treatment of the contaminated zone in the UCRS and RGA presented in the 2005 ROD. As documented in the 2005 ROD, ERH operation would cease when monitoring indicates that heating has stabilized in the subsurface and when recovery diminishes to a point at which the rate of removal of TCE, as measured in the recovered vapor, becomes asymptotic. The most significant challenge associated with implementing this technology in the lower RGA during Phase IIb of the C-400 IRA concerns heating the lower RGA to target temperature for volatilizing the VOCs. Because water flows freely in the lower RGA, unheated water flows toward the heated zone making the heating system less effective. The ERH technology relies on volatilization for removal of VOCs; therefore, if the target temperature is not attained, the technology is ineffective.

Due to the heating challenges identified above, a significant upgrade would be required to reach target temperatures in the lower RGA. These enhancements would be added to the base design of the 2005 remedial alternative. This upgrade calls for an increase in the number of electrodes

### **WHAT IS RISK AND HOW IS IT CALCULATED?**

A CERCLA human health risk assessment estimates “baseline risk.” This is an estimate of the likelihood of health problems occurring under realistic current and future use, if no cleanup action is taken at a site. To estimate the baseline risk at a CERCLA site, a four-step process is followed.

Step 1: Analyze Contamination

Step 2: Estimate Exposure

Step 3: Assess Potential Health Dangers

Step 4: Characterize Site Risk

In Step 1, the risk assessor looks at the concentrations of contaminants found at a site, as well as at past scientific studies on the effects these contaminants have had on people (or animals, when human health studies are unavailable). Comparisons between site-specific concentrations and concentrations reported in past studies enable the risk assessor to determine which contaminants are most likely to pose the greatest threat to human health.

In Step 2, the risk assessor considers the different ways that people might be exposed to the contaminants identified in Step 1, the concentrations that people might be exposed to, and the potential frequency and duration of exposure. Using this information, the risk assessor calculates dose from a “reasonable maximum exposure” (RME) scenario, which represents an estimate of the highest level of human exposure that reasonably could be expected to occur within a given time period.

In Step 3, the risk assessor uses the information from Step 2, combined with the information of the toxicity of each chemical, to assess potential health risks. Two types of risk are considered: cancer risk and noncancer risk. The likelihood of any kind of cancer resulting from a CERCLA site generally is expressed as an upper bound probability: for example, a “1 in 10,000 chance.” In other words, for every 10,000 people exposed under the RME scenario, one extra cancer may occur as a result of exposure to site contaminants. An extra cancer case means that one more person could get cancer than normally would be expected from all other causes. For noncancer health effects, the risk assessor calculates a hazard index (HI). The key concept for noncancer health effects is that a “threshold level” (measured as a HI of 1) exists; below this level, noncancer health effects are not expected.

In Step 4, the risk assessor determines whether the site risks are great enough to cause unacceptable health problems for people exposed at or near a site. To do this, the risk assessor combines and summarizes the risk results for the individual chemicals and routes of exposure within the RME scenario and compares the resulting scenario risk estimates to the generally acceptable risk range for site-related exposures.

### **WHAT ARE THE CONTAMINANTS OF CONCERN?**

DOE has identified chemicals in the subsurface at the C-400 area that pose potential risk to human health through migration of contamination to groundwater.

TCE is the COC for this interim remedial action. Discussions of other COCs found in other environmental media may be found in the RI report for the C-400 area [i.e., Waste Area Grouping (WAG) 6]. TCE is a halogenated organic compound used in the past for a variety of purposes at PGDP. During the WAG 6 RI, TCE was detected in subsurface soil in the C-400 area at concentration up to 11,055 mg/kg and in the RGA groundwater at 701 mg/L. Exposure to this compound has been associated with deleterious health effects in humans. Based on laboratory studies, TCE is a systemic toxicant and is considered a probable human carcinogen. Over time, TCE naturally degrades to other organic compounds. TCE currently is not used at the PGDP.



and an increase in the number of vapor and groundwater extraction wells. The design also would require installing electrode borings upgradient of the treatment zone for preheating groundwater flowing into the area. Additionally, groundwater extraction farther upgradient of the preheating zone will reduce the amount of groundwater flowing into the treatment area that requires preheating. Augmenting the groundwater heating by hot water injection at the electrodes may be required, also.

Costs for the selected alternative in 2005 ROD with enhancements are summarized in Table 1.

**Table 1. Summary of Costs for 2005 ROD Selected Alternative with Enhancements**

| Cost Element                              | Cost, \$M    |
|---|--------------|
| Installation Costs                        | 11.37        |
| Operation and Maintenance Costs           | 5.28         |
| Decontamination and Decommissioning Costs | 1.58         |
| <b>Total Project Cost</b>                 | <b>18.23</b> |

**Recommended 2011 Alternative—Staged Implementation of Baseline/Rebound Analysis and *In Situ* Chemical Treatment**

The recommended alternative consists of multiple technologies used in stages to allow modification of the systems based on the data collected and observations made during previous stage. The two stages are these:

- Stage 1: Establish baseline and rebound conditions in the target treatment volume.
- Stage 2: Implement *in situ* chemical treatment.

Stage 1

- Stage 1 components utilized in establishing baseline and rebound conditions in the target treatment volume include the following:
  - Baseline sample collection from a monitoring array within the treatment zone followed by cycled operation of a

groundwater extraction system with aboveground treatment and associated rebound analysis; and/or

- Baseline sample collection from a monitoring array within the treatment zone followed first by injection of an initial oxidant dose to suppress dissolved-phase VOC concentrations in the treatment zone, and then followed by an assessment of groundwater concentration and associated rebound.

This process will increase the understanding of the distribution of dissolved and sorbed mass in the RGA within the Phase IIb treatment volume to allow for a refined selection and application of the amendment used in Stage 2. Stage 1 activities mitigate the risk associated with the uncertainty of the TCE source mass distribution.

Components of Stage 1 depend on the approach applied to suppressing the dissolved contaminant mass and are as follows:

- Groundwater extraction, treatment, and injection from within the C-400 Phase II RGA treatment area;
- Groundwater treatment system (current plans are to use the existing Phase I liquid phase treatment system);
- Treatment of groundwater according to ARARs and discharging through the outfall or reinjection; and/or
- Introduction and circulation of an initial oxidant dose of chemical (e.g., 10 to 15% of the total design dose) using a well network to suppress dissolved-phase VOC concentrations.

Common components associated with both of the approaches above include these:

- Assessment of groundwater contaminant concentrations and associated rebound,
- Secondary waste management,
- Long-term monitoring, and
- LUCs.

The primary advantage of implementing a conventional groundwater extraction system at the C-400 site is the lower capital cost and ease of operation. The disadvantage is the potential for lingering contamination and excessively long treatment time frames resulting from a slower removal rate of dissolved-phase contamination as extraction continues. The groundwater extraction system readily removes the dissolved contamination while the uncontaminated water surrounding the extraction well mixes with the dissolved TCE and decreases the influent concentration. These conditions are common to groundwater extraction systems.

Extracted groundwater would be routed through an aboveground treatment system consisting of an air stripper followed by vapor-phase granular activated carbon (GAC) units. Water would pass through the air stripper where TCE would be stripped from the influent and the resulting TCE-laden vapors would be treated using vapor-phase GAC vessels. Liquid-phase effluent from the air stripper would be reinjected upgradient of the source zone, as described above, or discharged to an outfall after treatment, as required by ARARs.

Utilizing the initial oxidant dose approach, no surface treatment is needed since the material is recirculated as needed to suppress the contaminant concentrations without treatment and release. In both approaches, a monitoring well network will be utilized to assess changes in the groundwater contaminant concentrations and associated rebound.

### Stage 2

Stage 2 consists of *in situ* chemical treatment followed by monitoring. Components of the stage are as follows:

- Groundwater extraction/injection wells in a pattern that will allow injecting a treatment chemical into the subsurface and the operational flexibility to recirculate the residual treatment chemical into the RGA as needed;
- Addition of treatment chemicals by injection and/or recirculation using a batch treatment chemical delivery system with an apparatus for recirculation;

- Secondary waste management;
- Long-term monitoring; and
- LUCs.

Options for treatment chemicals include, but may not be limited to, peroxide, persulfate, permanganate, surfactants, cosolvents, and emulsified zero-valent iron (EZVI). The amount of treatment chemical required will be based on the existing estimates of total contamination in place and potential chemical demand of the aquifer (e.g., natural oxidant demand). The selection of the actual treatment chemical will be determined in the remedial design.

The RAO for this interim action that applies to reduction in the extent and mass of the VOC source (primarily TCE and its breakdown products) in the RGA in the C-400 Cleaning Building area under Phase IIb will be accomplished during Stage 2 by *in situ* treatment using chemical amendment(s). Implementation of the preferred alternative is expected to result in reduction in the extent and mass of VOC source in the RGA at the C-400 Cleaning Building area and result in reduction of the migration of the VOC contaminants to off-site POEs. Technology-based performance criteria will be developed to support a determination of mass reduction and signify remedy completion during the design and work planning processes.

The well array and existing remedial infrastructure would be utilized to distribute treatment chemical in the subsurface. The specific treatment chemical used will have specific material handling and injection requirements; however, the equipment requirements are similar for injection of any of the treatment chemicals under consideration. The equipment used would be as follows:

- Water supply for dissolution and/or dilution of the treatment chemical,
- Treatment chemical mixing apparatus,
- Batch storage tanks, and
- Electrical supply or generator.

The well field pattern proposed for *in situ* chemical treatment is designed to be capable of flexible operations for a range of potential *in situ* treatment amendments. The wells would be positioned so that the areal extent of contamination is covered by the densest well arrangement, and so that impacts to active operations at the C-400 Building are minimized. The wells and the treatment chemical delivery system would include an apparatus for recirculation and that would allow wells to be used either to inject or to extract during a treatment event. The pattern will provide for operational flexibility and maximum control of treatment chemical delivery and contaminant monitoring in the subsurface.

This staged approach provides advantages by allowing the application of multiple technologies that can be matched with observed results and conditions to address the challenges associated with high concentrations of TCE in the RGA at the C-400 site. The first stage is composed of evaluating alternate cycles of extraction and rebound over an estimated 8-month period. Groundwater would be extracted at a constant rate while monitoring influent TCE concentrations. Each extraction stage will be of sufficient duration to recover multiple pore volumes of the target Phase IIb RGA treatment volume. A pore volume is expected to be extracted in a period of 10 days. Alternatively, the contaminant concentrations will be suppressed utilizing the injection and recirculation of an initial oxidant dose. Either process will increase the understanding of the distribution of dissolved and sorbed mass in the RGA within the Phase IIb treatment volume to allow for a refined selection and application of the amendment used in Stage 2. Stage 1 baseline and rebound conditions analysis mitigates the risk associated with the uncertainty of the TCE distribution. Stage 2 includes *in situ* treatment followed by long-term monitoring. Stage 2, *in situ* chemical treatment, would employ *in situ* chemical injection in order to treat DNAPL source material. The specific *in situ* chemical (e.g., persulfate, peroxide, permanganate, surfactant, cosolvent, or EZVI) will be determined in the remedial design.

Technologies for *in situ* chemical treatment would be chosen based on the ability to utilize a common infrastructure, compatibilities/incompatibilities, and cost. The Stage 1 extraction and/or initial

oxidant component of the alternative is to provide the information to design Stage 2 and not intended as an action for long-term dissolved-phase mass removal.

Costs for the recommended 2011 alternative are summarized in Table 2.

**Table 2. Summary of Costs for Staged Implementation Alternative**

| <b>Cost Element</b>                       | <b>Cost, \$M</b> |
|---|------------------|
| Installation Costs                        | 3.86             |
| Operation and Maintenance Costs           | 2.97             |
| Decontamination and Decommissioning Costs | 0.89             |
| <b>Total Project Cost</b>                 | <b>7.72</b>      |

## EVALUATION OF ALTERNATIVES

Based on an evaluation of the nine criteria established by the NCP, the preferred remedial alternative is Staged Implementation of Baseline/Rebound Analysis and *In Situ* Chemical Treatment, which includes operation of groundwater extraction and treatment in an aboveground treatment system, followed by *in situ* chemical treatment. The criteria are derived from the statutory requirements of CERCLA Section 121. This Revised PP documents the evaluation of the first seven criteria; the final two criteria (state and community acceptance) will be addressed after public comment. Brief descriptions of all nine criteria are in text box “How Does DOE Choose a Cleanup Plan?” The results of comparing the 2005 ERH alternative to 2011 Staged Implementation of Baseline/Rebound Analysis and *In Situ* Chemical Treatment for the Phase IIb treatment of the lower RGA contamination is shown in Table 3, NCP Comparison Summary.

The alternatives evaluated are acceptable because they are anticipated to have beneficial impact, and they are not expected to cause any further injury to a natural resource through their implementation than already might exist. Each alternative requires time to reduce DNAPL sources.

## SUMMARY OF THE PREFERRED ALTERNATIVE

Staged Implementation of Baseline/Rebound Analysis and *In Situ* Chemical Treatment is the preferred alternative for Phase IIb of the C-400 IRA. This preference could change, however, in response to public comments or receipt of new information. The multiple recovery mechanisms associated with the Staged Implementation Alternative provides a flexible system that can improve the chance of success for a site with multiple uncertainties, such as C-400. The highly permeable conditions in the lower RGA could have a positive impact on *in situ* treatment by injection of a treatment chemical (Stage 2) by allowing the treatment chemical to be spread or distributed more uniformly.

Both EPA and the Commonwealth of Kentucky have concurred with this recommendation. Based on information currently available, DOE believes the Staged Implementation Alternative meets the threshold criteria and provides the best balance of trade-offs among the other alternative with respect to the balancing and modifying criteria. DOE expects the Preferred Alternative to satisfy the following statutory requirements of CERCLA § 121(b): (1) be protective of human health and the environment; (2) comply with ARARs to the extent practicable for an interim action; (3) be cost-effective; (4) utilize permanent solutions and alternative treatment technologies or resource recovery technologies to the maximum extent practicable; and (5) satisfy the preference for treatment as a principal element. Additionally, the implementability of the preferred alternative in the lower RGA is higher than the alternative selected in 2005, while short-term effectiveness is similar for both. The ranking for the preferred alternative is the higher of the two.

Table 4 provides a summary of the comparative analysis of both alternatives with numerical rankings applied.

### Preliminary Identification of Preferred Alternative Design Criteria and Considerations

Design and construction considerations applicable to the preferred alternative include the following:

- Concentration and volume of treatment chemicals that might be required to remove

TCE mass in the C-400 lower RGA source zone,

- Transport distances in the subsurface for each treatment chemical, and
- Injection rate considerations—high chemical loading versus iterative loading.

The concentration and volume of the treatment chemical required is dependent on the following factors:

- Estimate of the mass of TCE (DNAPL source and dissolved-phase) in the treatment zone.
- Chemical reactions among the native groundwater, soil, and treatment chemical in the C-400 lower RGA source zone,
- Organic carbon present in soil at C-400 affecting reactions between soil and treatment chemicals,
- Decomposition rate of the selected treatment chemical, and
- Compatibility of oxidant combinations or surfactant amendments.

The transport distance of the treatment chemical in the subsurface is dependent on the following:

- Delivery method,
- Persistence of treatment chemical in the subsurface (based on stability, reaction speed, and half life),
- Groundwater flow rate,
- Density of reagent, and
- Diffusive characteristics of the chemical and porous media (e.g., greater conductivity and gradient result in farther the transport distance).

Process monitoring for quality control is performed in all phases of the operation and includes the following:

- Confirmation of oxidant injection concentration, volumes, and flow rates;

**Table 3. NCP Comparison Summary**

| Description   | Selected Remedial Alternative in 2005<br>ROD for Phase IIB, Lower RGA <sup>a</sup>  | Recommended 2011 Alternative for Phase<br>IIB, Lower RGA  |
|---|---|---|
|   | Electrical Resistance Heating   | Staged Implementation of<br>Baseline/Rebound Analysis and <i>In Situ</i><br>Chemical Treatment  |
| <b>1. Overall Protection of Human Health and Environment</b>    | Alternative meets the threshold criterion of overall protection of human health and the environment when combined with restrictions on groundwater use.   | Alternative meets the threshold criterion of overall protection of human health and the environment when combined with restrictions on groundwater use.   |
| <b>2. Compliance with ARARs</b>                                 | Alternative meets location-specific, chemical-specific, and action-specific ARARs, except for the requirement to achieve MCLs for applicable VOCs. Additionally, the alternative is an interim remedial action, which is part of the total GWOU remedial action that will result in attaining ARARs.  | Alternative meets location-specific, chemical-specific, and action-specific ARARs except for the requirement to achieve MCLs for applicable VOCs. Additionally, the alternative is an interim remedial action, which is part of the total GWOU remedial action that will result in attaining ARARs. |
| <b>3. Long-Term Effectiveness and Permanence</b>                | Alternative meets the criterion because implementing it will lessen the time to complete remediation by treatment of VOC contamination in the lower RGA at C-400. If the significant enhancements identified as a result of Phase I lessons learned are incorporated, the level of effectiveness would be expected to improve as compared to that provided by the Phase I design. | Alternative meets the criterion because implementing it will lessen the time to complete remediation by treatment of VOC contamination in the lower RGA at C-400.   |
| <b>4. Reduce Toxicity, Mobility or Volume Through Treatment</b> | Alternative provides treatment of contaminants following removal by vapor extraction system and groundwater removal.  | Alternative provides treatment of contaminants by surface treatment following groundwater extraction and <i>in situ</i> treatment utilizing chemicals.  |
| <b>5. Short-term Effectiveness</b>                              | Alternative prevents exposure to contaminated groundwater through the use of LUCs. It also reduces mass of VOC source in the RGA by removal and treatment. The technology could result in an increase in risk to the on-site worker from exposure during construction and treatment operations; however, risks are manageable by adherence to health and safety requirements.     | Alternative prevents exposure to contaminated groundwater through the use of LUCs. It also reduces mass of VOC source in the RGA by removal and treatment and by <i>in situ</i> treatment.  |

**Table 3. NCP Comparison Summary (Continued)**

| Description                    | Selected Remedial Alternative in 2005 ROD for Phase IIB, Lower RGA <sup>a</sup>  | Recommended 2011 Alternative for Phase IIB, Lower RGA  |
|--------------------------------|--|--|
|                                | Electrical Resistance Heating  | Staged Implementation of Baseline/Rebound Analysis and <i>In Situ</i> Chemical Treatment   |
| <b>6. Implementability</b>     | Alternative is technically and administratively implementable, but would require changes to the previously completed design based upon results of Phase I and the lessons learned during its implementation. On-site and off-site disposal capacity is available for treatment residuals and secondary wastes. | Alternative is technically and administratively implementable. On-site and off-site disposal capacity is available for treatment residuals and secondary wastes. |
| <b>7. Cost</b>                 | \$18.23M <sup>b</sup>  | \$7.72M  |
| <b>8. State Acceptance</b>     | Alternative was agreed to by the Commonwealth of Kentucky in the 2005 ROD.   | It is anticipated that the Commonwealth of Kentucky will agree to the recommended alternative.   |
| <b>9. Community Acceptance</b> | Alternative was accepted by the Community.   | It is anticipated the community will accept the alternative.   |

<sup>a</sup> Selected Remedial Alternative in 2005 ROD will be implemented for Phase IIA, UCRS, and upper RGA contamination.

<sup>b</sup> Costs for 2005 ROD-selected remedy with enhancements.

**Table 4. Summary of the Comparative Analysis of Alternatives and Rankings**

| Criteria <sup>a</sup>   | Electrical Resistance Heating | Staged Implementation of Baseline/Rebound Analysis and <i>In Situ</i> Chemical Treatment |
|---|-------------------------------|--|
| Overall Protection of Human Health and the Environment        | Yes                           | Yes  |
| Compliance with ARARs   | Yes <sup>b</sup>              | Yes <sup>b</sup>   |
| Long-term Effectiveness                                       | Moderate to High (7)          | Moderate to High (7)   |
| Short-term Effectiveness                                      | Moderate (5)                  | Moderate to High (7)   |
| Reduction in Toxicity, Mobility, and Volume through Treatment | Moderate (5)                  | High (9)   |
| Implementability  | Low (1)                       | Moderate (7)   |
| Cost <sup>c</sup>   | Low (1)                       | Moderate to High (7)   |
| <b>Total of Numerical Ratings</b>                             | <b>19</b>                     | <b>37</b>  |

<sup>a</sup> Modifying criteria include state and community acceptance, which are not included in this analysis.

<sup>b</sup> Although these IRA alternatives are not expected to meet the groundwater MCL for TCE, the alternatives satisfy the requirement set forth in 40 *CFR* § 300.430(f)(1)(ii) for interim measures that will become part of the total remedial action that will attain ARARs for groundwater, including MCLs for TCE, or satisfy the requirements of an ARAR waiver.

<sup>c</sup> A high overall cost rating corresponds to a low project cost relative to the site evaluated.

**Alternative Rating Guide:**

Balancing criteria are scored from 1 (worst) to 9 (best) for each alternative. The qualitative and numerical ratings correspond as follows:

9 – High

7 – Moderate to High

5 – Moderate

3 – Moderate to Low

1 – Low

## HOW DOES DOE CHOOSE A CLEANUP PLAN?

### **Threshold Criteria (standards that must be met for an action to be eligible for selection):**

**(1) Overall protection of human health and the environment.** This criterion requires that the remedial alternative adequately protect human health and the environment, in both the short-term and long-term. The elimination, reduction, or control of unacceptable risks must be demonstrated.

**(2) Compliance with applicable or relevant and appropriate requirements (ARARs).** This criterion specifies that the remedial alternative be assessed to determine if it will comply with ARARs of both state and federal law to the extent practicable. If the action is an interim action, CERCLA requires the action to meet ARARs to the extent practicable.

### **Balancing Criteria (standards for measure of balance between effectiveness and reduction of toxicity, mobility, or volume through treatment; implementability; and cost):**

**(3) Long-term effectiveness and permanence.** This criterion focuses on the level of risk remaining after implementing the remedial alternative and the adequacy and reliability of controls used to manage remaining waste (untreated waste and treatment residuals) over the long-term (i.e., after remedial objectives are met). Remedial actions that produce the highest degree of long-term effectiveness and permanence are those that leave little or no waste at the site, make long-term maintenance and monitoring unnecessary, and minimize the need for institutional controls.

**(4) Reduction of contaminant toxicity, mobility, or volume through treatment.** This criterion evaluates the degree to which the remedial alternative makes use of recycling or treatment to reduce the toxicity, mobility, or volume of the contamination.

**(5) Short-term effectiveness.** This criterion assesses the effect of implementing the remedial alternative relative to the potential risks to the general public, potential threat to workers, potential environmental impacts, and the time required until protection is achieved.

**(6) Implementability.** This criterion evaluates potential difficulties associated with implementing the remedial alternative, including technical feasibility, administrative feasibility, and the availability of services and materials.

**(7) Cost.** This criterion measures the estimated costs of the remedial alternative. Expenditures include the capital cost and annual operation and maintenance costs.

### **Modifying Criteria (standards to address state and community acceptance):**

**(8) State Acceptance.** This criterion provides for consideration of any formal comments on this Revised PP by the Commonwealth of Kentucky.

**(9) Community Acceptance.** This criterion provides for consideration of any formal comments from the community on this Revised PP. Table 3 presents a comparison of the remedial alternatives for the first seven criteria. Criteria 8 and 9 will be evaluated after the public comment period and presented in the “Responsiveness Summary” section of the upcoming Record of Decision Amendment.

- Measurement of oxidant concentrations in groundwater; and
- Measurement of oxidant persistence.

### **COMMUNITY PARTICIPATION**

Community involvement is a critical aspect of the cleanup process at PGDP. DOE, EPA, and Commonwealth of Kentucky encourage the public to read and comment on this Revised PP. Information regarding the proposed action has been presented to the PGDP Citizens Advisory Board. The preferred alternative discussed in this document represents a preliminary decision that is subject to public comment. A Notice of Availability will be published in *The Paducah Sun* announcing the 45-day public review period

for this document. A public comment period will be scheduled after approval of the Revised PP.

A public meeting will be conducted if requested in writing. All comments at the meeting will be recorded. KDEP's Division of Waste Management will conduct a public hearing immediately following the public meeting, if requested. A hearing is a formal gathering during which public comments are recorded officially by a hearing officer (to be designated by KEEC), as required by RCRA and Kentucky Hazardous Waste regulations. Written requests for a public hearing should state the issues to be discussed. If either a meeting or a hearing is requested, a notice will appear in *The Paducah Sun*. To request a public meeting and/or submit comments on this Revised PP, please contact the Paducah DOE Site Office, P.O. Box 1410, Paducah, KY 42001, phone (270) 441-6800.



**This document serves both as a Proposed Plan and as a Statement of Basis.**

To send written comments or obtain further information about this Revised Proposed Plan, contact:

David Dollins  
U.S. Department of Energy  
Paducah Site Office  
P.O. Box 1410  
Paducah, KY 42001  
(270) 441-6800

To send written comments about this Statement of Basis, contact:

Tony Hatton  
Kentucky Department for Environmental Protection  
Division of Waste Management  
200 Fair Oaks Lane, 2<sup>nd</sup> Floor  
Frankfort, KY 40601  
(502) 564-6716

**Administrative Record Availability**

Information about this site considered during the response action determinations for this project, including the Revised Proposed Plan, is available for review at the

DOE Environmental Information Center  
115 Memorial Drive, Barkley Centre, Paducah, KY 42001 (270) 554-6979

Hours: 8:00 A.M. to 12:00 P.M. Monday through Friday  
or at the Web site—<http://www.paducaeic.com>

The Revised Proposed Plan also is available at the  
McCracken County Public Library  
555 Washington Street, Paducah, KY 42001  
(270) 442-2510

Hours: 9:00 A.M. to 9:00 P.M. Monday through Thursday  
9:00 A.M. to 6:00 P.M. Friday and Saturday  
1:00 P.M. to 6:00 P.M. Sunday

\*\*\*

**Regulatory Contacts**

Kentucky Department for Environmental Protection  
Division of Waste Management  
200 Fair Oaks, 2<sup>nd</sup> Floor  
Frankfort, KY 40601-1190  
Attention: Edward Winner  
(502) 564-6716

(Record reviews at the Kentucky Department for Environmental Protection are by appointment only.)

United States Environmental Protection Agency  
61 Forsyth Street, S.W., Atlanta, GA 30303-8960  
Attention: Turpin Ballard (4 WD-FFB)  
[ballard.turpin@epa.gov](mailto:ballard.turpin@epa.gov)  
(404) 562-8550

The ROD and the proposed modification to the Kentucky Hazardous Waste Management Permit will be made available at the Environmental Information Center and at the Paducah Public Library after they have been signed by the United States Department of Energy, the United States Environmental Protection Agency, and the Kentucky Department for Environmental Protection.

*The United States Department of Energy, the United States Environmental Protection Agency, and the Kentucky Energy and Environment Cabinet do not discriminate upon the basis of race, color, national origin, sex, age, religion, or disability in the provision of services. Upon request, reasonable accommodations will be provided. These accommodations include auxiliary aids and services necessary to afford an individual with a disability an equal opportunity to participate in all services, programs, and activities. To request appropriate accommodations for a public hearing or meeting (such as an interpreter) or alternate formats for printed information, contact Matthew Hackathorn at (502) 564-6716 or the LATA Environmental Services of Kentucky, LLC, Public Information Officer at (270) 441-5000.*

**APPENDIX**

**EVALUATION OF THE TECHNOLOGIES AND  
ALTERNATIVES FOR C-400 PHASE IIB,  
REGIONAL GRAVEL AQUIFER,  
AT THE PADUCAH GASEOUS DIFFUSION PLANT,  
PADUCAH, KENTUCKY**

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## ACRONYMS

|            |   |
|------------|---|
| ARAR       | applicable or relevant and appropriate requirement                    |
| ARD        | anaerobic reductive dechlorination                                    |
| CERCLA     | Comprehensive Environmental Response, Compensation, and Liability Act |
| <i>CFR</i> | <i>Code of Federal Regulations</i>                                    |
| CSM        | conceptual site model   |
| DNAPL      | dense nonaqueous-phase liquid   |
| DOE        | U.S. Department of Energy   |
| ERH        | electrical resistance heating   |
| EZVI       | emulsified zero valent iron   |
| FFA        | Federal Facility Agreement  |
| FS         | feasibility study   |
| GAC        | granular activated carbon   |
| GWOU       | Groundwater Operable Unit   |
| H&S        | health and safety   |
| HU         | hydrologic units  |
| IRA        | interim remedial action   |
| ISCO       | <i>in situ</i> chemical oxidation                                     |
| ISRM       | <i>in situ</i> redox manipulation                                     |
| ITR        | independent technical review  |
| KPDES      | Kentucky Pollutant Discharge Elimination System                       |
| LUC        | land use control  |
| LUCIP      | land use control implementation plan                                  |
| NAPL       | nonaqueous phase liquid   |
| NCP        | National Contingency Plan   |
| NOD        | natural oxidant demand  |
| ORP        | oxidation reduction potential   |
| O&M        | operation and maintenance   |
| PGDP       | Paducah Gaseous Diffusion Plant                                       |
| POE        | point of exposure   |
| PPE        | personal protective equipment   |
| RAO        | remedial action objective   |
| RAWP       | remedial action work plan   |
| RDR        | remedial design report  |
| RDSI       | Remedial Design Support Investigation                                 |
| RGA        | Regional Gravel Aquifer   |
| RI         | remedial investigation  |
| ROD        | record of decision  |
| SVE        | soil vapor extraction   |
| TCE        | trichloroethene   |
| TT         | target temperature  |
| UCRS       | Upper Continental Recharge System                                     |
| VOC        | volatile organic compound   |
| WAG        | waste area group  |
| ZVI        | zero valent iron  |



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## EXECUTIVE SUMMARY

This *Evaluation of the Technologies and Alternatives for C-400 Phase IIb, Regional Gravel Aquifer, at the Paducah Gaseous Diffusion Plant, Paducah, Kentucky* has been prepared in support of U.S. Department of Energy (DOE) environmental remediation efforts at the Paducah Gaseous Diffusion Plant in Paducah, Kentucky. A Record of Decision (ROD) for an interim action was signed in August 2005. The *Record of Decision for Interim Remedial Action for the Groundwater Operable Unit for the Volatile Organic Compound Contamination at the C-400 Cleaning Building at the Paducah Gaseous Diffusion Plant, Paducah, Kentucky*, DOE/OR/07-2150&D2/R2, selected electrical resistance heating (ERH) technology to address the source area comprised of trichloroethene (TCE) and other volatile organic compounds (VOCs) found at the C-400 Cleaning Building.

The C-400 Interim Remedial Action (IRA) is being implemented in two phases. Phase I, which concluded in December 2010, addressed the east and southwest treatment areas. DOE evaluated attainment of remedial action objectives (RAOs) in mid-2011 for Phase I operations in the east and southwest treatment areas. The determination was that RAOs were met for the Upper Continental Recharge System (UCRS) and upper Regional Gravel Aquifer (RGA) in these areas. Phase II will address the southeast treatment area. Based on the evaluation of the lessons learned from Phase I performance, it has been determined that, with minor adjustments to the base design, ERH will be successful in removing contaminants in the UCRS. Without extensive changes to the base design, however, lessons learned indicate that ERH will not be effective in the lower RGA. Based on these conclusions, a recommendation has been made to consider splitting Phase II into two separate actions: (1) a UCRS and upper RGA action (Phase IIa) and (2) a lower RGA action (Phase IIb). It is recommended that Phase IIa implement ERH in the C-400 southeast treatment area and that a change be made on the treatment technology for Phase IIb.

This document presents an introduction; a brief summary of lessons learned from Phase I of the C-400 IRA; and identification, preliminary screening, evaluation, development and analysis of other technologies/alternatives that will be effective in remediating the RGA in the southeast treatment area. Attachments include preliminary cost estimates, a mass volume estimate, and applicable or relevant and appropriate requirements (ARARs).

The following technologies are discussed in Table A.ES.1.

**Table A.ES.1. Summary of the Technologies Retained and Screened from Further Consideration**

| TECHNOLOGY                                      | RETAINED FOR<br>CONSIDERATION | SCREENED FROM<br>FURTHER<br>CONSIDERATION |
|---|-------------------------------|---|
| <b>Physical/Chemical Treatment Technologies</b> |                               |   |
| Groundwater Extraction                          | X                             |   |
| Groundwater Recirculation                       | X                             |   |
| Air Sparging                                    |                               | X   |
| Chemical Oxidation/Reduction                    | X                             |   |
| Zero Valent Iron                                | X                             |   |
| Bioremediation                                  |                               | X   |

**Table A.ES.1. Summary of the Technologies Retained and Screened from Further Consideration (Continued)**

| TECHNOLOGY                                      | RETAINED FOR CONSIDERATION | SCREENED FROM FURTHER CONSIDERATION |
|---|----------------------------|-------------------------------------|
| <b>Physical/Chemical Treatment Technologies</b> |                            |                                     |
| Soil Flushing                                   | X                          |                                     |
| <b>Thermal Treatment Technologies</b>           |                            |                                     |
| Electrical Resistance Heating                   | X                          |                                     |
| Steam Injection                                 |                            | X                                   |
| Hot Air Injection                               |                            | X                                   |
| Hot Water Injection                             |                            | X                                   |

The retained technologies listed above then were evaluated in more detail and assembled into potential alternatives for TCE source removal in the RGA. Five alternatives were considered for detailed evaluation: (1) no action; (2) groundwater extraction and *ex situ* treatment; (3) *in situ* chemical oxidation; (4) electrical resistance heating; and (5) staged implementation of baseline/rebound analysis and *in situ* chemical treatment. These five alternatives then were analyzed with respect to the seven CERCLA threshold and balancing criteria. Modifying criteria, which include state and community acceptance, are not included in this analysis. A summary of the comparative analysis is presented in Table A.ES.2.

Overall, Alternative 5 offers a cost-effective solution with comparatively lower project risk than the others. In addition, the expected site conditions in the RGA at the C-400 site are optimal to the technologies that are included in Alternative 5. The saturated permeable conditions present in the RGA would be amenable to *in situ* chemical treatment via injection of a reagent. Alternative 5 will be implemented in two stages:

Stage 1. Establish baseline and rebound conditions; and

Stage 2. Implement *in situ* chemical treatment through focused delivery of an appropriate amendment (e.g., potassium permanganate oxidant, and monitoring).

Information gained during Stage 1 of Alternative 5, groundwater extraction and rebound analysis, will mitigate the risks associated with the uncertainty of TCE source mass distribution in the RGA prior to *in situ* chemical treatment.



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## A.1. INTRODUCTION

This document evaluates technologies and identifies alternatives for remediation of residual sorbed trichloroethene (TCE) mass and dense nonaqueous-phase liquid (DNAPL) in the lower Regional Gravel Aquifer (RGA) in the Phase IIb treatment area. This evaluation includes a brief summary of lessons learned from Phase I of the C-400 Interim Remedial Action (IRA); identification, preliminary screening, evaluation, development, and analysis of other technologies/alternatives that will be effective in remediating the RGA in the southeast treatment area; preliminary costs estimates; a mass volume estimate for the Phase II area; and applicable or relevant and appropriate requirements (ARARs). A thorough description of the background information for the project is presented in the *Technical Performance Evaluation for Phase I of the, C-400 Interim Remedial Action, at the Paducah Gaseous Diffusion Plant, Paducah, Kentucky*, DOE/LX/07-1260&D1 (Technical Performance Evaluation) (DOE 2011a).

### A.1.1 DOCUMENT ORGANIZATION

This evaluation of technologies and alternatives is organized as follows:

- Section A.2—discusses lessons learned that were identified as part of the Phase I operations in the east and southwest treatment areas and provides updated information relative to the conceptual site model.
- Section A.3—identifies and screens remedial technologies that potentially could be implemented for Phase IIb of the C-400 IRA.
- Section A.4—presents an evaluation of the disadvantages and advantages associated with technologies retained from Section 3.
- Section A.5—describes five remedial alternatives assembled from the retained technologies.
- Section A.6—presents an analysis of the alternatives with respect to the seven Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) threshold and balancing criteria.

### A.1.2 BACKGROUND

A Record of Decision (ROD) for an interim action was signed in August 2005. The *Record of Decision for Interim Remedial Action for the Groundwater Operable Unit for the Volatile Organic Compound Contamination at the C-400 Cleaning Building at the Paducah Gaseous Diffusion Plant, Paducah, Kentucky*, DOE/OR/07-2150&D2/R2, selected electrical resistance heating (ERH) technology to address the source area comprised of TCE and other volatile organic compounds (VOCs) found at the C-400 Cleaning Building. Figure A.1 shows the location of the C-400 Cleaning Building within the Paducah Gaseous Diffusion Plant (PGDP) complex. In accordance with the Remedial Design Report (RDR) (DOE 2008) and Remedial Action Work Plan (RAWP) (DOE 2011b) for this project, a phased deployment of ERH was to be implemented. Phase I and II treatment areas are shown on Figure A.2.

Phase I, completed in December 2010, required the implementation of the design presented in the RDR (DOE 2008), referred to as the base design, in the southwest and east treatment areas of C-400 Cleaning Building. The RAWP (DOE 2011b) was utilized during Phase I. Phase I involved the removal of

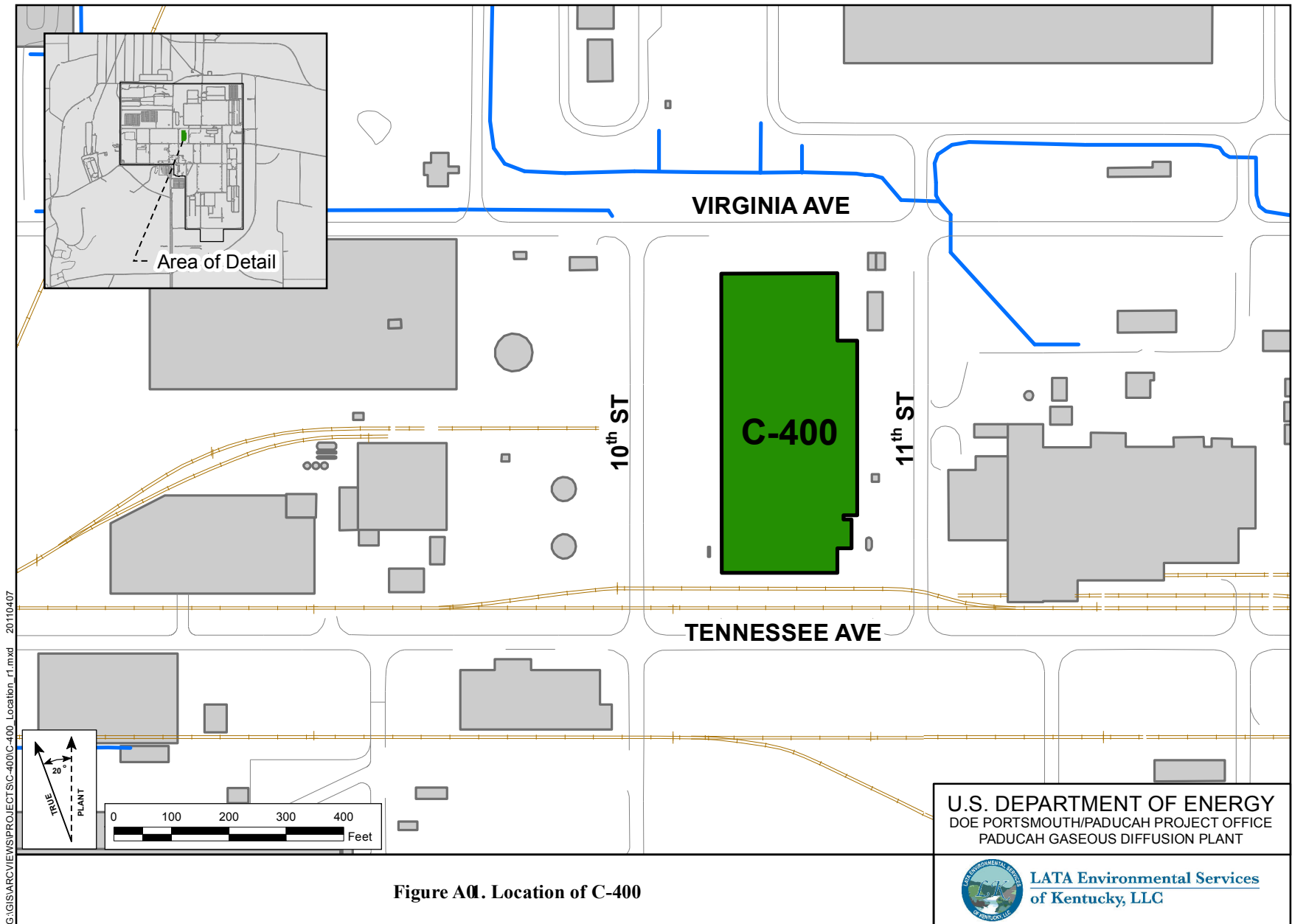


Figure A01. Location of C-400

U.S. DEPARTMENT OF ENERGY  
DOE PORTSMOUTH/PADUCAH PROJECT OFFICE  
PADUCAH GASEOUS DIFFUSION PLANT



LATA Environmental Services  
of Kentucky, LLC

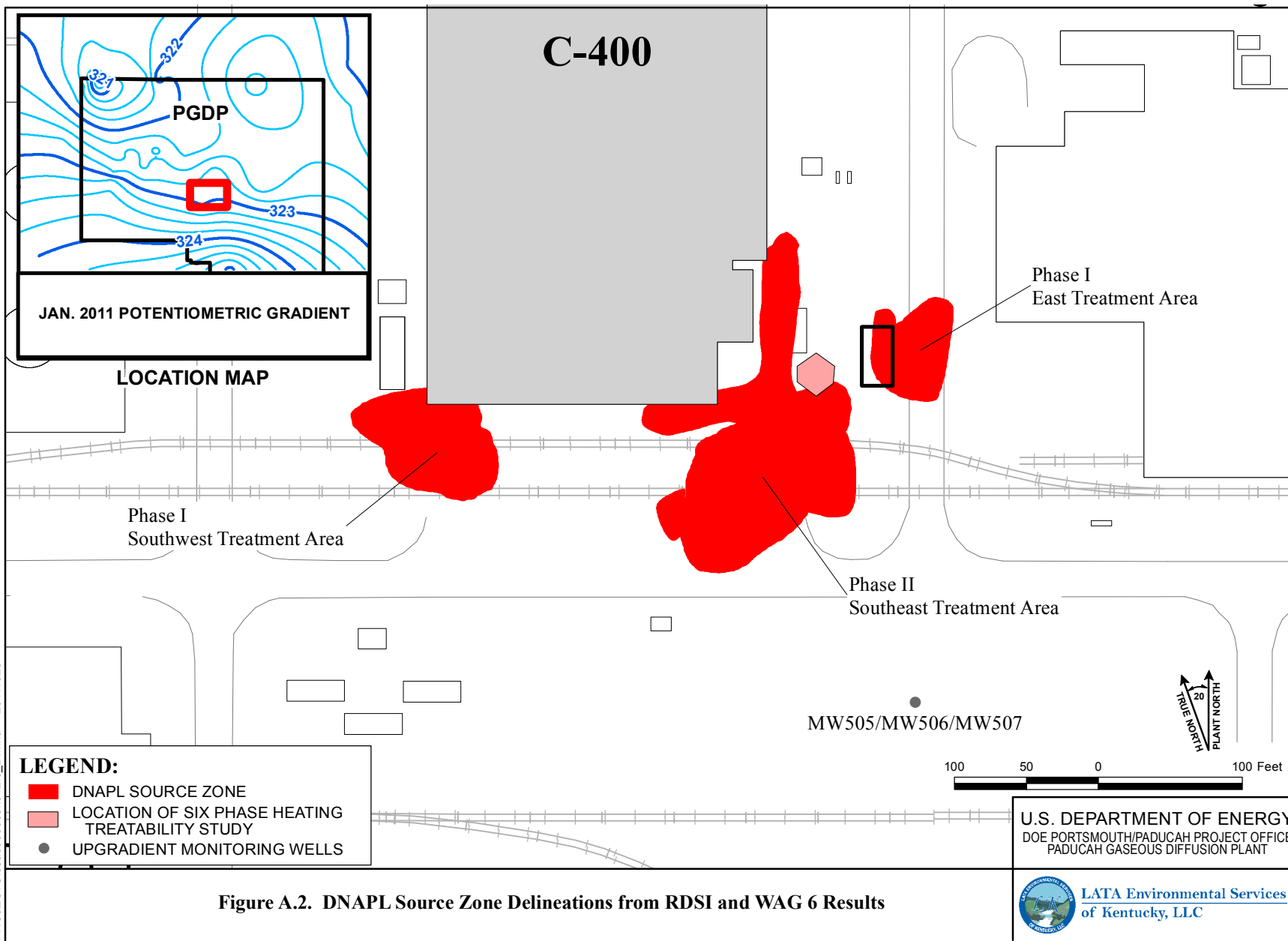


Figure A.2. DNAPL Source Zone Delineations from RDSI and WAG 6 Results

PROJECT/c5ac90005sk012r9\_D.mxd 20111026



contaminants only in the Upper Continental Recharge System (UCRS) of these treatment areas. Phase I, however, included another important objective: to evaluate the heating performance of the ERH base design through the RGA down to the McNairy Formation interface in the southwest treatment area. Lessons learned from Phase I were to be evaluated and appropriate contingency actions implemented prior to start up of the second phase. A thorough description of the background information and performance of Phase I is presented in the Technical Performance Evaluation (DOE 2011a).

According to the current RDR and RAWP, Phase II requires the implementation of ERH technology near the southeast corner of the C-400 Cleaning Building. This phase would include removal of contaminants from the southeast treatment area in both the UCRS and RGA. Based on the evaluation of the lessons learned from the Phase I performance, it has been determined that, with minor adjustments to the base design, ERH will be successful in removing contaminants in the UCRS and upper RGA. Lessons learned, as summarized in Section 2 of this document however, indicate that without extensive changes to the base design, ERH will not be effective in the lower portions of the RGA. Based on these conclusions, the DOE is recommending to the Federal Facility Agreement (FFA) parties that Phase II be split into two actions:

- (1) A UCRS and upper RGA action (Phase IIa) using ERH and
- (2) A lower RGA action (Phase IIb) using an alternate technology.

## **A.2. PHASE I LESSONS LEARNED**

Although the remedial goals for the east and southwest treatment areas were achieved, efficiencies and uncertainties were identified that resulted in lessons learned. The following section discusses lessons learned that were identified as part of the Phase I operations in the east and southwest treatment areas. In addition, Phase I operations and subsequent Phase II data collection efforts during early 2011 provided information that is being used to update the conceptual site model (CSM).

### **A.2.1 PHASE I ERH PERFORMANCE**

Phase I ERH operations started on March 29, 2010, and were completed on December 9, 2010. The U.S. Department of Energy (DOE) evaluated attainment of remedial action objectives (RAOs) in mid-2011 for Phase I operations in the east and southwest treatment areas. The determination was that RAOs were met for targeted source material in the UCRS and upper RGA in Phase I treatment areas.

Another important objective of Phase I was to evaluate the heating performance of the base design, as defined in the RDR (DOE 2008) through the RGA down to the contact with the McNairy Formation in the southwest treatment area. Treatment in the east treatment area involved only the UCRS. Temperature goals were not achieved in the lower RGA in the southwest treatment area during Phase I operations with the electrodes installed according to the base design (in the RGA below ~ 70 ft bgs). A thorough description of the Phase I performance and lessons learned is included in the Technical Performance Evaluation (DOE 2011a).

A significant finding and lesson learned associated with Phase I of the C-400 IRA concerns the heating of the RGA to target temperature for volatilizing the VOCs. In large part, the challenge posed regarding heating of the lower RGA is related to the inherent uncertainty regarding characterization of groundwater velocity and the potential for heat-induced convective velocity (convective flow) in the RGA. A model-based calculation of horizontal groundwater velocity predicted the velocity to be approximately 3.0 ft per day in the middle and lower RGA (see Appendix A of the Technical Performance Evaluation, DOE 2011a). An additional challenge with depth is the fact that the target temperature (TT) at the potentiometric surface at ~ 53 ft bgs is 87°C (189°F), but increases to 115°C (239°F) at 98 ft bgs. The ERH technology relies on vaporization for removal of VOCs; therefore, if the TT is not attained, the technology is ineffective.

