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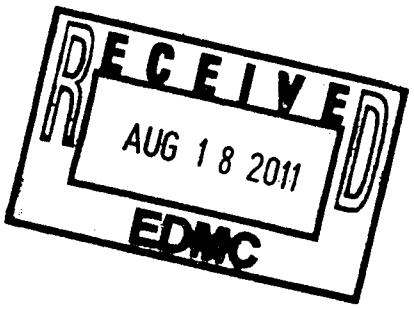
Rev. 0

Preliminary Evaluation of Soil-Heating Technologies for the 200-ZP-2 Carbon Tetrachloride Expedited Response Action



Prepared for the U.S. Department of Energy
Office of Environmental Restoration and
Waste Management

Bechtel Hanford, Inc.
Richland, Washington

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Author(s): G. J. Jackson
M. E. Todd
R. K. Tranbarger

Approval: J. D. Isaacs, Groundwater Project Engineer

Signature 8-30-96 Date

G. C. Henckel III, Manager, Groundwater Project

Signature 8/30/96 Date

The approval signature(s) on this page indicates that this document has been authorized for information release to the public through appropriate channels. No other forms or signatures are required to document this information release.

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Authors
G. J. Jackson
M. E. Todd
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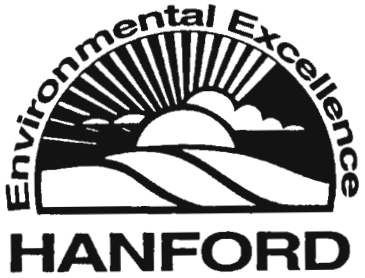

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ACRONYMS

ARAR	applicable or relevant and appropriate requirements
CERCLA	*Comprehensive Environmental Response, Compensation, and Liability Act of 1980*
EPA	U.S. Environmental Protection Agency
ERA	expedited response action
GAC	granular activated carbon
MAT	minimum allowable temperature
PCE	perchloroethylene
PNNL	Pacific Northwest National Laboratory
ppmv	parts per million by volume
RF	radio frequency
SVE	soil vapor extraction
TCE	trichlorethylene
VOC	volatile organic compound
WSU	Washington State University

1.0 INTRODUCTION