Phase I operating experience in the southwest treatment area and subsequent modeling results using a groundwater velocity of 3.0 ft per day indicate that the ERH installation would require significant scale up to achieve target temperatures in the RGA. This scaled-up model-based design for heating the RGA calls for more borings and more electrodes and also would require upgradient electrode borings for preheating and upgradient groundwater extraction to reduce the flux of groundwater through the target volume. The model-based design simulated RGA electrodes, which would be surrounded by a high conductivity graphite material, would be operated at higher voltage levels than during Phase I, and would receive continuous saltwater injections. Additionally, the ERH subcontractor suggests augmenting the heating by providing hot water injection at the electrodes.

Based on the Phase I experience and results, ERH should be deployed in the UCRS soils of the southeast treatment area. Lessons learned during Phase I relative to RGA heating identified the following observations for consideration as part of the determination of a path forward for Phase II and associated design development.

- The range of groundwater velocity in the formation and potential for heat-induced velocity (convective flow) are considered to be a substantial contributing factors in the inability to attain target temperature in the RGA.
- Utility and building operations avoidance posed more significant coordination challenges than originally assumed and additional logistical challenges would be posed as part of Phase II based on the greater boring density that would be necessary for heating the RGA.
- The RGA has a naturally high resistance to the flow of electrical current, leading to difficulty in attaining target temperatures and requiring contingency actions such as additional power and saltwater injection to improve electrical conductivity.
- Continuous saltwater injection at the RGA electrodes would be required. The viability of continuous saltwater injection to increase formation electrical conductivity has not been tested.
- Phase I failed to attain target temperatures. In fact, the temperatures attained were nominally 100°F below the TT required for volatilization in the lower RGA.

These considerations, as well as the fact that thermal technologies are ineffective if target temperatures are not attained, decrease the probability of success and support the need to evaluate alternative technologies or combinations of technologies to identify a remedy that is a better suited to treat the RGA.

DOE chartered a team of subject matter experts to evaluate the Phase I performance, Phase II numerical simulation study, and potential design. The review was conducted in August and September of 2010 and the final report, *Independent Technical Review of the C-400 Interim Remedial Project Phase I Results, Paducah, Kentucky* was completed in October 2010 and provided to the FFA parties (DOE 2010). Following is a summary of the Independent Technical Review (ITR) Team's conclusions and recommendations.

- “ERH (or any of the other thermally enhanced removal technologies) is poorly matched to the RGA conditions in the vicinity of the C-400 building—The ITR recommends that heating technology be eliminated from Phase II for this particular zone. Instead, the ITR recommends that the PGDP project team and their regulators and stakeholders, address the TCE source in the RGA using a technology that is better matched to the RGA target zone—one that will lead to better performance, lower costs, reduced collateral impacts (e.g., energy use), reduced drilling, etc.
- “Specific technologies that take advantage of high permeability saturated RGA conditions include: oxidation using chemical reagents, solubilization using cosolvents or surfactants, and others. The ITR recommends identification and implementation of a more appropriate technology for addressing the Phase II RGA TCE source material.
- “UCRS and uppermost RGA (50 to 70 ft depth) were heated to the target temperature and the gas phase concentration and mass removal decreased over time stabilizing at relatively low levels (i.e., “asymptosis”). If confirmatory borings in the UCRS indicate significant TCE source reduction, then Phase I can be considered successful in achieving the regulatory/technical objectives in this zone.
- “Temperature goals were generally not achieved in the RGA (particularly in the deep RGA from 70 to 100 ft depth) during Phase I. The data confirm that in a high permeability—high flow aquifer, thermal remediation is inefficient as a significant proportion of the applied energy was lost from the target zone.

- “Application of a simplified scoping model/calculation to predict ambient groundwater velocities in the RGA from Phase I field temperature data was not valid.
- “The modifications for Phase II that were indicated by the modeling (more electrodes, closer spacing, upgradient water extraction, higher voltages, higher water and vapor extraction, injection of preheated water, increased saline injection, etc.) would potentially increase costs dramatically for Phase II.”

## **A.2.2 UPDATE OF CONCEPTUAL SITE MODEL**

It is prudent to continue to update the CSM from initial identification through the remedial action for any site adjusts as additional data become available. The initial CSM developed during the remedial investigation (RI) for Waste Area Group (WAG) 6 postulated a release from the TCE supply tank pipeline and additional loss at the loading area based on reported releases from C-400 sump pump discharges in 1970-1980. Figure A.3 shows the C-400 Cleaning Building, former location of the TCE supply tank, pipeline, loading area, and an outline of six-phase heating treatability study area. The pipeline was replaced during the operating history of the TCE supply tank. The initial assessment with process knowledge, but with limited data, anticipated significant quantities of TCE released to the environment. The six-phase heating treatability study (2003), in the vicinity of the pipeline leak, conducted ERH and removed an estimated 1,900 gal ( $\approx$  23,000 lb at 12.2 lb per gal) of TCE. These data along with the membrane interface probe investigation resulted in an estimate of 75,000 gal ( $\approx$  915,000 lb) of TCE in the subsurface in the vicinity of the southern part of C-400 (DOE 2008).

This conceptual understanding then was modified with the implementation of the Phase I ERH, which recovered approximately 580 gal ( $\approx$  7,000 lb) of TCE from the southwest and east areas within the UCRS. An estimate, based on the CSM, anticipated approximately 23,000 gals ( $\approx$  280,000 lb) of TCE in the Phase I areas. This discrepancy in mass led to the reevaluation and update of the CSM. This section discusses a further evaluation of the CSM including geologic structure, refining the mass estimate, and attempting to further understand the anticipated DNAPL. The revised CSM then is used to help guide the decisions for remedial alternatives to address the contamination.

### **A.2.2.1 Key Site Characteristics**

Key characteristics of the C-400 CSM include:

- The origin of the TCE in the subsurface is postulated to be from TCE pipeline leak(s) and spills at the loading point. The six-phase heating treatability study was implemented in close proximity to the area of the former pipeline leak and recovered an estimated 1,900 gal ( $\approx$  23,000 lb) of TCE from the UCRS and upper RGA.
- The TCE release traveled vertically through the UCRS as DNAPL due to its density and the porous permeable character of the surface and near surface sediments and construction backfill in this area. When encountering a less permeable lense (e.g., clay), the DNAPL would travel laterally until encountering a discontinuity in that lense and then resume its downward migration.
- Over time the DNAPL in the UCRS continues to dissolve into the water phase with subsequent infiltration events (precipitation or plant line losses) resulting in dissolved phase transport of TCE into the RGA.

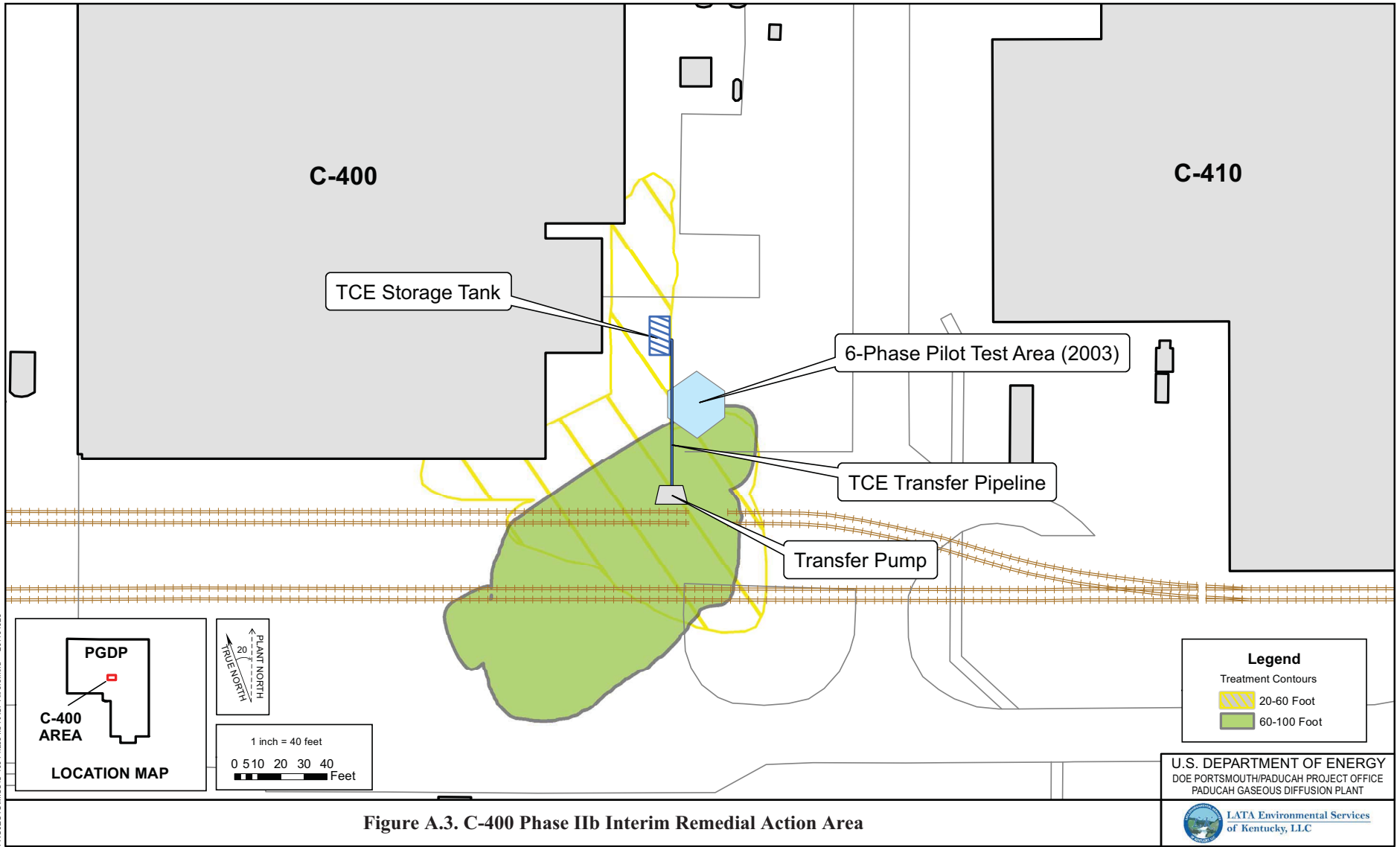


Figure A.3. C-400 Phase IIb Interim Remedial Action Area

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- As the DNAPL disperses laterally in the finger grained sediments of the upper RGA, fine-grained zones may retain residual DNAPL.
- In the gravelly (more permeable) RGA, the DNAPL may be dispersed in the groundwater, may be transported vertically as DNAPL, or may be present as residual DNAPL in the form of disconnected blobs and ganglia trapped by the capillary forces in the pore spaces (EPA 2009).
- If the DNAPL had sufficient mass for continuous interconnection, it would continue traveling vertically through the permeable RGA until it reaches a tighter matrix (i.e., McNairy) where it may pool. In the absence of significant depression in the top of the McNairy, pooling would be limited to a thickness of 3 cm (McConnell and Numbere 1995).

The current observed concentrations of TCE in the RGA could be from a continuing release from the UCRS, from DNAPL pooled in segments of the RGA, from discrete DNAPL ganglia, or from residual sorbed mass on the soil matrix.

Figure A.4 provides a conceptualization of the CSM. Although some uncertainty remains, the level of understanding of the TCE migration routes and current mass present can be bracketed sufficiently to select a remedial alternative. For example, the ERH technology selected for Phase IIa is independent of the mass present, so the refinement of the mass in the UCRS does not change the approach. For the lower RGA, bracketing the mass estimate is sufficient to select an alternative.

#### **A.2.2.2 Structural Controls on Contaminant Transport**

Based on the concept that the DNAPL would travel vertically through a permeable geologic unit and then horizontally when encountering a tighter (clay or silt unit), it is important to refine the geologic stratigraphic mapping. Through convention, the site has been mapped with six hydrologic units (HUs) at the site:

- HU1—surface fill and loess
- HU2 and HU3 UCRS
  - HU2—sand and silt with occasional gravel
  - HU3—silty and sandy clay, semi-confining aquitard
- HU4 and HU5—RGA
  - HU4—fine-grained sand cap layer of RGA, not laterally continuous
  - HU5—dominant gravel aquifer
- HU6—McNairy Formation: silty clay, tight, basal aquitard

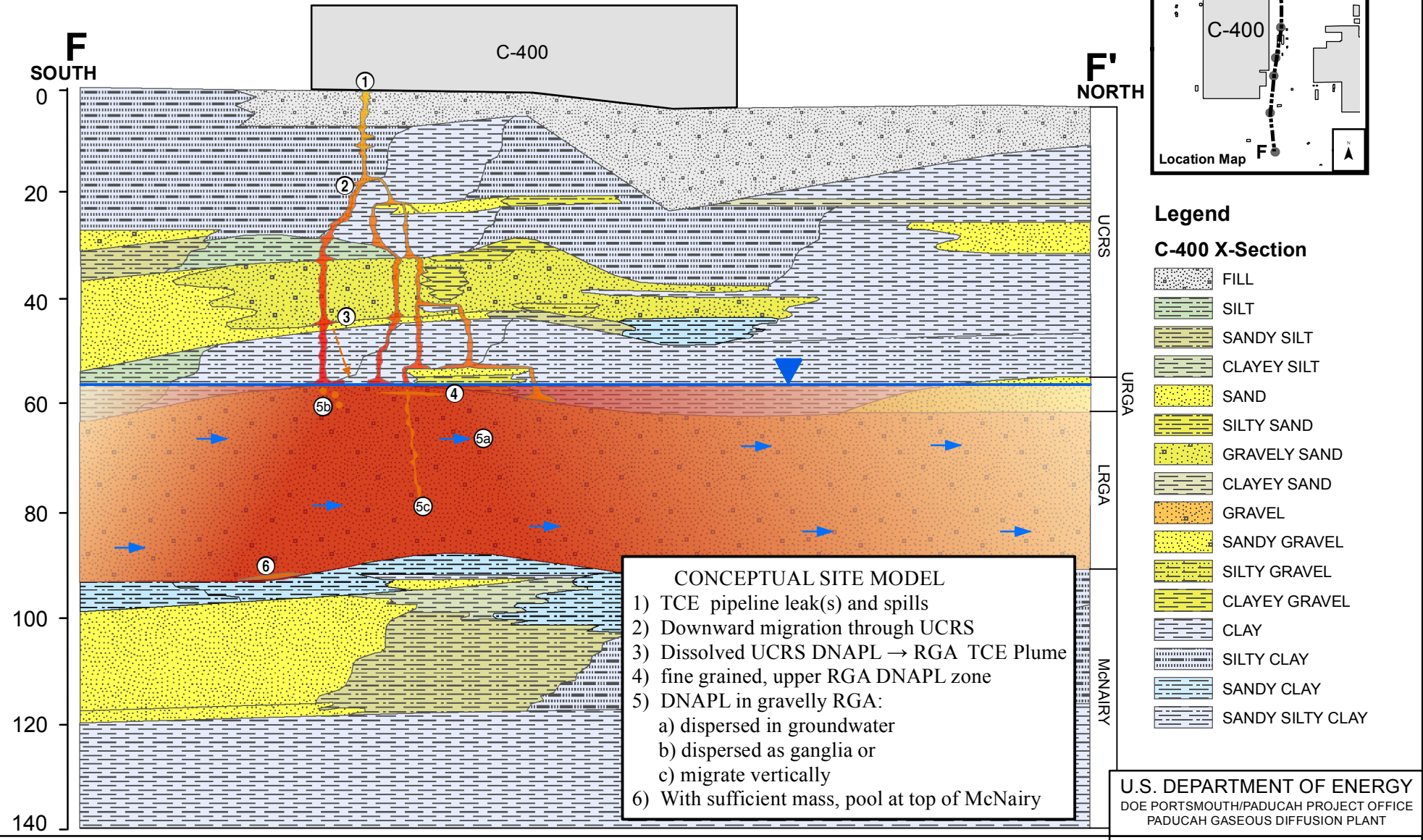


Figure A.4. C-400 Conceptual Site Model Cross-section View

Using information generated from 50 borings in the vicinity of the Phase II treatment area (including the WAG 6 RI (in 1997), Six-Phase Heating Treatability Study (in 2003), C-400 Phase I Remedial Design Support Investigation (RDSI) (in 2006), and confirmation borings from C-400 Phase 1 (in 2011)], the stratigraphic units were refined. Figure A.5 provides a 3-dimensional view (looking north) of the different HUs. Some observations of the structure are as follows:

- The HU layers undulate (notable amounts of relief displayed on the HU2 through HU6 surfaces).
- The HU3 has a linear depression or trough directly beneath the pipeline loading point. A trough structure in the HU3 may represent a point of accumulation for residual DNAPL.
- The HU4 is absent in some areas, specifically directly below the pipeline loading point. The windows through HU4 provide a direct conduit for the vertical migration of DNAPL from the UCRS into the HU5 aquifer.
- The structural top of HU6 (McNairy) is an erosional surface and displays scour and channel features.

Figure A.6 provides a conceptual presentation of the hand contoured 1,000 µg/kg TCE mass contours superimposed on this structural geologic model. Following are some observations.

- The current mass is greater below the repaired pipeline. The mass is less dispersed in the UCRS.
- The TCE footprint is larger in the RGA. The larger area of contamination in the RGA is presumed to be due to greater dispersion with depth within these more permeable aquifer sediments.

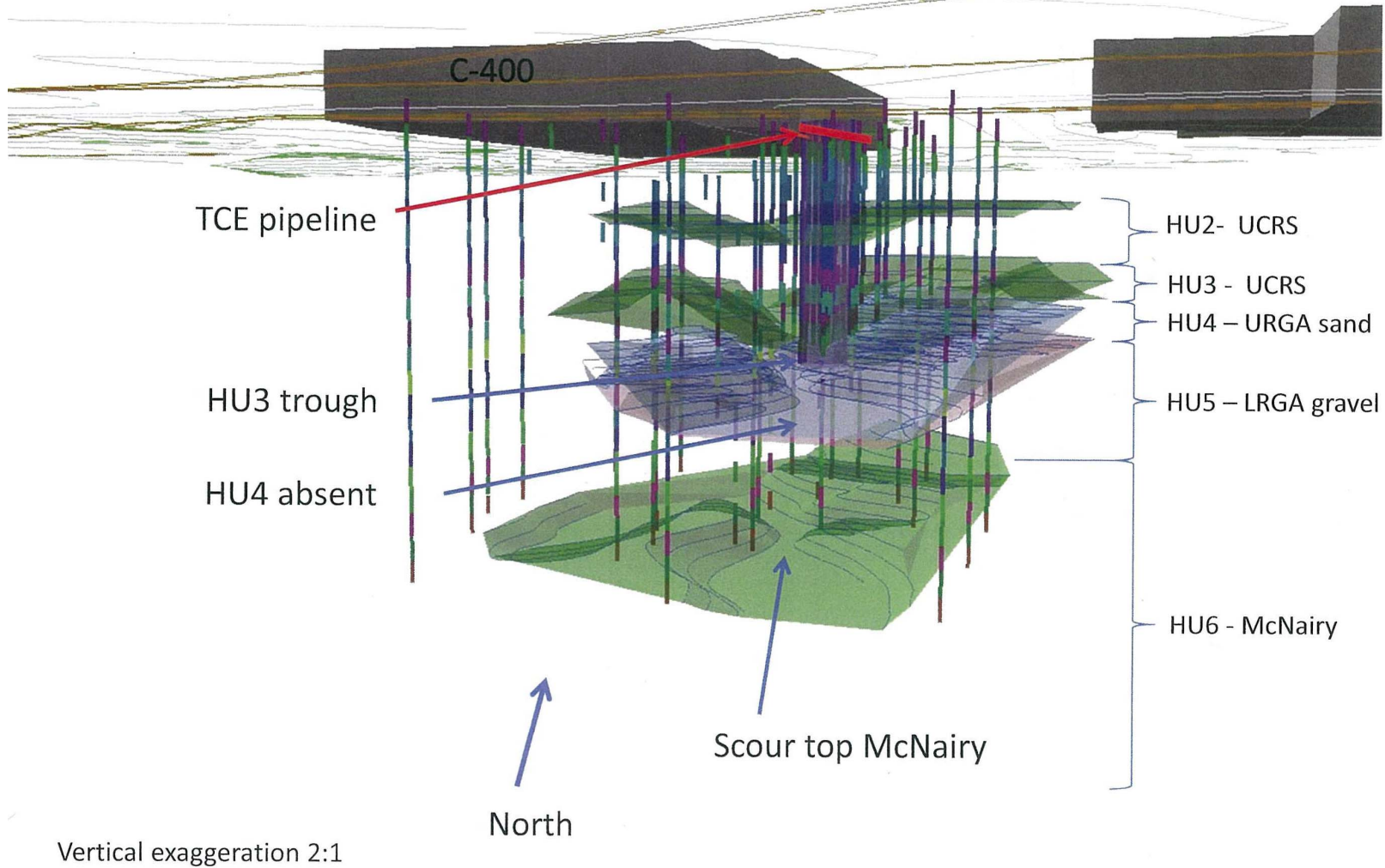
#### **A.2.2.3 Mass Volume Estimate**

DOE evaluated the mass volume of the Phase II area based on the analyses of soil samples obtained during the field characterization effort conducted in early 2011 to refine the CSM and support the basis of technology identification and selection. Three approaches were used to assess TCE mass volume for the treatment area and determined that a reasonable estimate of the range of TCE mass remaining in the Phase II treatment area is between 600 and 7,000 gal. The TCE mass volume estimate calculations are documented further in Attachment A2. Summary findings are provided here. The lower end of the range of the estimate, 600 gal ( $\approx$  7,300 lb), is based on soil and groundwater samples collected to date (including the WAG 6 RI, the Six-Phase Heating Treatability Study, and additional data collected in 2011). The higher end of the range of the estimate includes observation of TCE in groundwater and assumptions of potential DNAPL occurrence that, although not encountered in the samples collected to date, are considered to be representative of conditions based on the site conceptual model. These observation and assumptions include the following:

- Persistent TCE mass flux associated with the Northwest Plume (approximately 4,000 lbs/330 gal per year for as long as 50 years),
- Past recovery of DNAPL from MW408, which is located in the SE treatment area, and
- The knowledge that DNAPL distribution in subsurface environments is typically heterogeneous and difficult to characterize using conventional sampling techniques.



# Subsurface View of C-400 Looking North



A-24

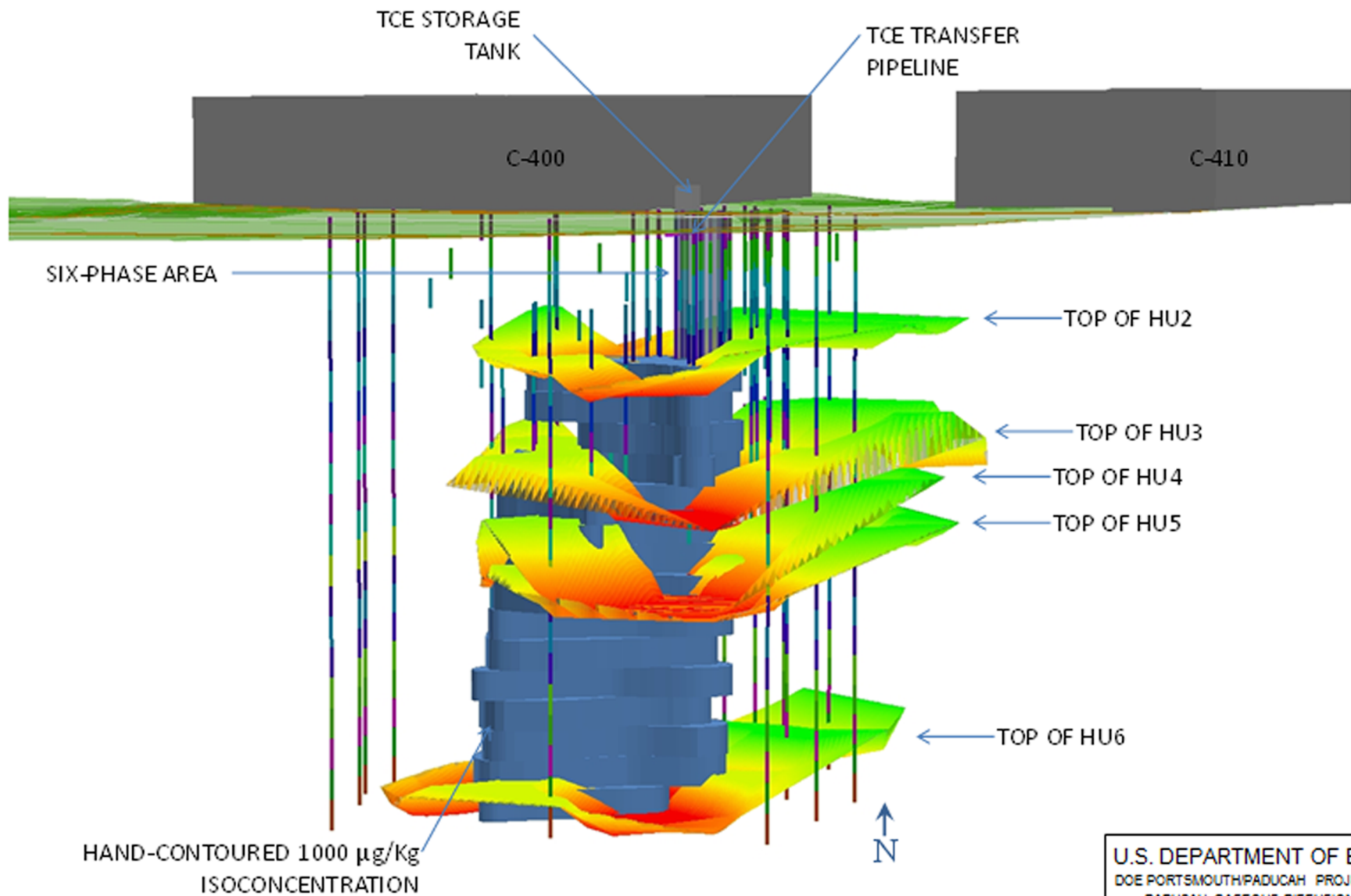
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Figure A.5. C-400 Area Hydrologic Units



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# C-400 3-D DISPLAY



HAND-CONTOURED 1000  $\mu\text{g}/\text{Kg}$   
ISOCONCENTRATION

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Figure A.6. C-400 Conceptual TCE Mass Displayed within the Geologic Subunits

A breakdown of DNAPL mass volume in the UCRS and RGA is as follows:

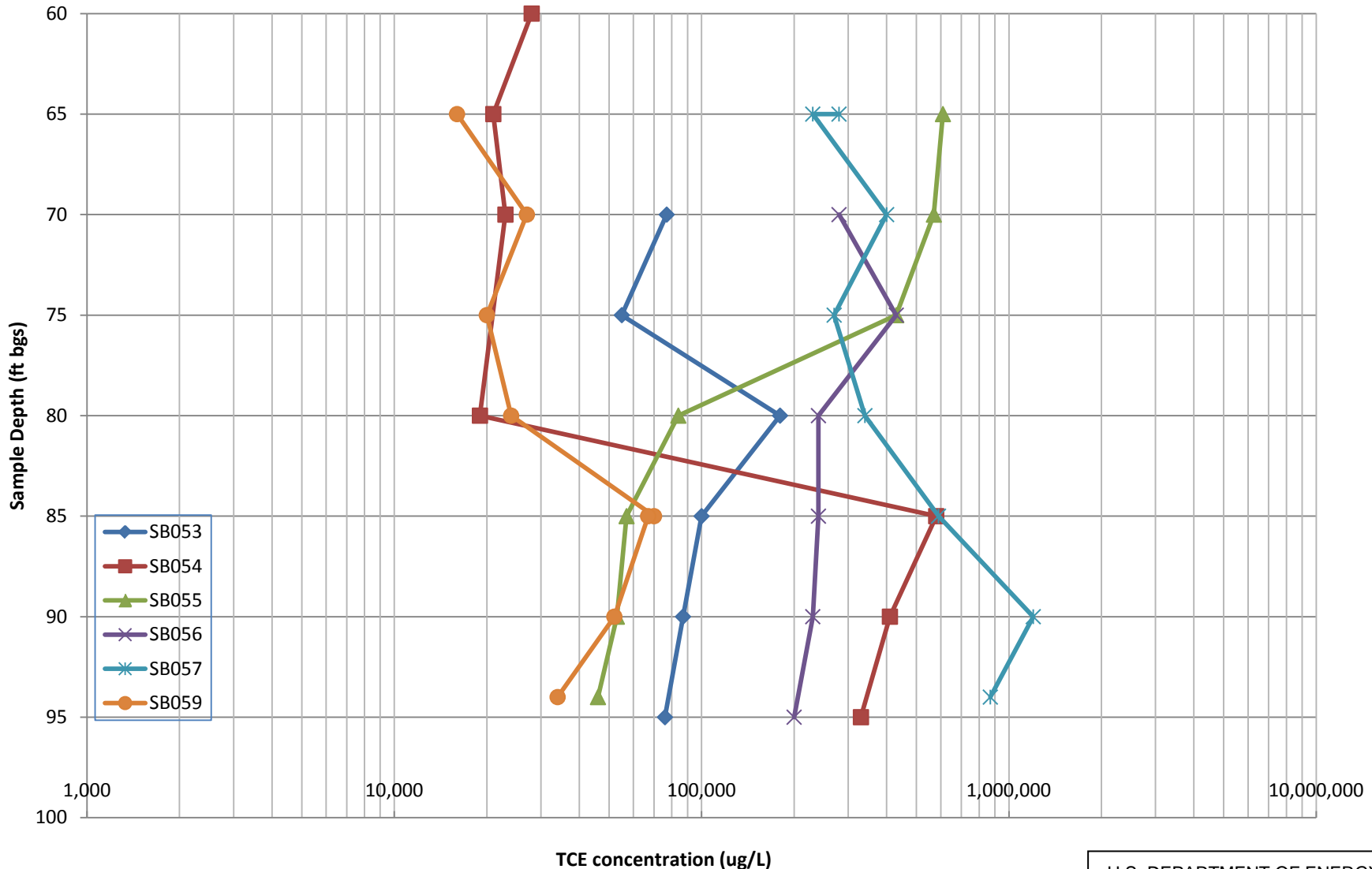
- For the interval 0 to 60 ft bgs, which is primarily the UCRS, the estimate is 290 to 30,500 lbs (24 to 2,500 gal).
- For the interval 60 to 100 ft bgs, which is the RGA, the estimate is 7,000 to 55,000 lbs (576 to 4,500 gal).

Figure A.7 presents the results of depth discrete water samples collected during the 2011 investigation. There were 6–8 discrete vertical samples (within the RGA from 65 to 95 ft bgs) collected in each of the 6 borings (SB53 to SB59) within the Phase II treatment area. Figure A.7 displays the results of discrete vertical groundwater samples collected from the six borings. Note that the concentrations are presented on a log scale. The data indicate the following:

- The range of values for all samples indicates groundwater that is impacted by DNAPL.
- The profile for SB55 has higher concentrations of TCE in the upper portion of the formation, which is potentially indicative of discrete accumulations of DNAPL ganglia or pooled DNAPL in the lower UCRS/upper RGA.
- SB54 and SB57 reflect higher concentrations of TCE in the lower portions of the formation which is potentially indicative of discrete accumulations of DNAPL ganglia or pooled DNAPL in the lower RGA.
- TCE concentrations in water samples from SB53, SB56, and SB59 generally are similar throughout the profile, which potentially is indicative of dispersed DNAPL ganglia throughout the RGA.

These observations are consistent with the CSM and provide support for the assumptions that were used to develop the higher end of the range of the mass volume estimate.

## C-400 TCE Concentrations vs Depth (depth discrete water samples Phase II)



A-27

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## **A.3. IDENTIFICATION AND PRELIMINARY SCREENING OF TECHNOLOGIES**

The following section identifies and screens remedial technologies that potentially could be implemented for Phase IIb of the C-400 IRA. The technology identification and screening provided in this document is consistent with and expands upon the assessment presented in the *Feasibility Study for the Groundwater Operable Unit at the Paducah Gaseous Diffusion Plant, Paducah, Kentucky*, DOE/OR/07-1857&D2 [hereafter referred to as the Groundwater Operable Unit Feasibility Study (GWOU FS)] (DOE 2001). A review of the GWOU FS has determined that refinement of the technology analysis based on CERCLA balancing criteria with respect to Phase IIb of the C-400 IRA is warranted. ERH has been carried through technology and alternative development and evaluation in order to provide a comparative evaluation of the initial proposed remedy and the revised treatment strategy developed in response to Phase I operating experience with ERH heating in the lower RGA.

### **A.3.1 LAND USE CONTROL TECHNOLOGIES**

Land use controls (LUCs) have been implemented during Phase I of the C-400 IRA. These controls will remain in place during Phase II and will be implemented in conjunction with the selected remedial alternative for Phase IIb. These controls are described in detail in Appendix H of the C-400 RDR (DOE 2008).

### **A.3.2 PHYSICAL/CHEMICAL TREATMENT TECHNOLOGIES**

Physical/chemical technologies are evaluated for potential applicability for treatment of TCE contamination within the RGA at the C-400 IRA project site. The technologies considered include several options that could be combined to form potential surface treatment alternatives or *in situ* treatment alternatives. Physical/chemical technologies include the following:

- Groundwater extraction
- Groundwater recirculation
- Air sparging
- Chemical oxidation/reduction
- Zero Valent Iron
- Bioremediation
- Soil flushing

#### **A.3.2.1 Groundwater Extraction**

Groundwater extraction often is used to remediate dissolved-phase contaminants and/or to contain contaminants hydraulically. Dissolved-phase VOC contamination is remediated via extraction and *ex situ* treatment. *Ex situ* VOC treatment technologies often include an air stripper and granular activated carbon (GAC) vessels. The extracted groundwater is routed through the surface treatment system and then discharged to an appropriate outfall, or be reinjected as a form of hydraulic containment of groundwater contamination. Hydraulic containment is used to control the movement of contaminated groundwater and prevent the continued expansion of the contaminated zone (EPA 1996). Capture zone analysis, optimization modeling, and data from existing monitoring wells often is used to identify the optimal locations for proposed groundwater extraction and injection wells. Phased extraction rates and operation

of individual wells can be used to enhance containment, avoid stagnation zones, and ensure removal of the most contaminated groundwater (EPA 1996).

Groundwater extraction often is coupled with other technologies to enhance contaminant removal. Variations and enhancements can include hydraulic fracturing or chemical/biological enhancements.

This technology is technically implementable within the RGA, commercially available, and is retained for further evaluation.

### A.3.2.2 Groundwater Recirculation

Groundwater recirculation can be divided into two general categories: (1) vertical recirculation with *in situ* treatment or (2) close-coupled extraction and reinjection with aboveground treatment. Vertical recirculation is a treatment technique that uses in-well or *ex situ* air stripping of contaminated VOCs, while close-coupled extraction and injection is a delivery mechanism that can be used in conjunction with treatment amendments.

**Vertical Recirculation.** Vertical recirculation systems extract, treat, and reinject groundwater within the same well. Treatment is considered *in situ* because the water is drawn into the well, stripped of VOCs using an air injection blower, and reintroduced into the aquifer, without extracting the groundwater to the surface for treatment. Vertical recirculation wells are double-cased with upper and lower screened intervals that are separated hydraulically via a packer. The typical well configuration utilizes an air injection blower to introduce air into the inner casing. The rising bubbles lower the density of the groundwater causing it to rise and transfer contamination from the dissolved phase to the vapor phase. This type of configuration often is referred to as an airlift recirculation well and is similar to the oil industry gas lift process. Contaminated vapors then can be extracted and treated using an aboveground system (e.g., vapor-phase carbon adsorption units). The partially stripped groundwater is routed through the outer casing and discharged into the vadose zone. The density gradient created by injecting air into the inner casing causes the discharged groundwater to flow downward through the subsurface and be drawn back into the bottom of the well. This method allows for continuous cycling of groundwater to be repeatedly circulated through the in-well system until sufficient contaminant removal has occurred. Several patented vertical recirculation systems are commercially available, including NoVOCs™, Unterdruck-Verdampfer-Brunnen (UVB™) (also known as vacuum vaporizer well), Density Driven Convection, and C-Sparge™. Hightower et al. (2001) reviewed recirculation well technologies and performance data and recommended C-Sparge™ for potential implementation in the saturated portions of contamination present at the PGDP.

Vertical recirculation wells can be combined with ozone injection, carbon adsorption, or biological treatments.

A field scale demonstration of this technology was conducted at DOE's Westinghouse Savannah River Site in Aiken, SC. The demonstration consisted of two 8-inch diameter airlift recirculation wells installed to a depth of approximately 175-ft. The upper and lower screen intervals provided 10-ft inlets at the bottom and top of the aquifer. Equipment and utility problems were encountered and the upper screens of the wells plugged after a few weeks of operation. One well was redeveloped and was operated successfully. Over a 14-month duration, TCE concentrations were reduced by 30–80% within a 300-ft zone of influence (EPA 1998a). Exhaust stream measurements indicated that TCE was stripped from the groundwater at a rate of 1 to 2 lb/day (EPA 1998a).

There are no known examples of successful DNAPL remediation using vertical recirculation wells. Vertical recirculation technology was not retained for further consideration.

**Close-coupled Extraction and Reinjection.** This recirculation technique involves injecting amendments in upgradient wells while downgradient wells extract groundwater. The extracted groundwater can be mixed with additional amendment and reinjected in an injection well. The wells keep the water in the aquifer in contact with the amendment and also may prevent the larger agglomerated particles of the amendment from settling out, allowing continuous contact with the contaminant. This technique typically is applied to saturated and hydraulically conductive formations, like the RGA, and used with relatively stable oxidants, such as potassium permanganate. Soil flushing also can be conducted using this type of system configuration. Chemical oxidation and surfactant/cosolvent mixtures are discussed below in more detail in Chemical Oxidation/Reduction and Soil Flushing, respectively. Close-coupled extraction and reinjection has been retained for further consideration for potential combination with other technologies.

### A.3.2.3 Air Sparging

Air sparging injects air into contaminated groundwater. Injected air traverses horizontally and vertically in channels through the soil column allowing TCE and other VOCs to distribute into the vapor phase, creating an underground stripper that removes contaminants by volatilization and transport. This injected air helps to volatilize the contaminants that travel into the unsaturated zone, where they typically are removed by an soil vapor extraction (SVE) system. This technology is designed to operate at high flow rates to maintain increased contact between groundwater and soil and strip more groundwater by sparging.

Although air sparging can act on aqueous, DNAPL, and sorbed-phase VOCs by promoting volatilization of VOCs into the vapor phase, the technology may not be the best choice where free-phase DNAPL is present due to the potential for mobilization by the vigorous air movement.

Air sparging can be enhanced via the use of oxygen or ozone. Oxygen added to contaminated groundwater and vadose zone soils can enhance biodegradation of some contaminants below and above the water table. Ozone may be generated on-site and added to air injection or sparging systems to oxidize contaminants *in situ*.

The target contaminant groups for air sparging are VOCs and fuels. Methane can be used as an amendment to the sparged air to enhance cometabolism of chlorinated organics.

Characteristics that should be determined while considering this technology include vadose zone gas permeability, depth to water, groundwater flow rate, radial influence of the sparging well, aquifer permeability and heterogeneities, presence of low permeability layers, presence of DNAPLs, depth of contamination, and contaminant volatility and solubility. Additionally, it is often useful to collect air-saturation data in the saturated zone during an air sparging test using a neutron probe.

This technology is demonstrated at numerous sites, though only a few sites are well documented. Air sparging has demonstrated sensitivity to minute permeability changes, which can result in localized stripping between the sparge and monitoring wells. Air sparging has a medium-to-long duration that may last up to a few years (FRTR 2008). Estimates for C-Sparge<sup>®</sup> remediation for seven different site scenarios that included variations on saturation, concentration of TCE, and proximity to source zones for areas of the UCRS and RGA were provided by MK/K-V Associates in 1999. Remedy time frames assumed for costing purposes ranged from 1 year for UCRS to 30 years for RGA (MK Corporation 1999).

Air sparging is a viable technology at many VOC impacted sites; however, the more successful applications occur when the sparge points can be positioned well below the impacted zone. This placement allows the injected air to sweep upward and spread out giving confluent coverage. When



contamination is located at the same depth as the sparge points, groundwater on the same level and somewhat above the sparge points is likely to be poorly treated. The RGA is impacted to the top of the McNairy Formation; therefore, effective treatment throughout the entire impacted thickness is not likely. The gravelly composition of the RGA reduces the treatment area around a sparge point because air tends to “bubble” straight up rather than disperse as in finer grained aquifers. The depth of the sparge points also affects performance. For these reasons, air sparging was not retained for further consideration.

#### A.3.2.4 Chemical Oxidation/Reduction

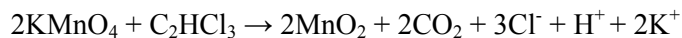
Chemical oxidation/reduction processes, such as *in situ* chemical oxidation (ISCO), use oxidants or reductants to degrade organic contaminants within the subsurface. Table A.1 provides a comparative evaluation of several commercially available amendments including zero valent iron (ZVI). Although ZVI is not an oxidant, it is included in the comparative table because delivery mechanisms are similar. The criteria provided in the comparative evaluation can be used to screen certain amendments based on site conditions and the selected delivery mechanism, as applicable.

Commercially available chemical technologies described in this section include the following:

- Permanganate
- Fenton’s reagent
- Ozonation
- Persulfate
- Redox manipulation

ISCO has been used at many sites, and oxidants are available from a variety of vendors. Water-based oxidants can react directly with the dissolved-phase of nonaqueous-phase liquid (NAPL) contaminants. The organics and the water have limited solubility in one another. This property limits their activity to the oxidant solution/DNAPL interface; however, significant mass reduction has been reported for application of ISCO at sites with dissolved-phase VOCs and DNAPL residual ganglia (EPA CLU-IN 2008). Data needs include heterogeneity of the site subsurface, soil natural oxidant demand, stability of the oxidant, and type and concentration of the contaminant.

**Permanganate.** Permanganate typically is provided as a water solution or a solid potassium permanganate, but also is available in sodium, calcium, or magnesium salts. The following equation represents the chemical oxidation of TCE using potassium permanganate:



The use of permanganate to degrade TCE causes the generation of salts and hydrogen or hydroxyl ions (acids or bases) with minor pH shifts. The direct application of permanganate commonly has been used for contaminant levels up to 100 mg/L to avoid off-gassing. It only recently has been applied to contaminant levels exceeding 1,000 mg/L. Permanganate can be delivered to the contaminated zone by injection probes, soil fracturing, soil mixing, and groundwater recirculation (EPA 2004). Permanganate has an effective pH range of 3.5 to 12 (KRCEE 2005). This technology potentially may be effective and technically implementable in the RGA, but it has the same limitations as other aqueous-phase oxidants. Secondary effects may include discoloration of water for some time after treatment. There are limitations on the effectiveness of permanganate in treating DNAPL because the residual manganese dioxide precipitant left by the TCE/permanganate reaction will form an ash layer around the TCE globules that will restrict further reaction. In addition, with permanganate, as well as with other reactants, there is a potential for introduction of secondary impurities due to their presence in commercial grade chemicals.

**Table A.1. Comparative Evaluation of Commercially Available Chemical Amendments**

| Evaluation Criteria                         | Potassium Permanganate <sup>1</sup>   | Sodium Permanganate <sup>1</sup> | Sodium Persulfate/Activator <sup>a,1</sup> | Hydrogen Peroxide/Ferrous Iron <sup>1</sup>                | Ozone/Hydrogen Peroxide <sup>1</sup>   | Zero Valent Iron (ZVI) <sup>2,3</sup>                                |
|---|---|----------------------------------|--|--|--|--|
| <b>Degradation of TCE</b>                   | Yes   | Yes                              | Yes  | Yes  | Yes  | Yes  |
| <b>Persistence</b>                          | Very stable   | Very stable                      | Very stable                                | Easily degraded in soil/groundwater unless inhibitors used | Easily degraded in soil/groundwater  | Dependent on particle size and presence of oxidative molecules       |
| <b>Vadose Zone Considerations</b>           | Hydration required via (1) injection of large quantities of oxidant, <sup>b</sup> (2) artificial hydration, or (3) surfactants. |                                  |  |  | Hydration not required (but water may increase hydroxyl radical production)  | Water is required, but amount should be minimized. <sup>c</sup>      |
| <b>Low Soil Permeability Considerations</b> | Low soil permeability is a barrier. <sup>d</sup>  |                                  |  |  | Low soil permeability is a barrier; <sup>d</sup> however, higher permeability to gas (i.e., ozone) than to liquid. | Low soil permeability is a barrier. <sup>d</sup>                     |
| <b>Metal Mobilization Considerations</b>    | Metals can be mobilized within the treatment zone due to a change in oxidation states and/or pH.                                |                                  |  |  |  | Much lower potential for toxic metal mobility, especially with EZVI. |
| <b>Oxidant Loading Requirements</b>         | Optimal loading, considering both target and nontarget compounds, should be determined before injection.                        |                                  |  |  |  | Based on soil amount. <sup>e</sup>                                   |

<sup>a</sup> Heat, ferrous iron, or elevated pH.

<sup>b</sup> Generally ineffective and has potential to increase contaminant release and migration.

<sup>c</sup> Oxygen, nitrates, and sulfates present in the water can oxidize the ZVI. If large volume of water is necessary, it should be deoxygenated.

<sup>d</sup> The oxidant must be dispersed evenly throughout the contaminated soil matrix with minimal forced migration of the contamination outside the treatment area.

<sup>e</sup> A reducing environment that is strong enough to minimize the formation of chlorinated intermediates (e.g., dichloroethene or vinyl chloride) may be optimal. Based on Navy field demonstrations, enough ZVI mass should be injected to lower the oxidation-reduction potential below -400 mV; an iron-to-soil ratio of 0.004 is necessary to create the required potential. Iron requirements are not based on contaminant mass.

References

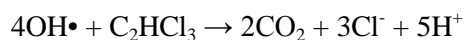
1. ITRC (Interstate Technology & Regulatory Council) 2005. Technical and Regulatory Guidance for *In Situ* Chemical Oxidation of Contaminated Soil and Groundwater, 2nd ed. ISCO-2, Washington, DC: ITRC, *In Situ* Chemical Oxidation Team, Available at <http://www.itrcweb.org>.
2. NAVFAC ESC (Naval Facilities Engineering Command/Engineering Service Center) 2005. Cost and Performance Report, Nanoscale Zero Valent Iron Technologies for Source Remediation, Contract Report CR-05-007-ENV.
3. NAVFAC ESC 2005. Nanoscale Zero Valent Iron Training Tool, Environmental Restoration Technology Transfer (ERT2), Multimedia Training Tools Web site, Available at <http://www.ert2.org/ert2portal/DesktopDefault.aspx>.

This issue should be further evaluated once the mass of permanganate (or other chemicals to be added) is estimated.

**Fenton's Reagent.** Hydrogen peroxide was one of the first chemical oxidants to be used in industry and was commercialized in the early 1800s. Hydrogen peroxide works as a remedial chemical oxidant in two ways: (1) direct chemical oxidation as hydrogen peroxide and (2) in the presence of native or supplemental ferrous iron ( $\text{Fe}^{2+}$ ), as Fenton's reagent, which yields hydroxyl free radicals ( $\text{OH}\cdot$ ). These strong, nonspecific oxidants can rapidly degrade a variety of organic compounds. Fenton's reagent oxidation is most effective under very acidic pH and becomes ineffective under moderate to strongly alkaline conditions.

The most common field applications of chemical oxidation have been based on Fenton's reagent. When peroxide is injected into the subsurface at concentrations of 10% to 35% in the presence of ferrous iron, the hydroxyl free radical oxidizes the VOCs to carbon dioxide ( $\text{CO}_2$ ) and water. The residual hydrogen peroxide decomposes into oxygen and water, and the remaining iron precipitates (Jacobs and Testa 2003).

The oxidation reaction for TCE forms several unstable daughter products, such as epoxides, that break down to aldehydes and ketones, which then decompose to carbon dioxide, chloride ions, and water, as shown in the following reaction (Jacobs and Testa 2003).



The optimal pH range is from 3.5 to 5.0. The exothermic nature of the oxidation process causes a rise in subsurface temperature, which may decompose the peroxide. Field research has determined the optimal reaction temperature to be in the range of 35°C to 41°C (Jacobs and Testa 2003).

This technology potentially may be effective and technically implementable in the RGA, but has the same limitations as other aqueous-phase oxidants.

**Ozonation.** Ozone is a strong oxidizer having an oxidation potential about 1.2 times that of hydrogen peroxide. Because of its instability, ozone typically is generated on-site and delivered to the contaminated zone through sparge wells. Air containing up to 5% ozone is injected through strategically placed sparge wells. Ozone dissolves in the groundwater and oxidizes the contaminant while decomposing to oxygen. Ozone also can be injected with air during vertical recirculation, as discussed above.

This technology potentially may be effective and technically implementable in the RGA, but has the same limitations as other aqueous-phase oxidants.

**Sodium Persulfate.** Persulfate is a strong oxidant with a higher oxidation potential than hydrogen peroxide and a potentially lower soil oxygen demand than permanganate or peroxide. Persulfate reaction is slow unless placed in the presence of a catalyst, such as ferrous iron, or heated to produce sulfate free radicals that are highly reactive and capable of degrading many organic compounds. The ferrous iron catalyst, when used, will degrade with time and precipitate. Persulfate becomes especially reactive at temperatures above 40°C (104°F), and can degrade most organics (EPA CLU-IN 2008).

This technology potentially may be effective and technically implementable in the RGA, but has the same limitations as other aqueous-phase oxidants.

**Redox Manipulation.** *In situ* redox manipulation (ISRM) manipulates natural processes to change the mobility or form of contaminants in the subsurface. ISRM creates a permeable treatment zone by injection of chemical reagents, such as sodium dithionite and/or microbial nutrients into the subsurface

downgradient of the contaminant source. The chemical reagent then reacts with iron naturally present in the aquifer sediments in the form of various minerals present as clays, oxides, or other forms. Redox sensitive metals that migrate through the reduced zone in the aquifer may become immobilized and organic species may be destroyed (DOE 2000).

This technology is potentially technically implementable and commercially available and is retained for further evaluation.

#### **A.3.2.5 Zero Valent Iron**

ZVI often is used in conjunction with a permeable reactive barrier to dechlorinate chlorinated hydrocarbons in the subsurface; however, the technology also may be applied as direct injection of particulate iron, mixing of iron with clay slurries or incorporating ZVI into an oil emulsion prior to injection. A form of ZVI may be injected into the subsurface downgradient of the contaminant source to create a zone of treatment.

Emulsified ZVI (EZVI) is an innovative remedial technology that combines the capabilities of three remediation techniques: (1) abiotic degradation, (2) biodegradation, and (3) oil sequestration by mobility reduction. Field and laboratory research have demonstrated that zero valent metals can effectively reduce chlorinated TCE DNAPL to ethenes by enhancing contact between the ZVI particles and the DNAPL (ESTCP 2010). EZVI is composed of food-grade surfactant, water, biodegradable oil, and microparticulate ZVI, which form emulsion particles. Each emulsion particle contains ZVI particles in water surrounded by an oil-liquid membrane. These droplets are miscible with DNAPL. DNAPLs, such as TCE, diffuse or sequester through the exterior oil membrane into the aqueous droplet where it reaches the surface of the enclosed Fe ion, thereby allowing dehalogenation to take place. The hydrocarbon by-products of this reaction then diffuse out of the emulsion particle into the surrounding substrate. The ZVI in the aqueous emulsion droplet will continue to remain reactive, while the chlorinated compounds will continue to degrade. EZVI can be implemented using micro-scale, nano-scale, or a mixture of micro/nano-scale particles.

Some of the major issues that potentially could affect the fate and transport of EZVI in the subsurface include contaminant concentration, ionic strength of the groundwater, hydraulic properties of the aquifer, and other geochemical properties, such as pH, dissolved oxygen (DO), oxidation reduction potential (ORP), and the presence of competing oxidants (ESTCP 2010).

The National Aeronautics and Space Administration developed and patented the use of nano EZVI in 2001 at the Kennedy Space Complex through tests conducted jointly with Central Florida University at Cape Canaveral Launch Complex 34 (ESTCP 2010). To date, over 17 applications of the technology have been applied successfully in the United States. Field demonstrations at Cape Canaveral Launch Complex 34 resulted in an average TCE reduction of 58%. In addition, EZVI was applied at a site at Patrick Air Force Base, Brevard, FL, where 98% removal of TCE was measured.

This technology is potentially technically implementable within the RGA, commercially available, and is retained for further evaluation.

#### **A.3.2.6 Bioremediation**

Enhanced biodegradation of chlorinated ethenes in the subsurface occurs through one or more of three different pathways, which may occur simultaneously (ITRC 2005).

- The contaminant is used as an electron acceptor and is reduced by the microbe, but not used as a carbon source [i.e., the anaerobic reductive dechlorination (ARD) process].
- The contaminant is used as an electron donor and is oxidized by the microbe, which obtains energy and organic carbon from the contaminant.
- The contaminant is cometabolized; this is a process where an enzyme or other factor used by the microbe for some other purpose fortuitously destroys the contaminant while providing no benefit to the microbe itself. Cooxidation is a form of cometabolism.

Bioremediation acts on dissolved aqueous-phase VOCs, but does not act directly on DNAPL. Instead, the technology relies on degradation and solubilization processes that occur near the water-DNAPL interface.

The DNAPL contaminant mass must transfer into the aqueous phase before it can be subjected to the dechlorination or oxidation processes. Biodegradation of dissolved-phase VOCs in DNAPL zones or VOCs sorbed to solids increases the rate of dissolution by maintaining a relatively high concentration gradient between the DNAPL, or sorbed phase, and the aqueous phase (i.e., maintaining contaminant concentrations in the aqueous phase as low as possible). Significant destruction of contaminant mass in the source area can be achieved by increasing the rate of contaminant dissolution. Even with increased dissolution rates, however, source areas at many sites are expected to persist for many decades, due to the large amount of DNAPL mass present and the difficulty of establishing conditions favorable for biodegradation throughout the contaminated areas.

For the reasons discussed above, bioremediation is screened from further consideration as a primary source-based mass removal technology.

### **A.3.2.7 Soil Flushing**

*In situ* soil flushing is the extraction of contaminants from soil with water or other suitable aqueous solutions. Soil flushing is accomplished by passing the extraction fluid through in-place soils using an injection or infiltration process. Typically, extraction fluids are recovered from the underlying aquifer and, when possible, recycled. Many soil flushing techniques are adapted from enhanced oil recovery methods used by the petroleum industry for many years. Soil flushing agents including cosolvents and surfactants are discussed here.

Cosolvent flushing involves injecting a solvent mixture (e.g., water plus a miscible organic solvent such as alcohol) into either vadose zone, saturated zone, or both to extract organic contaminants through solubilization into the cosolvent. Cosolvent flushing can be applied to soils to dissolve either the source of contamination or the contaminant plume emanating from it. The cosolvent mixture normally is injected upgradient of the contaminated area, and the solvent with dissolved contaminants is extracted downgradient and treated aboveground.

Surfactant flushing acts by reducing the interfacial tension between DNAPL and water or DNAPL and soil, thereby increasing the surface area for solubilization. Surfactant flushing can result in mobilization of DNAPL, and the process requires physical or hydraulic containment. Some soil flushing agents also can act on sorbed-phase VOCs.

Recovered contaminated groundwater and flushing fluids may need treatment to meet appropriate discharge standards prior to recycle or release to wastewater treatment works or receiving streams. Recovered fluids are reused in the flushing process to the extent practicable. The separation of surfactants from recovered flushing fluid, for reuse in the process, can be a major factor in the cost of soil flushing.

Treatment of the recovered fluids results in process sludges and residual solids, such as spent carbon and spent ion exchange resin, which must be treated appropriately before disposal. Air emissions of volatile contaminants from recovered flushing fluids should be collected and treated, as appropriate, to meet applicable regulatory standards. Residual flushing additives in the soil may be a concern and should be evaluated on a site-specific basis.

The duration of soil flushing process is generally short- to medium-term. Costs are high relative to most other *in situ* treatments. Flushing solutions may alter the physical/chemical properties of the soil system.

Treatability tests may be considered to determine the feasibility of the specific soil-flushing process being considered. Physical and chemical soil characterization parameters that should be established include soil permeability, soil structure, soil texture, soil porosity, moisture content, total organic carbon, cation exchange capacity, pH, and buffering capacity.

Contaminant characteristics that should be established when considering this technology include concentration, solubility, partition coefficient, solubility products, reduction potential, and complex stability constants. Soil and contaminant characteristics will determine the flushing fluids required, flushing fluid compatibility, and changes in flushing fluids with changes in contaminants.

Soil flushing is a developing technology that has had limited use in the United States. Typically, laboratory and possibly field treatability studies are performed under site-specific conditions before soil flushing is selected as the sole remedy of choice. To date, the technology has been selected as part of the source control remedy at 12 Superfund sites.

Soil flushing is very similar to groundwater extraction technology with the recirculation or injection of a surfactant solution. Negative aspects of using this technology include (1) the high cost of surfactant and difficulty in reusing surfactant recovered by the extraction system; (2) the need for homogeneous contact throughout the aquifer to mobilize all DNAPL ganglia; and (3) the potential to mobilize DNAPL that may migrate outside the capture zone. Although these negative aspects would eliminate soil flushing from further consideration as a stand-alone technology for Phase IIb at C-400, there is a promising emerging remediation strategy that combines or couples soil flushing using surfactants with the implementation of ISCO. Under this strategy, these two technologies are implemented, either sequentially or concurrently, to take advantage of the strengths of the individual technologies (SERDP 2006; Collins and Hoag NDA; and CARUS NAD). Soil flushing is being retained for further consideration for potential coupling with other appropriate technologies.

### **A.3.3 THERMAL TREATMENT TECHNOLOGIES**

Thermal treatment technologies are evaluated for potential applicability for treatment of TCE contamination within the RGA at the C-400 IRA project site. The ROD for the C-400 IRA identified ERH as the remedial technology for implementation. This evaluation identifies additional thermal technologies for consideration. Thermal treatment technologies include the following:

- Electrical resistance heating
- Steam injection
- Hot air injection
- Hot water injection

### **A.3.3.1 Electrical Resistance Heating**

The primary recovery mechanism associated with implementation of ERH is volatilization of the VOCs present in the subsurface as aqueous phase, sorbed phase, or DNAPL. Electrodes are placed directly into the soil matrix and energized so that electrical current passes through the soil, creating a resistance that then heats the soil. The heat created by ERH forces trapped liquids, including DNAPLs, to vaporize and move to the steam zone for removal by SVE. ERH applies electrical energy in arrays of three (three-phase) or six (six-phase) electrodes to heat soils. The temperature of the soil and contaminant is increased, thereby increasing the contaminant's vapor pressure and its removal rate. ERH also creates an *in situ* source of steam to strip contaminants from soil. Heating via ERH also can improve air flow in high moisture soils by evaporating water, thereby improving SVE performance. ERH can act on aqueous, DNAPL, and sorbed phase VOCs. Contaminants in low-permeability soils, such as clays and fine-grained sediments, can be vaporized and recovered by vacuum extraction using this method. The heat may dry out the soil causing it to fracture. These fractures make the soil more permeable allowing the use of SVE to remove the contaminants.

If target temperatures required for volatilization of a contaminant are not attained, the raised temperature would impact properties such as viscosity, dissolution rates, and desorption rates, but the primary recovery mechanism would not be utilized and the effectiveness of the remedy would decrease substantially.

Data requirements include the depth and areal extent of contamination, the concentration of the contaminants, depth to the water table, and soil type and properties including structure, texture, permeability, organic carbon content, electrical properties, moisture content, and water velocity in saturated conditions.

Durations of thermally enhanced remediation projects are highly dependent upon the site-specific soil and chemical properties. The typical site consisting of 20,000 tons of contaminated media would require approximately nine months of remediation (FRTR 2008). This technology has been demonstrated at PGDP for removal of DNAPL TCE and its degradation products with success in the UCRS (see Section 3 for details).

This technology is retained because it is the selected technology in the current ROD. Other technologies are compared to ERH during the evaluation and remedy selection.

### **A.3.3.2 Steam Injection**

Steam injection can be used to recover organic contaminants present in the subsurface in aqueous, DNAPL, sorbed, and vapor phases. Steam is injected at or below the contaminated zone to heat contaminated soil and thereby enhance the release of VOCs and some semivolatile organic compounds from the soil matrix. Desorbed or volatilized VOCs typically are removed through SVE (FRTR 2008). Steam injection has been used to enhance oil recovery for many years and was investigated for environmental remediation beginning in the 1980s. To date, approximately 10 applications of this technology for recovery of fuels, solvents, and creosote are reported in EPA (2005), with varied results.

The primary recovery mechanisms associated with steam injection include physical displacement, steam distillation, and steam stripping. Physical displacement occurs first by the "cold-water front" created by the movement of the groundwater initially present in the subsurface that is displaced by the injection of steam, then by the "hot-water front" formed by steam condensation and, finally, by the steam itself (EPA 1998b). In the saturated zone, DNAPL and dissolved-phase contamination are displaced, and in the vadose zone soil air is displaced. This physical displacement is enhanced during steam injection by the

increase in temperature. A decrease in the capillary and interfacial forces between fluids and porous media, thermal expansion of DNAPL and the associated increase in saturation, and a decrease in the viscosity will occur with an increase in temperature (EPA 1998b). Steam distillation occurs when the boiling point of the mixture of immiscible liquid and water is reached and volatilization of the contaminant can occur. Steam stripping also enhances the recovery of vapor phase contamination by sweeping, or removing, the vapor phase from contact with the aqueous phase, thus preventing equilibrium and allowing volatilization to continue. Steam stripping is an important recovery mechanism that is not necessarily associated with the presence of an immiscible liquid (EPA 1998b).

The most important design aspects of a steam flood for environmental remediation involve creating a system that will efficiently target steam to the contamination without excessive heat loss of the steam or mobilized NAPL. The design must account for gravitational stability and steam override. The buoyant force of the steam tends to result in a radial angle of influence from a vertical steam injection point.

It is well known in petroleum engineering that steam injected into a horizontal, confined system will tend to override the liquid phases (van Lookeren, 1983). This tendency is a result of the large density difference between steam and liquid water or oil and can be characterized by the gravity number ( $N_g$ ) (van Lookeren 1983).

$$N_g = N_b/N_c = (\rho_w - \rho_s)gK/(m_s\mu_s/\rho_s)$$

Where:

$P_w$  = density of water

$P_s$  = density of steam

$g$  = acceleration due to gravity

$m_s$  = steam mass flux

$\mu_s$  = viscosity

$k$  = permeability

Using van Lookeren's gravity number assumed at 1, the result is a 45% tilting of the steam-water interface in a linear horizontal system. Stated another way, a steam flood within the RGA at C-400 with steam discharged from vertical points at the bottom of the RGA (95 ft) would spread to 30 ft away at the top of the RGA (~ 65 ft bgs) and then enter into the UCRS because the system is only semiconfined. The lack of the fully confining layer leads to steam loss and steam front development. In order to address the bottom 10 ft of the RGA, injection points would be needed on 10 ft centers, which is impractical.

Although initially considered as a viable technology for C-400, the applicability of steam injection has been reconsidered based on lessons learned from Phase I. Specifically, due to the isotropic nature of the RGA and the difficulty in achieving target temperatures observed during Phase I, the application of steam injection for heating in the lower RGA is considered to have the potential to be significantly complicated by buoyancy and convection.

For the reasons discussed above, *in situ* steam injection is screened from further consideration.

### **A.3.3.3 Hot Air Injection**

Hot air injection can be used to volatilize organic contaminants in subsurface soils or sediments. With deeper subsurface applications, hot air is introduced at high pressure through wells or soil fractures. The heated air is injected and circulated through the contamination zone and causes the volatilization of organic compounds that then are extracted using SVE. Hot air has been used to recover only contaminants present in the vapor phase (EPA 1997). Additionally, injection of hot air is field limited by relatively low



heat capacity when compared to steam. The heat capacity of steam is approximately four times that of air (EPA 1997).

For these reasons, hot air injection is screened from further evaluation.

#### **A.3.3.4 Hot Water Injection**

Hot water injection is used commonly to recover oils with low volatility and very low solubility. While hot water flushing within a contaminated aquifer is primarily utilized to hydraulically remove NAPL, this method also can enhance recovery of dissolved-phase and sorbed-phase contamination. Similar to steam injection, hot water injection consists of injecting heated water into the saturated subsurface at or below the contaminated zone using injection and extraction points. The technique draws water that has been heated to sub-boiling temperatures through the zone of contamination to favorably alter the properties of aqueous and DNAPL phase contamination (Bjorn 2000).

The main mechanism for contaminant recovery using hot water injection is physical displacement (EPA 1997). The hot water aids in NAPL extraction by reducing the viscosity, decreasing capillary pressure and interfacial tension between the NAPL and water, expanding the NAPL, and reducing the residual NAPL saturation in pore spaces (Bjorn 2000). Recovery of dissolved-phase contamination also may be enhanced via hot water injection. The solubility of organic contaminants could be increased along with an increase in the kinetic mass transfer rates between DNAPL and aqueous-phase contamination. Increased temperature also would decrease sorption of a contaminant, although complete desorption is not achievable at the temperatures attained during hot water injection (Bjorn 2000).

This technology has been eliminated from further consideration due limited effectiveness resulting from incomplete desorption and high energy requirements.

## **A.4. EVALUATION OF TECHNOLOGIES**

The following section presents an evaluation of the disadvantages and advantages associated with each of the technologies retained in Section 3 with respect to potential implementation at the C-400 RGA source zone area. Specific limiting factors associated with known conditions at the C-400 site are evaluated, as well as the extent to which uncertainties at the C-400 site could impact successful implementation of a technology.

The following evaluations provide descriptions that focus on the primary disadvantages and advantages associated with implementation of each technology during Phase IIb of the C-400 project. In addition to the major concerns presented in the text, a list of additional advantages, disadvantages, and considerations is provided in table format.

### **A.4.1 AQUIFER CONDITIONS**

The following is a list of conditions that are assumed to present in the RGA source zone at the C-400 site based on data obtained as part of prior investigations and the site-specific CSM. These characteristics play a significant role in the basis for the technology evaluations presented in the following sections.

- **Geology**—The RGA is composed of highly permeable gravelly sand or chert gravel with limited heterogeneity; the depth to the top of the RGA in the C-400 area ranges from approximately 56 ft to 66 ft bgs with a thickness of approximately 25 ft to 36 ft.
- **Hydrogeology**—The RGA is fairly transmissive with a hydraulic conductivity estimated to range from 100 to 750 ft/day.
- **Geochemistry**—Based on data generated from wells in the vicinity of the C-400 source zone from 2005 through 2009, the range of median values for DO, pH, and ORP were 0.37 to 1.27 mg/L, 6.0 to 6.5, and 90 to 358 mV, respectively.
- **Contamination**—TCE is present as aqueous phase, sorbed phase, and pooled and residual DNAPL. The extent of source zone contamination has been characterized and delineated. Metals are not present in significant amounts.

### **A.4.2 GROUNDWATER EXTRACTION**

The primary disadvantage of implementing a conventional groundwater extraction system at the C-400 site is the potential for lingering contamination and excessively long treatment time frames associated with tailing and rebound. Tailing is the progressively slower rate of decline in a dissolved-phase contamination with continued operation of a groundwater extraction system (i.e., reaching asymptotic concentrations in extracted groundwater). Rebound is the rapid increase in contaminant concentration that occurs after pumping has been discontinued. The presence of DNAPLs, desorption, matrix diffusion, and groundwater velocity variations contribute to tailing and rebound. The presence of potential DNAPL and sorbed mass at the C-400 site likely would result in tailing. Extraction would increase the groundwater velocity, which would result in an initial decrease in TCE concentrations and the rate of mass removal by the system would reach asymptotic conditions dependent on the dissolution rate of the TCE.

A groundwater extraction system would not have a significant direct impact on the mass of TCE present as DNAPL within the RGA at the C-400 site.

Advantages of implementing a groundwater extraction and treatment system at the C-400 RGA source zone include an initial decrease in TCE groundwater concentrations, low capital and operation and maintenance (O&M) costs, and ease of implementation. Groundwater extraction and treatment is a proven and conventional treatment method with little programmatic uncertainty associated with installation and operation.

Advantages and disadvantages of conventional groundwater extraction systems are summarized below.

| Advantages  | Disadvantages  |
|---|--|
| <ul style="list-style-type: none"> <li>• Proven technology.</li> <li>• Initial decreases in groundwater concentrations.</li> <li>• Low capital and annual O&amp;M costs.</li> <li>• High permeability and saturated thickness in the RGA will allow for adequate production and capture.</li> </ul> | <ul style="list-style-type: none"> <li>• Tailing and rebound can result in longer treatment times and significant residual concentrations.</li> <li>• DNAPL and sorbed phase contamination would not be impacted significantly by a groundwater extraction remedy.</li> <li>• Aboveground treatment systems required.</li> </ul> |

### A.4.3 CHEMICAL OXIDATION

A major limitation of ISCO implementation is the inability to remediate mobile or pooled DNAPL. Rather, ISCO is more applicable to residual DNAPLs, aqueous, and sorbed-phase contamination (EPA 2006). Another potential disadvantage with ISCO using permanganate, one of the most commonly used oxidants, is the precipitation of manganese dioxide solids (MnO<sub>2</sub>) that could limit formation permeability and could result in a crust or reaction rind at the interface between DNAPL and the reagent. This reaction rind limits additional reaction of DNAPL by permanganate. The deposition of MnO<sub>2</sub> solids may be suppressed through the addition of a dispersant such as sodium hexametaphosphate (Dugan and Crimi 2011). Rebound is also a possible disadvantage associated with implementation of an ISCO treatment remedy. Rebound can occur following the end of active ISCO operations when groundwater and DNAPL/sorbed-phase contamination is allowed to reach equilibrium with dissolved-phase concentrations.

In addition, although not necessarily disadvantageous, there are several design considerations that must be evaluated prior to implementation of ISCO. ISCO design challenges, or considerations, include health and safety concerns associated with proper handling and storage of hazardous chemicals, the reactivity and potential limited persistence of an oxidant in the subsurface, the potential for DNAPL mobilization, and the potential decrease in permeability as a result of colloid generation.

The geologic and hydrogeologic conditions at C-400 within the RGA could be conducive to effective distribution of oxidants in the subsurface. The high permeability, limited heterogeneities, and saturated thicknesses found in the RGA present favorable conditions for efficient injection of reagent. Another advantage of using ISCO is the potential to treat aqueous phase, sorbed phase, and residual DNAPL ganglia TCE contamination. As contaminants in the aqueous phase are oxidized, the concentration gradient between the aqueous and sorbed/DNAPL phases increases, causing enhanced mass transfer and eventual oxidation of those contaminants (i.e., sorbed phase TCE is desorbed and DNAPLs are dissolved).

Advantages and disadvantages associated with implementation of an ISCO remedy are summarized below.

| Advantages  | Disadvantages   |
|---|---|
| <ul style="list-style-type: none"> <li>• Contaminants are destroyed <i>in situ</i>.</li> <li>• Aqueous phase contamination directly transformed via oxidation reactions.</li> <li>• Enhanced mass transfer.</li> <li>• Treatment time frames can be short.</li> <li>• No need for installation of extensive SVE wells because of RGA depth; associated condensation of TCE within the UCRS would result in dissolved-phase contamination, not vapor.</li> <li>• Permeable, saturated, conditions with limited heterogeneities present within the RGA could be conducive to ISCO treatment.</li> <li>• ISCO has the capability to treat residual DNAPL ganglia.</li> <li>• TCE is amenable to degradation by all the oxidants discussed in this document.</li> </ul> | <ul style="list-style-type: none"> <li>• Rebound can occur following the end of active ISCO treatment.</li> <li>• If DNAPL pools are present, ISCO treatment, without combining it with additional technologies, may have limited effectiveness.</li> <li>• Health and safety (H&amp;S) considerations associated with handling of hazardous chemicals.</li> <li>• Delivery issues associated with rapid reaction rates, and short persistence of some oxidants in the subsurface.</li> <li>• Potential permeability reduction associated with injection of potassium permanganate.</li> <li>• Contaminant mobilization is a design consideration.</li> <li>• Some oxidation reactions are pH dependent.</li> </ul> |

#### A.4.4 EMULSIFIED ZERO VALENT IRON

The primary disadvantage associated with injection of an EZVI amendment into the RGA at the C-400 site is the difficulty associated with delivery of the EZVI into the subsurface due to the viscous nature of the EZVI and the uncertainty related to distribution of DNAPL in the RGA.

A potential advantage of utilizing EZVI is the ability to treat TCE DNAPL and dissolved-phase contamination using one amendment. In addition, the emulsification of ZVI in oil (EZVI) helps counteract geochemical compatibility issues related to aerobic aquifer conditions.

Advantages and disadvantages associated with implementation of an EZVI remedy are summarized below.

| Advantages  | Disadvantages   |
|---|---|
| <ul style="list-style-type: none"> <li>• May be cost competitive, with the potential for overall lower costs than technologies such as groundwater extraction that require long-term O&amp;M costs or technologies with high capital expenditures (e.g., ERH).</li> <li>• Emulsification of ZVI in oil (EZVI) helps counteract compatibility issues related to aerobic aquifer conditions.</li> <li>• Can result in reduced treatment times.</li> <li>• Contaminants will be destroyed rather than transferred to another medium.</li> <li>• Produces less toxic and more easily degradable by-products.</li> <li>• Is environmentally safe.</li> <li>• Directly treats contaminant source, as well as potential dissolved-phase chemicals.</li> <li>• Could potentially be effective in oxidative or saline environments.</li> </ul> | <ul style="list-style-type: none"> <li>• Highly aerobic conditions in the RGA are not amenable to degradation via ZVI (unemulsified).</li> <li>• Difficulty in distributing the viscous EZVI to all areas impacted by potential DNAPL.</li> <li>• A potential to adversely impact secondary groundwater quality by mobilizing metals and the production of sulfides or methane if additional vegetable oil is added.</li> </ul> |

#### A.4.5 SOIL FLUSHING

A major consideration associated with soil flushing is the potential for uncontrolled mobilization of DNAPL, downward and/or laterally outside of the targeted treatment zone. This component of soil flushing has the potential to be a significant disadvantage if the technology were to be applied in the wrong hydrogeological setting. Surfactant induced mobilization can remove significant amounts of DNAPL in less time; however, there is greater risk of uncontrolled downward movement of DNAPL, as DNAPL is being physically displaced by the surfactant solution. Thus, to conduct a mobilization flood, it is necessary to have a competent aquitard as a barrier to prevent vertical DNAPL migration. For proper implementation of this technology the site should possess the following characteristics (NAVFAC 2002):

- High permeability ( $> 10^{-3}$  cm/s)
- Relatively homogeneous aquifer
- A competent aquitard
- Hydraulic control should be feasible

Hydrogeological characteristics of the RGA are amenable to the attainment of hydraulic control (e.g., high permeability, limited heterogeneity). The presence of a competent aquitard (the McNairy Formation) below the RGA would prevent significant downward mobilization of DNAPL.

The primary advantage associated with injection of a surfactant/cosolvent mixture is the potential for significant removal of DNAPL pools and residuals. Another potential advantage is the ability to use information from surfactant treatability and pilot-scale studies that have been conducted for PGDP in the past (INTERA et al. 1995; DOE 1999).

Advantages and disadvantages associated with implementation of a soil flushing remedy are summarized below.

| Advantages  | Disadvantages   |
|---|---|
| <ul style="list-style-type: none"> <li>• Significant potential removal of DNAPL pools and residuals.</li> <li>• Surfactant treatability and pilot-scale testing have been completed at the PGDP for the RGA.</li> <li>• TCE properties are amenable to removal via soil flushing.</li> <li>• High permeability and limited heterogeneity in the RGA could be amenable to soil flushing (i.e., hydraulic control more easily attained).</li> <li>• The McNairy Formation provides a competent aquitard that would prevent significant downward mobilization of DNAPL.</li> </ul> | <ul style="list-style-type: none"> <li>• Potential for uncontrolled DNAPL mobilization beyond the target treatment zone.</li> <li>• Aboveground separation and treatment costs can be substantial depending on the surfactant/cosolvent selected.</li> <li>• Surfactants can adhere to soil can reduce the effective porosity.</li> </ul> |

#### A.4.6 ELECTRICAL RESISTANCE HEATING

ERH was the specified treatment of the source area in the UCRS and RGA presented in the ROD (DOE 2005). Phase I of the remedy was completed December 9, 2010. The lessons learned during Phase I of the C-400 IRA are presented in the Technical Performance Evaluation (DOE 2011a). Lessons learned during Phase I and a revised simulation study conducted by the ERH subcontractor indicated that significant uncertainty remains with respect to being able to reach target temperatures in the lower RGA (70 ft to 100 ft bgs interval) using ERH as a stand-alone heating technology. The Technical Performance Evaluation (DOE 2011a) provides further assessment of uncertainties associated with the application of ERH in the lower RGA. Temperature levels most likely would not be achieved due to higher than anticipated groundwater flow through the treatment zone, higher than anticipated soil resistivity, and the excessive extraction of energy as a result of the hydraulic and pneumatic control requirements of the remedy. Therefore, the primary disadvantage associated with implementing an ERH remedy is the high programmatic risk associated with not attaining target temperatures. Additionally, possible contingency actions that could be implemented prior to the start of Phase II are likely cost prohibitive relative to other potential technologies.

The primary advantage of ERH is the ability to address all phases of contamination present in the RGA, including DNAPL, with one technology.

Advantages and disadvantages associated with implementation of an ERH remedy are summarized below.

| Advantages   | Disadvantages  |
|--|--|
| <ul style="list-style-type: none"> <li>• All phases of TCE contamination, including DNAPL, in the RGA potentially would be addressed.</li> <li>• If target temperatures could be attained and maintained, the potential for high removal efficiencies in the RGA exist.</li> </ul> | <ul style="list-style-type: none"> <li>• High energy input needed to achieve target temperatures.</li> <li>• Substantial risk associated with not reaching target temperatures. ERH system relies on volatilization of TCE as the primary recovery mechanism.</li> <li>• It was determined during Phase I that the groundwater flow and electrical resistivity in the RGA at the C-400 site are not amenable to implementation of ERH.</li> <li>• Capture and aboveground treatment of groundwater/vapor is required.</li> <li>• Substantial capital costs.</li> </ul> |

#### A.4.7 TECHNOLOGY EVALUATION CONCLUSION

The primary conditions associated with development of a successful remedy at the C-400 site in the RGA are the presence of TCE in multiple phases, including residual DNAPL, the highly permeable nature of the RGA, the associated flow velocity in the RGA, and the aerobic conditions of the aquifer. These conditions proved challenging during Phase I where ERH was deployed. Based on these conditions and knowledge of the technologies evaluated for Phase IIb, a combination of technologies will be required to effectively address the DNAPL source in the lower RGA.

One basic combination of technologies that may be deployed involves the use of close-coupled groundwater extraction and reinjection to effectively deploy chemical amendments to remediate TCE source material. Another promising emerging remediation strategy involves combining the implementation of soil flushing using a surfactant with the implementation of ISCO. These two *in situ* chemical treatment technologies potentially can be coupled, either concurrently or sequentially, to take advantage of each of their individual strengths (SERDP 2006; Collins and Hoag NDA; and CARUS NAD).

## A.5. DEVELOPMENT OF ALTERNATIVES

This section describes five remedial alternatives assembled from the retained technologies. The alternatives considered for detailed evaluation include these:

- (1) No action
- (2) Groundwater extraction and treatment
- (3) *In situ* chemical oxidation
- (4) ERH
- (5) Staged implementation of groundwater extraction and *in situ* chemical treatment

The alternatives developed for this evaluation are consistent with the National Contingency Plan (NCP) process of selecting and identifying remedial actions that are protective of human health and the environment, that maintain protection over time, and that minimize untreated waste.

### A.5.1 DEVELOPMENT OF ALTERNATIVES

The technologies evaluated in Section A.4 have been combined to formulate remedial alternatives that satisfy the RAOs for the C-400 site. The following RAOs were developed for the C-400 remedy in the ROD for the C-400 IRA (DOE 2005):

- Prevent exposure to contaminated groundwater by on-site industrial workers through institutional controls (e.g., excavation/penetration permit program);
- Reduce VOC contamination (primarily TCE and its breakdown products) in UCRS soil at the C-400 Cleaning Building area to minimize the migration of these contaminants to RGA groundwater and to off-site points of exposure (POEs); and
- Reduce the extent and mass of the VOC source (primarily TCE and its breakdown products) in the RGA in the C-400 Cleaning Building area to reduce the migration of the VOC contaminants to off-site POEs.

Effectiveness, implementability, and cost are criteria used to guide the development of remedial alternatives.

Conceptual designs have been developed for each alternative with sufficient detail to allow for detailed and comparative analysis. Cost estimates with a -30% to +50% range of accuracy also have been developed consistent with the *Guide to Developing and Documenting Cost Estimates During the Feasibility Study*, EPA 540-R-00-002 (EPA 2000). Assumptions used in the development of costs and more detailed breakdowns of alternative costs are provided in Attachment A1.

Alternatives 2, 3, 4, and 5 include the use of LUCs, as described in Appendix H of the C-400 RDR (DOE 2008). The LUCs described in the Land Use Control Implementation Plan (LUCIP) (DOE 2006) provide for the following:

- Access control during installation and operation of treatment systems at select locations within the C-400 Area,
- Warning and informational signage,



- Temporary fencing and/or barricades, and
- Visitor sign-in controls.

As interim controls, warning signs for the C-400 area will be posted before beginning C-400 IRA field activities that involve worker exposure to contaminated groundwater and soils. Upon completion of the remedial action, these interim actions will cease and long-term access controls may be selected as LUCs to be maintained in accordance with the requirements of the LUCIP.

#### **A.5.1.1 Alternative 1—No Action**

Formulation of a no action alternative is required by the NCP [40 *CFR* § 300.430(e)(6)] and CERCLA FS guidance (EPA 1988). The no action alternative was evaluated in the GWOU FS and also is included in this evaluation to serve as a baseline for evaluation of other remedial action alternatives. This alternative includes no actions that would be taken to reduce exposure and, therefore, includes no costs.

#### **A.5.1.2 Alternative 2—Groundwater Extraction and *Ex Situ* Treatment**

Alternative 2 consists of groundwater extraction and *ex situ* treatment. Components of the remedy are listed below:

- Groundwater extraction from within the C-400 Phase II RGA source treatment area using up to three wells;
- Groundwater treatment system (current plans are to use the existing pack tower air strippers and vapor phase carbon systems from the Phase IIa ERH infrastructure);
- Discharge of treated groundwater through a Kentucky Pollutant Discharge Elimination System (KPDES) outfall or reinjection;
- Secondary waste management; and
- LUCs.

A cross-section schematic of the Alternative 2 is provided in Figure A.8.

The primary advantage of implementing a conventional groundwater extraction system at the C-400 site is the lower capital cost and ease of operation when compared to the other active remedies evaluated in this document. The disadvantage is the potential for lingering contamination and excessively long treatment time frames associated with tailing and rebound leading to long-term costs. Tailing is the progressively slower rate of decline in a dissolved-phase contamination with continued operation of a groundwater extraction system (i.e., reaching asymptotic concentrations in extracted groundwater). Rebound is the rapid increase in contaminant concentration that occurs after pumping has been discontinued. The presence of DNAPLs, desorption, matrix diffusion, and groundwater velocity variations contribute to tailing and rebound. The presence of residual DNAPL ganglia at the C-400 site very likely would result in tailing. Groundwater extraction would result in effective recovery of dissolved phase mass, but likely would not be effective in recovery of mass associated with residual DNAPL.

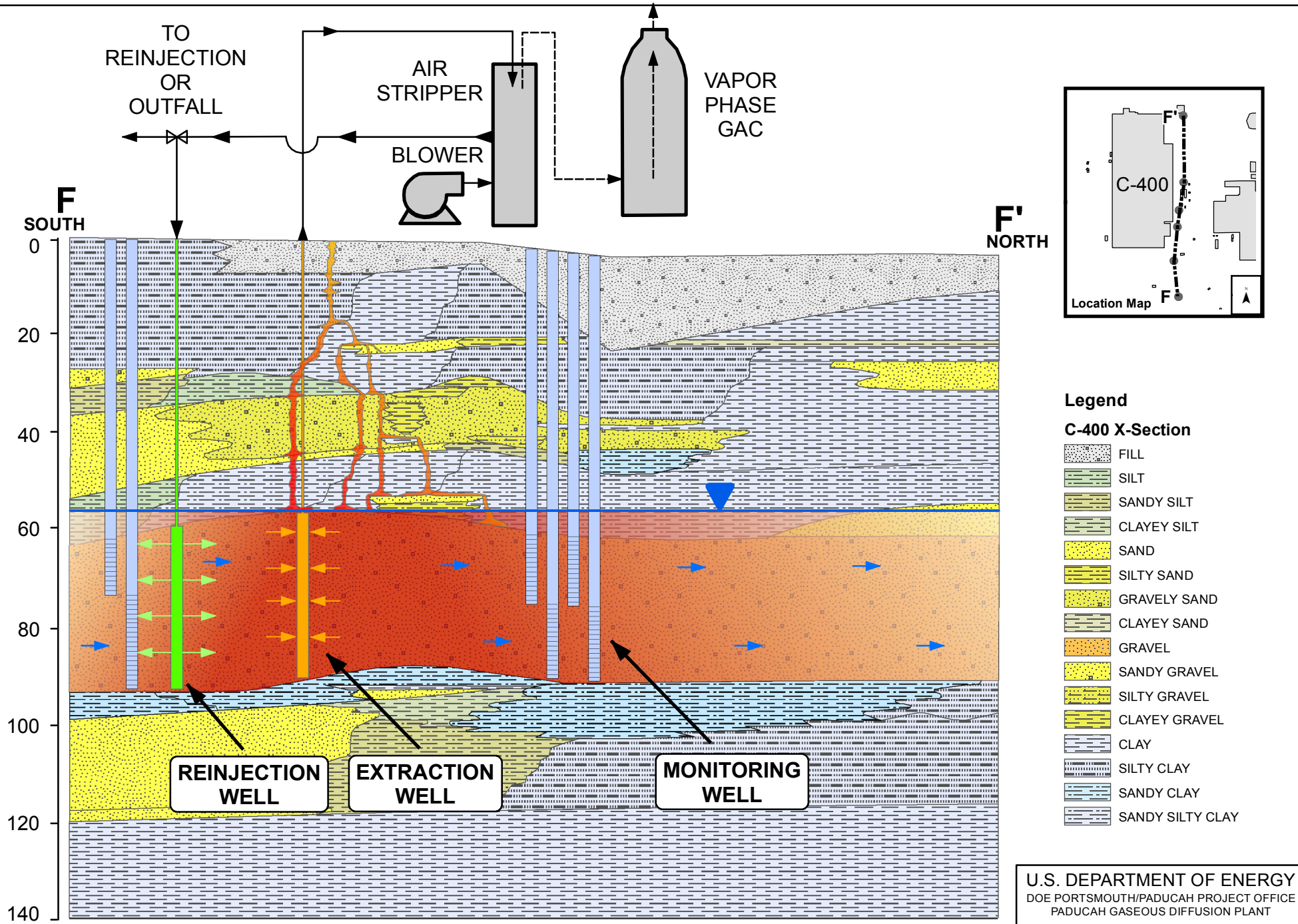
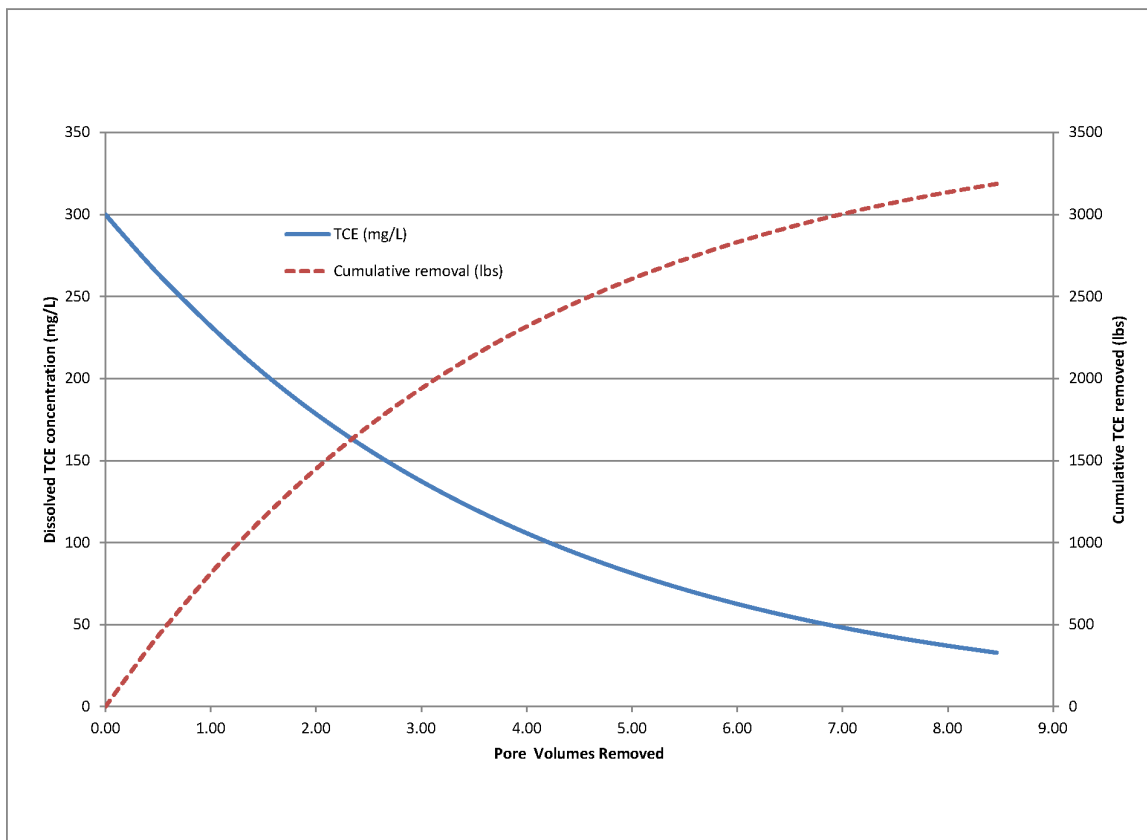


Figure A.8. C-400 Phase IIb Interim Remedial Action Schematic Cross-section View of Alternative 2 - Groundwater Extraction and Injection with ex-situ Treatment

Figure A.9 provides an example of TCE concentration and mass removal from continuous groundwater extraction at C-400 assuming a combination of sorbed and dissolved mass in the matrix. The curves were developed by considering the 140 ft x 140 ft x 35 ft Phase IIb treatment area and an initial concentration of TCE in the dissolved phase of 300 mg/L. Initially the system is in equilibrium and the groundwater extraction system removes the dissolved fraction readily. As pumping continues, water outside the treatment unit mixes with the dissolved TCE and decreases the concentration. Further in the extraction process, the removal rate from the dissolved fraction exceeds the dissolution rate from the sorbed phase. Although the curves were based on an assumed mass and desorption rates, the resulting curves are common to groundwater extraction systems. The tailing from desorption is considered a long-term disadvantage of conventional groundwater extraction if there is a significant sorbed mass.

Data collected prior to and during groundwater extraction operations would be used to establish baseline and operational conditions with respect to TCE in groundwater. Comparison of baseline and operational TCE concentrations would be used to determine the effectiveness of Alternative 2.



**Figure A.9. Example TCE Concentration and Mass Removal Trends from Continuous Groundwater Extraction Approach**

**Infrastructure.** The groundwater extraction and injection system would be designed to provide aboveground treatment and hydraulic containment of Phase IIb lower RGA source zone TCE contamination. Extraction wells would operate at a total of approximately 60 to 80 gal per minute (gpm). The treated water will be discharged to an existing outfall (re injection will be evaluated in the remedial design to optimize mass recovery and hydraulic performance). An extraction flow rate of 60 to 80 gpm would be expected to create the capture zone necessary to draw groundwater flowing through the C-400

RGA source treatment zone into extraction wells. Factors that would affect the size and shape of a capture zone at the C-400 site include the following (EPA 1996):

- Initial hydraulic gradient and hydraulic conductivity,
- Heterogeneities,
- The location and pumping rate of extraction and injection wells, and
- The screened interval of extraction and injection wells.

The proposed extraction-injection system for the C-400 site was developed using information available from the existing PGDP Northwest Plume Pump-and-Treat System. The hydraulic gradient (0.0001), hydraulic conductivity (100–750 ft/day), and aquifer thickness (25 ft to 36 ft) present at the C-400 site would be comparable to those at the Northwest Plume treatment site. Based on this assumption, a horizontal capture zone of approximately 500 ft potentially could be attained in the area of the C-400 RGA source zone. Groundwater quality samples and hydraulic head measurements would be used to verify TCE mass removed and hydraulic containment of the source treatment zone area during extraction. The current conceptual design includes three extraction/injection wells and an option to discharge to an existing KPDES outfall. The RDR, however, will include an evaluation of various extraction and injection scenarios to determine the optimal configuration.

Extracted groundwater would be routed through an aboveground treatment system consisting of an air stripper and off-gas treatment, such as granular activated carbon, to remove TCE before discharge of the treated vapor to the atmosphere (see Figure A.8). Treated water from the air stripper would be passed through ion exchange resin for technetium-99 removal prior to reinjection into the aquifer. Before water is discharged to the KPDES outfall, it also will undergo treatment via liquid phase activated carbon for additional TCE removal.

**Long-Term Groundwater Monitoring.** Alternative 2 includes the use of long-term groundwater monitoring to measure changes in the rate of TCE contamination migrating from the C-400 RGA source zone area to downgradient portions of the RGA. Existing downgradient monitoring wells would be used for this task. A three-well cluster (MW505/MW506/MW507) has been installed upgradient of the C-400 source zone. Potential existing downgradient wells that could be sampled include those near the treatment area (e.g., MW155, MW156, MW405, MW406, MW407, and MW408) and those downgradient wells more distal from the source treatment area (e.g., MW175, MW421 through MW425, MW342, and MW343). These wells would provide groundwater quality results from the upper, middle, and lower portions of the RGA. The current 2012 Environmental Monitoring Plan includes sampling the near source wells for VOC analysis quarterly and the distal downgradient wells semiannually. Specific groundwater monitoring requirements would be included in the RAWP.

#### **A.5.1.3 Alternative 3—*In Situ* Chemical Oxidation**

Alternative 3 consists of *in situ* treatment followed by monitoring. Components of the remedy are listed below:

- Thirteen groundwater extraction/injection wells in a five-spot pattern to allow for subsurface amendment addition;
- Addition of oxidants through injection and/or recirculation using a batch oxidant delivery system with a recirculation manifold;
- Secondary waste management;

- Long-term monitoring.

A cross-section schematic of the Alternative 3 is provided in Figure A.10.

The amount of oxidizer injected will be based on the existing sorbed and dissolved mass estimate. Options for chemicals include peroxide, persulfate, or permanganate. The actual selection of the treatment additive will be determined in the remedial design and adjusted based on actual concentration data. Following injection, the system will be monitored initially to confirm residual oxidant. When the oxidant is no longer present, the groundwater will be analyzed for TCE. If the TCE is sorbed to the soils and dissolved in the groundwater, this alternative is expected to be successful. If the mass also includes dispersed DNAPL ganglia, the technology will be successful, albeit requiring more amendment. If, however, the residual DNAPL is in isolated pools, the selection of the amendment will have to be considered. There are limitations on the effectiveness of permanganate in treating DNAPL because the residual manganese dioxide precipitant left by the TCE/permanganate reaction will form an ash layer around the TCE globules that will restrict further reaction.

**Infrastructure.** A critical factor to the success of *in situ* treatment projects is the effective distribution of amendments in the subsurface to allow for sufficient contaminant-amendment contact. The following conceptual approach and infrastructure have been developed in an effort to optimize these aspects of *in situ* treatment while still providing enough flexibility to allow for effective groundwater extraction and recirculation.

The conceptualized 13 well, 5-spot pattern of injection, extraction, and monitoring wells presented in Figure A.11 would be utilized to provide sufficient distribution of oxidant reagent in the subsurface. The type and physical form of an oxidant has specific material handling and injection requirements. The equipment required for injection of permanganate, peroxide, Fenton's reagent, and persulfate are similar. The 5-spot grid is located such that the smallest well spacing that still overlies the areal extent of contamination is achieved. Additionally, the well field pattern is located such that impacts to active operations at the C-400 Building would be limited (i.e., wells are not located in the area of the roll-up doorways along the south side of the building). The wells and the reagent delivery system would include a recirculation manifold that would allow for wells either to inject or extract during a reagent delivery event. This pattern is designed to allow for operational flexibility and maximum control of the transport of reagents to the contaminants in the subsurface. The well spacing and locations will be evaluated and optimized with the aid of numerical modeling simulations as a part of the design and work plan development process.

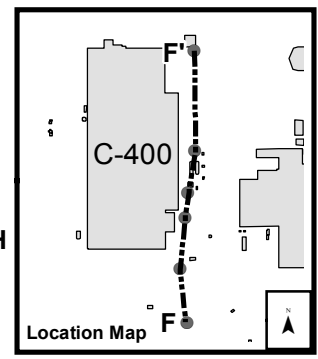
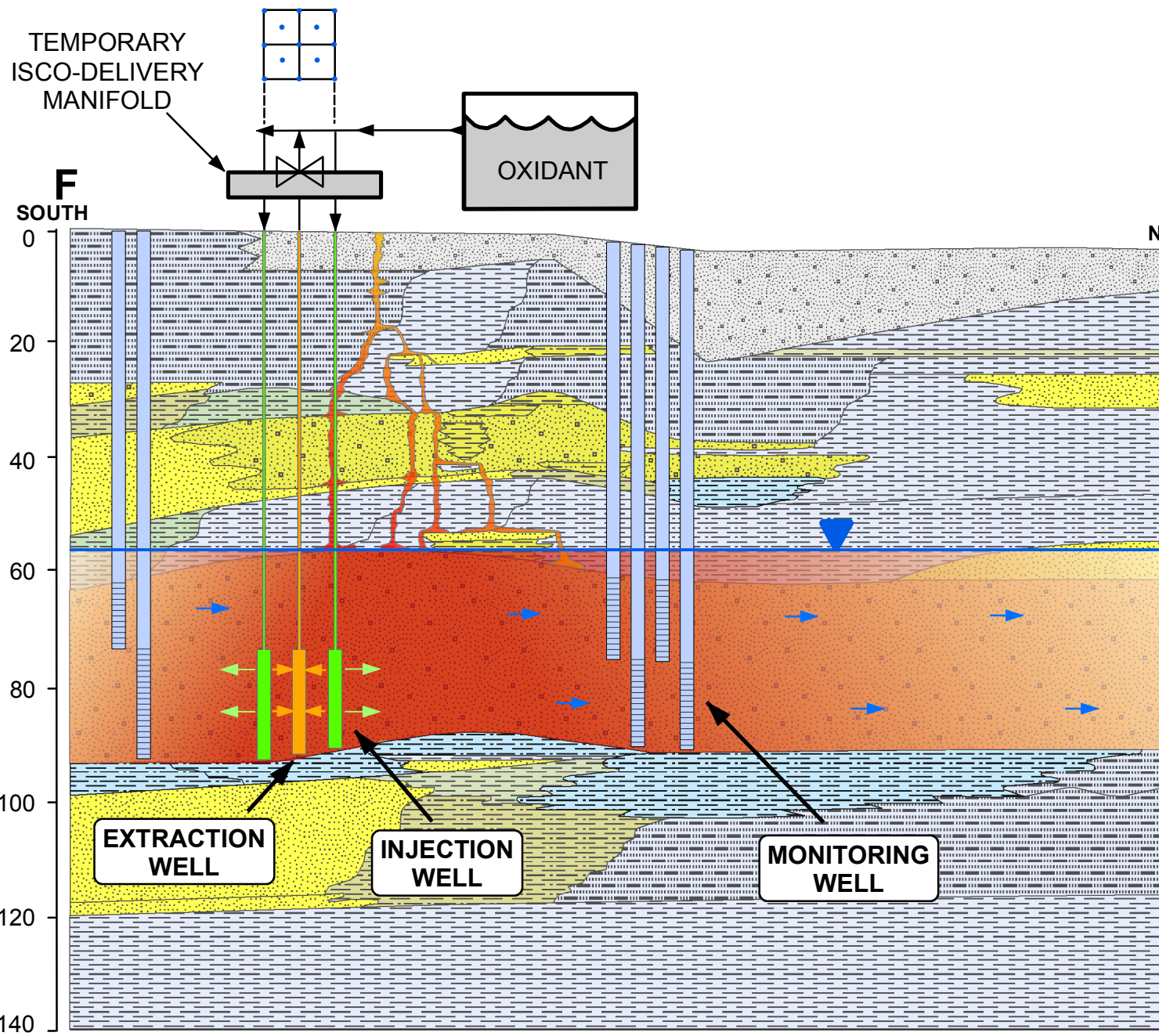
Wells and other *in situ* treatment system infrastructure would be constructed of materials that are compatible with the conditions and processes to which they would be exposed during the action. To the extent practicable, wells should be screened adjacent to the contamination at intervals that are appropriate for groundwater extraction and/or amendment circulation. Specific screening intervals would be evaluated during remedial design.

Other equipment and utilities required during *in situ* treatment activities include the following:

- Water supply for dissolution and/or dilution of the reagent,
- Amendment mixing apparatus,
- Batch storage tanks, and
- Electrical supply or generator.

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- Legend**
- C-400 X-Section**
- FILL
  - SILT
  - SANDY SILT
  - CLAYEY SILT
  - SAND
  - SILTY SAND
  - GRAVELY SAND
  - CLAYEY SAND
  - GRAVEL
  - SANDY GRAVEL
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  - CLAYEY GRAVEL
  - CLAY
  - SILTY CLAY
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  - SANDY SILTY CLAY

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Figure A.10. C-400 Phase IIb Interim Remedial Action Schematic Cross-section View of Alternative 3-ISCO Injection

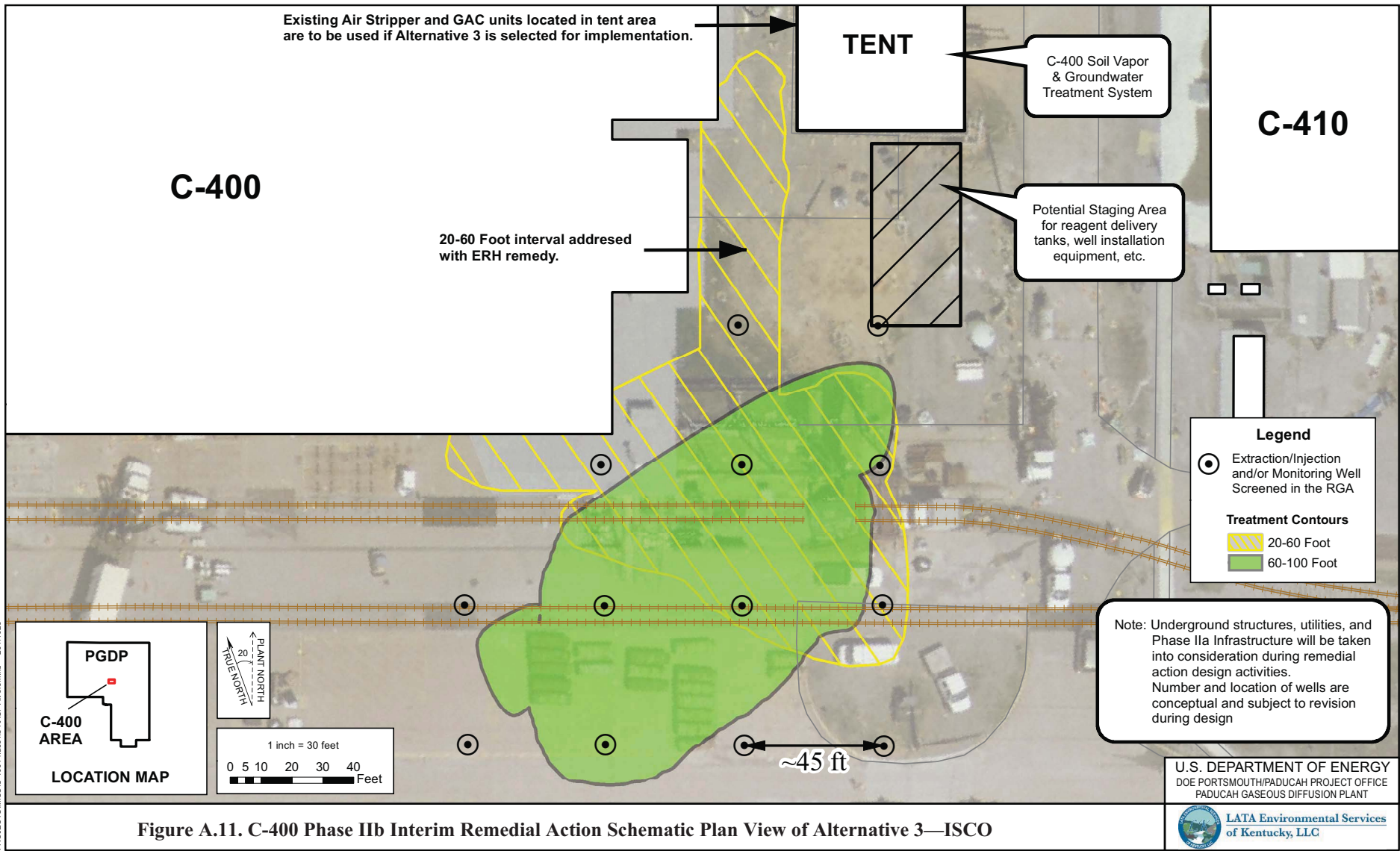


Figure A.11. C-400 Phase IIb Interim Remedial Action Schematic Plan View of Alternative 3—ISCO

**ISCO Treatment Design Considerations.** The following factors represent design challenges and considerations that would have to be taken into account if Alternative 3 were selected:

- Anticipated concentration and volume of amendment that potentially would be required to oxidize the estimated TCE mass present in the C-400 RGA source zone,
- Expected transport distances for each amendment, and
- Injection rate considerations.

The concentration and volume of oxidant required is dependent on the following factors:

- Stoichiometric demand on contaminants present in the C-400 RGA source zone,
- Soil oxidant demand,
- Oxidizable organic carbon, and
- Decomposition rate of the selected oxidant.

The transport distance of the oxidant in the subsurface is dependent on the following:

- Delivery method,
- Persistence of oxidant in the subsurface (based on oxidant stability, reaction speed, and oxidant half life),
- Groundwater flow rate,
- Density of reagent, and
- Characteristics of the porous media (e.g., greater conductivity results in increased transport distance).

During the design phase of an *in situ* chemical treatment project, consideration must be given to the chemical injection method and rate. Specifically, the advantages and disadvantages associated with pressurized injection versus gravity feed should be evaluated thoroughly. Potential advantages of using pressurized injection include potentially faster lateral transport and less plug flow displacement. Typical concerns with this delivery technique related to hydraulic fracturing are moot because the high hydraulic conductivity of the RGA will allow injection of significant volumes of amendment with little change in hydraulic head. In some cases, a gravity feed injection system may facilitate greater contaminant contact because the chemical is not being “forced” to travel along a path of least resistance. For the purposes of this conceptual design, pressurized injection of reagent has been assumed. Groundwater extraction and recirculation could be implemented to control/enhance the directional transport of the oxidant.

For cost estimating purposes, potassium permanganate is the assumed oxidant. The amount of potassium permanganate is based on 4,000 gal (48,800 lbs) of TCE and an oxidation efficiency of 20%. Results of Permanganate Natural Oxidant Demand testing from the Phase II area were all < 5g potassium permanganate/kg soil.

**Long-Term Groundwater Monitoring.** Alternative 3 includes the use of long-term groundwater monitoring to measure changes in the rate of TCE contamination migrating from the C-400 RGA source zone area to downgradient portions of the RGA. Existing downgradient monitoring wells would be used for this task. A three-well cluster (MW505/MW506/MW507) has been installed upgradient of the C-400 source zone. Potential existing downgradient wells that could be sampled include those near the treatment area (e.g., MW155, MW156, MW405, MW406, MW407, and MW408) and those downgradient wells more distal from the source treatment area (e.g., MW175, MW421 through MW425, MW342, and



MW343). These wells would provide groundwater quality results from the upper, middle, and lower portions of the RGA. The current 2012 Environmental Monitoring Plan includes sampling the near source wells for VOC analysis quarterly and the distal downgradient wells semiannually. Specific groundwater monitoring requirements would be included in the RAWP.

#### **A.5.1.4 Alternative 4—ERH**

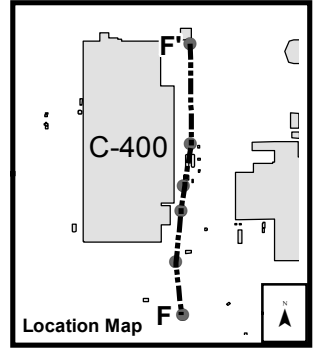
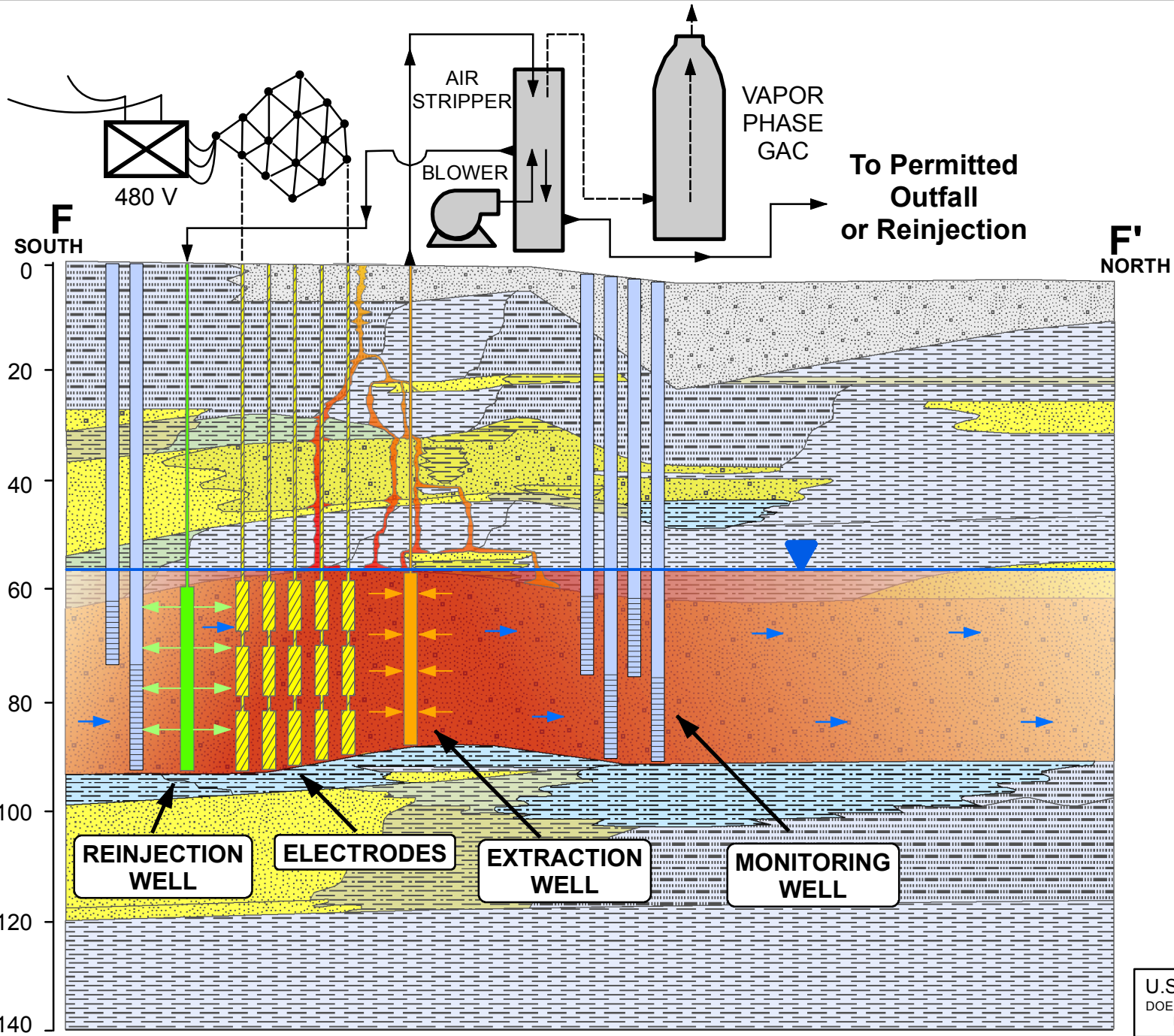
Alternative 4 consists of the remedy selected in the C-400 IRA ROD (Alternative 3) with enhancements based on numerical simulation results for the lower RGA and based on lessons learned from Phase I of the C-400 IRA. A thorough description of the background information and performance of Phase I is presented in the Technical Performance Evaluation (DOE 2011a).

Cross-section and plan view schematics of the alternative are provided in Figures A.12 and A.13, respectively.

As described in Section 2.9.3 of the C-400 IRA ROD, the ERH alternative consists of the following:

- Installation of the ERH array;
- Withdrawal of TCE and other VOCs and steam by high vacuum extraction;
- Treatment of soil vapor by an appropriate, applicable technology (e.g., catalytic oxidation, thermal oxidation, and/or activated carbon);
- Treatment of steam condensate and water by an appropriate, applicable technology (e.g., ion exchange, air stripping, and/or activated carbon);
- Discharge of treated groundwater through a KPDES outfall;
- Removal and disposition, as appropriate, of interfering, nonessential, miscellaneous infrastructure(s) in the area to be treated;
- Long-term monitoring; and
- LUCs.

Enhancements to the ERH design necessary for RGA heating identified as a result of Phase I lessons learned and based on numerical modeling results included an increased number of electrodes and extraction wells, and increases in the required energy input, vapor extraction rates, groundwater extraction rates, and vacuum level at the extraction wells. A comparison of the original design and the simulation-based upgrade for heating the lower RGA is provided in Table A.2.



- Legend**
- C-400 X-Section**
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  - SANDY SILT
  - CLAYEY SILT
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  - SILTY SAND
  - GRAVELLY SAND
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  - CLAYEY GRAVEL
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  - SILTY CLAY
  - SANDY CLAY
  - SANDY SILTY CLAY

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Figure A.12. C-400 Phase IIb Interim Remedial Action Schematic Cross-section View of Alternative 4-ERH

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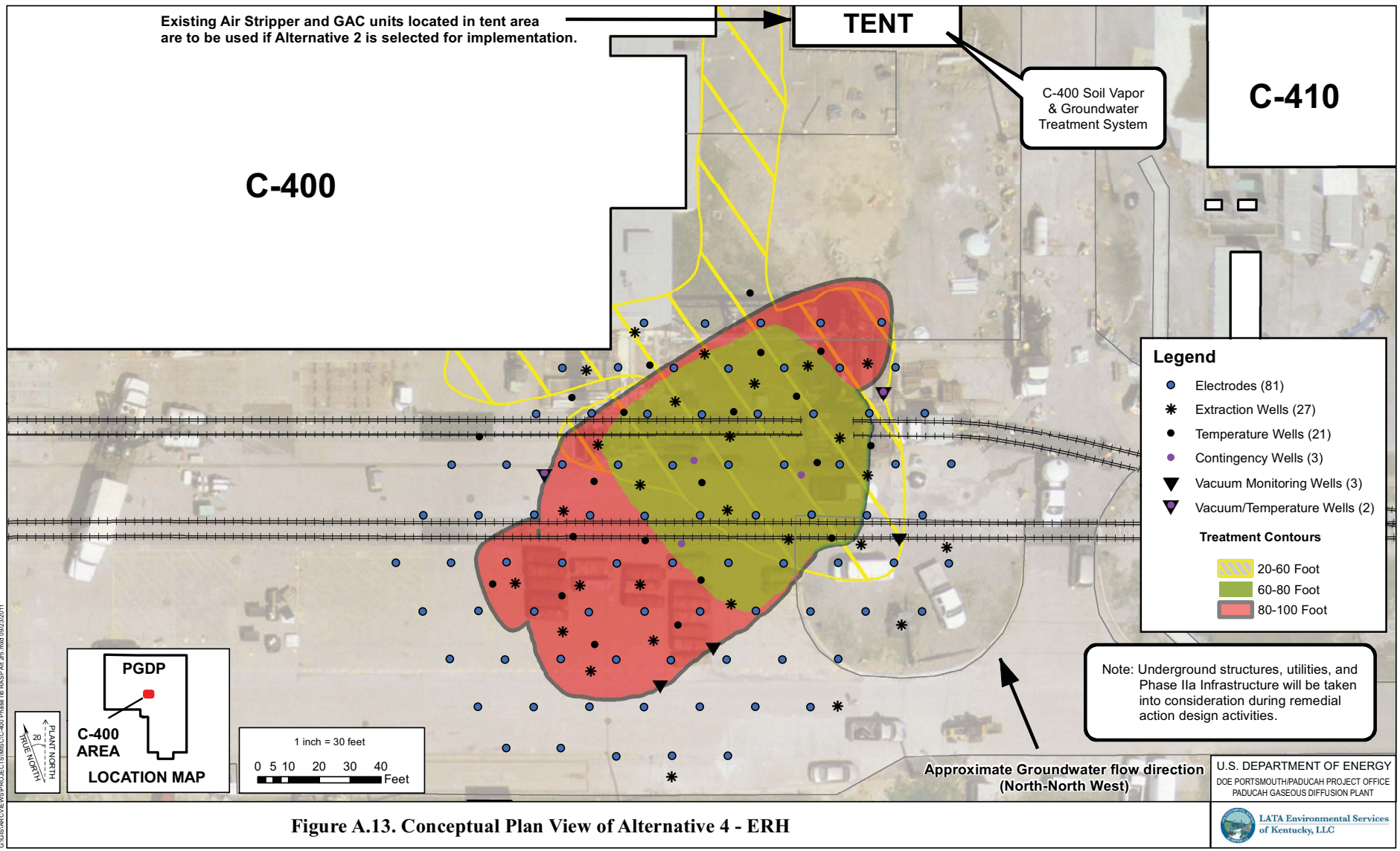


Figure A.13. Conceptual Plan View of Alternative 4 - ERH

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**Table A.2. Phase II Design Revisions**

| <b>Component</b>                      | <b>Original Phase IIb Design<br/>(Lower RGA)</b> | <b>Revised Phase IIb Design<br/>(Lower RGA)</b> |
|---------------------------------------|--|---|
| Electrode Borings                     | 46   | 81 <sup>a</sup>                                 |
| Electrodes:                           | 136  | 239   |
| U-D Electrodes                        | 46   | 81  |
| R-S Electrodes                        | 46   | 81  |
| R-D Electrodes                        | 44   | 77  |
| Extraction Wells                      | 16   | 27  |
| Vapor Only                            | 0  | 2   |
| Groundwater Only                      | 0  | 4   |
| Groundwater & Vapor                   | 16   | 21  |
| Contingency Extraction Wells          | 4  | 3   |
| DigiTAM™ Wells                        | 19   | 21  |
| Vacuum Monitoring Wells               | 4  | 3   |
| DigiTAM™/Vacuum Monitoring Wells      | 2  | 2   |
| Peak Power                            | 1,261 kW   | 2,623 kW  |
| U-D Electrodes                        | 7.2 kW/electrode                                 | 8.0 kW/electrode                                |
| R-SD Electrodes                       | 9.3 kW/electrode                                 | 12.5 kW/electrode                               |
| Average Power                         | 1,095 kW   | 2,242 kW  |
| U-D Electrodes                        | 6.2 kW/electrode                                 | 7.0 kW/electrode                                |
| R-SD Electrodes                       | 8.1 kW/electrode                                 | 10.6 kW/electrode                               |
| Total Energy (Nine Months Operations) | 7,096 MW-Hr                                      | 14,528 MW-Hr<br>(2812 MW-Hr) <sup>b</sup>       |
| Vapor Extraction Rate                 | 387 scfm   | 500 scfm  |
| Vacuum level at Extraction Wells      | 10 to 12 inches Hg                               | 12 to 18 inches Hg                              |
| Groundwater Extraction Rate           | 51 gpm   | 79.3 gpm  |
| Upgradient Wells                      | 9 gpm<br>(2 wells @ 4.5 gpm/well)                | 22 gpm<br>(4 wells @ 5.5 gpm/well)              |
| Other R-SD Wells                      | 42.0 gpm<br>(14 wells @ 3.0 gpm/well)            | 57.3 gpm<br>(19 wells @ 3.0 gpm/well)           |

D = deep; gpm = gal per minute; inches Hg = pressure in inches of mercury; kW = kilowatt; M = middle; MW-Hr = megawatt hours; R = RGA; ROM = Rough Order of Magnitude; S = Shallow; scfm = standard ft<sup>3</sup> per minute; U = UCRS

<sup>a</sup> The number of borings was increased from 78 to 81 after the numeric simulation as contingency to provide additional upgradient preheating of groundwater.

<sup>b</sup> Electricity for additional UCRS electrodes is required as a result of higher RGA electrode density.

### A.5.1.5 Alternative 5—Staged Implementation of Baseline/Rebound Analysis and *In Situ* Chemical Treatment

Alternative 5 is a staged approach consisting of the following:

- Stage 1: Establish baseline and rebound conditions in the target treatment volume by the following:
  - Baseline sample collection from a monitoring array within the treatment zone followed by cycled operation of a groundwater extraction system with aboveground treatment and associated rebound analysis, and/or
  - Baseline sample collection from a monitoring array within the treatment zone followed injection of an initial oxidant dose to suppress dissolved-phase VOC concentrations in the treatment zone, followed by an assessment of groundwater concentration and associated rebound.

It is envisioned that each of these approaches offer advantages for optimizing the implementation of Stage 2.

- Stage 2: Implement *in situ* chemical treatment:
  - Injection of chemical amendment using information obtained during Stage 1 regarding source mass distribution
  - Circulation of groundwater to distribute the chemical amendment and enhance contact of the amendment with the contaminant

This approach provides advantages by allowing the application of multiple technologies that can be matched with observed results and conditions to address the challenges associated with high dissolved concentrations of TCE and DNAPL in the RGA at the C-400 site.

Stage 1: The first stage is intended to increase the understanding of the distribution of TCE dissolved phase and source mass in the RGA within the Phase IIb treatment volume to allow for a refined selection and application of the amendment used in Stage 2. Stage 1 is expected to mitigate the risk associated with the uncertainty of TCE source mass distribution in the target treatment area.

A network of injection, extraction, and monitoring wells will be utilized to evaluate baseline and rebound conditions. Cross-section and plan views showing a conceptual implementation of the alternative are provided in Figures A.14 and A.15, respectively.

Baseline and rebound conditions will be evaluated by conducting cycled operation of a groundwater extraction system with aboveground treatment followed by rebound analysis. An alternate approach to obtaining information about baseline and rebound conditions would involve the introduction and circulation of an initial oxidant dose of chemical (e.g., 10 to 15% of the total design dose) to suppress dissolved-phase VOC concentrations followed by an assessment of groundwater concentrations and associated rebound. The specific approach, or combination of approaches, will be defined during the design and work plan development process.

Conceptually, the extraction and rebound analysis approach would consist of alternating cycles of centralized groundwater extraction with *ex situ* treatment and rebound evaluation. Groundwater would be extracted at 60 to 80 gpm from a centrally located well, while monitoring influent TCE concentrations. A

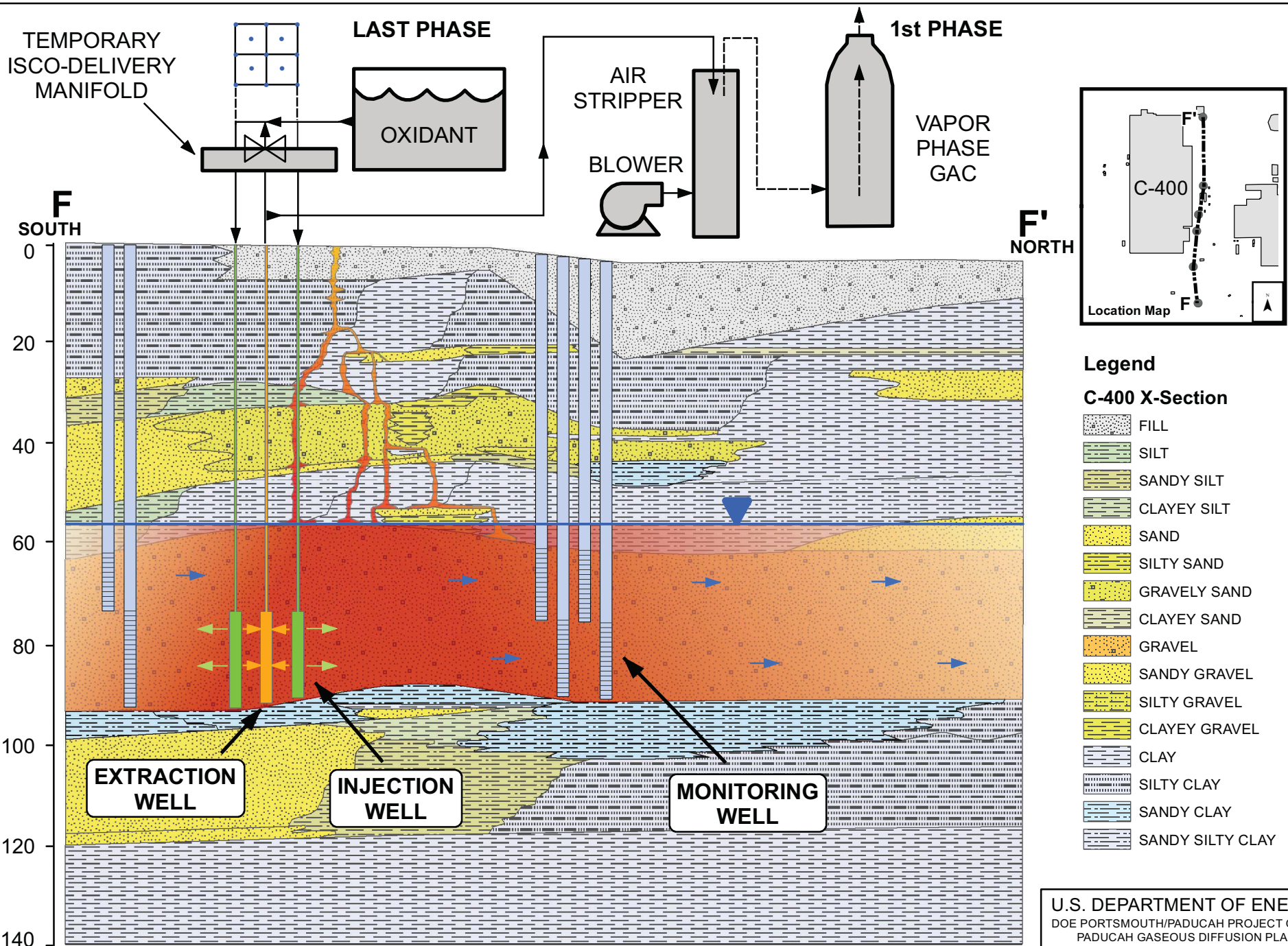


Figure A.14. C-400 Phase IIb Interim Remedial Action Schematic Cross-section View of Alternative 5—Staged Implementation of Baseline/Rebound Analysis and *In Situ* Chemical Treatment

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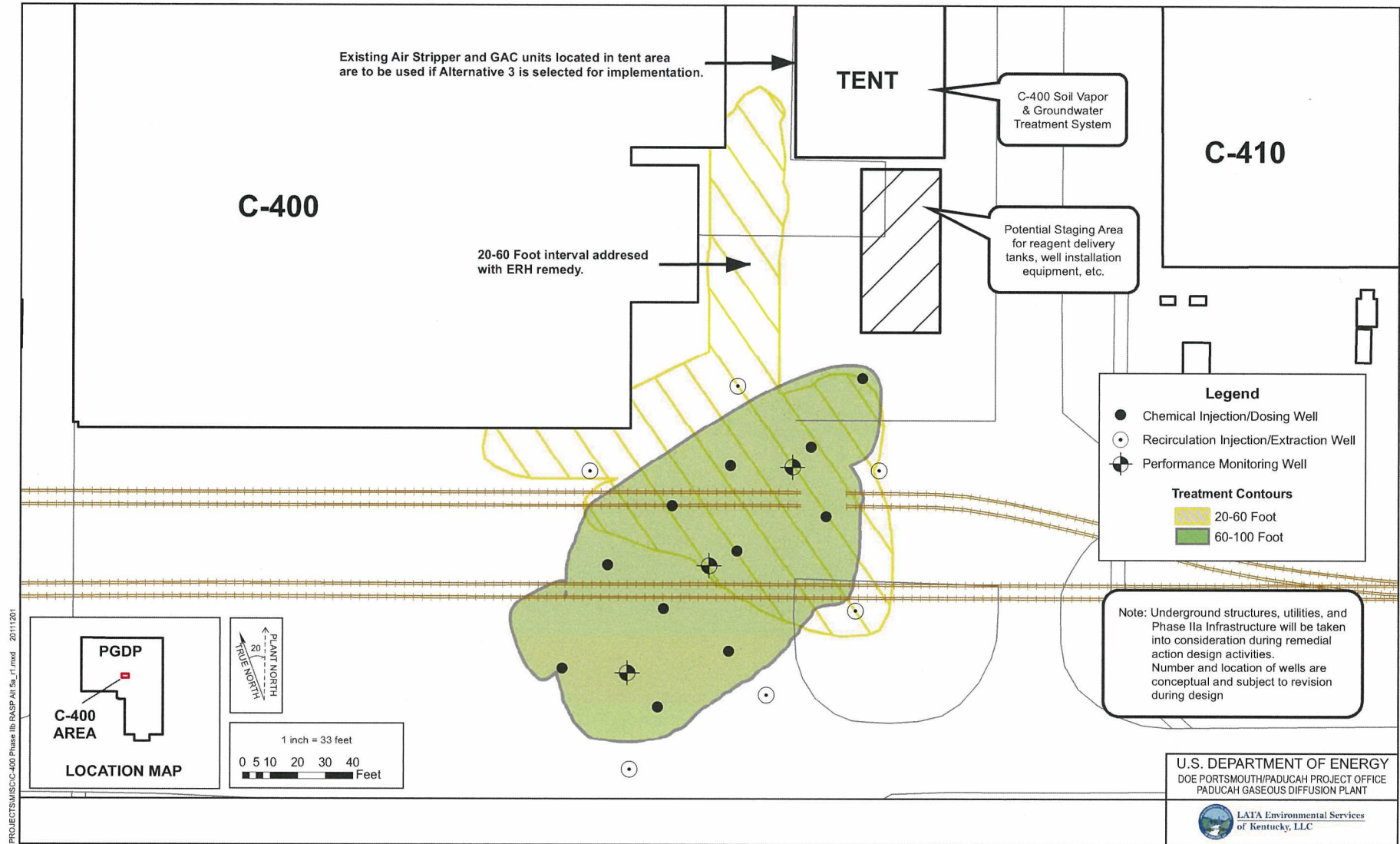


Figure A.15. C-400 Phase IIb Interim Remedial Action Schematic Plan View Alternative 5—Staged Implementation of Baseline/Rebound Analysis and *In Situ* Chemical Treatment

pore volume is expected to be extracted in a period of 10 days. Each extraction stage would be of a duration sufficient to recover multiple pore volumes from the target Phase IIb RGA treatment volume. In this approach for assessing baseline conditions, approximately 8 pore volumes would be extracted in a series of cycled extraction events. Monitoring results obtained between the extraction events would be used to evaluate rebound of the dissolved TCE in the RGA. Rebound analyses would be performed during three 30-day periods. Figure A.16 illustrates an example plot of TCE concentration versus pore volumes pumped. Rebound assessment would be conducted at performance monitoring wells to help determine the distribution of source-based mass compared to dissolved-phase mass. The rebound periods provide time for dissolution of TCE source-based mass into groundwater. Evaluation of the rebound concentrations in specific monitoring wells within the treatment volume will provide further understanding of the distribution of TCE mass in the subsurface.

The initial dosing and recirculation approach to evaluating baseline and rebound conditions would involve the injection and recirculation of an oxidant dose intended to satisfy the natural oxidant demand (NOD) and suppress dissolved-phase TCE concentrations in the treatment zone. The amount of oxidant to be injected would be determined during remedy design. Similar to the cycled extraction and rebound analysis approach, monitoring well sampling would be conducted to assess changes in groundwater concentration and associated rebound. If locations with low TCE concentrations are effectively treated by the initial dose and have a slow rebound effect that is not highly elevated, the location is probably not adjacent to a TCE source. If concentrations in MWs are initially elevated and increase and/or remain largely unchanged, these reflect strong indicators that the MW is screened within or adjacent to source material (with the need to focus the follow up chemical dosing events in this area). Similarly, if elevated concentrations drop significantly, but then rebound to initial levels, the data would suggest that a source of mass is located distal to the MW.

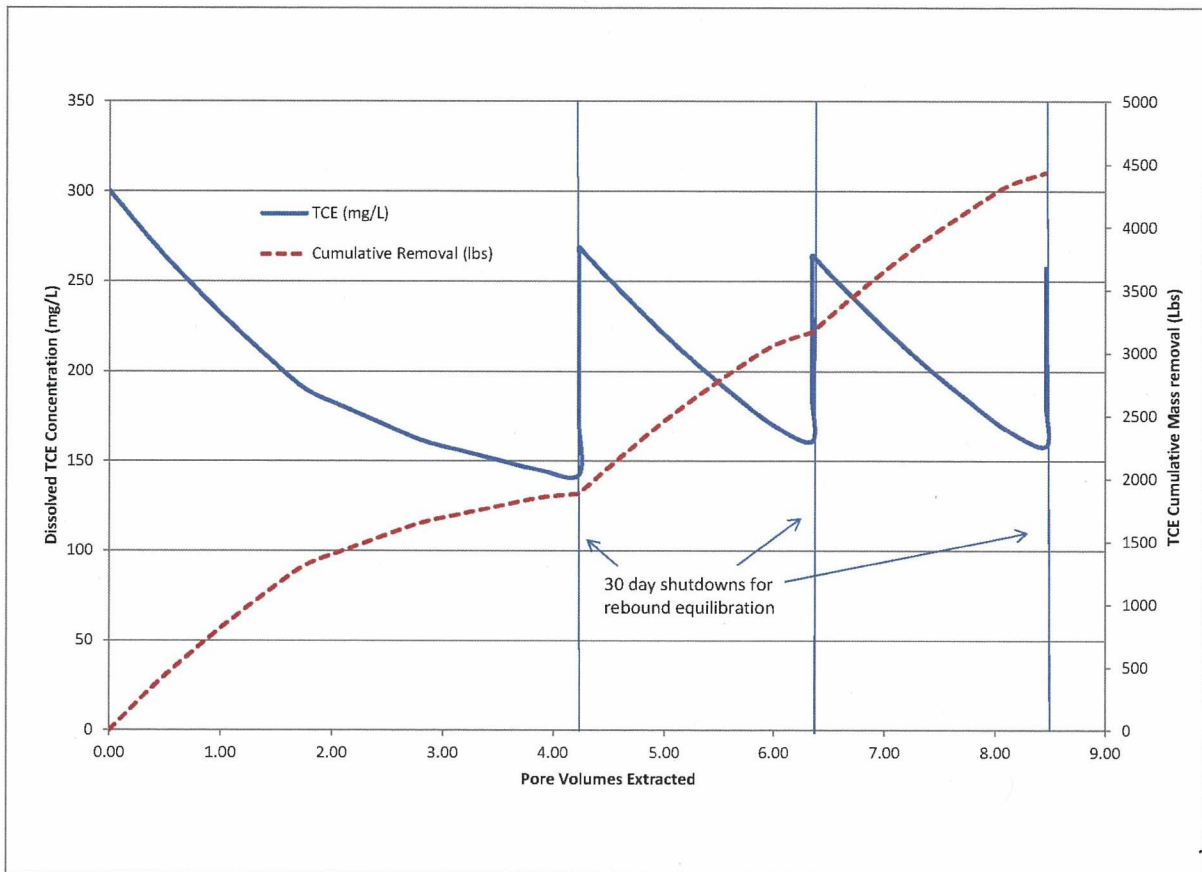
The extraction component of Alternative 5 is intended to provide information to facilitate Stage 2 and is not intended as an action for long-term dissolved-phase mass removal. The decision logic for moving to Stage 2 would be refined in the remedial design process.

Stage 2: Stage 2 of Alternative 5 would employ *in situ* chemical technologies to remove residual DNAPL source material followed by long-term monitoring. The specific *in situ* chemical or chemical combination (e.g., persulfate, peroxide, permanganate, EZVI, surfactant, or cosolvent) will be determined in the remedial design phase of the action. This stage of the alternative will utilize the flexible infrastructure such as extraction, injection, and monitoring well network used during Stage 1.

For cost estimating and comparison purposes, the following assumptions were made with respect to Alternative 5 (refer to Attachment A1 for additional estimate assumptions and cost details):

- To establish baseline and rebound conditions during Stage 1, the cycled groundwater extraction and rebound analysis approach is used.
- A network of chemical injection/dosing wells, extraction/recirculation wells, and performance monitoring wells is installed.
- The Stage 2 chemical amendment is potassium permanganate.
- The amount of potassium permanganate needed is based on the stoichiometric requirements for oxidizing 3,640 gal ( $\approx$  44,400 lb) of TCE, which accounts for approximately 360 gal ( $\approx$  4,400 lb) of TCE removed during groundwater extraction stages.
- An oxidation efficiency of 20% was used to account for NOD and delivery/contact inefficiencies.





**Figure A.16. Example TCE Concentration and Mass Removal Trends from Pulsed Groundwater Extraction Approach**

- An iterative oxidant loading approach is employed (4 events to inject the amount of potassium permanganate represented by bullet two).

**Infrastructure.** A critical factor to the success of *in situ* treatment projects is the effective distribution of amendments in the subsurface. Effective distribution is necessary in order to allow for sufficient contaminant-amendment contact. Figures A.14 and A.15 are intended to convey the conceptual approach and infrastructure needed for an *in situ* chemical treatment system, which provides enough flexibility during chemical injection, recirculation, groundwater extraction, and treatment.

The two stages of Alternative 5 would utilize a common infrastructure. The well field network for Alternative 5 would be designed to be capable of flexible operations for a variety of potential *in situ* treatment amendments. Wells would be constructed of materials that are compatible with the chemicals and injection processes utilized during Stage 2. Wells would be screened adjacent to the contamination at intervals that are appropriate for groundwater extraction and/or amendment recirculation. Specific screening intervals will be evaluated during remedial design. The example conceptual plan view shown in Figure A.15 consists of injection/extraction/monitoring wells positioned such that they overlie the areal extent of contamination and minimize impacts to active operations at the C-400 Building (i.e., wells are not located in the area of the roll-up doorways along the south side of the building). Chemical amendment would be injected and pulled through the subsurface by the use of recirculation extraction/injection wells. The well network and recirculation piping should be designed to allow for operational flexibility and

maximum control of and transport of reagents and contaminants in the subsurface. Actual well spacing and locations will be evaluated with the aid of numerical modeling simulations as part of the design process.

The system would be designed to provide flexibility to recirculate extracted groundwater with residual chemical amendments, if appropriate, or allow the water to be routed through an aboveground treatment system (likely consisting of an air stripper and vapor-phase GAC units). As shown on Figure A.14, water would pass through the air stripper where TCE would be stripped from the influent and the resulting TCE-laden vapors would be treated using vapor-phase GAC vessels. Liquid-phase effluent from the air stripper would be discharged to a KPDES outfall or may be reinjected to facilitate hydraulic control, if necessary.

**Long-Term Groundwater Monitoring.** Alternative 5 includes the use of long-term groundwater monitoring to measure changes in the rate of TCE contamination migrating from the C-400 RGA source zone area to downgradient portions of the RGA. Existing downgradient monitoring wells would be used for this task. A three-well cluster (MW505/MW506/MW507) has been installed upgradient of the C-400 source zone. Potential existing downgradient wells that could be sampled include those near the treatment area (e.g., MW155, MW156, MW405, MW406, MW407, and MW408) and those downgradient wells more distal from the source treatment area (e.g., MW175, MW421 through MW425, MW342, and MW343). These wells would provide groundwater quality results from the upper, middle, and lower portions of the RGA. The current 2012 Environmental Monitoring Plan includes sampling the near source wells for VOC analysis quarterly and the distal downgradient wells semiannually. Specific groundwater monitoring requirements would be included in the RAWP.

**Chemical Treatment Design Considerations.** The following factors represent design challenges and considerations that would have to be taken into account if Alternative 5 were selected:

- Anticipated concentration and volume of amendment that potentially would be required to remediate the estimated TCE mass present in the C-400 RGA source zone;
- Expected transport distances for each amendment; and
- Injection approach—high chemical amendment loading versus iterative loading.

The concentration and volume of amendment required may be dependent on some of the following factors:

- Stoichiometric demand on contaminants present in the C-400 RGA source zone,
- Soil oxidant demand,
- Oxidizable organic carbon,
- Decomposition rate of the chemical amendment, and
- Compatibility of surfactant and oxidant combinations.

The transport distance of the chemical amendment in the subsurface is dependent on the following:

- Delivery method,
- Persistence of the amendment in the subsurface (based on oxidant stability, reaction speed, and oxidant half life),
- Groundwater flow rate,

- Density of reagent, and
- Diffusive characteristics of the chemical and porous media (e.g., greater conductivity and gradient result in farther the transport distance).

During the design phase of an *in situ* chemical treatment project, consideration must be given to the chemical injection method and rate. Specifically, the advantages and disadvantages associated with pressurized injection versus gravity feed should be thoroughly evaluated. Potential advantages of using pressurized injection include potentially faster lateral transport and less plug flow displacement. Typical concerns with this delivery technique related to hydraulic fracturing are moot because the high hydraulic conductivity of the RGA will allow injection of significant volumes of amendment with little change in hydraulic head. In some cases, a gravity feed injection system may facilitate greater contaminant contact because the chemical is not being “forced” through a path of least resistance.

## **A.6. ANALYSIS OF ALTERNATIVES**

The following section presents an analysis of the alternatives developed in Section 5. The alternatives are analyzed with respect to the seven CERCLA threshold and balancing criteria. Modifying criteria include state and community acceptance, which are not included in this analysis. The relative performance of each alternative is presented, as well. The comparative evaluation identifies key tradeoffs decision makers must balance when selecting a remedy.

It should be noted that assessment of the no action alternative has not been modified from the evaluation presented in the GWOU FS (DOE 2001). Implementation of this alternative would not provide overall protection of human health or the environment. Risks would remain uncontrolled, and RAOs would not be achieved. RAOs for the C-400 site are provided in Section 5.2.

### **A.6.1 THRESHOLD CRITERIA**

#### **A.6.1.1 Overall Protection of Human Health and the Environment**

Because Alternative 1 would not prevent exposure to the contaminants, it alone does not meet the threshold criterion of providing overall protection of human health and the environment. Alternatives 2, 3, 4, and 5 meet the threshold criterion of overall protection of human health and the environment when combined with restrictions on groundwater use. Alternatives 2, 3, 4, and 5 also would meet this threshold criterion through reduction of the VOC mass present in the C-400 RGA source area. The reduction in mass would result in a reduction in the migration of VOC contaminants to off-site POEs; thus, Alternatives 2, 3, 4, and 5 meet RAOs. Additionally, these alternatives will employ existing LUCs to achieve the objectives for this action listed in the current LUCIP. Alternatives 2, 3, 4, and 5 will leave residual amounts of TCE and other VOCs in the treated source zone that, if left alone, could continue to result in concentrations in groundwater greater than the MCL for TCE. Any residual TCE and other VOCs remaining at the completion of these alternatives would be addressed during other evaluations of the Groundwater OU and/or the Comprehensive Site Operable Unit.

#### **A.6.1.2 Compliance with Applicable or Relevant and Appropriate Requirements**

ARARs contained in the ROD for C-400 are assumed to be appropriate and form an adequate basis for this analysis. ARARs will be reviewed for the selected alternative to determine if requirements should be added or deleted in addition to those listed in the current ROD. Attachment A3, Tables A3.1 through A3.3, contains the ARARs from the ROD and Table A3.4 contains additional ARARs for chemical treatment.

Alternative 1 would not be compliant with ARARs.

Alternatives 2, 3, 4, and 5 would meet this threshold criterion. Tables A3.1 through A3.3 presented in Attachment A3 of this document are taken from Appendix A of the C-400 IRA ROD and summarize compliance with chemical-specific, action-specific, and location-specific ARARs, respectively (DOE 2005). Although not included originally in the GWOU FS as fully developed alternatives, groundwater extraction and surface treatment (Alternative 2) was included in the GWOU FS; therefore, Alternatives 2 through 5 meet the ARARs included in Attachment A3.

## **A.6.2 BALANCING CRITERIA**

### **A.6.2.1 Long-Term Effectiveness and Permanence**

Long-term effectiveness and permanence refers to the period after the remedial action is complete.

Alternative 1 would not reduce the migration of the VOC contaminants to off-site POEs. Exposure to contaminated groundwater by on-site industrial workers would not be prevented with the implementation of the no action alternative.

Alternative 2 would yield moderate long-term effectiveness due to long-term tailing of concentrations inherent with a groundwater extraction strategy. Additionally, any residual mass following implementation of this option would result in rebound to the groundwater.

Alternative 3 would yield a higher long-term effectiveness for C-400 than Alternative 2 due to the *in situ* technology addressing both dissolved phase mass along with mass sorbed to the matrix. The technology destroys the contaminants resulting in long-term permanence.

The long-term effectiveness of Alternative 4 has the potential to be affected adversely by conditions in the RGA at the C-400 site that hinder overall mass removal. The deep, highly permeable, high flow conditions present in the lower RGA have been shown to have substantial impact on the ability to attain target temperatures. The overall mass removal during ERH is substantially dependent on the attainment of target temperatures. If target temperatures were not reached in the lower RGA, reduction in VOC mass would occur only through groundwater extraction, which would be limited by low flow rates (3 gpm per extraction well) and the dissolution rate of DNAPL contamination into the aqueous phase. In this respect, if target temperatures were not achieved in the lower RGA, the ERH alternative essentially would become a thermally enhanced groundwater extraction remedy that likely would be less efficient than Alternatives 2 and 3. Although the potential for effective remediation of the lower RGA is low, possible contingency actions could be taken to increase the possibility of reaching target temperatures. These actions are described in Section 4. If contingent actions were implemented and target temperatures were reached throughout the RGA, significant mass removal could be achieved using ERH; however, the spacing of wells/electrodes could be limited by subsurface utilities that are located within the Phase IIb source area. Electrodes potentially would be offset from the modeled location due to the presence of subsurface utilities, which would decrease the effectiveness of the remedy.

Alternative 5 results in enhanced long-term effectiveness in comparison to Alternative 3, based on collection of key information regarding DNAPL distribution during Stage 1. Stage 1 of Alternative 5 mitigates the risk associated with the uncertainty of the TCE source mass distribution. The technologies included in Stages 1 and 2 of Alternative 5 have proven industry applications, and provide redundancy that addresses the limitations of each technology as a stand-alone remedy. The implementation of this sequential, staged approach provides flexibility that would be capable of managing uncertainties associated with remediation of the RGA at the C-400 site, which results in a high probability of substantial removal of VOC mass. Therefore, Alternative 5 has a greater potential for more overall mass removal compared to the other alternatives.

### **A.6.2.2 Short-Term Effectiveness**

No further actions would be implemented under Alternative 1; therefore, no additional risks to workers, the public, or the environment would be incurred. No administrative or engineering controls would be implemented as part of alternative; thus, there would be the potential for an unacceptable risk to excavation workers and off-site residents.

LUCs, monitoring, and process controls employed during remediation of Alternatives 2, 3, 4, and 5 would be protective of the public throughout construction and implementation of the remedy. The C-400 site is not located near any residential population, and the effects of construction and installation activities during implementation of Alternatives 2 through 5 on outlying communities would be negligible because of the continued access restrictions, which would eliminate the exposure risks.

Although the H&S risks posed to workers during active remediation are considered manageable for Alternatives 2, 3, 4, and 5, the potential for worker exposure during infrastructure construction would be higher for Alternative 4 than for Alternatives 2, 3, and 5 due to the significant amount of drilling required. Workers would be required to use Level B personal protective equipment (PPE) during drilling at the C-400 site. Alternative 4 includes substantially more drilling activity than Alternatives 2, 3, and 5, which increases the potential for heat stress in Level B PPE and increases the potential for worker exposure to contaminants present in the subsurface at the C-400 site. Thermal and electrical hazards also would be a concern while implementing Alternative 4. Alternatives 2 through 5 involve the installation of wells, which has the potential to expose workers to subsurface contamination present at the C-400 site. In addition, Alternatives 3 and 5 would involve the storage and management of hazardous materials associated with chemical oxidation, which would need to be addressed as part of the site H&S strategy.

No ecological impacts at the C-400 site are anticipated under Alternatives 1 through 5. The C-400 site is located at an active operational facility already disturbed by construction and operational activities and does not support any unique or significant ecological resources. No known archaeological or historical sites or threatened and endangered species would be impacted by this alternative.

#### **A.6.2.3 Reduction of Toxicity, Mobility, and Volume through Treatment**

Treatment would not be implemented with Alternative 1. Reduction in contaminant mass and concentration would be achieved very slowly through natural attenuation processes, such as dilution, dispersion, and biodegradation of VOCs in RGA soils and groundwater.

Alternatives 2 and 3 both provide reductions of contamination mass through treatment. Alternative 4 would provide thermally enhanced removal of VOCs with aboveground treatment. Alternative 5 would provide treatment via extraction coupled with aboveground treatment during Stage 1 and *in situ* destruction of VOC mass during Stage 2.

The anticipated performance of the specific treatment technologies employed in combination by Alternative 5 provides a greater probability of substantial mass removal than Alternative 4. As discussed in Section 6.2.1, Long-Term Effectiveness and Permanence, the overall mass removed during ERH is substantially dependent on the attainment of target temperatures which, based on conclusions drawn as a result of Phase I operations and a simulation study, presents significant uncertainty associated with the reduction in VOC mass. If temperatures could be attained, ERH potentially could remove substantial amounts of VOC mass in the RGA.

#### **A.6.2.4 Implementability**

Implementability is a measure of both the technical and administrative feasibility of constructing, operating and maintaining a remedial alternative and is used during screening to evaluate combinations of process options with respect to site conditions. Technical feasibility refers to the ability to construct, reliably operate, and meet the technology-specific regulations for process options until the remedial action is complete. It also includes O&M, component replacement, and monitoring. The determination that an alternative is not technically feasible and is not available will usually preclude it from further consideration unless steps can be taken to change the conditions responsible for the determination.

Typically this type of “fatal flaw” would have been identified during the technology screening and the infeasible alternative would not have been assembled.

Alternative 1 would involve no actions and, therefore, is technically implementable.

Implementability constraints for Alternatives 2 and 3 would include operational considerations adjacent to the C-400 Building; however, the prior implementation of ERH in Phase I demonstrates that the operational hurdles can be addressed safely. Alternative 2 has fewer extraction points and surface equipment. Alternative 3 includes more drilling, but does not have the additional surface equipment. Both Alternatives 2 and 3 are proven technologies and considered relatively straightforward to implement. Alternative 3 has additional considerations in the handling and injecting oxidant.

Alternative 4 is more complex than Alternatives 2 and 3 with respect to drilling, electrodes, and surface equipment. The technical complexity of Alternative 4, operational considerations at the C-400 Building, few vendors offering the technology, and the worker protection issues discussed previously under short-term effectiveness lead to additional challenges for Alternative 4. Existing surfaces and infrastructure potentially could be affected significantly by the substantial drilling activities required to implement Alternative 4, as well as have a negative impact on active operations at the C-400 Building. The installation of several wells/electrodes would have to be conducted in the roll-up door access area on the southeast corner of the C-400 Building, which could result in increased logistical and scheduling considerations.

Alternative 4 also would involve a fairly high level of technical complexity. Active operations at the C-400 Building would be a logistical factor that would impact implementation of Alternative 4 as well. The location of extraction-injection wells is not within the roll-up door access area on the southeast corner of the C-400 Building, which potentially would lessen negative impacts to the logistics and schedule of Alternative 4.

Based on the evaluation of the ERH in Phase I and the technical hurdles to attaining target temperatures for this technology to be effective, Alternative 4 is considered to have a “fatal flaw” for implementation success in addressing the permeable lower RGA unit in Phase IIb; however, the alternative is included in this analysis to allow comparison to the prior selected remedy for C-400 IRA ROD.

Equipment, personnel, and services required to implement Alternatives 2, 3, 4, or 5 are readily available commercially. No additional development of the technologies incorporated into these alternatives would be required. Contractors possessing the required skills and experience are available. Long-term O&M would be required for Alternative 2. No O&M would be required after completion of Alternatives 3, 4, or 5; however, long-term groundwater monitoring and five-year reviews would be required until selection of a final remedy.

It is anticipated that Alternatives 2, 3, and 5 would be more implementable than Alternative 4.

#### **A.6.2.5 Preliminary Costs**

Preliminary rough order of magnitude capital and O&M costs for Alternatives 2 through 5 are provided in Attachment A1. Costs are preliminary in nature due to the uncertainties associated with the amount of contamination present in the RGA at the C-400 site. Phase II sampling is complete and provides sufficient basis to determine the remedy most likely to be effective, implementable, and cost-effective in the RGA

at the C-400 site.<sup>1</sup> Long-term monitoring costs have not been estimated for this source action. This is consistent with the evaluation of costs as presented in the current ROD.

Alternative 2 costs include the following:

- Three wells used for extraction/injection (included in capital costs),
- Surface treatment equipment capable of processing 60 to 80 gpm flow (air stripper with vapor phase granular activated carbon for offgas treatment), and
- O&M costs for groundwater extraction for 20 years.

Alternative 3 costs include the following:

- Thirteen injection/recirculation wells arranged in a five-spot (included in capital costs),
- Batch injection/recirculation of oxidant and amendment mixing and distribution equipment,
- Short-term monitoring to assess the performance of the *in situ* remedy, and
- O&M costs for ISCO for an assumed contaminant mass scenarios 4,500 gal ( $\approx$  54,900 lb) of TCE.

The lessons learned during Phase I of the C-400 IRA have been accounted for in the development of Alternative 4—ERH costs. ERH costs are based on the extensive changes in the base design recommended by the ERH subcontractor following completion of Phase I. The costs assume heating would be required across the entire RGA interval. Unlike Alternatives 2, 3, and 5, the O&M costs for ERH are independent of the mass present in the C-400 RGA source zone area.

Alternative 5 costs include the following:

- Six recirculation injection/extraction wells, eleven chemical dosing wells, and three performance monitoring wells (included in capital costs);
- Surface treatment equipment capable of processing 60 to 80 gpm flow (air stripper with vapor phase granular activated carbon for offgas treatment);
- O&M costs for groundwater extraction and surface treatment of for four months; and
- O&M costs for potassium permanganate to oxidize an assumed contaminant mass 4,140 gal ( $\approx$  50,508 lb) of TCE, which accounts for approximately 360 gal ( $\approx$  4,400 lb) of TCE removed during groundwater extraction stages.

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<sup>1</sup> CERCLA, at Section 121(a), states that “the President shall select appropriate remedial actions...which are in accordance with this section and, to the extent practicable, the national contingency plan, and which provide for cost-effective response.” Thus, cost-effectiveness is established as a condition for remedy selection, not merely as a consideration during remedial design and implementation. Further in the statute, at Section 121(b)(1), Congress again repeats the requirement that only cost-effective remedies are to be selected, as follows, “The President shall select a remedial action that is protective of human health and the environment, that is cost effective, and that utilizes permanent solutions and alternative treatment...to the maximum extent practicable.” Again, cost-effectiveness is cited along with protectiveness as a key factor to consider in selecting the remedy. EPA believes that the statutory language supports the use of concepts of “cost” and “effectiveness” in this rule’s nine evaluation criteria that provide the basis for the remedy selection decision, rather than as factors to be applied after the remedy has been selected.



Alternative 5 capital costs include the infrastructure used for all stages of the remedy, as well as the additional treatment components that may be necessary during mixing of oxidant and batch injection/recirculation. The capital and O&M ranges have been combined into the Alternative 5 scenario. A range of O&M costs are provided because the ISCO costs are directly dependent on the amount of mass present in the C-400 RGA source zone area.

A summary of the preliminary project costs for each alternative are presented in Table A.3.

**Table A.3. Summary of Present Value Costs for Alternatives 2 through 5**

| <b>Alternatives</b>   | <b>Mass Scenario</b>   | <b>Installation Costs</b> | <b>O&amp;M Costs</b> | <b>D&amp;D Costs</b> | <b>Total Project Cost</b> | <b>Comments</b>  |
|---|--|---------------------------|----------------------|----------------------|---------------------------|--|
| Alternative 2—<br>Groundwater<br>Extraction and <i>Ex Situ</i><br>Treatment   | Large mass,<br>slowly<br>depleting                                       | \$1.09M                   | \$13.36M             | \$0.40M              | \$14.85M                  | Readily implementable but limited by dissolution rate of TCE into groundwater.   |
| Alternative 3—<br><i>In Situ</i> Chemical<br>Oxidation  | 4,500 gal<br>(≈ 54,900 lb)<br>TCE present in<br>the lower RGA<br>only    | \$2.80M                   | \$2.37M              | \$0.77M              | \$5.94M                   | ISCO is cost-effective for lower mass.   |
| Alternative 4—<br>Electrical<br>Resistance<br>Heating   | Independent of<br>mass/assumes<br>heating is<br>required in<br>lower RGA | \$11.37M                  | \$5.28M              | \$1.58M              | \$18.23M                  | High risk if target temperature is not attained [ $< 1\%$ removal if $90^{\circ}\text{C}$ ( $194^{\circ}\text{F}$ ) is not reached in middle RGA and $95^{\circ}\text{C}$ in lower RGA]. |
| Alternative 5—<br>Staged<br>Implementation of<br>Baseline/Rebound<br>Analysis and <i>In Situ</i><br>Chemical<br>Treatment | 4,500 gal<br>(≈ 54,900 lb)<br>TCE present in<br>the lower RGA<br>only    | \$3.86M                   | \$2.97M              | \$0.89M              | \$7.72M                   | Provides further assessment of nature of TCE source. ISCO is cost-effective for lower mass.  |

### **A.6.3 SUMMARY OF COMPARATIVE ANALYSIS OF ALTERNATIVES**

Overall, Alternative 5 offers a cost-effective solution with lower project risk. In addition, many of the expected site conditions in the RGA at the C-400 site are optimal to the technologies that are included in Alternative 5. The saturated permeable conditions present in the RGA would be amenable to *in situ* treatment via injection of a reagent. Stage 1 of Alternative 5 mitigates the risk associated with the uncertainty of the TCE source mass distribution. Conversely, the Alternative 4 treatment technology is impacted adversely by conditions at the C-400 site, and there is significant uncertainty and associated

with reaching target temperatures in the RGA This uncertainty leads to a high project risk associated with Alternative 4.

Additionally, the implementability and short-term effectiveness ranking for Alternative 5 is higher than Alternatives 2, 3, and 4. Alternative 4 has a fatal technology flaw for implementation due to a high risk of not meeting the target temperature thus rendering ERH ineffective. The substantial amount of drilling that would be required to implement Alternative 4 would result in negative impacts on operations at the C-400 Building and increased worker H&S considerations. Alternative 2 requires limited penetrations (extraction/injection wells) with surface treatment equipment. Alternative 3 does require less surface equipment, but includes more subsurface penetrations. Alternative 5 includes the components of Alternatives 2 and 3, but much less infrastructure than required to implement Alternative 4.

Table A.4 provides a summary of the comparative analysis of Alternatives 1 through 5.

**Table A.4. Summary of the Comparative Analysis of Alternatives**

| <b>Criteria<sup>a</sup></b>                                   | <b>Alternative 1—No Action</b> | <b>Alternative 2—Groundwater Extraction and <i>Ex Situ</i> Treatment</b> | <b>Alternative 3—<i>In situ</i> Chemical Oxidation</b> | <b>Alternative 4—Electrical Resistance Heating</b> | <b>Alternative 5—Staged Implementation of Baseline/Rebound Analysis and <i>In Situ</i> Chemical Treatment</b> |
|---|--------------------------------|--|--|--|---|
| Overall Protection of Human Health and the Environment        | No                             | Yes  | Yes  | Yes  | Yes   |
| Compliance with ARARs   | No                             | Yes <sup>b</sup>   | Yes <sup>b</sup>                                       | Yes <sup>b</sup>                                   | Yes <sup>b</sup>  |
| Long-Term Effectiveness                                       | Low (1)                        | Low to Moderate (3)  | Moderate (5)   | Moderate to High (7)                               | Moderate to High (7)  |
| Short-Term Effectiveness                                      | Low (1)                        | Moderate (5)   | Moderate to High (7)                                   | Moderate(5)  | Moderate to High (7)  |
| Reduction in Toxicity, Mobility, and Volume through Treatment | Low (1)                        | Moderate(5)  | Moderate to High (7)                                   | Moderate(5)  | High (9)  |
| Implementability  | High (9)                       | Moderate (5)   | Moderate to High (7)                                   | Low (1)  | Moderate to High (7)  |
| Cost Effectiveness <sup>c</sup>                               | High (9)                       | Low to Moderate (3)  | Moderate to High (7)                                   | Low (1)  | Moderate to High (7)  |
| <b>Weighted average</b>                                       | <b>4.2</b>                     | <b>4.2</b>   | <b>6.6</b>   | <b>3.8</b>   | <b>7.4</b>  |

<sup>a</sup> Modifying criteria include state and community acceptance, which are not included in this analysis.

<sup>b</sup> Although these alternatives are not expected to meet the groundwater MCL for TCE, the alternatives satisfy the requirement set forth in 40 *CFR* § 300.430(f)(1)(ii) for interim measures that will become part of the total remedial action that will attain ARARs for groundwater, including MCLs for TCE, or satisfy the requirements of an ARAR waiver.

<sup>c</sup> A high overall cost rating corresponds to a low project cost relative to the site evaluated.

**Alternative Rating Guide:**

Balancing criteria are scored from 1 (worst) to 9 (best) for each alternative. The qualitative and numerical ratings correspond as follows:

- 9 – High
- 7 – Moderate to High
- 5 – Moderate
- 3 – Moderate to Low
- 1 – Low

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\* NDA = no date available

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**ATTACHMENT A1**

**PRELIMINARY COST ESTIMATES  
FOR ALTERNATIVES 2 THROUGH 5**



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**ALTERNATIVE 2**  
**GROUNDWATER EXTRACTION AND *EX SITU* TREATMENT**

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## Alternative 2 - Groundwater Extraction and Ex-situ Treatment

### Assumptions

#### **General**

- Developed in accordance with US EPA Guidance document EPA 540-R-00-002, *A Guide to Developing and Documenting Cost Estimates during the Feasibility Study*
- Contingency (Scope + Bid) was applied at 25%
- Professional and technical services were estimated based on guidelines in EPA 540-R-00-002 unless otherwise noted
  
- Present value analysis was performed using calendar year 2011 Real Discount Rates as provided in Appendix C of OMB Circular No. A-094. For the 21-year duration associated with this alternative the discount rate used was 2.1 percent.
- Estimate performed at the Detailed Analysis of Alternatives phase to provide a -30% to +50% estimate
- Does not include installation of additional monitoring wells as long-term monitoring will be in accordance with the current Environmental Monitoring Plan for the site

#### **System Installation**

- 3 extraction/injection wells
- Utilize existing SVGTS with planned steam regenerated carbon off gas treatment (no cost added for SVGTS)

#### **Operations and Maintenance**

- GW extraction assumed to be ongoing (for estimating purposes a 20-year operating period is assumed)
- Weekly samples collected from 4 sample locations (3 wells and system effluent)
- Samples analyzed for TCE only with 8-day turnaround time (1.5 times markup)

#### **Decommission, Dismantle, and Restore Site**

- Assume to occur in year 21
- All SVGTS equipment will be disposed of as scrap metal or in the onsite landfill

### Estimate Results

|  |    |                   |
|--|----|-------------------|
| Construction/Installation                      | \$ | 1,094,169         |
| GW Extraction and Ex-situ Treatment (20 years) | \$ | 13,357,734        |
| D&D and Site Restoration                       | \$ | 396,016           |
|  | \$ | <u>14,847,919</u> |

Present Value Analysis  
Alternative 2 - Groundwater Extraction and Ex-situ Treatment

| Year         | Capital Cost       | Annual O&M Cost     | Periodic Cost    | Total Cost          | Discount Factor at 2.1% | Total Present Value |
|--------------|--------------------|---------------------|------------------|---------------------|-------------------------|---------------------|
| 0            | \$1,094,169        | \$0                 | \$112,852        | \$1,207,021         | 1.00                    | \$1,207,021         |
| 1            | \$0                | \$817,851           | \$0              | \$817,851           | 0.98                    | \$801,030           |
| 2            | \$0                | \$817,851           | \$0              | \$817,851           | 0.96                    | \$784,554           |
| 3            | \$0                | \$817,851           | \$0              | \$817,851           | 0.94                    | \$768,417           |
| 4            | \$0                | \$817,851           | \$0              | \$817,851           | 0.92                    | \$752,613           |
| 5            | \$0                | \$817,851           | \$0              | \$817,851           | 0.90                    | \$737,133           |
| 6            | \$0                | \$817,851           | \$0              | \$817,851           | 0.88                    | \$721,971           |
| 7            | \$0                | \$817,851           | \$0              | \$817,851           | 0.86                    | \$707,122           |
| 8            | \$0                | \$817,851           | \$0              | \$817,851           | 0.85                    | \$692,578           |
| 9            | \$0                | \$817,851           | \$0              | \$817,851           | 0.83                    | \$678,333           |
| 10           | \$0                | \$817,851           | \$0              | \$817,851           | 0.81                    | \$664,381           |
| 11           | \$0                | \$817,851           | \$0              | \$817,851           | 0.80                    | \$650,716           |
| 12           | \$0                | \$817,851           | \$0              | \$817,851           | 0.78                    | \$637,332           |
| 13           | \$0                | \$817,851           | \$0              | \$817,851           | 0.76                    | \$624,223           |
| 14           | \$0                | \$817,851           | \$0              | \$817,851           | 0.75                    | \$611,384           |
| 15           | \$0                | \$817,851           | \$0              | \$817,851           | 0.73                    | \$598,809           |
| 16           | \$0                | \$817,851           | \$0              | \$817,851           | 0.72                    | \$586,493           |
| 17           | \$0                | \$817,851           | \$0              | \$817,851           | 0.70                    | \$574,430           |
| 18           | \$0                | \$817,851           | \$0              | \$817,851           | 0.69                    | \$562,615           |
| 19           | \$0                | \$817,851           | \$0              | \$817,851           | 0.67                    | \$551,043           |
| 20           | \$0                | \$817,851           | \$0              | \$817,851           | 0.66                    | \$539,709           |
| 21           | \$0                |                     | \$612,708        | \$612,708           | 0.65                    | \$396,016           |
| <b>Total</b> | <b>\$1,094,169</b> | <b>\$16,357,028</b> | <b>\$725,560</b> | <b>\$18,176,757</b> |                         | <b>\$14,847,919</b> |

| <b>Alternative 2 - Groundwater Extraction and Ex-situ Treatment</b> |      |             |               |               |       |              |                        |  |
|---|------|-------------|---------------|---------------|-------|--------------|------------------------|--|
| <b>Installation/Construction</b>                                    |      |             |               |               |       |              |                        |  |
| Description   | Qty. | Material    |               | Total         | Labor |              | Total Cost (M+L)       | Cost Basis   |
|   |      | Unit        | Unit Price    |               | hours | Total        |                        |  |
| <b>Construction</b>   |      |             |               |               |       |              |                        |  |
| Geologist   |      |             |               | \$ -          |       | \$ -         | \$ -                   | Assume construction to take 5 weeks at 50 hours per week (FTE = 250 hours) |
| Pipefitter  |      |             |               | \$ -          | 250   | \$ 17,500.00 | \$ 17,500.00           | 1 FTE  |
| Mechanic  |      |             |               | \$ -          | 750   | \$ 42,997.50 | \$ 42,997.50           | 3 FTE  |
| Electrician   |      |             |               | \$ -          | 750   | \$ 42,997.50 | \$ 42,997.50           | 3 FTE  |
| Laborer   |      |             |               | \$ -          | 500   | \$ 28,665.00 | \$ 28,665.00           | 2 FTE  |
| Escorts   |      |             |               | \$ -          | 500   | \$ 19,250.00 | \$ 19,250.00           | 2 FTE  |
| Radcon Technician   |      |             |               | \$ -          | 500   | \$ 28,665.00 | \$ 28,665.00           | 2 FTE  |
| PPE for CM - 2 changes per day - 10 FTEs for 25 days - Level D      | 500  | per man-day | \$ 15.78      | \$ 7,890.00   |       | \$ -         | \$ 7,890.00            |  |
|   |      |             |               |               |       |              | <b>\$ 230,962.50</b>   |  |
| <b>Drilling and Well Completion</b>                                 |      |             |               |               |       |              |                        |  |
| Mobilization -  | 1    | each        | \$ 39,620.00  | \$ 39,620.00  |       | \$ -         | \$ 39,620.00           |  |
| Injection/extraction well construction                              | 3    | each        | \$ 61,125.50  | \$ 183,376.50 |       | \$ -         | \$ 183,376.50          |  |
| Injection/extraction well development                               | 3    | each        | \$ 4,225.00   | \$ 12,675.00  |       | \$ -         | \$ 12,675.00           |  |
| Extraction well pumps/discharge piping                              | 3    | each        | \$ 7,589.45   | \$ 22,768.35  |       | \$ -         | \$ 22,768.35           |  |
| PPE upgrade markup  | 1    | LS          | \$ 3,127.70   | \$ 3,127.70   |       | \$ -         | \$ 3,127.70            | Scaled to 2.2% of ERH installation (3 borings versus 137 borings)          |
| Demobilization  | 1    | each        | \$ 15,000.00  | \$ 15,000.00  |       | \$ -         | \$ 15,000.00           |  |
| Solid/liquid waste management/disposition                           | 1    | LS          | \$ 37,180.26  | \$ 37,180.26  |       | \$ -         | \$ 37,180.26           | Scaled to 2.2% of ERH waste costs (3 borings versus 137 borings)           |
|   |      |             |               |               |       |              | <b>\$ 313,747.81</b>   |  |
| <b>Mechanical/Electrical Contractor</b>                             |      |             |               |               |       |              |                        |  |
| Surface header piping, valves, and other appurtanences              | 1    | LS          | \$ 100,000.00 | \$ 100,000.00 |       | \$ -         | \$ 100,000.00          |  |
| Instrumentation and control systems at wells                        | 1    | LS          | \$ 50,000.00  | \$ 50,000.00  |       | \$ -         | \$ 50,000.00           | Allowance  |
|   |      |             |               |               |       |              | <b>\$ 150,000.00</b>   |  |
|   |      |             |               |               |       |              | <b>\$ 694,710.31</b>   |  |
| <b>Professional and Technical Services</b>                          |      |             |               |               |       |              |                        |  |
| Project Management (6%)   |      |             |               |               |       |              | \$ 41,682.62           |  |
| Remedial Design (12%)   |      |             |               |               |       |              | \$ 83,365.24           |  |
| Construction Management (8%)  |      |             |               |               |       |              | \$ 55,576.82           |  |
|   |      |             |               |               |       |              | <b>\$ 180,624.68</b>   |  |
|   |      |             |               |               |       |              | <b>\$ 875,334.99</b>   |  |
| <b>Contingency</b>  |      |             |               |               |       |              |                        |  |
| Scope + Bid = (25%)   |      |             |               |               |       |              | <b>\$ 218,833.75</b>   |  |
| <b>Total</b>  |      |             |               |               |       |              | <b>\$ 1,094,168.74</b> |  |

| <b>Alternative 2 - Groundwater Extraction and Ex-situ Treatment</b> |        |          |             |              |       |              |                      |   |
|---|--------|----------|-------------|--------------|-------|--------------|----------------------|---|
| <b>Operations and Maintenance</b>                                   |        |          |             |              |       |              |                      |   |
| Description   | Qty.   | Material |             | Total        | Labor |              | Total Cost (M+L)     | Cost Basis/Questions                                      |
|   |        | Unit     | Unit Price  |              | hours | Total        |                      |   |
| <b>Perform Startup/Testing/Training</b>                             |        |          |             | \$ -         |       | \$ -         | \$ -                 | Assume 11 days for start up and testing (FTE = 110 hours) |
| Engineer  |        |          |             | \$ -         | 220   | \$ 11,000.00 | \$ 11,000.00         | 2 FTE   |
| Operators   |        |          |             | \$ -         | 220   | \$ 12,612.60 | \$ 12,612.60         | 2 FTE   |
| ES&H  |        |          |             | \$ -         | 110   | \$ 6,930.00  | \$ 6,930.00          | 1 FTE   |
| Radcon Technician   |        |          |             | \$ -         | 110   | \$ 6,306.30  | \$ 6,306.30          | 1 FTE   |
| Mechanical Support  |        |          |             | \$ -         | 220   | \$ 12,612.60 | \$ 12,612.60         | 2 FTE   |
| Electrician   |        |          |             | \$ -         | 220   | \$ 12,612.60 | \$ 12,612.60         | 2 FTE   |
| Spare parts and material  | 1      | ls       | \$20,000.00 | \$ 20,000.00 | 0     | \$ -         | \$ 20,000.00         |   |
|   |        |          |             |              |       |              | <b>\$ 82,074.10</b>  |   |
| <b>Professional and Technical Services</b>                          |        |          |             |              |       |              |                      |   |
| Project Management (10%)  |        |          |             |              |       |              | \$ 8,207.41          |   |
|   |        |          |             |              |       |              | <b>\$ 90,281.51</b>  |   |
| <b>Contingency</b>  |        |          |             |              |       |              |                      |   |
| Scope + Bid = (25%)   |        |          |             |              |       |              | \$ 22,570.38         |   |
|   |        |          |             |              |       |              | <b>\$ 112,851.89</b> |   |
| <b>O&amp;M of Extraction Wells and SVGTS</b>                        |        |          |             |              |       |              |                      | Assume 154 hours per month for an FTE                     |
| H&S Personnel   |        |          |             | \$ -         | 77    | \$ 4,851.00  | \$ 4,851.00          | 0.5 FTE   |
| Project Engineer/Data Coordinator                                   |        |          |             | \$ -         | 77    | \$ 3,850.00  | \$ 3,850.00          | 0.5 FTE   |
| Radcon Technician   |        |          |             | \$ -         | 38.5  | \$ 2,207.21  | \$ 2,207.21          | 0.25 FTE  |
| Operating Personnel   |        |          |             | \$ -         | 308   | \$ 17,657.64 | \$ 17,657.64         | 2 FTE   |
| Mechanical Support  |        |          |             | \$ -         | 38.5  | \$ 2,207.21  | \$ 2,207.21          | 0.25 FTE  |
| Electrician   |        |          |             | \$ -         | 38.5  | \$ 2,207.21  | \$ 2,207.21          | 0.25 FTE  |
| Electricity   | 145.92 | Mw-Hr    | \$ 75.00    | \$ 10,944.00 |       |              | \$ 10,944.00         | 0.200 MW power yields 146 MW-Hrs per month                |
| Analytical with 8-day turn (1.5 times markup)                       | 17.2   | ea       | \$ 207.00   | \$ 3,560.40  |       |              | \$ 3,560.40          | Weekly samples from 4 locations                           |
| Spare Parts/Materials Allowance                                     | 1      | month    | \$ 3,000.00 | \$ 3,000.00  | 154   | \$ -         | \$ 3,000.00          | Assume \$3000 per month for material/parts                |
| <b>Monthly O&amp;M Costs</b>  |        |          |             |              |       |              | <b>\$ 50,484.66</b>  |   |
| <b>Annual O&amp;M Costs</b>   |        |          |             |              |       |              | <b>\$ 605,815.86</b> |   |
| <b>Professional and Technical Services</b>                          |        |          |             |              |       |              |                      |   |
| Project Management (8%)   |        |          |             |              |       |              | \$ 48,465.27         |   |
|   |        |          |             |              |       |              | <b>\$ 654,281.13</b> |   |
| <b>Contingency</b>  |        |          |             |              |       |              |                      |   |
| Scope + Bid = (25%)   |        |          |             |              |       |              | \$ 163,570.28        |   |
|   |        |          |             |              |       |              |                      |   |
|   |        |          |             |              |       |              |                      |   |
| <b>Total Annual O&amp;M Costs</b>                                   |        |          |             |              |       |              | <b>\$ 817,851.41</b> |   |

| <b>Alternative 2 - Groundwater Extraction and Ex-situ Treatment</b> |      |             |              |              |       |              |                  |   |
|---|------|-------------|--------------|--------------|-------|--------------|------------------|---|
| <b>D&amp;D and Site Restoration (year 21)</b>                       |      |             |              |              |       |              |                  |   |
| Description   | Qty. | Material    |              | Total        | Labor |              | Total Cost (M+L) | Cost Basis  |
|   |      | Unit        | Unit Price   |              | hours | Total        |                  |   |
| <b>D&amp;D and Site Restoration Labor</b>                           |      |             |              |              |       |              |                  |   |
|   |      |             |              | \$ -         |       | \$ -         | \$ -             | Assume D&D to take 6 weeks at 50 hours per week (FTE = 300 hours)                                 |
| Geologist   |      |             |              | \$ -         | 300   | \$ 21,000.00 | \$ 21,000.00     | 1 FTE   |
| Pipefitter  |      |             |              | \$ -         | 600   | \$ 34,398.00 | \$ 34,398.00     | 2 FTE   |
| Mechanic  |      |             |              | \$ -         | 900   | \$ 51,597.00 | \$ 51,597.00     | 3 FTE   |
| Electrician   |      |             |              | \$ -         | 900   | \$ 51,597.00 | \$ 51,597.00     | 3 FTE   |
| Laborer   |      |             |              | \$ -         | 600   | \$ 34,398.00 | \$ 34,398.00     | 2 FTE   |
| Escorts   |      |             |              | \$ -         | 600   | \$ 23,100.00 | \$ 23,100.00     | 2 FTE   |
| Radcon Technician   |      |             |              | \$ -         | 600   | \$ 34,398.00 | \$ 34,398.00     | 2 FTE   |
| PPE   | 720  | per man-day | \$ 15.78     | \$ 11,361.60 |       | \$ -         | \$ 11,361.60     | 2 changes per day - 12 FTEs for 30 days - Level D   |
|   |      |             |              |              |       |              | \$ 261,849.60    |   |
| <b>Drilling/Site Restoration Subcontractor</b>                      |      |             |              |              |       |              |                  |   |
| Mobilization/Demobilization   | 1    | each        | \$ 20,449.00 | \$ 20,449.00 |       | \$ -         | \$ 20,449.00     |   |
| Abandon Wells   | 4.5  | days        | \$ 5,504.00  | \$ 24,768.00 |       | \$ -         | \$ 24,768.00     | 3 wells at 1.5 days per well = 4.5 days   |
| Supplies/Material   | 3    | each        | \$ 500.00    | \$ 1,500.00  |       | \$ -         | \$ 1,500.00      | \$500 allowance per well  |
|   |      |             |              |              |       |              | \$ 46,717.00     |   |
| <b>Waste Management/Disposition</b>                                 |      |             |              |              |       |              |                  |   |
| Waste characterization  |      |             |              |              |       |              |                  |   |
| Waste Mgt Field Coordinator   |      |             |              |              | 20    | \$ 1,146.60  | \$ 1,146.60      | 1 FTE   |
| Waste Operators   |      |             |              |              | 20    | \$ 1,146.60  | \$ 1,146.60      | 1 FTE   |
| Waste Engineer  |      |             |              |              | 20    | \$ 1,550.00  | \$ 1,550.00      | 1 FTE   |
| Waste Samplers  |      |             |              |              | 40    | \$ 2,293.20  | \$ 2,293.20      | 2 FTE   |
| Radcon Technician   |      |             |              |              | 20    | \$ 1,146.60  | \$ 1,146.60      | 1 FTE   |
| Drill Cutting Sample Analyses                                       | 31.5 | ea          | \$ 506.00    | \$ 15,939.00 |       |              | \$ 15,939.00     | 5 samples from each of 6 intermodals plus 5% QA, analysis for VOCs and SVOCs                      |
| Drill Cutting Sample Analyses                                       | 6.3  | ea          | \$ 2,490.00  | \$ 15,687.00 |       |              | \$ 15,687.00     | 1 sample from each of 6 intermodals plus 5% QA, analysis for Rads and Metals                      |
| Waste Water Sample Analyses   | 3    | ea          | \$ 914.00    | \$ 2,742.00  |       |              | \$ 2,742.00      | 2 frac tanks of waste water generated, 1 sample from each plus QA, analyses for permit parameters |
| Waste Disposition   |      |             |              |              |       |              |                  |   |
| Waste Mgt Field Coordinator   |      |             |              |              | 80    | \$ 4,586.40  | \$ 4,586.40      | 1 FTE   |
| Waste Operators/Truck Driver  |      |             |              |              | 320   | \$ 18,345.60 | \$ 18,345.60     | 4 FTE   |
|   |      |             |              |              |       |              | \$ 64,583.00     |   |
| <b>Remedial Action Completion Report</b>                            |      |             |              |              |       |              |                  |   |
|   |      |             |              | \$ -         |       | \$ -         | \$ -             |   |
| Geologist   |      |             |              | \$ -         | 120   | \$ 9,960.00  | \$ 9,960.00      |   |
| Remediation Engineer  |      |             |              | \$ -         | 540   | \$ 44,820.00 | \$ 44,820.00     |   |
| Senior Scientist  |      |             |              | \$ -         | 32    | \$ 3,232.00  | \$ 3,232.00      |   |
| Project Engineer  |      |             |              | \$ -         | 120   | \$ 6,000.00  | \$ 6,000.00      |   |
| Environmental Compliance Specialist                                 |      |             |              | \$ -         | 40    | \$ 2,840.00  | \$ 2,840.00      |   |
| QA Specialist   |      |             |              | \$ -         | 24    | \$ 1,536.00  | \$ 1,536.00      |   |
| Technical Editing/Document Production                               |      |             |              | \$ -         | 96    | \$ 6,720.00  | \$ 6,720.00      |   |
| Document Production Material  | 1    | LS          | \$ 5,600.00  | \$ 5,600.00  |       |              | \$ 5,600.00      |   |
|   |      |             |              |              |       |              | \$ 80,708.00     |   |
|   |      |             |              |              |       |              | \$ 453,857.60    |   |
| <b>Professional and Technical Services</b>                          |      |             |              |              |       |              |                  |   |
| Project Management (8%)   |      |             |              |              |       |              | \$ 36,308.61     |   |
|   |      |             |              |              |       |              | \$ 490,166.21    |   |
| <b>Contingency</b>  |      |             |              |              |       |              |                  |   |
| Scope + Bid = (25%)   |      |             |              |              |       |              | \$ 122,541.55    |   |
|   |      |             |              |              |       |              | \$ 612,707.76    |   |
| <b>Total</b>  |      |             |              |              |       |              | \$ 612,707.76    |   |



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**ALTERNATIVE 3**  
***IN SITU* CHEMICAL OXIDATION**

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### Alternative 3 - *In-situ* Chemical Oxidation

#### Assumptions

##### **General**

- Developed in accordance with US EPA Guidance document EPA 540-R-00-002, *A Guide to Developing and Documenting Cost Estimates during the Feasibility Study*
- Contingency (Scope + Bid) was applied at 25%
- Professional and technical services were estimated based on guidelines in EPA 540-R-00-002
- Present value analysis was performed using calendar year 2011 Real Discount Rates as provided in Appendix C of OMB Circular No. A-094. For the 3-year duration associated with this alternative the discount rate used was zero percent.
- Estimate performed at the Detailed Analysis of Alternatives phase to provide a -30% to +50% estimate
- Does not include installation of additional monitoring wells as long-term monitoring will be in accordance with the EMP

##### **System**

- 13 injection/extraction points
- Utilize existing SVGTS with planned steam regenerated carbon off gas treatment (no cost added for SVGTS)

##### **Operations and Maintenance**

- Operating scenario based on oxidation of 4,500 gallons TCE (54,900 pounds)
- Use KMnO4 with 20% contact efficiency and 2.4 pounds KMnO4 to oxidize 1 pound TCE
- 3% KMnO4 solution injected at 80 gpm
- Long term monitoring costs covered under existing EM program

#### Estimate Summary

|                                     |    |                     |
|-------------------------------------|----|---------------------|
| <b>Construction/Installation</b>    | \$ | <b>2,800,554.20</b> |
| <b>ISCO Operation</b>               | \$ | <b>2,374,469.83</b> |
| <b>D&amp;D and Site Restoration</b> | \$ | <b>767,767.41</b>   |
|                                     | \$ | <b>5,942,791.43</b> |

Present Value Analysis  
Alternative 3 - In-situ Chemical Oxidation

| <b>Year</b>  | <b>Capital Cost</b> | <b>Annual O&amp;M Cost</b> | <b>Periodic Cost</b> | <b>Total Cost</b>  | <b>Discount Factor at 0%</b> | <b>Total Present Value</b> |
|--------------|---------------------|----------------------------|----------------------|--------------------|------------------------------|----------------------------|
| 0            | \$2,800,554         | \$0                        | \$0                  | \$2,800,554        | 1.00                         | \$2,800,554                |
| 1            | \$0                 | \$2,374,470                | \$0                  | \$2,374,470        | 1.00                         | \$2,374,470                |
| 2            | \$0                 | \$0                        | \$767,767            | \$767,767          | 1.00                         | \$767,767                  |
| <b>Total</b> | <b>\$2,800,554</b>  | <b>\$2,374,470</b>         | <b>\$767,767</b>     | <b>\$5,942,791</b> |                              | <b>\$5,942,791</b>         |

| <b>Alternative 3 - In-situ Chemical Oxidation Installation/Construction</b> |      |             |               |               |       |              |                        |   |
|---|------|-------------|---------------|---------------|-------|--------------|------------------------|---|
| Description   | Qty. | Material    |               |               | Labor |              | Total Cost (M+L)       | Cost Basis  |
|   |      | Unit        | Unit Price    | Total         | hours | Total        |                        |   |
| <b>Construction</b>   |      |             |               |               |       |              |                        |   |
| <b>Construction</b>   |      |             |               | \$ -          |       | \$ -         | \$ -                   | per week at 10 hours per day (FTE = 500 hours)                                  |
| Geologist   |      |             |               | \$ -          | 500   | \$ 35,000.00 | \$ 35,000.00           | 1   |
| Pipefitter  |      |             |               | \$ -          | 1500  | \$ 85,995.00 | \$ 85,995.00           | 3   |
| Mechanic  |      |             |               | \$ -          | 1500  | \$ 85,995.00 | \$ 85,995.00           | 3   |
| Electrician   |      |             |               | \$ -          | 1500  | \$ 85,995.00 | \$ 85,995.00           | 3   |
| Laborers  |      |             |               | \$ -          | 1000  | \$ 57,330.00 | \$ 57,330.00           | 2   |
| Escorts   |      |             |               | \$ -          | 1000  | \$ 38,500.00 | \$ 38,500.00           | 2   |
| Radcon Technician   |      |             |               | \$ -          | 1000  | \$ 57,330.00 | \$ 57,330.00           | 2   |
| PPE for CM - 2 changes per day - 10 FTEs for 50 days - Level D              | 1000 | per man-day | \$ 15.78      | \$ 15,780.00  |       | \$ -         | \$ 15,780.00           |   |
|   |      |             |               |               |       |              | <b>\$ 461,925.00</b>   |   |
| <b>Drilling and Well Completion</b>   |      |             |               |               |       |              |                        |   |
| Mobilization -  | 1    | each        | \$ 39,620.00  | \$ 39,620.00  |       | \$ -         | \$ 39,620.00           |   |
| Injection/extraction well construction                                      | 13   | each        | \$ 61,125.50  | \$ 794,631.50 |       | \$ -         | \$ 794,631.50          |   |
| Injection/extraction well development                                       | 13   | each        | \$ 4,225.00   | \$ 54,925.00  |       | \$ -         | \$ 54,925.00           |   |
| Extraction well pumps/discharge piping                                      | 4    | each        | \$ 7,589.45   | \$ 30,357.80  |       | \$ -         | \$ 30,357.80           |   |
| Injection well down hole tooling (pipe, fittings, etc.)                     | 9    | each        | \$ 4,179.25   | \$ 37,613.25  |       | \$ -         | \$ 37,613.25           |   |
| Mixing and delivery system manifold   | 1    | LS          | \$ 100,000.00 | \$ 100,000.00 |       |              | \$ 100,000.00          |   |
| Mixing tanks and valves   | 1    | LS          | \$ 20,000.00  | \$ 20,000.00  |       |              | \$ 20,000.00           |   |
| SCADA controlled mixing system  | 1    | LS          | \$ 50,000.00  | \$ 50,000.00  |       |              | \$ 50,000.00           |   |
| PPE upgrade markup  | 1    | LS          | \$ 13,505.96  | \$ 13,505.96  |       | \$ -         | \$ 13,505.96           | Scaled to 9.5 of ERH installation cost estimate (13 borings versus 137 borings) |
| Demobilization  | 1    | each        | \$ 15,000.00  | \$ 15,000.00  |       | \$ -         | \$ 15,000.00           |   |
| Solid/liquid waste management/disposition                                   | 1    | LS          | \$ 160,551.14 | \$ 160,551.14 |       | \$ -         | \$ 160,551.14          | Scaled to 9.5% of ERH waste costs (13 borings versus 137 borings)               |
|   |      |             |               |               |       |              | <b>\$ 1,316,204.65</b> |   |
|   |      |             |               |               |       |              | <b>\$ 1,778,129.65</b> |   |
| <b>Professional and Technical Services</b>                                  |      |             |               |               |       |              |                        |   |
| Project Management (6%)   |      |             |               |               |       |              | \$ 106,687.78          |   |
| Remedial Design (12%)   |      |             |               |               |       |              | \$ 213,375.56          |   |
| Construction Management (8%)  |      |             |               |               |       |              | \$ 142,250.37          |   |
|   |      |             |               |               |       |              | <b>\$ 462,313.71</b>   |   |
|   |      |             |               |               |       |              | <b>\$ 2,240,443.36</b> |   |
| <b>Contingency</b>  |      |             |               |               |       |              |                        |   |
| Scope + Bid = (25%)   |      |             |               |               |       |              | <b>\$ 560,110.84</b>   |   |
| <b>Total</b>  |      |             |               |               |       |              | <b>\$ 2,800,554.20</b> |   |

| Alternative 3 - In-situ Chemical Oxidation                         |          |        |              |                 |       |                  |   |
|--|----------|--------|--------------|-----------------|-------|------------------|---|
| Operations and Maintenance   |          |        |              |                 |       |                  |   |
| Description  | Material |        |              | Labor           |       | Total Cost (M+L) | Cost Basis/Questions  |
|  | Qty.     | Unit   | Unit Price   | Total           | hours |                  |   |
| <b>O&amp;M of RGA Remedy</b>                                       |          |        |              |                 |       | \$ -             |   |
| <b>Perform Startup/Testing/Training</b>                            |          |        |              | \$ -            |       | \$ -             | Assume 11 days for start up and testing (FTE = 110 hours)   |
| Engineer   |          |        |              | \$ -            | 220   | \$ 11,000.00     | \$ 11,000.00 2 FTE  |
| Operators  |          |        |              | \$ -            | 220   | \$ 12,612.60     | \$ 12,612.60 2 FTE  |
| ES&H   |          |        |              | \$ -            | 110   | \$ 6,930.00      | \$ 6,930.00 1 FTE   |
| Radcon Technician  |          |        |              | \$ -            | 110   | \$ 6,306.30      | \$ 6,306.30 1 FTE   |
| Mechanical Support   |          |        |              | \$ -            | 220   | \$ 12,612.60     | \$ 12,612.60 2 FTE  |
| Electrician  |          |        |              | \$ -            | 220   | \$ 12,612.60     | \$ 12,612.60 2 FTE  |
| Spare parts and material   | 1        | ls     | \$ 20,000.00 | \$ 20,000.00    | 0     | \$ -             | \$ 20,000.00  |
|  |          |        |              |                 |       |                  | <b>\$ 82,074.10</b>   |
| <b>Operation</b>   |          |        |              |                 |       |                  |   |
| <b>Chemical Injection to Oxidize 4,500 gal TCE (54,900 pounds)</b> |          |        |              |                 |       |                  | <b>Assume 55 events lasting 10 hours to inject 2,634,040 gallons of KMnO4/H2O solution at 80 gallons per minute.</b><br>Volume of Solution(gallons) = (((pounds KMnO4 X 454 grams per pound) / (3 grams KMnO4 per 100 mL water injection concentration)) / 1000 ml per L ) / 3.785 L per gallon |
| H&S Personnel  |          |        |              | \$ -            | 550   | \$ 34,650.00     | \$ 34,650.00 1 FTE 2634039.63   |
| Project Engineer/Data Coordinator                                  |          |        |              | \$ -            | 550   | \$ 27,500.00     | \$ 27,500.00 1 FTE  |
| Radcon Technician  |          |        |              | \$ -            | 550   | \$ 31,531.50     | \$ 31,531.50 1 FTE  |
| Operating Personnel  |          |        |              | \$ -            | 2200  | \$ 126,126.00    | \$ 126,126.00 4 FTE   |
| Mechanical Support during operations                               |          |        |              | \$ -            | 275   | \$ 15,765.75     | \$ 15,765.75 0.5 FTE  |
| Electrician for maintenance during operations                      |          |        |              | \$ -            | 275   | \$ 15,765.75     | \$ 15,765.75 0.5 FTE  |
| Potassium Permanganate Costs                                       | 658800   | pounds | \$ 2.17      | \$ 1,427,619.60 |       | \$ -             | \$ 1,427,619.60<br>KMnO4 Cost Basis:<br>- 4500 gallons TCE (54,900 lbs.) to be oxidized,<br>- stoichiometric demand is 2.4 lbs per lb of TCE<br>- assume 20% contact efficiency (accounts for NOD also),<br>- 3% solution is injected   |
| Analytical with 8-day turn (1.5 times markup)                      | 110      | ea     | \$ 207.00    | \$ 22,770.00    |       |                  | \$ 22,770.00<br>VOC samples collected after each injection event from 2 of the 13 wells   |
| Electricity  | 110      | Mw-Hr  | \$ 75.00     | \$ 8,250.00     |       |                  | \$ 8,250.00<br>0.200 MW power yields 110 MW-Hrs for the 55 events   |
|  |          |        |              |                 |       |                  | <b>\$ 1,709,978.60</b>  |
|  |          |        |              |                 |       |                  | <b>\$ 1,792,052.70</b>  |
| <b>Professional and Technical Services</b>                         |          |        |              |                 |       |                  |   |
| Project Management (6%)  |          |        |              |                 |       |                  | \$ 107,523.16   |
|  |          |        |              |                 |       |                  | <b>\$ 107,523.16</b>  |
|  |          |        |              |                 |       |                  | <b>\$ 1,899,575.86</b>  |
| <b>Contingency</b>   |          |        |              |                 |       |                  |   |
| Scope + Bid = (25%)  |          |        |              |                 |       |                  | <b>\$ 474,893.97</b>  |
| <b>Total</b>   |          |        |              |                 |       |                  | <b>\$ 2,374,469.83</b>  |





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**ALTERNATIVE 4**

**UPGRADED ERH CONFIGURATION**

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## Alternative 4 - Upgraded ERH Configuration

### Assumptions

#### General

- Developed in accordance with US EPA Guidance document EPA 540-R-00-002, *A Guide to Developing and Documenting Cost Estimates during the Feasibility Study*
- Contingency (Scope + Bid) was applied at 25%
- Professional and technical services were estimated based on guidelines in EPA 540-R-00-002 unless otherwise noted
- Present value analysis was performed using calendar year 2011 Real Discount Rates as provided in Appendix C of OMB Circular No. A-094. For the 3-year duration associated with this alternative the discount rate used was zero percent.
- Estimate performed at the Detailed Analysis of Alternatives phase to provide a -30% to +50% estimate
- Does not include installation of additional monitoring wells as long-term monitoring will be in accordance with the current Environmental Monitoring Plan for the site
- Waste management and disposition
  - 7588 cubic feet of cuttings and sludge, 60% requires no treatment, 30 % needs stabilization, 10% VTD
  - Six months of filter press operations to treat drilling and decon waste water
  - Transportation and disposal costs for 20,000 gallons of TCE

#### System

- ERH components installed for heating/treatment of the RGA (60 - 100 ft bgs)
- Includes estimate of incremental costs associated with impacts to UCRS design resulting from higher density RGA electrode borings
- Utilize existing SVGTS with planned steam regen carbon offgas treatment (no cost added for SVGTS)

#### Operations and Maintenance

- Assume 9 months operations including start up, testing, routine operations, and pulsed operations
- Electrical are included due to the energy intensive nature of this technology
- Long term monitoring costs covered under existing EM program

### Estimate Summary

|                                       |                               |
|---------------------------------------|-------------------------------|
| <b>Construction/Installation</b>      | <b>\$ 11,365,794.79</b>       |
| <b>ERH Operations and Maintenance</b> | <b>\$ 5,280,524.70</b>        |
| <b>D&amp;D and Site Restoration</b>   | <b><u>\$ 1,582,217.75</u></b> |
| <b>Total</b>                          | <b>\$ 18,228,537.23</b>       |

Present Value Analysis  
Alternative 4 - Upgraded ERH Configuration

| <b>Year</b>  | <b>Capital Cost</b> | <b>Annual O&amp;M Cost</b> | <b>Periodic Cost</b> | <b>Total Cost</b>   | <b>Discount Factor at 2.1%</b> | <b>Total Present Value</b> |
|--------------|---------------------|----------------------------|----------------------|---------------------|--------------------------------|----------------------------|
| 0            | \$11,365,795        | \$0                        | \$0                  | \$11,365,795        | 1.00                           | \$11,365,795               |
| 1            | \$0                 | \$5,280,525                | \$0                  | \$5,280,525         | 1.00                           | \$5,280,525                |
| 2            | \$0                 | \$0                        | \$1,582,218          | \$1,582,218         | 1.00                           | \$1,582,218                |
| <b>Total</b> | <b>\$11,365,795</b> | <b>\$5,280,525</b>         | <b>\$1,582,218</b>   | <b>\$18,228,537</b> |                                | <b>\$18,228,537</b>        |

| Alternative 4 - Upgraded ERH Configuration Construction/Installation |       |             |               |                 |       |               |                  |  |
|--|-------|-------------|---------------|-----------------|-------|---------------|------------------|--|
| Description  | Qty.  | Material    |               | Total           | Labor |               | Total Cost (M+L) | Cost Basis   |
|  |       | Unit        | Unit Price    |                 | hours | Total         |                  |  |
| <b>Construction</b>  |       |             |               |                 |       |               |                  |  |
| Engineer   |       |             |               | \$ -            |       | \$ -          | \$ -             | Assume construction to take 32 weeks   |
| Geologist  |       |             |               | \$ -            | 3200  | \$ 160,000.00 | \$ 160,000.00    | 2.5 FTE  |
| Escorts  |       |             |               | \$ -            | 4224  | \$ 224,000.00 | \$ 224,000.00    | 2.5 FTE  |
| Rad Tech   |       |             |               | \$ -            | 4224  | \$ 242,161.92 | \$ 242,161.92    | 3 FTE (assume 11 hrs/day = 44 hrs/wk)  |
| PPE for CM - 2 changes per day - 10 FTEs for 128 days - Level D      | 2560  | per man-day | \$ 15.78      | \$ 40,396.80    |       | \$ -          | \$ 40,396.80     | 3 FTE (assume 11 hrs/day = 44 hrs/wk)  |
|  |       |             |               |                 |       |               | \$ 829,182.72    |  |
| <b>Drilling and Well Completion</b>                                  |       |             |               |                 |       |               |                  |  |
|  |       |             |               | \$ -            |       | \$ -          | \$ -             |  |
| <b>Drilling Subcontractor Costs</b>                                  |       |             |               |                 |       |               |                  |  |
| Mobilization   | 1     | each        | \$ 39,620.00  | \$ 39,620.00    |       | \$ -          | \$ 39,620.00     |  |
| Electrode borings  | 81    | each        | \$ 24,263.00  | \$ 1,965,303.00 |       | \$ -          | \$ 1,965,303.00  | Subcontract unit rate + \$5K per boring for graphite/sand placement  |
| Installation of additional UCRS electrodes                           | 62    | each        | \$ 640.00     | \$ 39,680.00    |       | \$ -          | \$ 39,680.00     |  |
| UCRS extraction wells  | 2     | each        | \$ 9,500.00   | \$ 19,000.00    |       | \$ -          | \$ 19,000.00     |  |
| RGA extraction wells   | 25    | each        | \$ 10,483.00  | \$ 262,075.00   |       | \$ -          | \$ 262,075.00    |  |
| Well development   | 25    | each        | \$ 4,225.00   | \$ 105,625.00   |       | \$ -          | \$ 105,625.00    |  |
| Temperature monitoring well  | 21    | each        | \$ 6,975.00   | \$ 146,475.00   |       | \$ -          | \$ 146,475.00    |  |
| Vacuum piezometer/temperature well                                   | 2     | each        | \$ 9,450.00   | \$ 18,900.00    |       | \$ -          | \$ 18,900.00     |  |
| Vacuum monitoring/contingency well                                   | 6     | each        | \$ 7,150.00   | \$ 42,900.00    |       | \$ -          | \$ 42,900.00     |  |
| Concrete coring  | 1     | LS          | \$ 10,700.00  | \$ 10,700.00    |       | \$ -          | \$ 10,700.00     |  |
| Asphalt coring   | 1     | LS          | \$ 4,400.00   | \$ 4,400.00     |       | \$ -          | \$ 4,400.00      |  |
| PPE upgrade markup   | 1     | LS          | \$ 142,168.00 | \$ 142,168.00   |       | \$ -          | \$ 142,168.00    |  |
| Demobilization   | 1     | each        | \$ 15,000.00  | \$ 15,000.00    |       | \$ -          | \$ 15,000.00     |  |
|  |       |             |               |                 |       |               | \$ 2,811,846.00  |  |
| <b>ERH Subcontractor Costs</b>                                       |       |             |               |                 |       |               |                  |  |
| Mobilization   | 1     | each        | \$ 50,000.00  | \$ 50,000.00    |       | \$ -          | \$ 50,000.00     |  |
| Electrodes   | 239   | each        | \$ -          | \$ -            |       | \$ -          | \$ -             | 245 electrodes already purchased for Phase II  |
| Electrodes - Additional UCRS electrodes                              | 56    | each        | \$ 3,058.00   | \$ 171,248.00   |       | \$ -          | \$ 171,248.00    | 62 actually needed but 6 come from current inventory of 245  |
| Electrode borings (2-electrode boring)                               | 4     | each        | \$ 5,437.00   | \$ 21,748.00    |       | \$ -          | \$ 21,748.00     | Subcontract unit rate + \$1.5K per boring for graphite/sand placement  |
| Electrode borings (3-electrode boring)                               | 77    | each        | \$ 7,456.00   | \$ 574,112.00   |       | \$ -          | \$ 574,112.00    | Subcontract unit rate + \$2K per boring for graphite/sand placement  |
| Installation of additional UCRS electrodes                           | 62    | each        | \$ 4,969.00   | \$ 308,078.00   |       | \$ -          | \$ 308,078.00    | Additional UCRS electrodes needed due to closer spacing (thus more overall borings) required for heating the RGA |
| Extraction wells   | 27    | each        | \$ 16,562.00  | \$ 447,174.00   |       | \$ -          | \$ 447,174.00    |  |
| Temperature monitoring well  | 21    | each        | \$ 6,678.00   | \$ 140,238.00   |       | \$ -          | \$ 140,238.00    |  |
| Vacuum piezometer/temperature well                                   | 2     | each        | \$ 8,981.00   | \$ 17,962.00    |       | \$ -          | \$ 17,962.00     |  |
| Vacuum monitoring/contingency well                                   | 6     | each        | \$ 5,778.00   | \$ 34,668.00    |       | \$ -          | \$ 34,668.00     |  |
| PPE upgrade markup   | 1     | LS          | \$ 129,602.00 | \$ 129,602.00   |       | \$ -          | \$ 129,602.00    |  |
| Demobilization   | 1     | each        | \$ 15,000.00  | \$ 15,000.00    |       | \$ -          | \$ 15,000.00     |  |
|  |       |             |               |                 |       |               | \$ 1,909,830.00  |  |
| <b>Mechanical/Electrical Contractor</b>                              |       |             |               |                 |       |               |                  |  |
| Additional Subsurface Vault Completions                              | 15    | each        | \$ 10,000.00  | \$ 150,000.00   |       | \$ -          | \$ 150,000.00    |  |
| Additional Surface Piping and Electrical construction                | 1     | LS          | \$ 250,000.00 | \$ 250,000.00   |       | \$ -          | \$ 250,000.00    | Allowance  |
|  |       |             |               |                 |       |               | \$ 400,000.00    |  |
| <b>Waste Management/Disposition</b>                                  |       |             |               |                 |       |               |                  |  |
| Waste characterization   |       |             |               |                 |       |               |                  | 5 VOC samples taken from each of 14 intermodals, 2 intermodals sampled each day                                  |
| Waste Mgt Field Coordinator  |       |             |               |                 | 70    | \$ 4,013.10   | \$ 4,013.10      | 1 FTE  |
| Waste Operators  |       |             |               |                 | 70    | \$ 4,013.10   | \$ 4,013.10      | 1 FTE  |
| Waste Engineer   |       |             |               |                 | 70    | \$ 5,425.00   | \$ 5,425.00      | 1 FTE  |
| Waste Samplers   |       |             |               |                 | 140   | \$ 8,026.20   | \$ 8,026.20      | 2 FTE  |
| Radcon Technician  |       |             |               |                 | 70    | \$ 4,013.10   | \$ 4,013.10      | 1 FTE  |
| Drill Cutting Sample Analyses  | 73.5  | ea          | \$ 506.00     | \$ 37,191.00    |       |               | \$ 37,191.00     | 5 samples from each of 14 intermodals plus 5% QA, analysis for VOCs and SVOCs                                    |
| Drill Cutting Sample Analyses  | 14.7  | ea          | \$ 2,490.00   | \$ 36,603.00    |       |               | \$ 36,603.00     | 1 sample from each of 14 intermodals plus 5% QA, analysis for Rads and Metals                                    |
| Waste Water Sample Analyses  | 28    | ea          | \$ 914.00     | \$ 25,592.00    |       |               | \$ 25,592.00     | 25 frac tanks, 1 sample from each plus QA, analyses for permit parameters  |
| Packaging and transportation   | 1     | LS          | \$ 137,238.00 | \$ 137,238.00   |       | \$ -          | \$ 137,238.00    |  |
| Disposition at Clive, Utah   | 1     | LS          | \$ 824,403.00 | \$ 824,403.00   |       | \$ -          | \$ 824,403.00    |  |
| Filter press operation for 6 months (equipment)                      | 1     | LS          | \$ 200,488.00 | \$ 200,488.00   |       | \$ -          | \$ 200,488.00    |  |
| Filter press operation for 6 months (labor)                          |       |             |               |                 | 930   | \$ 53,316.90  | \$ 53,316.90     | 1 FTE  |
| Waste Mgt Field Coordinator  |       |             |               |                 | 3720  | \$ 213,267.60 | \$ 213,267.60    | 4 FTE  |
| Waste Operators  |       |             |               |                 | 465   | \$ 36,037.50  | \$ 36,037.50     | 5 FTE  |
| Waste Engineer   |       |             |               |                 | 232.5 | \$ 13,329.23  | \$ 13,329.23     | 25 FTE   |
| Waste Waste Operations Supervisor                                    |       |             |               |                 |       |               |                  |  |
| Wastewater Treatment Materials                                       | 1     | LS          | \$ 45,575.00  | \$ 45,575.00    |       | \$ -          | \$ 45,575.00     | 5 samples from each of 14 intermodals  |
| Transportation and disposal of recovered TCE                         | 61000 | lbs         | \$ 0.68       | \$ 41,480.00    |       | \$ -          | \$ 41,480.00     |  |
|  |       |             |               |                 |       |               | \$ 1,690,011.73  |  |
|  |       |             |               |                 |       |               | \$ 7,640,870.45  |  |
| <b>Professional and Technical Services</b>                           |       |             |               |                 |       |               |                  |  |
| Project Management (5%)  |       |             |               |                 |       |               | \$ 382,043.52    |  |
| Remedial Design (8%)   |       |             |               |                 |       |               | \$ 611,269.64    |  |
| Construction Management (6%)   |       |             |               |                 |       |               | \$ 458,452.23    |  |
|  |       |             |               |                 |       |               | \$ 1,451,765.38  |  |
|  |       |             |               |                 |       |               | \$ 9,092,635.83  |  |
| <b>Contingency</b>   |       |             |               |                 |       |               |                  |  |
| Scope + Bid = (25%)  |       |             |               |                 |       |               | \$ 2,273,158.96  |  |
| <b>Total</b>   |       |             |               |                 |       |               | \$ 11,365,794.79 |  |

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| <b>Alternative 4 - Upgraded ERH Configuration</b> |             |                 |                   |                 |              |               |                         |   |  |
|---|-------------|-----------------|-------------------|-----------------|--------------|---------------|-------------------------|---|--|
| <b>Operations and Maintenance</b>                 |             |                 |                   |                 |              |               |                         |   |  |
|   |             | <b>Material</b> |                   |                 |              | <b>Labor</b>  |                         |   |  |
| <b>Description</b>                                | <b>Qty.</b> | <b>Unit</b>     | <b>Unit Price</b> | <b>Total</b>    | <b>hours</b> | <b>Total</b>  | <b>Total Cost (M+L)</b> | <b>Cost Basis/Questions</b>                   |  |
| <b>O&amp;M of RGA Remedy</b>                      |             |                 |                   |                 |              |               | \$ -                    | Assume 9 months of Operations and Maintenance |  |
| Engineer  |             |                 |                   | \$ -            | 2092.5       | \$ 104,625.00 | \$ 104,625.00           | 1.5 FTE                                       |  |
| I&C Engineer                                      |             |                 |                   | \$ -            | 697.5        | \$ 51,098.85  | \$ 51,098.85            | .5 FTE  |  |
| Operators   |             |                 |                   | \$ -            | 5580         | \$ 319,901.40 | \$ 319,901.40           | 4 FTE   |  |
| ES&H  |             |                 |                   | \$ -            | 1395         | \$ 87,885.00  | \$ 87,885.00            | 1 FTE   |  |
| Radcon Technician                                 |             |                 |                   | \$ -            | 1395         | \$ 58,590.00  | \$ 58,590.00            | 1 FTE   |  |
| Mechanical Support                                |             |                 |                   | \$ -            | 697.5        | \$ 39,987.68  | \$ 39,987.68            | .5 FTE  |  |
| Electrician                                       |             |                 |                   | \$ -            | 697.5        | \$ 39,987.68  | \$ 39,987.68            | .5 FTE  |  |
| Spare parts and material                          | 9           | mth             | \$ 4,000.00       | \$ 36,000.00    | 0            | \$ -          | \$ 36,000.00            |   |  |
| Electricity (\$75 per MW-Hr)                      | 14528       | MW-Hr           | \$ 75.00          | \$ 1,089,600.00 | 0            | \$ -          | \$ 1,089,600.00         | RGA electrodes                                |  |
| Electricity (\$75 per MW-Hr) (UCRS Electrodes)    | 2812        | MW-Hr           | \$ 75.00          | \$ 210,900.00   | 0            | \$ -          | \$ 210,900.00           | 62 additional UCRS electrodes                 |  |
| <b>ERH Subcontractor O&amp;M Costs</b>            |             |                 |                   |                 |              |               |                         |   |  |
| Start Up and Testing                              | 1           | ls              | \$ 70,062.00      | \$ 70,062.00    | 0            | \$ -          | \$ 70,062.00            |   |  |
| Monthly O&M Fee                                   | 9           | mth             | \$ 173,992.00     | \$ 1,565,928.00 | 0            | \$ -          | \$ 1,565,928.00         |   |  |
| Routine Operational Samples                       | 9           | mths            | \$ 18,424.00      | \$ 165,816.00   |              |               | \$ 165,816.00           | Weekly samples, 4 locations, 24 month         |  |
|   |             |                 |                   |                 |              |               | <b>\$ 3,840,381.60</b>  |   |  |
| <b>Professional and Technical Services</b>        |             |                 |                   |                 |              |               |                         |   |  |
| Project Management (5%)                           |             |                 |                   |                 |              |               | \$ 384,038.16           |   |  |
|   |             |                 |                   |                 |              |               | <b>\$ 4,224,419.76</b>  |   |  |
| <b>Contingency</b>                                |             |                 |                   |                 |              |               |                         |   |  |
| Scope + Bid = (25%)                               |             |                 |                   |                 |              |               | <b>\$ 1,056,104.94</b>  |   |  |
|   |             |                 |                   |                 |              |               |                         |   |  |
| <b>Total</b>                                      |             |                 |                   |                 |              |               | <b>\$ 5,280,524.70</b>  |   |  |

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| Alternative 4 - Upgraded ERH Configuration     |          |             |              |               |       |                  |                 |  |
|--|----------|-------------|--------------|---------------|-------|------------------|-----------------|--|
| D&D and Site Restoration                       |          |             |              |               |       |                  |                 |  |
| Description                                    | Material |             |              | Labor         |       | Total Cost (M+L) | Cost Basis      |  |
|  | Qty.     | Unit        | Unit Price   | Total         | hours |                  |                 | Total  |
| <b>D&amp;D and Site Restoration Labor</b>      |          |             |              |               |       |                  |                 |  |
| Geologist                                      |          |             |              | \$ -          | 560   | \$ 39,200.00     | \$ 39,200.00    | 1 FTE  |
| Pipefitter                                     |          |             |              | \$ -          | 1120  | \$ 64,209.60     | \$ 64,209.60    | 2 FTE  |
| Mechanic                                       |          |             |              | \$ -          | 1680  | \$ 96,314.40     | \$ 96,314.40    | 3 FTE  |
| Electrician                                    |          |             |              | \$ -          | 1680  | \$ 96,314.40     | \$ 96,314.40    | 3 FTE  |
| Laborer  |          |             |              | \$ -          | 1120  | \$ 64,209.60     | \$ 64,209.60    | 2 FTE  |
| Escorts  |          |             |              | \$ -          | 1120  | \$ 43,120.00     | \$ 43,120.00    | 2 FTE  |
| Rad Tech                                       |          |             |              | \$ -          | 1120  | \$ 47,040.00     | \$ 47,040.00    | 2 FTE  |
| PPE  | 720      | per man-day | \$ 15.78     | \$ 11,361.60  |       | \$ -             | \$ 11,361.60    | 2 changes per day - 12 FTEs for 30 days - Level D  |
|  |          |             |              |               |       |                  | \$ 461,769.60   |  |
| <b>Drilling/Site Restoration Subcontractor</b> |          |             |              |               |       |                  |                 |  |
| Mobilization/Demobilization                    | 1        | each        | \$ 20,449.00 | \$ 20,449.00  |       | \$ -             | \$ 20,449.00    |  |
| Abandon Wells                                  | 66       | days        | \$ 5,504.00  | \$ 363,264.00 |       | \$ -             | \$ 363,264.00   | 2 wells per day  |
| Supplies/Material                              | 132      | each        | \$ 500.00    | \$ 66,000.00  |       | \$ -             | \$ 66,000.00    | \$500 allowance per well   |
|  |          |             |              |               |       |                  | \$ 449,713.00   |  |
| <b>Waste Management/Disposition</b>            |          |             |              |               |       |                  |                 |  |
| Waste characterization                         |          |             |              |               |       |                  |                 |  |
| Waste Mgt Field Coordinator                    |          |             |              |               | 80    | \$ 4,586.40      | \$ 4,586.40     | 1 FTE  |
| Waste Operators                                |          |             |              |               | 80    | \$ 4,586.40      | \$ 4,586.40     | 1 FTE  |
| Waste Engineer                                 |          |             |              |               | 80    | \$ 6,200.00      | \$ 6,200.00     | 1 FTE  |
| Waste Samplers                                 |          |             |              |               | 160   | \$ 9,172.80      | \$ 9,172.80     | 2 FTE  |
| Radcon Technician                              |          |             |              |               | 80    | \$ 4,586.40      | \$ 4,586.40     | 1 FTE  |
| Drill Cutting Sample Analyses                  | 105      | ea          | \$ 506.00    | \$ 53,130.00  |       |                  | \$ 53,130.00    | 5 samples from each of 20 intermodals plus 5% QA, analysis for VOCs and SVOCs                      |
| Drill Cutting Sample Analyses                  | 21       | ea          | \$ 2,490.00  | \$ 52,290.00  |       |                  | \$ 52,290.00    | 1 sample from each of 20 intermodals plus 5% QA, analysis for Rads and Metals                      |
| Waste Water Sample Analyses                    | 11       | ea          | \$ 914.00    | \$ 10,054.00  |       |                  | \$ 10,054.00    | 10 frac tanks of waste water generated, 1 sample from each plus QA, analyses for permit parameters |
| Waste Disposition                              |          |             |              |               |       |                  |                 |  |
| Waste Mgt Field Coordinator                    |          |             |              |               | 200   | \$ 11,466.00     | \$ 11,466.00    | 1 FTE  |
| Waste Operators/Truck Driver                   |          |             |              |               | 800   | \$ 45,864.00     | \$ 45,864.00    | 4 FTE  |
|  |          |             |              |               |       |                  | \$ 201,936.00   |  |
| <b>Remedial Action Completion Report</b>       |          |             |              |               |       |                  |                 |  |
| Geologist                                      |          |             |              | \$ -          | 120   | \$ 9,960.00      | \$ 9,960.00     |  |
| Remediation Engineer                           |          |             |              | \$ -          | 540   | \$ 44,820.00     | \$ 44,820.00    |  |
| Senior Scientist                               |          |             |              | \$ -          | 32    | \$ 3,232.00      | \$ 3,232.00     |  |
| Project Engineer                               |          |             |              | \$ -          | 120   | \$ 6,000.00      | \$ 6,000.00     |  |
| Environmental Compliance Specialist            |          |             |              | \$ -          | 40    | \$ 2,840.00      | \$ 2,840.00     |  |
| QA Specialist                                  |          |             |              | \$ -          | 24    | \$ 1,536.00      | \$ 1,536.00     |  |
| Technical Editing/Document Production          |          |             |              | \$ -          | 96    | \$ 6,720.00      | \$ 6,720.00     |  |
| Document Production Material                   | 1        | LS          | \$ 5,600.00  | \$ 5,600.00   |       |                  | \$ 5,600.00     |  |
|  |          |             |              |               |       |                  | \$ 80,708.00    |  |
| <b>Subtotal</b>                                |          |             |              |               |       |                  | \$ 1,194,126.60 |  |
| <b>Professional and Technical Services</b>     |          |             |              |               |       |                  |                 |  |
| Project Management (6%)                        |          |             |              |               |       |                  | \$ 71,647.60    |  |
|  |          |             |              |               |       |                  | \$ 1,265,774.20 |  |
| <b>Contingency</b>                             |          |             |              |               |       |                  |                 |  |
| Scope + Bid = (25%)                            |          |             |              |               |       |                  | \$ 316,443.55   |  |
| <b>Total</b>                                   |          |             |              |               |       |                  | \$ 1,582,217.75 |  |



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**ALTERNATIVE 5**

**STAGED IMPLEMENTATION OF BASELINE/REBOUND  
ANALYSIS AND *IN SITU* CHEMICAL TREATMENT**

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## Alternative 5 - Staged Implementation of Baseline/Rebound Analysis and In-situ Chemical Treatment

### Assumptions

#### General

- Developed in accordance with US EPA Guidance document EPA 540-R-00-002, *A Guide to Developing and Documenting Cost Estimates during the Feasibility Study*
- Contingency (Scope + Bid) was applied at 25%
- Professional and technical services were estimated based on guidelines in EPA 540-R-00-002
- Present value analysis was performed using calendar year 2011 Real Discount Rates as provided in Appendix C of OMB Circular No. A-094. For the 3-year duration associated with this alternative the discount rate used was zero percent.
- Estimate performed at the Detailed Analysis of Alternatives phase to provide a -30% to +50% estimate
- Does not include installation of additional monitoring wells as long-term monitoring will be in accordance with the EMP

#### System Installation

- 20 injection, extraction, and/or monitoring wells
- Utilize existing SVGTS with planned steam regen carbon offgas treatment (no cost added for SVGTS)

#### Baseline/Rebound Analysis

- GW extraction and rebound analyses activities assumed to take 7 months (4 months of active pumping and 3 months of rebound analysis)
- Weekly samples collected from extraction and monitoring wells (3 discrete depths sampled at MWs)
- Samples analyzed for TCE only with 8-day turnaround time (1.5 times markup)

#### Operations and Maintenance

- Chemical treatment operating scenario based on oxidation of 4,140 gallons TCE (50,508 pounds) after GW extraction operations have removed a portion of the mass
- Use KMnO4 with 20% contact efficiency, and 2.4 pounds KMnO4 to oxidize 1 pound TCE
- 3% KMnO4 solution injected at 80 gpm (total)
- Long term monitoring costs covered under existing EM program

### Estimate Summary

|  |                         |
|--|-------------------------|
| <b>Construction/Installation</b>                                       | <b>\$3,862,334</b>      |
| <b>Baseline/Rebound Analysis and <i>In-situ Chemical Treatment</i></b> | <b>\$2,971,374</b>      |
| <b>D&amp;D and Site Restoration</b>                                    | <b><u>\$889,600</u></b> |
|  | <b>\$7,723,307</b>      |

Present Value Analysis

Alternative 5 - Staged Implementation of Baseline/Rebound Analysis and In-situ Chemical Treatment

| Year         | Capital Cost       | Annual O&M Cost    | Periodic Cost    | Total Cost         | Discount Factor at 2.1% | Total Present Value |
|--------------|--------------------|--------------------|------------------|--------------------|-------------------------|---------------------|
| 0            | \$3,862,334        | \$0                | \$0              | \$3,862,334        | 1.00                    | \$3,862,334         |
| 1            | \$0                | \$2,971,374        | \$0              | \$2,971,374        | 1.00                    | \$2,971,374         |
| 2            | \$0                | \$0                | \$889,600        | \$889,600          | 1.00                    | \$889,600           |
| <b>Total</b> | <b>\$3,862,334</b> | <b>\$2,971,374</b> | <b>\$889,600</b> | <b>\$7,723,307</b> |                         | <b>\$7,723,307</b>  |

| <b>Alternative 5 - Staged Implementation of Baseline/Rebound Analysis and In-situ Chemical Treatment</b> |      |             |               |                 |       |               |                        |   |
|--|------|-------------|---------------|-----------------|-------|---------------|------------------------|---|
| <b>Installation/Construction</b>   |      |             |               |                 |       |               |                        |   |
| Description  | Qty. | Material    |               |                 | Labor |               | Total Cost (M+L)       | Cost Basis / Labor FTE  |
|  |      | Unit        | Unit Price    | Total           | hours | Total         |                        |   |
| <b>Construction</b>  |      |             |               | \$ -            |       | \$ -          | \$ -                   | per week at 10 hours per day (FTE = 600 hours)                                  |
| Geologist  |      |             |               | \$ -            | 600   | \$ 42,000.00  | \$ 42,000.00           | 1   |
| Pipefitter   |      |             |               | \$ -            | 1800  | \$ 103,194.00 | \$ 103,194.00          | 3   |
| Mechanic   |      |             |               | \$ -            | 1800  | \$ 103,194.00 | \$ 103,194.00          | 3   |
| Electrician  |      |             |               | \$ -            | 1800  | \$ 103,194.00 | \$ 103,194.00          | 3   |
| Laborers   |      |             |               | \$ -            | 1200  | \$ 68,796.00  | \$ 68,796.00           | 2   |
| Escorts  |      |             |               | \$ -            | 1200  | \$ 46,200.00  | \$ 46,200.00           | 2   |
| Radcon Technician  |      |             |               | \$ -            | 1200  | \$ 68,796.00  | \$ 68,796.00           | 2   |
| PPE for CM - 2 changes per day - 10 FTEs for 60 days - Level D   | 1200 | per man-day | \$ 15.78      | \$ 18,936.00    |       | \$ -          | \$ 18,936.00           |   |
|  |      |             |               |                 |       |               | <b>\$ 554,310.00</b>   |   |
| <b>Drilling and Well Completion</b>  |      |             |               | \$ -            |       | \$ -          | \$ -                   |   |
| Mobilization -   | 1    | each        | \$ 39,620.00  | \$ 39,620.00    |       | \$ -          | \$ 39,620.00           |   |
| Injection/extraction/monitoring well construction  | 20   | each        | \$ 61,125.50  | \$ 1,222,510.00 |       | \$ -          | \$ 1,222,510.00        |   |
| Injection/extraction/monitoring well development   | 20   | each        | \$ 4,225.00   | \$ 84,500.00    |       | \$ -          | \$ 84,500.00           |   |
| Injection/extraction well pumps/discharge piping   | 6    | each        | \$ 7,589.45   | \$ 45,536.70    |       | \$ -          | \$ 45,536.70           |   |
| Chemical dosing well down hole tooling (pipe, fittings, etc.)  | 11   | each        | \$ 4,179.25   | \$ 45,971.75    |       | \$ -          | \$ 45,971.75           |   |
| Mixing and delivery system   |      |             |               |                 |       |               |                        |   |
| Surface header pipe and chemical delivery manifold   | 1    | LS          | \$ 100,000.00 | \$ 100,000.00   |       |               | \$ 100,000.00          |   |
| Mixing tanks and valves  | 1    | LS          | \$ 20,000.00  | \$ 20,000.00    |       |               | \$ 20,000.00           |   |
| SCADA controlled mixing system   | 1    | LS          | \$ 50,000.00  | \$ 50,000.00    |       |               | \$ 50,000.00           |   |
| PPE upgrade markup   | 1    | LS          | \$ 21,325.20  | \$ 21,325.20    |       | \$ -          | \$ 21,325.20           | Scaled to 15% of ERH installation cost estimate (20 borings versus 137 borings) |
| Demobilization   | 1    | each        | \$ 15,000.00  | \$ 15,000.00    |       | \$ -          | \$ 15,000.00           |   |
| Solid/liquid waste management/disposition  | 1    | LS          | \$ 253,501.80 | \$ 253,501.80   |       | \$ -          | \$ 253,501.80          | Scaled to 15% of ERH waste costs (20 borings versus 137 borings)                |
|  |      |             |               |                 |       |               | <b>\$ 1,897,965.45</b> |   |
|  |      |             |               |                 |       |               | <b>\$ 2,452,275.45</b> |   |
| <b>Professional and Technical Services</b>   |      |             |               |                 |       |               |                        |   |
| Project Management (6%)  |      |             |               |                 |       |               | \$ 147,136.53          |   |
| Remedial Design (12%)  |      |             |               |                 |       |               | \$ 294,273.05          |   |
| Construction Management (8%)   |      |             |               |                 |       |               | \$ 196,182.04          |   |
|  |      |             |               |                 |       |               | <b>\$ 637,591.62</b>   |   |
|  |      |             |               |                 |       |               | <b>\$ 3,089,867.07</b> |   |
| <b>Contingency</b>   |      |             |               |                 |       |               |                        |   |
| Scope + Bid = (25%)  |      |             |               |                 |       |               | <b>\$ 772,466.77</b>   |   |
|  |      |             |               |                 |       |               | <b>\$ 3,862,333.83</b> |   |

| Alternative 5 - Staged Implementation of Baseline/Rebound Analysis and In-situ Chemical Treatment |        |          |             |               |       |          |              |                      |  | 520                                   |
|---|--------|----------|-------------|---------------|-------|----------|--------------|----------------------|--|---------------------------------------|
| EW and SVGTS Operations and Maintenance   |        |          |             |               |       |          |              |                      |  |                                       |
| Description   | Qty.   | Material |             |               | Total | Labor    |              | Total                | Total Cost (M+L)   | Cost Basis/Questions                  |
|   |        | Unit     | Unit Price  | hours         |       | Rate     |              |                      |  |                                       |
| <b>Perform Startup/Testing/Training</b>   |        |          |             | \$ -          |       |          | \$ -         | \$ -                 | Assume 11 days for start up and testing (FTE = 110 hours)                          |                                       |
| Engineer  |        |          |             | \$ -          | 220   | \$ 50.00 | \$ 11,000.00 | \$ 11,000.00         | 2 FTE  |                                       |
| Operators   |        |          |             | \$ -          | 220   | \$ 57.33 | \$ 12,612.60 | \$ 12,612.60         | 2 FTE  |                                       |
| ES&H  |        |          |             | \$ -          | 110   | \$ 63.00 | \$ 6,930.00  | \$ 6,930.00          | 1 FTE  |                                       |
| Radcon Technician   |        |          |             | \$ -          | 110   | \$ 57.33 | \$ 6,306.30  | \$ 6,306.30          | 1 FTE  |                                       |
| Mechanical Support  |        |          |             | \$ -          | 220   | \$ 57.33 | \$ 12,612.60 | \$ 12,612.60         | 2 FTE  |                                       |
| Electrician   |        |          |             | \$ -          | 220   | \$ 57.33 | \$ 12,612.60 | \$ 12,612.60         | 2 FTE  |                                       |
| Spare parts and material  | 1      | ls       | \$20,000.00 | \$ 20,000.00  | 0     | \$ -     | \$ -         | \$ 20,000.00         |  |                                       |
|   |        |          |             |               |       |          |              | <b>\$ 82,074.10</b>  |  |                                       |
| <b>O&amp;M of Extraction Wells and SVGTS</b>  |        |          |             |               |       |          |              |                      |  | Assume 154 hours per month for an FTE |
| H&S Personnel   |        |          |             | \$ -          | 77    | \$ 63.00 | \$ 4,851.00  | \$ 4,851.00          | 0.5 FTE  |                                       |
| Project Engineer/Data Coordinator   |        |          |             | \$ -          | 77    | \$ 50.00 | \$ 3,850.00  | \$ 3,850.00          | 0.5 FTE  |                                       |
| Radcon Technician   |        |          |             | \$ -          | 38.5  | \$ 57.33 | \$ 2,207.21  | \$ 2,207.21          | 0.25 FTE   |                                       |
| Operating Personnel   |        |          |             | \$ -          | 308   | \$ 57.33 | \$ 17,657.64 | \$ 17,657.64         | 2 FTE  |                                       |
| Mechanical Support  |        |          |             | \$ -          | 38.5  | \$ 57.33 | \$ 2,207.21  | \$ 2,207.21          | 0.25 FTE   |                                       |
| Electrician   |        |          |             | \$ -          | 38.5  | \$ 57.33 | \$ 2,207.21  | \$ 2,207.21          | 0.25 FTE   |                                       |
| Electricity   | 145.92 | Mw-Hr    | \$ 75.00    | \$ 10,944.00  |       |          |              | \$ 10,944.00         | 0.200 MW power yields 146 MW-Hrs per month   |                                       |
| Assume \$3000 per month for material/parts  | 1      | month    | \$ 3,000.00 | \$ 3,000.00   | 154   | \$ -     | \$ -         | \$ 3,000.00          |  |                                       |
| Analytical with 8-day turn (1.5 times markup)   | 4      | ea       | \$ 207.00   | \$ 828.00     |       |          |              | \$ 828.00            | Weekly samples of the system effluent  |                                       |
| <b>Total per Month</b>  |        |          |             |               |       |          |              | <b>\$ 47,752.26</b>  |  |                                       |
| <b>Total for 4 Months</b>   |        |          |             |               |       |          |              | <b>\$ 191,009.02</b> | Assume total of 4 month of GW extraction   |                                       |
| <b>Rebound Analyses</b>   |        |          |             |               |       |          |              |                      |  |                                       |
| Sample Management Office  |        |          |             | \$ -          | 120   | \$ 50.00 | \$ 6,000.00  | \$ 6,000.00          | 4 hours per week for 30 weeks  |                                       |
| Sample Technicians (2)  |        |          |             | \$ -          | 1200  | \$ 50.00 | \$ 60,000.00 | \$ 60,000.00         | (2) 10-hour days per week for two sample techs                                     |                                       |
| Geologist/Scientist   |        |          |             | \$ -          | 308   | \$ 70.00 | \$ 21,560.00 | \$ 21,560.00         | 1 FTE for 2 months to evaluate results   |                                       |
| Analytical with 8-day turn (1.5 times markup)   | 1085   | ea       | \$ 207.00   | \$ 224,595.00 |       |          |              | \$ 224,595.00        | Weekly influent and effluent for 31 weeks, weekly at 11 location - 3 depths for 31 |                                       |
| <b>Total</b>  |        |          |             |               |       |          |              | <b>\$ 312,155.00</b> |  |                                       |
|   |        |          |             |               |       |          |              | <b>\$ 585,238.12</b> |  |                                       |
| <b>Professional and Technical Services</b>  |        |          |             |               |       |          |              |                      |  |                                       |
| Project Management (6%)   |        |          |             |               |       |          |              | \$ 35,114.29         |  |                                       |
|   |        |          |             |               |       |          |              | <b>\$ 620,352.41</b> |  |                                       |
| <b>Contingency</b>  |        |          |             |               |       |          |              |                      |  |                                       |
| Scope + Bid = (25%)   |        |          |             |               |       |          |              | \$ 155,088.10        |  |                                       |
|   |        |          |             |               |       |          |              | <b>\$ 775,440.51</b> |  |                                       |

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| <b>Alternative 5 - Staged Implementation of Baseline/Rebound Analysis and In-situ Chemical Treatment</b>                              |          |        |              |                 |       |                  |  |
|---|----------|--------|--------------|-----------------|-------|------------------|--|
| <b>Operations and Maintenance of <i>in-situ</i> Chemical Treatment Systems</b>  |          |        |              |                 |       |                  |  |
| Description   | Material |        |              | Labor           |       | Total Cost (M+L) | Cost Basis/Questions   |
|   | Qty.     | Unit   | Unit Price   | Total           | hours |                  |  |
| <b>Perform Startup/Testing/Training</b>   |          |        |              | \$ -            |       | \$ -             | Assume 11 days for start up and testing (FTE = 110 hours)  |
| Engineer  |          |        |              | \$ -            | 220   | \$ 11,000.00     | \$ 11,000.00 2 FTE   |
| Operators   |          |        |              | \$ -            | 220   | \$ 12,612.60     | \$ 12,612.60 2 FTE   |
| ES&H  |          |        |              | \$ -            | 110   | \$ 6,930.00      | \$ 6,930.00 1 FTE  |
| Radcon Technician   |          |        |              | \$ -            | 110   | \$ 6,306.30      | \$ 6,306.30 1 FTE  |
| Mechanical Support  |          |        |              | \$ -            | 220   | \$ 12,612.60     | \$ 12,612.60 2 FTE   |
| Electrician   |          |        |              | \$ -            | 220   | \$ 12,612.60     | \$ 12,612.60 2 FTE   |
| Spare parts and material  | 1        | ls     | \$ 20,000.00 | \$ 20,000.00    | 0     | \$ -             | \$ 20,000.00   |
|   |          |        |              |                 |       |                  | <b>\$ 82,074.10</b>  |
| <b>Chemical Injection to Oxidize<br/>4,140 gal TCE (50,508 pounds)<br/>Assumes 360 gallons removed<br/>during Centralized Pumping</b> |          |        |              |                 |       |                  | <b>Assume 51 events lasting 10 hours to inject 2,423,316<br/>gallons of KMnO4/H2O solution at 80 gallons per<br/>minute.</b>   |
| H&S Personnel   |          |        |              | \$ -            | 510   | \$ 32,130.00     | \$ 32,130.00 1 FTE   |
| Project Engineer/Data Coordinator   |          |        |              | \$ -            | 510   | \$ 25,500.00     | \$ 25,500.00 1 FTE   |
| Radcon Technician   |          |        |              | \$ -            | 510   | \$ 29,238.30     | \$ 29,238.30 1 FTE   |
| Operating Personnel   |          |        |              | \$ -            | 2040  | \$ 116,953.20    | \$ 116,953.20 4 FTE  |
| Mechanical Support during operations  |          |        |              | \$ -            | 255   | \$ 14,619.15     | \$ 14,619.15 0.5 FTE   |
| Electrician for maintenance during  |          |        |              | \$ -            | 255   | \$ 14,619.15     | \$ 14,619.15 0.5 FTE   |
| Potassium Permanganate Costs  | 606096   | pounds | \$ 2.17      | \$ 1,313,410.03 |       | \$ -             | \$ 1,313,410.03<br>KMnO4 Cost Basis:<br>- 4140 gallons TCE (50,508lbs.) to be oxidized,<br>- stoichiometric demand is 2.4 lbs per lb of TCE<br>- assume 20% contact efficiency (accounts for NOD also),<br>- 3% solution is injected |
| Analytical with 8-day turn (1.5 times markup)   | 102      | ea     | \$ 207.00    | \$ 21,114.00    |       |                  | \$ 21,114.00<br>VOC samples collected after each injection event from 2 of the 13 wells  |
| Electricity   | 102      | Mw-Hr  | \$ 75.00     | \$ 7,650.00     |       |                  | \$ 7,650.00<br>0.200 MW power yields 102 MW-Hrs for the 51 events  |
|   |          |        |              |                 |       |                  | <b>\$ 1,575,233.83</b>   |
|   |          |        |              |                 |       |                  | <b>\$ 1,657,307.93</b>   |
| <b>Professional and Technical Services</b>  |          |        |              |                 |       |                  |  |
| Project Management (6%)   |          |        |              |                 |       |                  | \$ 99,438.48   |
|   |          |        |              |                 |       |                  | <b>\$ 1,756,746.41</b>   |
| <b>Contingency</b><br>Scope + Bid = (25%)   |          |        |              |                 |       |                  |  |
|   |          |        |              |                 |       |                  | <b>\$ 439,186.60</b>   |
|   |          |        |              |                 |       |                  | <b>\$ 2,195,933.01</b>   |



| Alternative 5 - Staged Implementation of Baseline/Rebound Analysis and In-situ Chemical Treatment |       |           |              |               |       |              |                  |   |
|---|-------|-----------|--------------|---------------|-------|--------------|------------------|---|
| D&D and Site Restoration  |       |           |              |               |       |              |                  |   |
| Description   | Qty.  | Material  |              |               | Labor |              | Total Cost (M+L) | Cost Basis  |
|   |       | Unit      | Unit Price   | Total         | hours | Total        |                  |   |
| <b>D&amp;D and Site Restoration Labor</b>   |       |           |              |               |       |              |                  | Assume D&D to take 6 weeks at 50 hours per week (FTE = 300 hours)   |
| Geologist   |       |           |              | \$ -          | 300   | \$ 21,000.00 | \$ 21,000.00     | 1 FTE   |
| Pipefitter  |       |           |              | \$ -          | 900   | \$ 51,597.00 | \$ 51,597.00     | 3 FTE   |
| Mechanic  |       |           |              | \$ -          | 900   | \$ 51,597.00 | \$ 51,597.00     | 3 FTE   |
| Electrician   |       |           |              | \$ -          | 900   | \$ 51,597.00 | \$ 51,597.00     | 3 FTE   |
| Laborer   |       |           |              | \$ -          | 600   | \$ 34,398.00 | \$ 34,398.00     | 2 FTE   |
| Escorts   |       |           |              | \$ -          | 600   | \$ 23,100.00 | \$ 23,100.00     | 2 FTE   |
| Radcon Technician   |       |           |              | \$ -          | 600   | \$ 34,398.00 | \$ 34,398.00     | 2 FTE   |
| PPE   | 720   | per man-d | \$ 15.78     | \$ 11,361.60  |       | \$ -         | \$ 11,361.60     | 2 changes per day - 12 FTEs for 30 days   |
|   |       |           |              |               |       |              | \$ 279,048.60    |   |
| <b>Drilling/Site Restoration Subcontractor</b>  |       |           |              |               |       |              |                  |   |
| Mobilization/Demobilization   | 1     | each      | \$ 20,449.00 | \$ 20,449.00  |       | \$ -         | \$ 20,449.00     |   |
| Abandon Wells   | 30    | days      | \$ 5,504.00  | \$ 165,120.00 |       | \$ -         | \$ 165,120.00    | 20 wells at 1.5 day per well  |
| Supplies/Material   | 20    | each      | \$ 500.00    | \$ 10,000.00  |       | \$ -         | \$ 10,000.00     | \$500 allowance per well  |
|   |       |           |              |               |       |              | \$ 195,569.00    |   |
| <b>Waste Management/Disposition</b>   |       |           |              |               |       |              |                  |   |
| Waste characterization  |       |           |              |               |       |              |                  | Assume 11 roll-off bins of D&D debris to be characterized, 5 days required to   |
| Waste Mgt Field Coordinator   |       |           |              |               | 50    | \$ 2,866.50  | \$ 2,866.50      | 1 FTE   |
| Waste Operators   |       |           |              |               | 50    | \$ 2,866.50  | \$ 2,866.50      | 1 FTE   |
| Waste Engineer  |       |           |              |               | 50    | \$ 3,875.00  | \$ 3,875.00      | 1 FTE   |
| Waste Samplers  |       |           |              |               | 100   | \$ 5,733.00  | \$ 5,733.00      | 2 FTE   |
| Radcon Technician   |       |           |              |               | 50    | \$ 2,866.50  | \$ 2,866.50      | 1 FTE   |
| Drill Cutting Sample Analyses   | 57.75 | ea        | \$ 506.00    | \$ 29,221.50  |       |              | \$ 29,221.50     | 5 samples from each of 11 intermodals plus 5% QA, analysis for VOCs and SVOCs   |
| Drill Cutting Sample Analyses   | 11.55 | ea        | \$ 2,490.00  | \$ 28,759.50  |       |              | \$ 28,759.50     | 1 sample from each of 11 intermodals plus 5% QA, analysis for Rads and Metals   |
| Waste Water Sample Analyses   | 6     | ea        | \$ 914.00    | \$ 5,484.00   |       |              | \$ 5,484.00      | 5 frac tanks of waste water generated, 1 sample from each plus QA, analyses for permit parameters   |
| Waste Disposition   |       |           |              |               |       |              |                  | Assume all debris taken to onsite landfill and all waste water sent to C-612 - no disposal costs assumed<br>Delivery of debris and wastewater assumed to take 3 weeks |
| Waste Mgt Field Coordinator   |       |           |              |               | 120   | \$ 6,879.60  | \$ 6,879.60      | 1 FTE   |
| Waste Operators/Truck Driver  |       |           |              |               | 480   | \$ 27,518.40 | \$ 27,518.40     | 4 FTE   |
|   |       |           |              |               |       |              | \$ 116,070.50    |   |
| <b>Remedial Action Completion Report</b>  |       |           |              |               |       |              |                  |   |
| Geologist   |       |           |              | \$ -          | 120   | \$ 9,960.00  | \$ 9,960.00      |   |
| Remediation Engineer  |       |           |              | \$ -          | 540   | \$ 44,820.00 | \$ 44,820.00     |   |
| Senior Scientist  |       |           |              | \$ -          | 32    | \$ 3,232.00  | \$ 3,232.00      |   |
| Project Engineer  |       |           |              | \$ -          | 120   | \$ 6,000.00  | \$ 6,000.00      |   |
| Environmental Compliance Specialist   |       |           |              | \$ -          | 40    | \$ 2,840.00  | \$ 2,840.00      |   |
| QA Specialist   |       |           |              | \$ -          | 24    | \$ 1,536.00  | \$ 1,536.00      |   |
| Technical Editing/Document Production   |       |           |              | \$ -          | 96    | \$ 6,720.00  | \$ 6,720.00      |   |
| Document Production Material  | 1     | LS        | \$ 5,600.00  | \$ 5,600.00   |       |              | \$ 5,600.00      |   |
|   |       |           |              |               |       |              | \$ 80,708.00     |   |
| <b>Subtotal</b>   |       |           |              |               |       |              | \$ 671,396.10    |   |
| <b>Professional and Technical Services</b>  |       |           |              |               |       |              |                  |   |
| Project Management (6%)   |       |           |              |               |       |              | \$ 40,283.77     |   |
|   |       |           |              |               |       |              | \$ 711,679.87    |   |
| <b>Contingency</b>  |       |           |              |               |       |              |                  |   |
| Scope + Bid = (25%)   |       |           |              |               |       |              | \$ 177,919.97    |   |
| <b>Total</b>  |       |           |              |               |       |              | \$ 889,599.83    |   |

**ATTACHMENT A2**  
**PHASE II MASS VOLUME ESTIMATE**

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## A2.1. INTRODUCTION

The purpose of this attachment is to present a summary of the revised estimates of trichloroethene (TCE) mass volume for the C-400 Interim Remedial Action Phase II treatment area based on the analyses of soil samples obtained during the field characterization effort conducted in early 2011. The Field Sampling Plan (FSP) (DOE 2011) describes the activities associated with the 2011 field characterization effort for the Phase II treatment area. Revised mass volume estimates for the Phase II area were generated to refine the conceptual site model (CSM) and support the basis of technology identification selection. This attachment supports the Draft *Evaluation of the Technologies and Alternatives for C-400 Phase IIb, Regional Gravel Aquifer, at the Paducah Gaseous Diffusion Plant, Paducah, Kentucky*.

The estimate of the total TCE mass volume of the Phase II treatment area is anticipated to range between 7,300 and 85,000 lb (600 and 7,000 gal). For the interval between 0–60 ft below ground surface (bgs),<sup>1</sup> which is primarily the Upper Continental Recharge System (UCRS), the estimate ranges from 290 to 30,500 lb (24 to 2,500 gal). For the interval from 60–100 ft bgs in the Regional Gravel Aquifer (RGA) the estimate ranges from 7,000 to 55,000 lb (576 to 4,500 gal). As indicated, the estimates of mass volume are provided as a range of values. For estimates of residual TCE dense nonaqueous-phase liquid (DNAPL) mass, similar to the C-400 Phase II site, the concept of a range of values is appropriate given the typically heterogeneous nature of DNAPL distribution in subsurface environments similar to that present at C-400 (ITRC 2003). Kueper et al. point out that the majority of the porous media within a DNAPL source zone will contain neither residual nor pooled DNAPL, and the probability of directly encountering residual or pooled DNAPL with a conventional drilling program is relatively small (Kueper et al. 2003). The range of estimates provided is considered to be valid to within an order of magnitude on the upper end. The lower end of the range is identified for informational purposes to indicate the estimate of mass based solely on the results of soil samples analyzed for TCE.

## A2.2. GOALS AND SAMPLING METHODS OF THE 2011 INVESTIGATION

LATA Environmental Services of Kentucky, LLC, performed the field characterization investigation of the C-400 Phase II treatment area during the period February through May 2011. Two of the goals of the investigation<sup>2</sup> were these:

- Development of predictive relationships of previous and proposed membrane interface probe (MIP) responses to current TCE concentrations, and
- Assessment of the TCE DNAPL mass and volume within the C-400 Phase II treatment area.

The investigation included MIP logging in six locations (collocated with soil borings) to collect data for development of predictive relationships; collection of soil and groundwater samples for TCE analysis

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<sup>1</sup> The three estimate approaches modeled the base of the UCRS at 56, 59, and 60 ft bgs. The Phase IIa remedial action will remove TCE from soils down to a depth of approximately 62 ft using electrical resistance heating (ERH).

<sup>2</sup> The investigation also collected soil samples for analyses of RGA grain size and natural oxidant demand and installed an upgradient well cluster.

from the UCRS, RGA, and the top of the McNairy Formation in six deep soil borings; and collection of soil samples from the UCRS for TCE analysis from an additional two shallow soil borings.

Table A2.1 summarizes the sampling requirements of the FSP. Figure A2.1 shows the location of the 2011 sampling activities, as well as other local MIP borehole locations from a 2006 Remedial Design Support Investigation.

### **A2.2.1 SAMPLE SUMMARY**

In total, the investigation collected soil samples from 250 discrete locations and groundwater samples from 40 discrete locations for analysis of TCE and degradation products. As anticipated, TCE was the dominant contaminant. Tables A2.2 and A2.3 summarize the TCE analyses.

TCE-in-soil concentrations of approximately 200,000 µg/kg are indicative of DNAPL presence in sandy aquifers (Parker et al. 2003). Only one of the analyses of TCE-in-soil (1,700,000 µg/kg TCE from a depth of 59 ft in SB55) is indicative of the presence of DNAPL (approximately 1% DNAPL saturation). While none of the groundwater samples collected DNAPL, all TCE-in-groundwater analyses exceeded 1% of the effective solubility of TCE (11,000 µg/L), a commonly recognized indication of the presence of DNAPL (EPA 2009).

### **A2.2.2 PREDICTIVE RELATIONSHIPS**

Visual comparison of plots of the MIP logs and TCE analyses revealed that the data were poorly related (Figure A2.2 demonstrates the overall lack of correlation of MIP data and TCE analyses.) Of the collocated soil and MIP borings, the best comparison was evident using the photoionization (PID) log of MIP-54 (paired with TCE analyses of SB55) (Figure A2.3). In general, the TCE concentrations in the investigation samples were below the sensitivity range of the MIP detectors.

The predictive relationship assessment included a linear regression analysis of PID measurements and TCE analyses for four MIP/soil boring pairs to qualify the correlation of the data sets. This analysis applied a linear trend line to plots of TCE soil concentrations versus MIP PID data and calculated the correlation coefficient ( $R^2$ ) value. The assessment successively compared each soil sample with three MIP PID readings: the “non-averaged” PID reading for the sample depth and PID values averaged over 5 ft (Figure A2.4) and 10 ft (Figure A2.5) intervals centered on the sample depth.

Correlations with high correlation coefficient values would be required to predict accurately TCE concentrations from the MIP PID data. Strong correlation coefficients of 0.9 and above were not found on a consistent basis. Because a consistent correlation between MIP readings and analytical data does not exist, the two data sets could not be used in a quantitative TCE mass and volume estimate.

### **A2.2.3 INITIAL MASS VOLUME ESTIMATE APPROACHES**

Three approaches were used to develop initial estimates of the TCE mass volume as follows:

- (1) Interpolation of TCE soil analyses within the broader southeast C-400 area, using data from the 2011 investigation and other area historical analyses;
- (2) Interpolation of TCE soil analyses within the anticipated treatment zone and its immediate perimeter, using only data from the 2011 investigation; and

**Table A2.1. Field Sampling Plan Sampling Requirements**

| C-400<br>PHASE II<br>(2011)<br>SOIL<br>BORING | C-400<br>PHASE II<br>(2011)<br>MIP<br>BORING | SOILS        |           |                    |                    |          |                               |                 |                                   | GROUNDWATER |                                   |                    | C-400<br>RDSI<br>(2006)<br>MIP<br>BORING |
|---|--|--------------|-----------|--------------------|--------------------|----------|-------------------------------|-----------------|-----------------------------------|-------------|-----------------------------------|--------------------|--|
|   |  | VOCs         |           |                    |                    | NOD      |                               | GRAIN SIZE/VOCs |                                   | VOCs        |                                   |                    |  |
|   |  | Horizons     | Frequency | Depths<br>(ft bgs) | Sample<br>Quantity | Horizons | Depths<br>(ft bgs)            | Horizons        | Depths<br>(ft bgs)                | Horizons    | Depths<br>(ft bgs)                | Sample<br>Quantity |  |
| SB53  | MIP-53                                       | UCRS/<br>McN | 1         | 20 – 65,<br>95     | 46                 | NS       | NS                            | RGA             | 65, 70, 75, 80,<br>85             | RGA         | 70, 75, 80, 85,<br>90, 94         | 6                  | MIP-13                                   |
| SB54  | MIP-55                                       | UCRS/<br>McN | 2         | 20 – 55,<br>97     | 19                 | NS       | NS                            | NS              | NS                                | RGA         | 60, 65, 70, 75,<br>80, 85, 90, 95 | 8                  | MIP-14                                   |
| SB55  | MIP-54                                       | UCRS/<br>McN | 1         | 0 – 62,<br>94      | 63                 | RGA      | 75 - 81                       | NS              | NS                                | RGA         | 65, 70, 75, 80,<br>85, 90, 95     | 7                  | MIP-16                                   |
| SB56  | MIP-56                                       | UCRS/<br>McN | 2         | 20 – 65,<br>96     | 24                 | NS       | NS                            | NS              | NS                                | RGA         | 70, 75, 80, 85,<br>90, 95         | 6                  | MIP-17                                   |
| SB57  | MIP-57                                       | UCRS/<br>McN | 2         | 20 – 57,<br>95     | 20                 | NS       | NS                            | RGA             | 60, 65, 70, 75,<br>85, 90, 94     | RGA         | 60, 65, 70, 75,<br>80, 85, 90, 94 | 8                  | MIP-21                                   |
| SB58  | MIP-58                                       | UCRS         | 2         | 20 - 61            | 21                 | NS       | NS                            | NS              | NS                                | NS          | NS                                | NS                 | MIP-43                                   |
| SB59  | NS   | UCRS/<br>McN | 2         | 20 – 61,<br>94     | 22                 | NS       | NS                            | RGA             | 62, 65, 70, 75,<br>80, 85, 90, 93 | RGA         | 65, 70, 75, 80,<br>85, 90, 93     | 7                  | MIP-48                                   |
| SB60  | NS   | UCRS         | 2         | 20 - 61            | 21                 | NS       | NS                            | NS              | NS                                | NS          | NS                                | NS                 | MIP-44                                   |
| MW507   | NS   | UCRS         | 1         | PID ≥<br>50 PPM    | TBD                | RGA      | 64 – 70<br>76 – 82<br>88 - 96 | NS              | NS                                | NS          | NS                                | NS                 | MIP-26                                   |

Notes:

Frequency = vertical spacing of samples (in ft)

McN = Upper 1 ft of McNairy Formation

MIP = membrane interface probe

NOD = Natural Oxidant Demand

NS = not sampled

PID = Photoionization Detector

PPM = parts per million

RGA = Regional Gravel Aquifer

TBD = to be determined in field (no soil exceeded 50 PPM on the PID and no samples were collected)

UCRS = Upper Continental Recharge System

VOCs = Volatile Organic Compounds

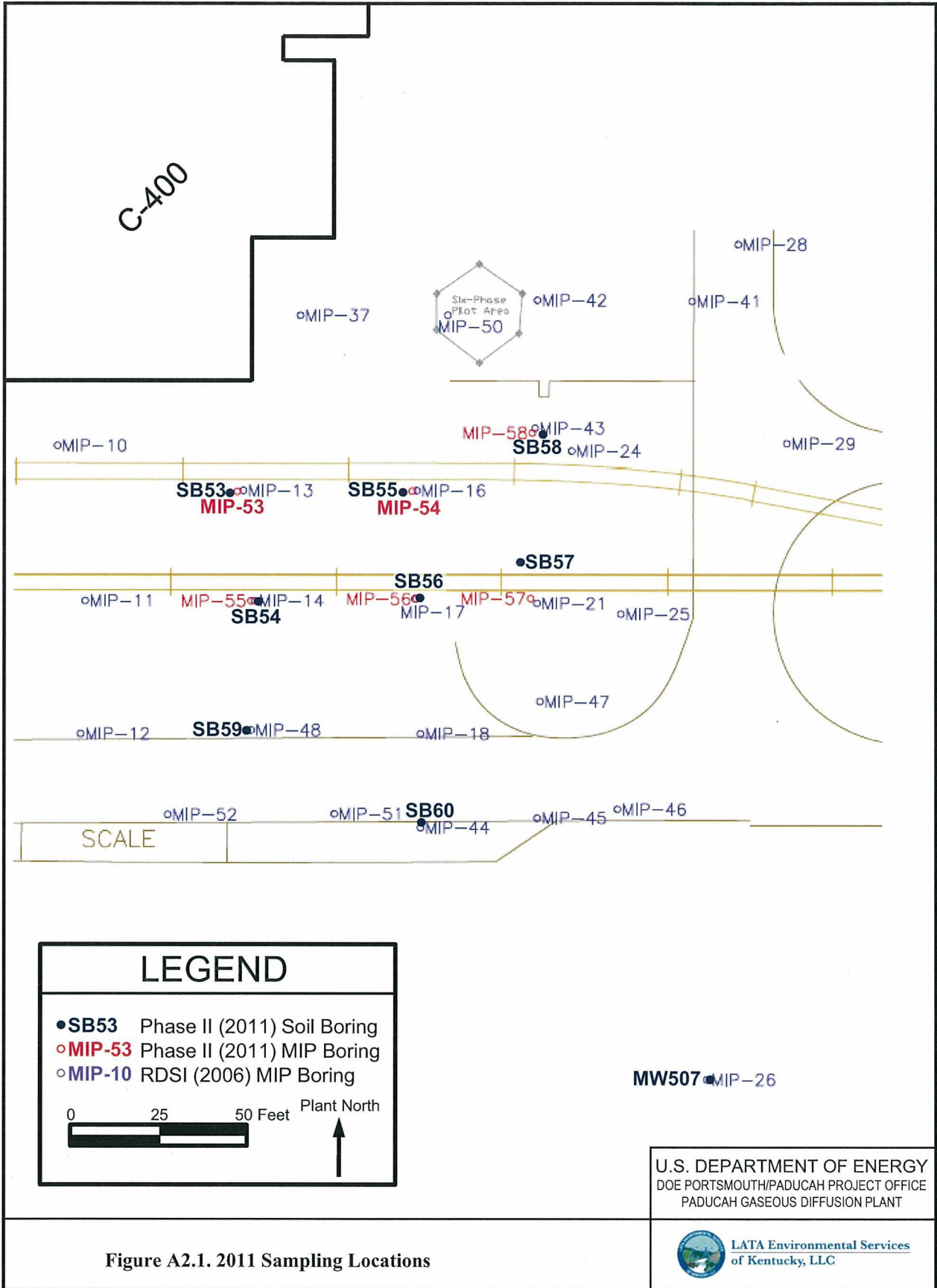


Figure A2.1. 2011 Sampling Locations

**Table A2.2. Soil Trichloroethene Analytical Results for the C-400 Phase II Area  
Showing Maximum Value by Depth**

| DEPTH<br>(ft bgs) | Soil Boring and Trichloroethene (µg/kg) |       |        |      |       |        |      |       |
|-------------------|---|-------|--------|------|-------|--------|------|-------|
|                   | SB53                                    | SB54  | SB55   | SB56 | SB57  | SB58   | SB59 | SB60  |
| 5                 | NS                                      | NS    | 9      | NS   | NS    | NS     | NS   | NS    |
| 6                 | NS                                      | NS    | 4      | NS   | NS    | NS     | NS   | NS    |
| 7                 | NS                                      | NS    | 10     | NS   | NS    | NS     | NS   | NS    |
| 8                 | NS                                      | NS    | 710    | NS   | NS    | NS     | NS   | NS    |
| 9                 | NS                                      | NS    | 480    | NS   | NS    | NS     | NS   | NS    |
| 10                | NS                                      | NS    | 640    | NS   | NS    | NS     | NS   | NS    |
| 11                | NS                                      | NS    | 820    | NS   | NS    | NS     | NS   | NS    |
| 12                | NS                                      | NS    | 1,200  | NS   | NS    | NS     | NS   | NS    |
| 13                | NS                                      | NS    | 1,300  | NS   | NS    | NS     | NS   | NS    |
| 14                | NS                                      | NS    | 2,000  | NS   | NS    | NS     | NS   | NS    |
| 15                | NS                                      | NS    | 1,500  | NS   | NS    | NS     | NS   | NS    |
| 16                | NS                                      | NS    | 1,500  | NS   | NS    | NS     | NS   | NS    |
| 17                | NS                                      | NS    | 2,100  | NS   | NS    | NS     | NS   | NS    |
| 18                | NS                                      | NS    | 1,900  | NS   | NS    | NS     | NS   | NS    |
| 19                | NS                                      | NS    | 280    | NS   | NS    | NS     | NS   | NS    |
| 20                | 12,000                                  | 2     | 1,400  | 49   | 530   | 1,300  | NS   | 220   |
| 21                | 12,000                                  | NS    | 1,600  | NS   | NS    | NS     | NS   | NS    |
| 22                | 14,000                                  | 1     | 2,300  | 79   | 490   | 2,700  | NS   | 400   |
| 23                | 18,000                                  | NS    | 8,700  | NS   | NS    | NS     | NS   | NS    |
| 24                | 14,000                                  | 5     | 10,000 | 74   | 5,500 | 8,600  | NS   | 640   |
| 25                | 1,800                                   | NS    | 26,000 | NS   | NS    | NS     | NS   | NS    |
| 26                | 4,000                                   | 1     | 30,000 | 40   | 1,200 | 2,200  | 4    | 410   |
| 27                | 5,000                                   | NS    | 14,000 | NS   | NS    | NS     | NS   | NS    |
| 28                | 170                                     | 1     | 12,000 | 100  | 910   | 14,000 | 2    | 130   |
| 29                | 1,100                                   | NS    | 31,000 | NS   | NS    | NS     | NS   | NS    |
| 30                | 320                                     | 8     | 790    | 2    | 1,400 | 3,300  | 5    | 180   |
| 31                | 1,100                                   | NS    | 1,300  | NS   | NS    | NS     | NS   | NS    |
| 32                | 5,600                                   | 200   | 70,000 | 81   | 2,800 | 6,400  | 14   | 290   |
| 33                | 54                                      | NS    | 99,000 | NS   | NS    | NS     | NS   | NS    |
| 34                | 110                                     | 270   | 33,000 | 43   | 1,900 | 2,600  | 6    | 7     |
| 35                | 1,200                                   | NS    | 55,000 | NS   | NS    | NS     | NS   | NS    |
| 36                | 49                                      | 3     | 82,000 | 58   | 2,200 | 23,000 | NS   | 44    |
| 36.1              | NS                                      | NS    | NS     | NS   | NS    | NS     | 2    | NS    |
| 36.6              | NS                                      | NS    | 93,000 | NS   | NS    | NS     | NS   | NS    |
| 37                | 280                                     | NS    | 74,000 | NS   | NS    | NS     | NS   | NS    |
| 38                | 730                                     | 34    | 30,000 | 71   | 600   | 12,000 | 9    | 1,100 |
| 39                | 860                                     | NS    | 15,000 | NS   | NS    | NS     | NS   | NS    |
| 39.6              | NS                                      | NS    | NS     | NS   | NS    | NS     | NS   | NS    |
| 40                | 240                                     | 64    | 57,000 | 55   | 750   | 29,000 | 170  | 110   |
| 41                | 1,100                                   | NS    | 20,000 | NS   | NS    | NS     | NS   | NS    |
| 41.9              | NS                                      | 3,000 | NS     | NS   | NS    | NS     | NS   | NS    |

µg/kg = microgram/kilogram

NS = not sampled



**Table A2.2. Soil Trichloroethene Analytical Results for the C-400 Phase II Area  
Showing Maximum Value by Depth (Continued)**

| DEPTH<br>(ft bgs) | Soil Boring and Trichloroethene (µg/kg) |       |           |         |        |        |        |        |  |
|-------------------|---|-------|-----------|---------|--------|--------|--------|--------|--|
|                   | SB53                                    | SB54  | SB55      | SB56    | SB57   | SB58   | SB59   | SB60   |  |
| 42                | 5,400                                   | 190   | 27,000    | 7       | 3,100  | 22,000 | NS     | 16     |  |
| 42.1              | NS                                      | NS    | NS        | NS      | NS     | NS     | 150    | NS     |  |
| 42.9              | NS                                      | NS    | NS        | NS      | NS     | NS     | 49     | NS     |  |
| 43                | 4,600                                   | NS    | 81,000    | NS      | NS     | NS     | NS     | NS     |  |
| 44                | 6,900                                   | 2,600 | 8,400     | 98      | 2,800  | 2,100  | 1,100  | 3      |  |
| 45                | 1,700                                   | NS    | 69,000    | NS      | NS     | NS     | NS     | NS     |  |
| 46                | 8,700                                   | 2,500 | NS        | 15      | 250    | 10,000 | 2,100  | 5,900  |  |
| 47                | 8,700                                   | NS    | NS        | NS      | NS     | NS     | NS     | NS     |  |
| 48                | 7,500                                   | 3,400 | NS        | 1,400   | 5,400  | 5,000  | 130    | 12,000 |  |
| 49                | 8,600                                   | NS    | NS        | NS      | NS     | NS     | NS     | NS     |  |
| 50                | 9,200                                   | 3,700 | NS        | 2,000   | 7,800  | 11,000 | 2,200  | 170    |  |
| 51                | 14,000                                  | NS    | 48,000    | NS      | NS     | NS     | NS     | NS     |  |
| 52                | 17,000                                  | 2,200 | 96,000    | 1,700   | 490    | 8,400  | 2,500  | 100    |  |
| 53                | 14,000                                  | NS    | 60,000    | NS      | NS     | NS     | NS     | NS     |  |
| 54                | 23,000                                  | 750   | 35,000    | 440     | 470    | 6,100  | 2,600  | 3,100  |  |
| 55                | 23,000                                  | 130   | 24,000    | NS      | 2,000  | NS     | NS     | NS     |  |
| 56                | 7,100                                   | NS    | 15,000    | 5,500   | NS     | 66,000 | 4,100  | 4,000  |  |
| 57                | 8,600                                   | NS    | 8,400     | NS      | NS     | NS     | NS     | NS     |  |
| 58                | 6,200                                   | NS    | 14,000    | 850     | NS     | 41,000 | 5,600  | 890    |  |
| 59                | 1,900                                   | NS    | 1,700,000 | NS      | NS     | NS     | NS     | NS     |  |
| 60                | 6,700                                   | NS    | 75,000    | 2,600   | NS     | 8,500  | 3,700  | 2,600  |  |
| 60.5              | NS                                      | NS    | NS        | NS      | NS     | NS     | NS     | 380    |  |
| 61                | 8,000                                   | NS    | 64,000    | NS      | NS     | NS     | 1,900  | 1,500  |  |
| 62                | 6,600                                   | NS    | 67,000    | 2,600   | NS     | 2,300  | NS     | NS     |  |
| 63                | 4,000                                   | NS    | NS        | NS      | NS     | NS     | NS     | NS     |  |
| 64                | 620                                     | NS    | NS        | 7,100   | NS     | NS     | NS     | NS     |  |
| 65                | 130                                     | NS    | NS        | NS      | NS     | NS     | NS     | NS     |  |
| 66                | 16,000                                  | NS    | NS        | NS      | NS     | NS     | NS     | NS     |  |
| 71                | 23,000                                  | NS    | NS        | NS      | NS     | NS     | NS     | NS     |  |
| 76                | NS                                      | NS    | NS        | NS      | NS     | NS     | 2,700  | NS     |  |
| 85                | 1,100                                   | NS    | NS        | NS      | 54,000 | NS     | NS     | NS     |  |
| 90                | NS                                      | NS    | NS        | NS      | 21,000 | NS     | NS     | NS     |  |
| 91                | NS                                      | NS    | NS        | NS      | NS     | NS     | 1,300  | NS     |  |
| 94                | 16,000                                  | NS    | 1,900     | NS      | NS     | NS     | 2,900  | NS     |  |
| 95                | NS                                      | 5,100 | NS        | NS      | NS     | NS     | NS     | NS     |  |
| 95.1              | NS                                      | NS    | NS        | NS      | 9,100  | NS     | NS     | NS     |  |
| 95.2              | NS                                      | NS    | NS        | NS      | NS     | NS     | 1,900  | NS     |  |
| 95.4              | NS                                      | NS    | 2,000     | NS      | NS     | NS     | 14,000 | NS     |  |
| 95.6              | NS                                      | NS    | NS        | NS      | 48     | NS     | NS     | NS     |  |
| 95.8              | NS                                      | 7,900 | NS        | NS      | NS     | NS     | NS     | NS     |  |
| 96                | NS                                      | NS    | NS        | 150,000 | NS     | NS     | NS     | NS     |  |
| 96.3              | NS                                      | NS    | NS        | 1,300   | NS     | NS     | NS     | NS     |  |

µg/kg = microgram/kilogram

NS = not sampled

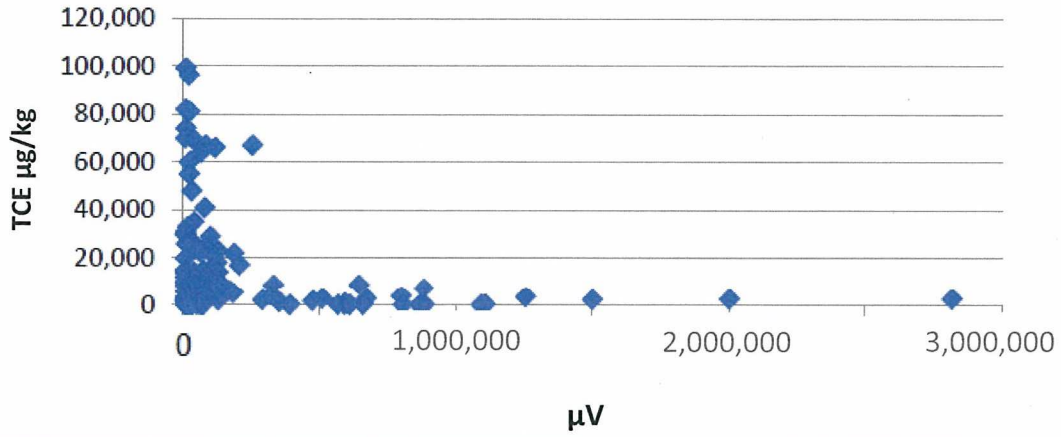
**Table A2.3. Groundwater Trichloroethene Analytical Results for the C-400 Phase II Area  
Showing Maximum Value by Depth**

| DEPTH<br>(ft) | Soil Boring and Trichloroethene (µg/L) |         |         |         |           |        |
|---------------|--|---------|---------|---------|-----------|--------|
|               | SB53                                   | SB54    | SB55    | SB56    | SB57      | SB59   |
| 60            | NS                                     | 28,000  | NS      | NS      | NS        | NS     |
| 65            | NS                                     | 21,000  | 610,000 | NS      | 280,000   | 16,000 |
| 70            | 77,000                                 | 23,000  | 570,000 | 280,000 | 400,000   | 27,000 |
| 75            | 55,000                                 | NS      | 430,000 | 430,000 | 270,000   | 20,000 |
| 79            | 180,000                                | 19,000  | NS      | NS      | NS        | NS     |
| 80            | NS                                     | NS      | 84,000  | 240,000 | 340,000   | 24,000 |
| 84            | 100,000                                | NS      | NS      | NS      | NS        | NS     |
| 85            | NS                                     | 580,000 | 57,000  | 240,000 | 590,000   | 70,000 |
| 89            | 87,000                                 | NS      | NS      | NS      | NS        | NS     |
| 90            | NS                                     | 410,000 | 53,000  | 230,000 | 1,200,000 | 52,000 |
| 93            | NS                                     | NS      | NS      | NS      | NS        | 34,000 |
| 94            | 76,000                                 | NS      | 46,000  | NS      | 870,000   | NS     |
| 95            | NS                                     | 330,000 | NS      | 200,000 | NS        | NS     |

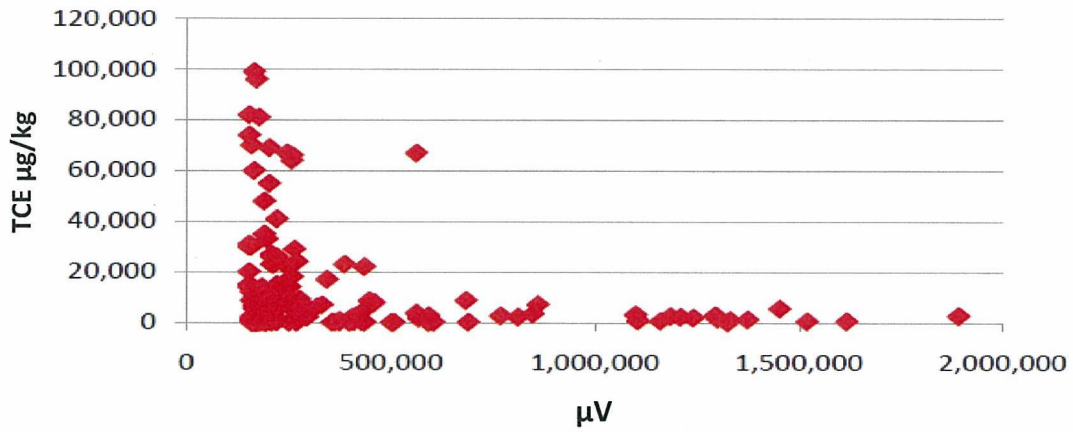
µg/L = microgram/liter

NS = not sampled

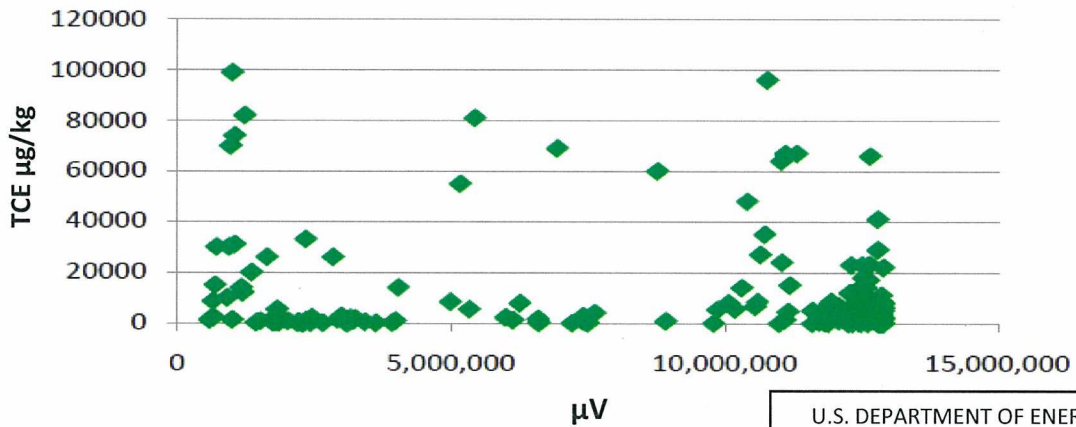
### Photoionization Detector



### Flame Ionization Detector



### Electron Capture Detector

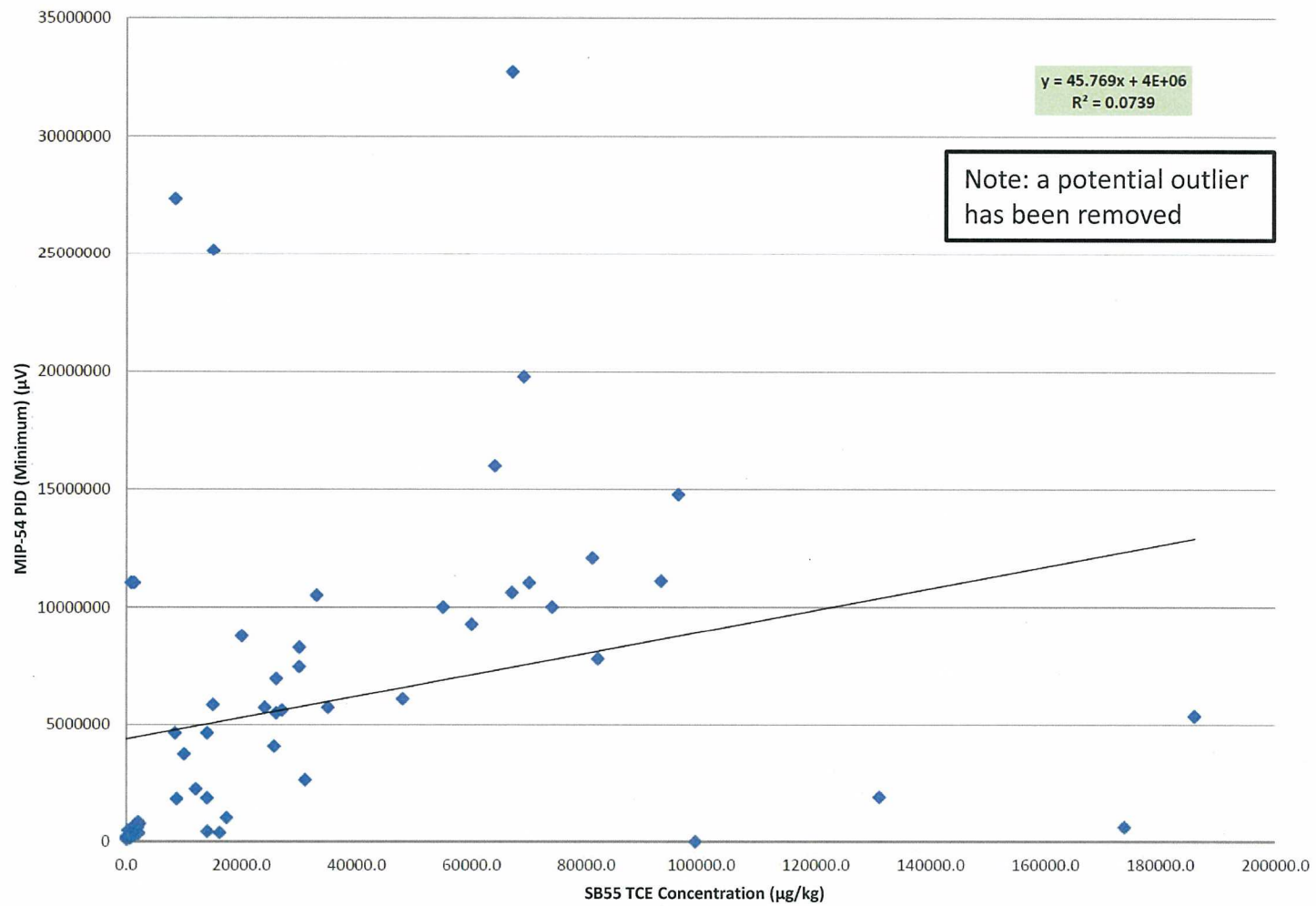


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Figure A2.2. 2011 C-400 Phase II Investigation Trichloroethene Concentrations in Soil versus MIP Detector Responses



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Figure A2.3. Linear Regression of C-400 Phase II Trichloroethene Concentrations in Soil at SB55 versus Photoionization Detector Response in MIP-54



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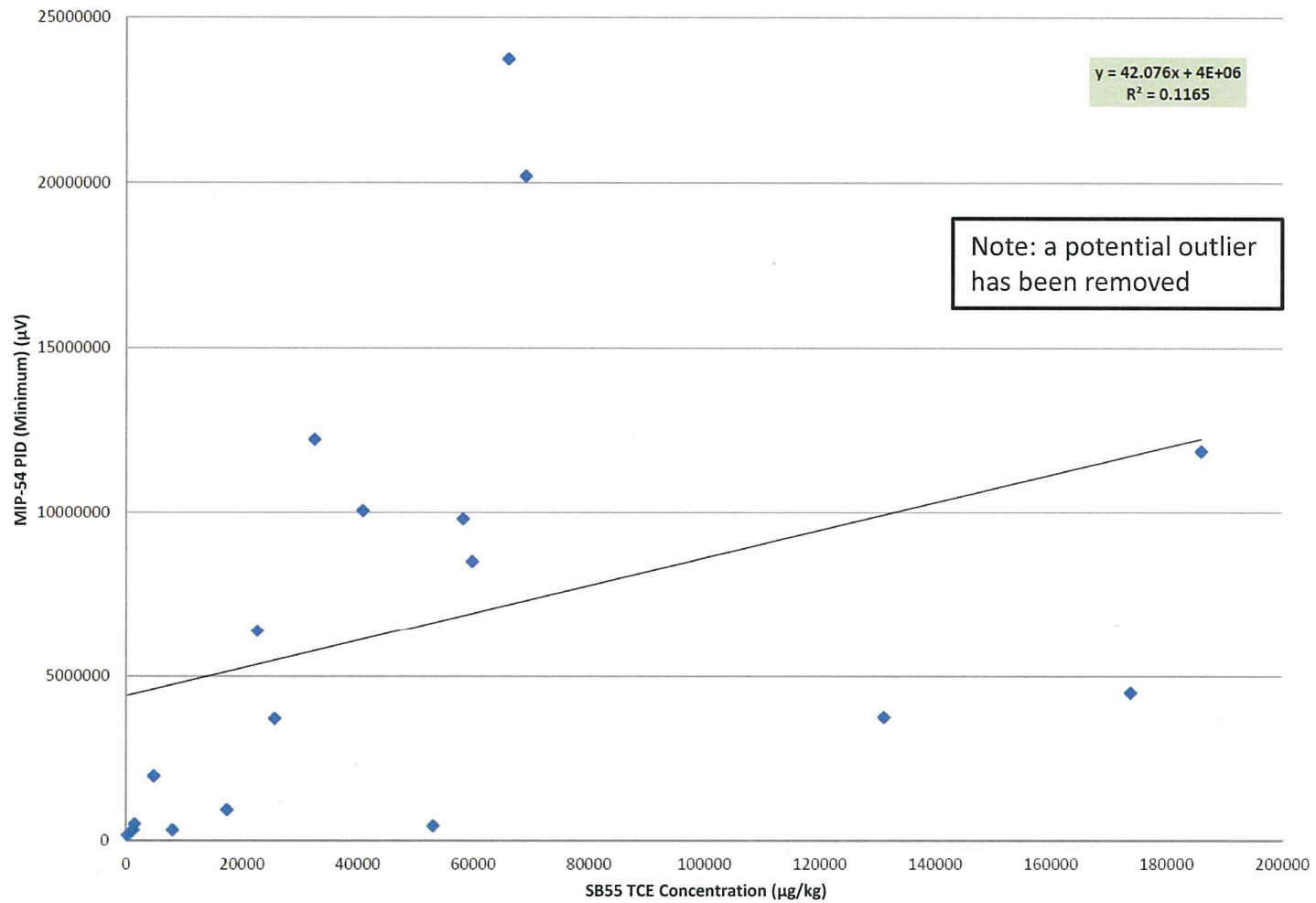


Figure A2.4. Linear Regression of C-400 Phase II Trichloroethene Concentrations in Soil at SB55 versus 5-ft Average Photoionization Detector Response in MIP-54

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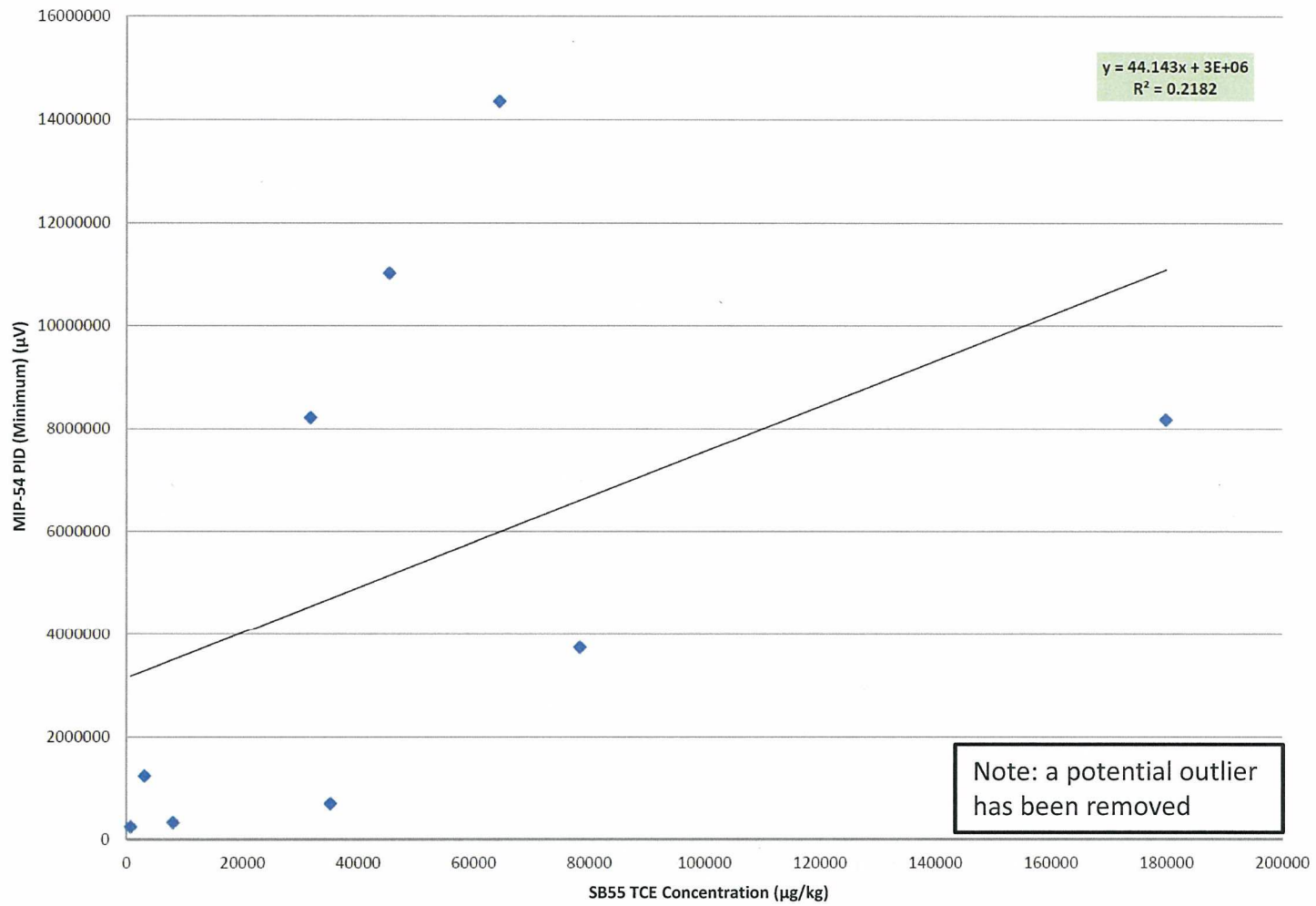


Figure A2.5. Linear Regression of C-400 Phase II Trichloroethene Concentrations in Soil at SB55 versus 10-ft Average Photoionization Detector Response in MIP-54

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- (3) Interpolation of TCE soil analyses from three soil borings of the 2011 investigation, based on a CSM incorporating a point of DNAPL release.

### **Approach 1**

The assessment of the broader southeast C-400 area used Esri ArcGIS to discretize the model volume into 5-ft depth intervals down to the base of the RGA and to interpolate (contour) soil analyses across each of the 5-ft intervals (Figure A2.6). Inverse distance weighted interpolation was used, with MIP borings providing outer boundary points for the area of interpolation. For each 5-ft depth interval, the assessment calculated the TCE mass within soil volumes of equal concentration as follows:

$$\text{TCE Mass (lb)} = \text{Area of Equal Concentration [ft}^2\text{]} \times \text{Interval Depth [ft]} \times \text{Soil Weight [kg/ft}^3\text{]} \times \text{Average Concentration [\mu g/kg]} \times \text{Micrograms to Pounds Conversion Factor [lb/\mu g]}$$

(Soil weight was specific to the UCRS and RGA)

and summed the TCE mass calculations. Table A2.4 summarizes the results of the mass calculation. Because few soil analyses are available for the RGA, the assessment included calculated soil concentrations, derived from the available groundwater analyses by use of a partitioning coefficient.

The Esri ArcGIS-based assessment estimated 780 lb (64 gal) of TCE are present in the UCRS down to a depth of 56 ft and 7,000 lb (570 gal) of TCE are present in the RGA below 56 ft.

### **Approach 2**

The assessment limited to the anticipated treatment zone (and perimeter) used the U.S. Geological Survey's Modular Three-Dimensional Groundwater Flow Model (MODFLOW) to discretize the Phase II treatment area volume into 1-ft x 1-ft x 1-ft model cells down to the base of the RGA and to linearly interpolate the 2011 investigation soil TCE analyses within each 1-ft depth interval throughout all of the treatment area's model cells (Figure A2.7). (This model assumed that the TCE-in-soil concentration of each of the perimeter model cells was 0.1  $\mu\text{g/kg}$ .) Where the 2011 investigation did not provide a soil analysis within a 1-ft depth interval for a soil boring, the assessment created a synthetic soil analysis by (vertical) linear interpolation between analyses for the closest soil samples. MODFLOW converted the interpolated TCE-in-soil concentrations into TCE mass for each of the area's model cells using the following equation:

$$\text{TCE Mass (lb)/Model Cell} = \text{Model Cell TCE Concentration [\mu g/kg]} \times \text{Soil Weight [kg/ft}^3\text{]} \times \text{Volume of Model Cell [ft}^3\text{]} \times \text{Micrograms to Pounds Conversion Factor [lb/\mu g]}$$

(Soil weight is specific to the UCRS and RGA.)

Figure A2.8 shows the vertical distribution of the model-derived TCE mass.

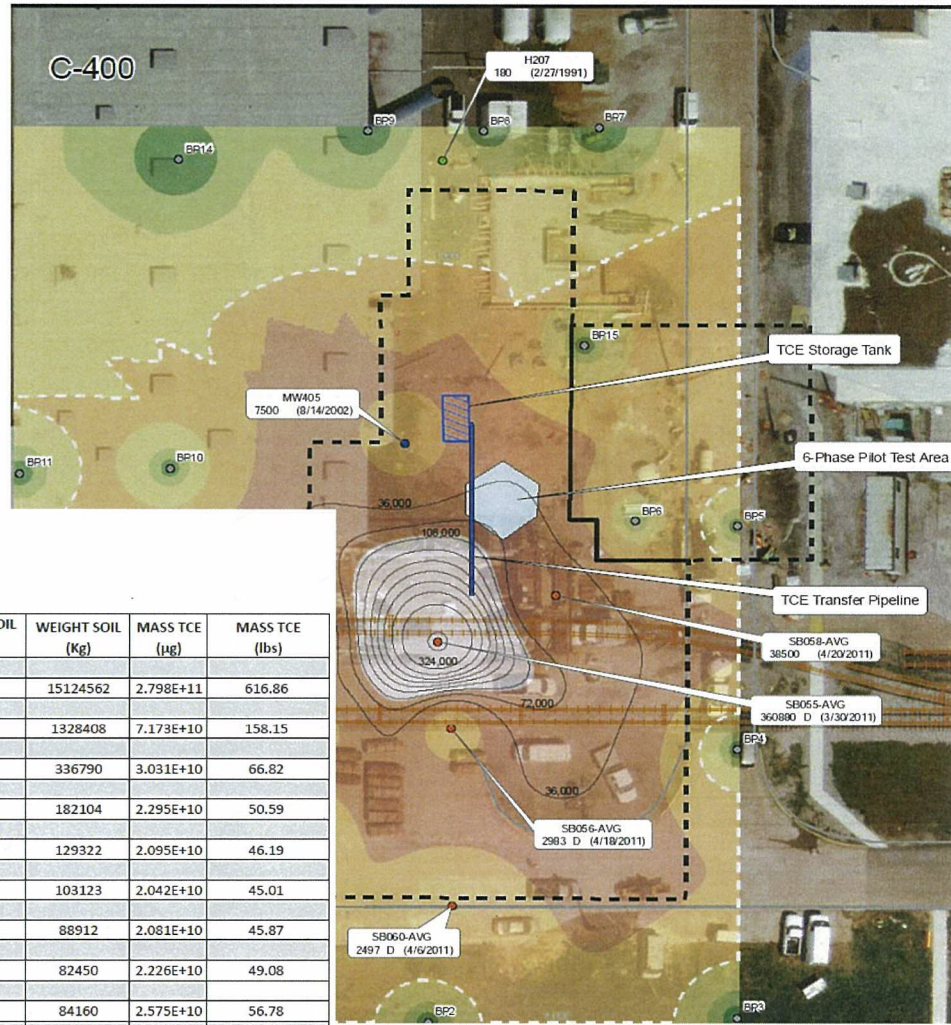
The MODFLOW-based assessment estimated 290 lb (24 gal) of TCE are present in the UCRS down to a depth of 59 ft and 75 lb (6 gal) of TCE are present in the RGA below 59 ft.

VERTICAL INTERVAL ELEVATION: 319-324 ft AMSL  
 VERTICAL INTERVAL DEPTH: 5 ft  
 ESTIMATED SOIL DENSITY: 54.9 Kg/ft<sup>3</sup>  
 CONVERSION  $\mu\text{g}$  per lb: 453,592,370  
 CONTOUR INTERVAL: 36,000

| CONCENTRATION<br>( $\mu\text{g}/\text{Kg}$ ) | AVERAGE CONCENTRATION<br>( $\mu\text{g}/\text{Kg}$ ) | AREA OF EQUAL<br>CONCENTRATION (FT <sup>2</sup> ) | $\Delta$ AREA (ft <sup>2</sup> ) | VOLUME SOIL<br>(ft <sup>3</sup> ) | WEIGHT SOIL<br>(Kg) | MASS TCE<br>( $\mu\text{g}$ ) | MASS TCE<br>(lbs) |
|--|--|---|----------------------------------|-----------------------------------|---------------------|-------------------------------|-------------------|
| 1000   |  | 64106   |                                  |                                   |                     |                               |                   |
|  | 18500  |   | 55123                            | 275617                            | 15124562            | 2.798E+11                     | 616.86            |
| 36000  |  | 8982  |                                  |                                   |                     |                               |                   |
|  | 54000  |   | 4842                             | 24208                             | 1328408             | 7.173E+10                     | 158.15            |
| 72000  |  | 4141  |                                  |                                   |                     |                               |                   |
|  | 90000  |   | 1227                             | 6137                              | 336790              | 3.031E+10                     | 66.82             |
| 108000                                       |  | 2913  |                                  |                                   |                     |                               |                   |
|  | 126000   |   | 664                              | 3319                              | 182104              | 2.295E+10                     | 50.59             |
| 144000                                       |  | 2250  |                                  |                                   |                     |                               |                   |
|  | 162000   |   | 471                              | 2357                              | 129322              | 2.095E+10                     | 46.19             |
| 180000                                       |  | 1778  |                                  |                                   |                     |                               |                   |
|  | 198000   |   | 376                              | 1879                              | 103123              | 2.042E+10                     | 45.01             |
| 216000                                       |  | 1402  |                                  |                                   |                     |                               |                   |
|  | 234000   |   | 324                              | 1620                              | 88912               | 2.081E+10                     | 45.87             |
| 252000                                       |  | 1078  |                                  |                                   |                     |                               |                   |
|  | 270000   |   | 301                              | 1503                              | 82450               | 2.226E+10                     | 49.08             |
| 288000                                       |  | 778   |                                  |                                   |                     |                               |                   |
|  | 306000   |   | 307                              | 1534                              | 84160               | 2.575E+10                     | 56.78             |
| 324000                                       |  | 471   |                                  |                                   |                     |                               |                   |
|  | 342000   |   | 435                              | 2173                              | 119241              | 4.078E+10                     | 89.91             |
| 360000                                       |  | 36  |                                  |                                   |                     |                               |                   |

INTERVAL MASS TOTAL = 1,225 lbs  
 100 gallons

ft AMSL = feet above mean sea level



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Figure A2.6. Southeast C-400 Model Example Calculation Worksheet and Contour Interpolation for the 319-324 ft AMSL Layer



**Table A2.4. Southeast C-400 Model TCE Mass and Volume Summary**

| Vertical Interval |          | TCE Mass<br>(lbs) | TCE Mass<br>(gallons) | Cumulative<br>TCE Mass<br>(gallons) | Cumulative<br>TCE Mass<br>(%) | Formation |
|-------------------|----------|-------------------|-----------------------|-------------------------------------|-------------------------------|-----------|
| (ft amsl)         | (ft bgs) |                   |                       |                                     |                               |           |
| 274 – 284         | 96 – 106 | 321               | 26                    | 634                                 | 100%                          | RGA       |
| 284 – 289         | 91 – 96  | 915               | 75                    | 608                                 | 96%                           | RGA       |
| 289 – 294         | 86 – 91  | 1,034             | 85                    | 533                                 | 84%                           | RGA       |
| 294 – 299         | 81 – 86  | 667               | 55                    | 448                                 | 71%                           | RGA       |
| 299 – 304         | 76 – 81  | 717               | 59                    | 393                                 | 62%                           | RGA       |
| 304 – 309         | 71 – 76  | 833               | 68                    | 334                                 | 53%                           | RGA       |
| 309 – 314         | 66 – 71  | 905               | 74                    | 266                                 | 42%                           | RGA       |
| 314 – 319         | 61 – 66  | 337               | 28                    | 192                                 | 30%                           | RGA       |
| 319 – 324         | 56 – 61  | 1,225             | 100                   | 164                                 | 26%                           | RGA (HU4) |
| 324 – 329         | 51 – 56  | 196               | 16                    | 64                                  | 10%                           | UCRS      |
| 329 – 334         | 46 – 51  | 84                | 6.9                   | 48                                  | 8%                            | UCRS      |
| 334 – 339         | 41 – 46  | 109               | 8.9                   | 41                                  | 6%                            | UCRS      |
| 339 – 344         | 36 – 41  | 91                | 7.5                   | 32                                  | 5%                            | UCRS      |
| 344 – 349         | 31 – 36  | 75                | 6.1                   | 25                                  | 4%                            | UCRS      |
| 349 – 354         | 26 – 31  | 32                | 2.6                   | 18                                  | 3%                            | UCRS      |
| 354 – 359         | 21 – 26  | 46                | 3.7                   | 16                                  | 2%                            | UCRS      |
| 359 – 364         | 16 – 21  | 27                | 2.2                   | 12                                  | 2%                            | UCRS      |
| 364 – 369         | 11 – 16  | 27                | 2.3                   | 10                                  | 2%                            | UCRS      |
| 369 – 374         | 6 – 11   | 75                | 6.2                   | 8                                   | 1%                            | UCRS      |
| 374 – 380         | 0 - 6    | 17                | 1.4                   | 1                                   | 0%                            | UCRS      |

|                     |              |            |
|---------------------|--------------|------------|
| <b>TOTAL MASS =</b> | <b>7,735</b> | <b>634</b> |
|---------------------|--------------|------------|

|            |       |     |
|------------|-------|-----|
| RGA Mass = | 5,730 | 570 |
|------------|-------|-----|

|             |       |    |
|-------------|-------|----|
| UCRS Mass = | 2,005 | 64 |
|-------------|-------|----|

ft amsl = feet above mean sea level

ft bgs = feet below ground surface

% = percent

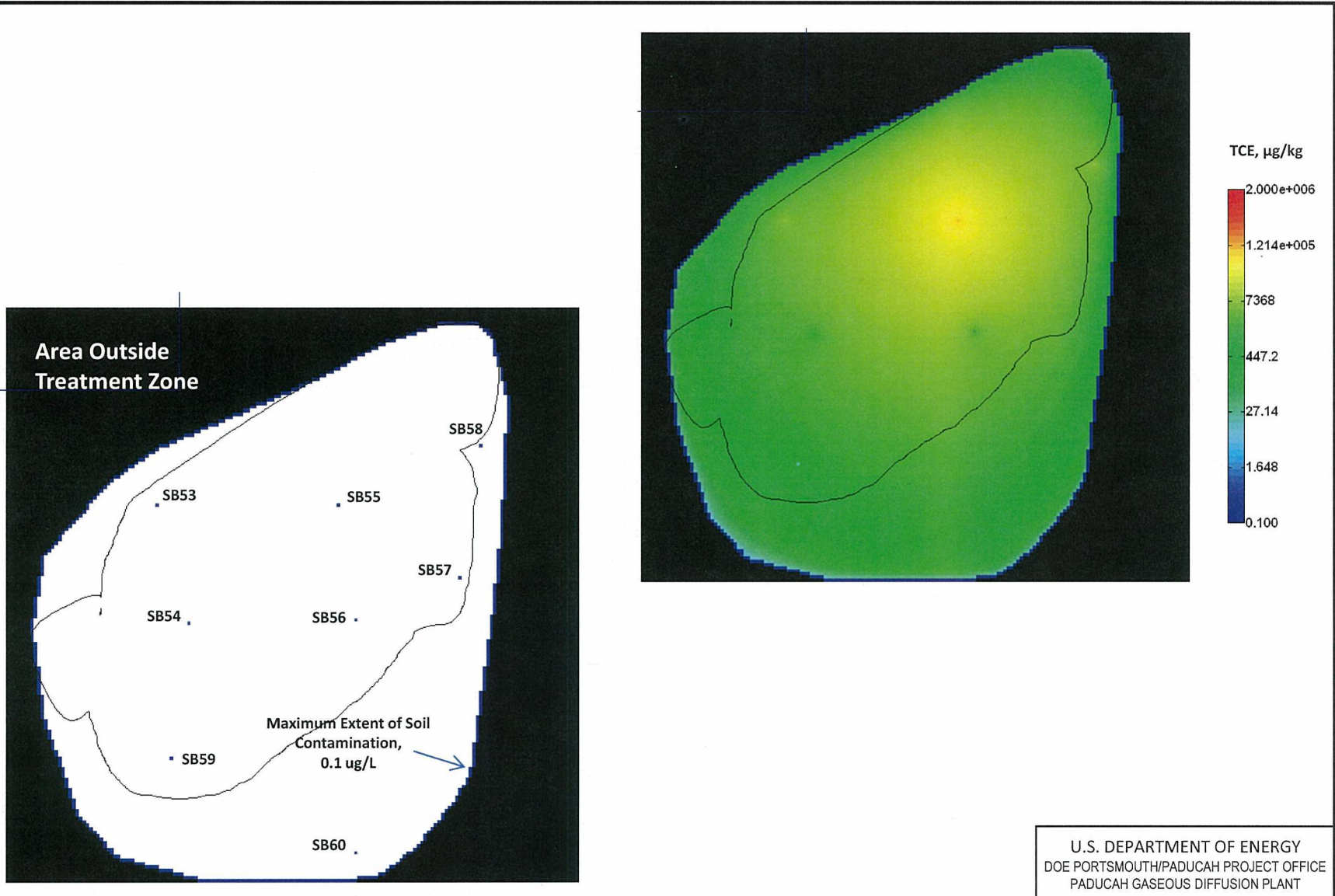


Figure A2.7. Treatment Zone Model Domain and Example TCE Interpolation

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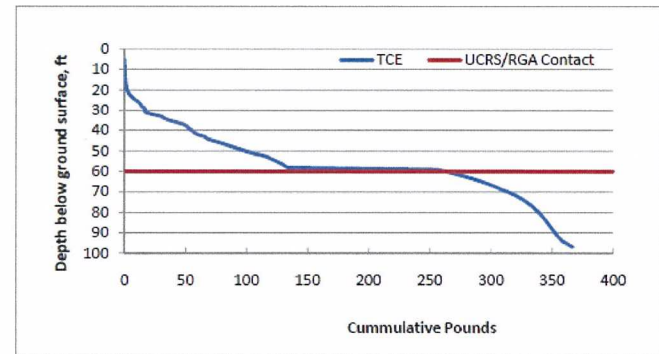
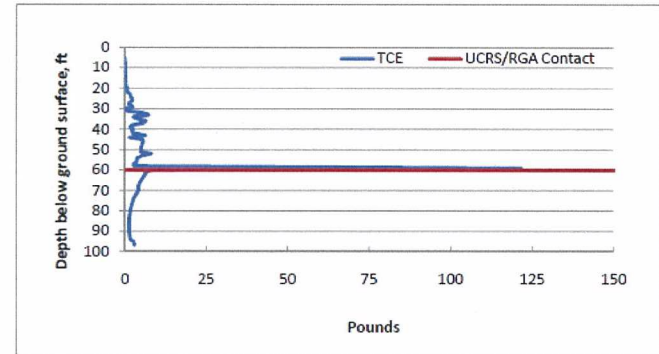


CALCULATION OF TCE MASS AND VOLUME FOR 5 FT DEPTH (MODEL LAYER 1) TO 97 FT DEPTH (MODEL LAYER 93)

| Layer | Depth (ft bgs) | POUNDS OF TCE IN SOIL* (LBS-SOIL) | GALLONS OF TCE IN SOIL (GAL-SOIL) | CUMMULATIVE POUNDS OF TCE IN SOIL (CUM LBS-SOIL) | Layer | Depth (ft bgs) | POUNDS OF TCE IN SOIL* (LBS-SOIL) | GALLONS OF TCE IN SOIL (GAL-SOIL) | CUMMULATIVE POUNDS OF TCE IN SOIL (CUM LBS-SOIL) |
|-------|----------------|-----------------------------------|-----------------------------------|--|-------|----------------|-----------------------------------|-----------------------------------|--|
| 1     | 5              | 0                                 | 0                                 | 0  | 48    | 52             | 8                                 | 1                                 | 112  |
| 2     | 6              | 0                                 | 0                                 | 0  | 49    | 53             | 5                                 | 0                                 | 117  |
| 3     | 7              | 0                                 | 0                                 | 0  | 50    | 54             | 4                                 | 0                                 | 121  |
| 4     | 8              | 0                                 | 0                                 | 0  | 51    | 55             | 4                                 | 0                                 | 124  |
| 5     | 9              | 0                                 | 0                                 | 0  | 52    | 56             | 4                                 | 0                                 | 128  |
| 6     | 10             | 0                                 | 0                                 | 0  | 53    | 57             | 3                                 | 0                                 | 131  |
| 7     | 11             | 0                                 | 0                                 | 0  | 54    | 58             | 3                                 | 0                                 | 133  |
| 8     | 12             | 0                                 | 0                                 | 0  | 55    | 59             | 122                               | 10                                | 255  |
| 9     | 13             | 0                                 | 0                                 | 0  | 56    | 60             | 8                                 | 1                                 | 264  |
| 10    | 14             | 0                                 | 0                                 | 1  | 57    | 61             | 6                                 | 1                                 | 270  |
| 11    | 15             | 0                                 | 0                                 | 1  | 58    | 62             | 6                                 | 1                                 | 276  |
| 12    | 16             | 0                                 | 0                                 | 1  | 59    | 63             | 6                                 | 0                                 | 282  |
| 13    | 17             | 0                                 | 0                                 | 1  | 60    | 64             | 5                                 | 0                                 | 287  |
| 14    | 18             | 0                                 | 0                                 | 1  | 61    | 65             | 5                                 | 0                                 | 292  |
| 15    | 19             | 0                                 | 0                                 | 1  | 62    | 66             | 5                                 | 0                                 | 297  |
| 16    | 20             | 1                                 | 0                                 | 2  | 63    | 67             | 4                                 | 0                                 | 301  |
| 17    | 21             | 1                                 | 0                                 | 3  | 64    | 68             | 4                                 | 0                                 | 306  |
| 18    | 22             | 1                                 | 0                                 | 4  | 65    | 69             | 4                                 | 0                                 | 310  |
| 19    | 23             | 2                                 | 0                                 | 5  | 66    | 70             | 4                                 | 0                                 | 314  |
| 20    | 24             | 2                                 | 0                                 | 7  | 67    | 71             | 4                                 | 0                                 | 318  |
| 21    | 25             | 2                                 | 0                                 | 9  | 68    | 72             | 3                                 | 0                                 | 321  |
| 22    | 26             | 2                                 | 0                                 | 11   | 69    | 73             | 3                                 | 0                                 | 324  |
| 23    | 27             | 1                                 | 0                                 | 13   | 70    | 74             | 3                                 | 0                                 | 327  |
| 24    | 28             | 1                                 | 0                                 | 14   | 71    | 75             | 3                                 | 0                                 | 329  |
| 25    | 29             | 2                                 | 0                                 | 16   | 72    | 76             | 2                                 | 0                                 | 332  |
| 26    | 30             | 0                                 | 0                                 | 17   | 73    | 77             | 2                                 | 0                                 | 334  |
| 27    | 31             | 0                                 | 0                                 | 17   | 74    | 78             | 2                                 | 0                                 | 336  |
| 28    | 32             | 6                                 | 0                                 | 22   | 75    | 79             | 2                                 | 0                                 | 337  |
| 29    | 33             | 7                                 | 1                                 | 30   | 76    | 80             | 2                                 | 0                                 | 339  |
| 30    | 34             | 2                                 | 0                                 | 32   | 77    | 81             | 2                                 | 0                                 | 341  |
| 31    | 35             | 4                                 | 0                                 | 36   | 78    | 82             | 1                                 | 0                                 | 342  |
| 32    | 36             | 6                                 | 1                                 | 43   | 79    | 83             | 1                                 | 0                                 | 344  |
| 33    | 37             | 6                                 | 0                                 | 48   | 80    | 84             | 1                                 | 0                                 | 345  |
| 34    | 38             | 2                                 | 0                                 | 51   | 81    | 85             | 1                                 | 0                                 | 346  |
| 35    | 39             | 2                                 | 0                                 | 52   | 82    | 86             | 1                                 | 0                                 | 347  |
| 36    | 40             | 3                                 | 0                                 | 55   | 83    | 87             | 1                                 | 0                                 | 349  |
| 37    | 41             | 2                                 | 0                                 | 57   | 84    | 88             | 1                                 | 0                                 | 350  |
| 38    | 42             | 3                                 | 0                                 | 60   | 85    | 89             | 1                                 | 0                                 | 351  |
| 39    | 43             | 6                                 | 1                                 | 66   | 86    | 90             | 1                                 | 0                                 | 353  |
| 40    | 44             | 1                                 | 0                                 | 67   | 87    | 91             | 1                                 | 0                                 | 354  |
| 41    | 45             | 5                                 | 0                                 | 73   | 88    | 92             | 1                                 | 0                                 | 355  |
| 42    | 46             | 6                                 | 0                                 | 78   | 89    | 93             | 2                                 | 0                                 | 357  |
| 43    | 47             | 5                                 | 0                                 | 84   | 90    | 94             | 2                                 | 0                                 | 359  |
| 44    | 48             | 5                                 | 0                                 | 89   | 91    | 95             | 3                                 | 0                                 | 361  |
| 45    | 49             | 5                                 | 0                                 | 94   | 92    | 96             | 3                                 | 0                                 | 364  |
| 46    | 50             | 5                                 | 0                                 | 99   | 93    | 97             | 3                                 | 0                                 | 367  |
| 47    | 51             | 5                                 | 0                                 | 104  |       |                |                                   |                                   |  |

\*POUNDS OF TCE IN SOIL (LBS-SOIL) is derived from MODFLOW-2000 MODular three-dimensional finite-difference ground-water FLOW model --2000 updated version

| UCRS | RGA | TOTAL   |
|------|-----|---------|
| 255  | 112 | 367 LBS |
| 21   | 9   | 30 GAL  |



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Figure A2.8. Treatment Zone TCE Mass and Volume Summary

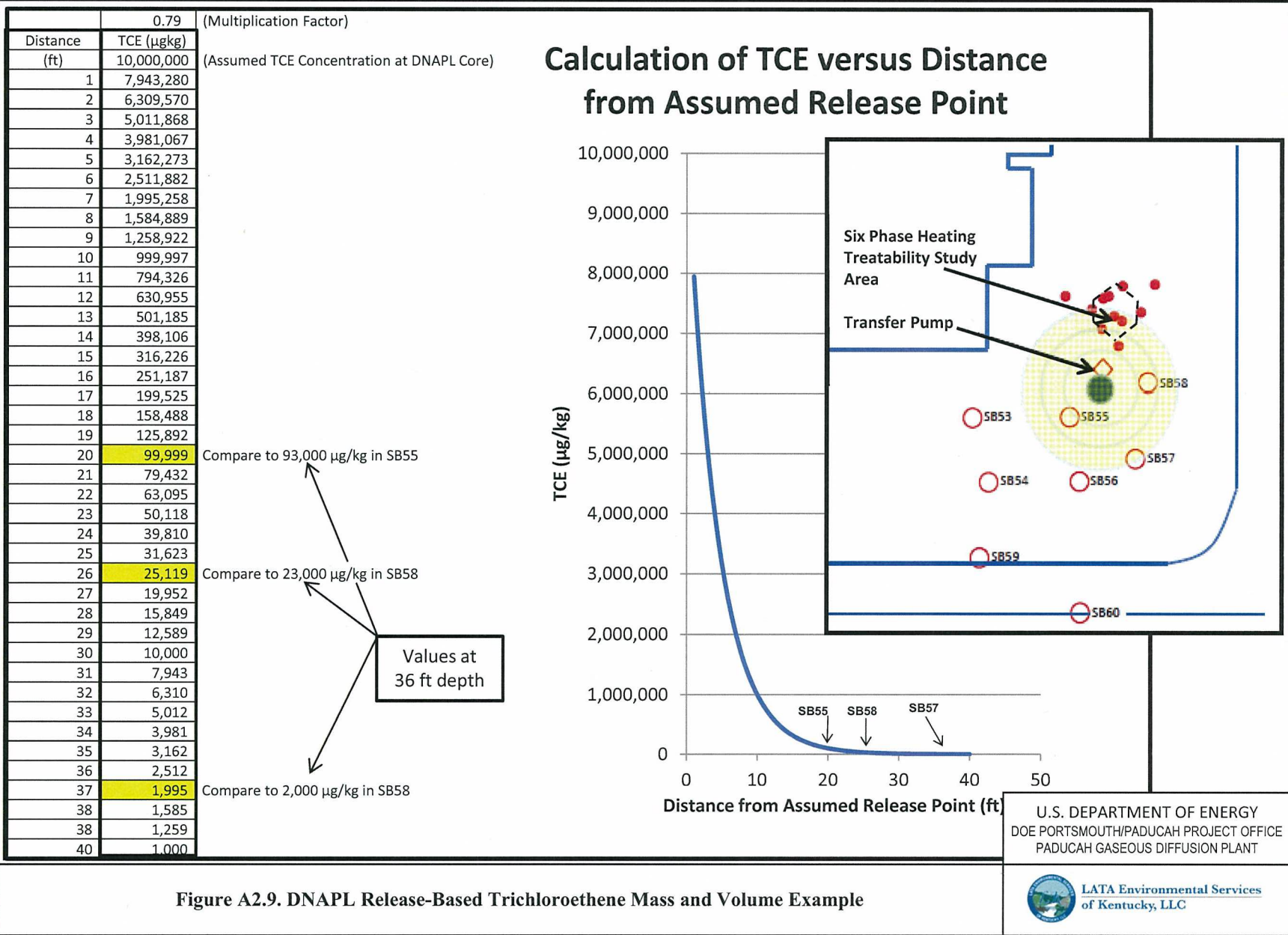


Figure A2.9. DNAPL Release-Based Trichloroethene Mass and Volume Example

### Approach 3

The DNAPL release-based model used Microsoft® Excel to interpolate soil TCE analyses in a transect between a modeled DNAPL zone near the location of the former TCE transfer pump (assigned soil TCE concentration of 10,000,000 µg/kg) and the three closest soil borings of the 2011 investigation (Figure A2.9). This model assessed TCE mass down to a depth of 60 ft, which was discretized into 13 horizons of varied thickness. Soil TCE trends and geology defined the thickness of each of the 13 model horizons.

Table A2.5 presents the depth, soil, and TCE characteristics of each model horizon. The model assumed the TCE contamination was symmetrically distributed around the DNAPL zone to extrapolate the soil TCE transect to a volume of contaminated soil. Each horizon was discretized into 1-ft wide rings/model cells. Because the most distal of the three soil borings was located 40 ft from the modeled DNAPL zone, each horizon was discretized into 40 model cells/rings per each of the 13 model horizons for calculation of soil mass and TCE mass volume.

Three interpolation techniques (exponential trend line, power function trend line, and constant percent reduction) were used to assess different TCE mass distributions away from the DNAPL zone. Each of the three interpolation techniques assumed a central TCE-in-soil concentration of 10,000,000 µg/kg [the highest observed TCE-in-soil concentration in the Southeast C-400 area (~ 4% DNAPL saturation)] and used the TCE-in-soil values derived from the three closest soil borings.

This model calculated the TCE mass for each model cell using the following equation:

$$\begin{aligned} \text{TCE Mass (g)/Model Cell} &= \text{Model Cell Volume (ft}^3\text{)} \times \text{Volume Conversion (cc/ft}^3\text{)} \times \\ &\text{Soil Weight (g/cc)} \times \text{Model Cell TCE Concentration (}\mu\text{g/kg)} \times \text{Mass Conversion} \\ &\text{(1 kg/10}^9\text{ }\mu\text{g)} \end{aligned}$$

Each of the model cell masses in a model horizon were summed for a total mass/horizon value and converted to lb of TCE and volume of TCE (liters and gallons). Table A2.6 summarizes the calculated TCE mass per model horizon. The model estimated 3,200 to 31,000 lb (260 to 2,500 gal) of TCE is present in the UCRS down to a depth of 60 ft.

A separate Excel model of three zones of vertical DNAPL migration was created to assess TCE mass below 60 ft, consistent with TCE-in-groundwater trends observed in samples of the 2011 investigation (Table A2.7). The model assumed each vertical migration pathway had a radius of 5 ft, with 4% DNAPL saturation at the core, declining (using constant percent reduction) to 0.67% DNAPL saturation [equal to the maximum observed TCE-in-soil concentration (1,700,000 µg/kg) from the 2011 investigation] at the perimeter. Each model cell consisted of a 1-ft wide ring centered on the vertical migration pathway (as in the UCRS model) but only 1-ft high. There were five concentric rings of model cells for each 1-ft depth interval for each vertical migration pathway.

The calculation of TCE volume for each model cell was as follows:

$$\begin{aligned} \text{TCE Volume (ft}^3\text{)} &= \text{Model Cell Volume (ft}^3\text{)} \times \text{RGA Porosity (fraction percentage)} \times \\ &\text{DNAPL Saturation (fraction percentage)} \end{aligned}$$

Each modeled 1-ft depth interval of each migration pathway contained 0.3 ft<sup>3</sup> (2.4 gal) of TCE. The total TCE for each migration pathway was the height of the pathway multiplied by 0.3 ft<sup>3</sup> (2.4 gal). In addition, the model included a basal RGA DNAPL pool with a DNAPL saturation of 10% measuring 10 ft x 80 ft and 1-ft thick. This model estimated 3,900 lb (320 gal) are present in the RGA between 60 and 96 ft depth.

**Table A2.5. Dense Nonaqueous-Phase Liquid Release-Based Model Horizons**

| <b>Model Horizon</b> | <b>Depth Range (ft)</b> | <b>PGDP Hydrogeologic Unit</b> | <b>Soil Type</b>        | <b>Representative TCE Concentration (µg/kg) in SB55*</b> |
|----------------------|-------------------------|--------------------------------|-------------------------|--|
| 1                    | 0–7.50                  | 1                              | Silt                    | 9  |
| 2                    | 7.50–11.50              | 1                              | Silt                    | 675  |
| 3                    | 11.50–23.00             | 1                              | Silt                    | 1,500  |
| 4                    | 23.00–24.60             | 1                              | Clayey Silt             | 9,350  |
| 5                    | 24.60–29.05             | 2                              | Fine Sand and Silt      | 26,000   |
| 6                    | 29.05–33.00             | 2                              | Sand                    | 24,030   |
| 7                    | 33.00–44.85             | 2                              | Sand with Gravel        | 55,000   |
| 8                    | 44.85–46.05             | 3                              | Silty Sand              | 69,000   |
| 9                    | 46.05–47.40             | 3                              | Silty Sand              | 4,294,068  |
| 10                   | 47.40–53.30             | 3                              | Silty Clay to Fine Sand | 60,000   |
| 11                   | 53.30–58.50             | 3                              | Fine Sand               | 15,000   |
| 12                   | 58.50–59.50             | 3                              | Fine Sand               | 1,700,000  |
| 13                   | 59.50–60.00             | 3                              | Fine Sand               | 71,000   |

TCE = trichloroethene

\*SB55 is the closest soil boring to the modeled DNAPL release site.

**Table A2.6. TCE Mass Volume Summary for Dense Nonaqueous-Phase Liquid Release-Based Model**

| <b>Model Horizon</b> | <b>Depth Range (ft)</b> | <b>Trichloroethene Mass Volume</b> |                |
|----------------------|-------------------------|------------------------------------|----------------|
|                      |                         | <b>Pounds</b>                      | <b>Gallons</b> |
| 1                    | 0–7.50                  | 0.3                                | 0.0            |
| 2                    | 7.50–11.50              | 12.5                               | 1.0            |
| 3                    | 11.50–23.00             | 79.9                               | 6.6            |
| 4                    | 23.00–24.60             | 59.4–278.8                         | 4.9–22.9       |
| 5                    | 24.60–29.05             | 127.2–902.3                        | 10.4–74.1      |
| 6                    | 29.05–33.00             | 238.6–1,338.8                      | 19.6–109.9     |
| 7                    | 33.00–44.85             | 675.0–3,462.8                      | 55.4–284.2     |
| 8                    | 44.85–46.05             | 29.3–352.2                         | 2.4–28.9       |
| 9                    | 46.05–47.40             | 116.3–18,504.0                     | 9.5–1,518.7    |
| 10                   | 47.40–53.30             | 361.1–1,628.0                      | 29.6–133.6     |
| 11                   | 53.30–58.50             | 222.1–1,243.5                      | 18.2–102.1     |
| 12                   | 58.50–59.50             | 1,030.0–4,254.8                    | 84.5–349.2     |
| 13                   | 59.50–60.00             | 46.5–228.1                         | 3.8–18.7       |

**Table A2.7. Modeled RGA Migration Pathways, DNAPL Release-Based Model**

| Soil Borings | SB53       | SB54           | SB55           | SB56    | SB57             | SB59   |
|--------------|------------|----------------|----------------|---------|------------------|--------|
| Depth (ft)   | TCE (µg/L) |                |                |         |                  |        |
| 60           | NS         | 28,000         | NS             | NS      | NS               | NS     |
| 61           | NS         | NS             | NS             | NS      | NS               | NS     |
| 62           | NS         | NS             | NS             | NS      | NS               | NS     |
| 63           | NS         | NS             | NS             | NS      | NS               | NS     |
| 64           | NS         | NS             | NS             | NS      | NS               | NS     |
| 65           | NS         | 21,000         | <b>610,000</b> | NS      | 280,000          | 16,000 |
| 66           | NS         | NS             | NS             | NS      | NS               | NS     |
| 67           | NS         | NS             | NS             | NS      | NS               | NS     |
| 68           | NS         | NS             | NS             | NS      | NS               | NS     |
| 69           | NS         | NS             | NS             | NS      | 400,000          | NS     |
| 70           | 77,000     | 23,000         | <b>570,000</b> | 280,000 | NS               | 27,000 |
| 71           | NS         | NS             | NS             | NS      | NS               | NS     |
| 72           | NS         | NS             | NS             | NS      | NS               | NS     |
| 73           | NS         | NS             | NS             | NS      | NS               | NS     |
| 74           | NS         | NS             | NS             | NS      | 270,000          | NS     |
| 75           | 55,000     | NS             | <b>430,000</b> | 430,000 | NS               | 20,000 |
| 76           | NS         | NS             | NS             | NS      | NS               | NS     |
| 77           | NS         | NS             | NS             | NS      | NS               | NS     |
| 78           | NS         | NS             | NS             | NS      | NS               | NS     |
| 79           | NS         | NS             | NS             | NS      | NS               | NS     |
| 80           | 180,000    | 19,000         | 84,000         | 240,000 | 340,000          | 24,000 |
| 81           | NS         | NS             | NS             | NS      | NS               | NS     |
| 82           | NS         | NS             | NS             | NS      | NS               | NS     |
| 83           | NS         | NS             | NS             | NS      | NS               | NS     |
| 84           | NS         | NS             | NS             | NS      | <b>590,000</b>   | NS     |
| 85           | 100,000    | <b>580,000</b> | 57,000         | 240,000 | NS               | 70,000 |
| 86           | NS         | NS             | NS             | NS      | NS               | NS     |
| 87           | NS         | NS             | NS             | NS      | NS               | NS     |
| 88           | NS         | NS             | NS             | NS      | NS               | NS     |
| 89           | NS         | NS             | NS             | NS      | <b>1,200,000</b> | NS     |
| 90           | 87,000     | <b>410,000</b> | 53,000         | 230,000 | NS               | 52,000 |
| 91           | NS         | NS             | NS             | NS      | NS               | NS     |
| 92           | NS         | NS             | 46,000         | NS      | NS               | NS     |
| 93           | NS         | NS             | NS             | NS      | NS               | 34,000 |
| 94           | 76,000     | NS             | NS             | NS      | <b>870,000</b>   | NS     |
| 95           | NS         | NS             | NS             | NS      | NS               | NS     |
| 96           | NS         | NS             | NS             | 200,000 | NS               | NS     |

Modeled interval of vertical migration DNAPL zone (based on TCE analyses and MIP PID logs)

Modeled location of basal RGA DNAPL pool (based on TCE analyses and MIP PID logs)

NS = not sampled

### **A2.3. EVALUATION OF ESTIMATES**

The range of TCE mass volume for the RGA in the initial estimates (summarized above) was determined to be inconsistent with the CSM based on characteristics of the Northwest Plume, the primary dissolved-phase contamination derived from the C-400 area, as follows:

- (1) The Northwest Plume contains approximately 13,000 lb of dissolved TCE mass (based on the 2009 TCE plume footprint); and
- (2) The dissolution rate for the C-400 TCE source has been approximately 4,000 lb/year (330 gal/year) (based on the annual flux of dissolved phase mass) for 50 years.

These observations suggest that the TCE mass volume spill associated with the C-400 site was at least 200,000 lb (16,500 gal). The persistence of the dissolved-phase plumes associated with the Phase II treatment area indicates the presence of a continuing large TCE source, significantly greater than the TCE mass volume estimates for the RGA (above).

These observations led to a critical review of the sources of uncertainty in the initial TCE mass volume estimates and prompted additional calculations to assess the upper bound of TCE mass volume that may be present under several DNAPL scenarios.

### **A2.4. UNCERTAINTY ANALYSIS**

The heterogeneous nature of subsurface geologic environments, combined with the selective and tortuous nature of DNAPL migration, creates uncertainty with regard to the distribution of residual and pooled DNAPL in the subsurface and the representativeness of the corresponding data set. In the RGA, DNAPL may be retained as dispersed droplets (ganglia) reflecting prior migration pathways or as pools where migration is impeded, depending on mass volume and aquifer characteristics (i.e., interfacial tension of aquifer materials). In the RGA, the presence of pooled DNAPL is considered to be limited to a few vertical inches in the absence of potential irregularities associated with the topography of the top of the McNairy Formation and based on the generally coarse-grained nature of the unit and associated low interstitial tension of the gravel. Where DNAPL is present, industry experience strongly indicates that conventional sampling strategies may be ineffective for obtaining information that is representative of DNAPL occurrence. In general, the water-saturated gravel matrix of the RGA is a difficult medium to sample for volatile organic contamination. During RGA sample extraction, escaping pore water may “wash” sorbed contamination and influence the detection of DNAPL that may have been present in the sample. Both the heterogeneity of the TCE contamination and the difficulty of sampling (especially in the RGA) contribute to appreciable uncertainty in regard to characterizing DNAPL distribution.

To understand the potential impacts of uncertainty and further test the assessment of mass potentially present in the Phase II area based on plume extent and duration, the mass volume estimates generated from the results of soil analysis for TCE can be compared to TCE mass/volume recovered from the Phase I remedial action and the Six-Phase Heating Treatability Study. Current CSMs for the areas of the Phase I and II remedial actions suggest that significantly greater mass volume should be present in the Phase II treatment area. The 2010 Phase I remedial action extracted approximately 7,040 lb of TCE (approximately 580 gal) from the subsurface (primarily UCRS) in the southwest and east treatment areas. CSMs for the area of the Six-Phase Heating Treatability Study and the Phase II treatment area are similar. The 2003 Six-Phase Heating Treatability Study removed approximately 23,000 lb (1,900 gal) of TCE



from the subsurface (both UCRS and RGA) in a 43-ft diameter treatment area near the southeast corner of the C-400 Building. With this in mind, it seems plausible that the larger Phase II treatment area may yield significantly more mass.

Additionally, a variety of approaches was used to explore the basis for an upper bound for the mass volume at the Phase II area. The approaches are as follows:

- (1) Modeling of a single vertical pathway of DNAPL migration through the UCRS and RGA with assumed ranges of cross-sectional thicknesses (0.5 to 12 inches) and DNAPL saturation (5 to 20%).

$$\text{Potential impact of DNAPL ganglia on the TCE mass estimate} = \text{Volume of Soil Column [ft}^3\text{]} \times \text{Soil Weight [kg/ft}^3\text{]} \times \text{Threshold DNAPL Saturation Concentration [\mu\text{g/kg}] } \times \text{Micrograms to Pounds Conversion Factor [lb/\mu\text{g}]}$$

This approach estimates a possible range of 100 to 250,000 lb (10 to 20,000 gal) of TCE mass volume. Table A2.8 presents the results of the migration pathway calculations. The approach assumes that all the dispersed residual or pooled DNAPL in the UCRS and RGA could be represented as a single continuous vertical body of DNAPL with saturations that are consistent with published ranges. Because this approach is not based on any Phase II sampling results, the significance of this analysis remains uncertain.

**Table A2.8. Residual DNAPL Ganglia Mass Sensitivity Analysis Summary**

| Radius (inches) | Formation/ Thickness | TCE Mass (Gallons) |                |                |
|-----------------|----------------------|--------------------|----------------|----------------|
|                 |                      | 5% Saturation      | 10% Saturation | 20% Saturation |
| 0.5             | UCRS—56 ft           | 4.4                | 8.6            | 17             |
|                 | RGA—50 ft            | 4.3                | 8.5            | 17             |
| 1               | UCRS—56 ft           | 17                 | 34             | 67             |
|                 | RGA—50 ft            | 17                 | 33             | 66             |
| 12              | UCRS—56 ft           | 2,475              | 4,875          | 9,680          |
|                 | RGA—50 ft            | 2,445              | 4,820          | 9,571          |

- (2) Extrapolation of the frequency of detection of DNAPL in TCE soil analyses in the UCRS for the 2011 C-400 Phase II investigation (1 detection at a concentration indicative of DNAPL in 480 actual and projected analyses) to a model of the soil/aquifer volume potentially impacted by DNAPL migration (approximated by a cone shaped zone of impact emanating from the point of release) and calculation of the resulting mass volume potentially present within the DNAPL zone. This model assumed that the potential DNAPL-impacted area was 60 ft deep (depth of the UCRS) and 120 ft wide (the approximate width of the Phase II treatment area). The model calculated the TCE mass as follows:

$$\text{Total TCE Mass} = \text{Volume of Potential DNAPL-Impacted Area (ft}^3\text{)} \times \text{Probability of Encountering DNAPL (1/480)} \times \text{TCE Mass/Encounter (lb)}$$

Based on the model of the anticipated treatment zone (and perimeter), each DNAPL encounter represented approximately 120 lb of TCE. This approach yielded an estimate of potential TCE mass volume of 56,000 lb (4,600 gal) for the UCRS only.

- (3) Modeling of a DNAPL pool, 2-inches high, with a diameter equal to the width of the Phase II treatment area (120 ft). The model calculated the volume as follows:

$$\text{Volume of DNAPL Pool (gal)} = \text{Volume of DNAPL Zone (ft}^3\text{)} \times \text{RGA porosity (fraction percentage)} \times \text{DNAPL saturation (fraction percentage)}$$

This approach estimates up to an additional 51,000 lb (4,200 gal) of TCE mass volume may be present in the RGA.

## A2.5. CONCLUSION

Calculations based on interpolation of the available TCE analyses, alone, determine that a minimum of 290 to 780 lb (24 to 64 gal) of TCE mass volume is present in the UCRS and 75 to 7,000 lb (6 to 570 gal) of TCE mass volume is present in the RGA. The estimate of potential TCE mass volume of the Phase II treatment area is anticipated to range between 7,300 and 85,000 lb (600 and 7,000 gal). Approximately 30,500 lb (2,500 gal) may be present in the UCRS, and approximately 55,000 lb (4,500 gal) may be present in the RGA. The estimate addresses the potential presence of TCE source-related mass that may be present as residual and/or pooled DNAPL in the UCRS and RGA. The range of values exceeds an order of magnitude and is indicative of the difficulty in characterizing DNAPL distribution in subsurface environments. A calculation record that provides a detailed accounting of inputs, assumptions, and results for the summary presented above is currently in preparation.

## A2.6. REFERENCES

- DOE (U.S. Department of Energy) 2011. *Remedial Action Work Plan for the Interim Remedial Action for the Volatile Organic Compound Contamination at the C-400 Cleaning Building at the Paducah Gaseous Diffusion Plant, Paducah, Kentucky*, DOE/LX/07-004&D2/R2/A1, Appendix E, Field Sampling Plan, U.S. Department of Energy, Paducah, Kentucky, November.
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**APPENDIX A3**

**APPLICABLE OR RELEVANT AND APPROPRIATE REQUIREMENTS**

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## **APPLICABLE OR RELEVANT AND APPROPRIATE REQUIREMENTS**

The Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980, as amended, requires, in part, that remedial actions for cleanup of hazardous substances comply with promulgated requirements and/or standards under federal or more stringent state environmental laws and regulations where the requirements are applicable or relevant and appropriate (ARAR). These requirements are identified as those being specific to the hazardous substances or particular circumstances at a site and must be complied with, or be waived, as part of a total remedial action, under the CERCLA decision-making process (40 *CFR* § 300.430(f)(1)(ii)(B)). ARARs include only federal and state environmental or facility siting laws/regulations and do not include occupational safety or worker radiation protection requirements. Per 40 *CFR* § 300.405(g)(3), non-promulgated advisories, criteria, or guidance, known as to be considered (TBC), may be considered in determining remedies. Because this remedial action will be conducted on-site, it is exempted from procedural requirements to obtain federal, state, and local permits, consistent with Section XXI of the *Federal Facility Agreement for the Paducah Gaseous Diffusion Plant* (FFA) and Section 121(e)(1) of CERCLA.

### **ADDITIONAL ARARS**

The only change to the ARARs in the original ROD is the addition of ARARs related to underground injection control.

#### **Underground Injection Control**

Alternatives 3 and 5 in the Technical Evaluation would inject reagents along with contaminated groundwater into the groundwater. For this reason, underground injection control regulations, 40 *CFR* § 144.12(a), are ARAR for these alternatives. The reinjection would be considered to be a Class IV injection well as defined in 40 *CFR* § 144.6(d). These ARARs are listed in Table A3.1.

**Table A3.1. Additional ARARs**

| Standards, Requirement, Criteria, or Limitation   | Citation  | Description of Requirement  | Comments  |
|---|---|---|---|
| <p>Underground Injection Control</p> <p>Injection/Reinjection of surfactants, cosolvents and reagents with contaminated groundwater</p> | <p>40 <i>CFR</i> § 144.12(a)</p><br><p>40 <i>CFR</i> § 144.13(c)<br/>RCRA § 3020(b)</p><br><p>40 <i>CFR</i> §144.23(b)(1)</p><br><p>40 <i>CFR</i> § 146.10(b)</p> | <p>No owner or operator shall construct, operate, maintain, convert, plug, abandon, or conduct any other injection activity in a manner that allows the movement of fluid containing any contaminant into underground sources of drinking water, if the presence of that contaminant may cause a violation of any primary drinking water regulation under 40 <i>CFR</i> Part 142 or may otherwise adversely affect the health of persons.</p> <p>Wells are not prohibited if injection is approved by EPA or a State pursuant to provisions for cleanup of releases under CERCLA or RCRA.</p> <p><i>NOTE: EPA approval will be obtained by approval of the FFA CERCLA document.</i></p> <p>Prior to abandonment any Class IV well, the owner or operator shall plug or otherwise close the well in a manner acceptable to the Regional Administrator.</p> <p><i>NOTE: EPA approval of well closure will be obtained by approval of the FFA CERCLA document.</i></p> <p>Prior to abandoning the well, the owner or operator shall close the well in accordance with 40 <i>CFR</i> § 144.23(b).</p> | <p>Underground injection into an underground source of drinking water—<b>relevant and appropriate.</b></p><br><p>Class IV wells [as defined in 40 <i>CFR</i> § 144.6(d)] used to inject surfactants, cosolvents, and reagents along with contaminated groundwater into the same formation from which it was drawn—<b>relevant and appropriate.</b></p><br><p>Class IV wells [as defined in 40 <i>CFR</i> § 144.6(d)] used to inject surfactants, cosolvents, and reagents along with contaminated groundwater into the same formation from which it was drawn—<b>relevant and appropriate.</b></p><br><p>Operation of a Class IV injection well [as defined in 40 <i>CFR</i> § 144.6(d)]—<b>relevant and appropriate.</b></p> |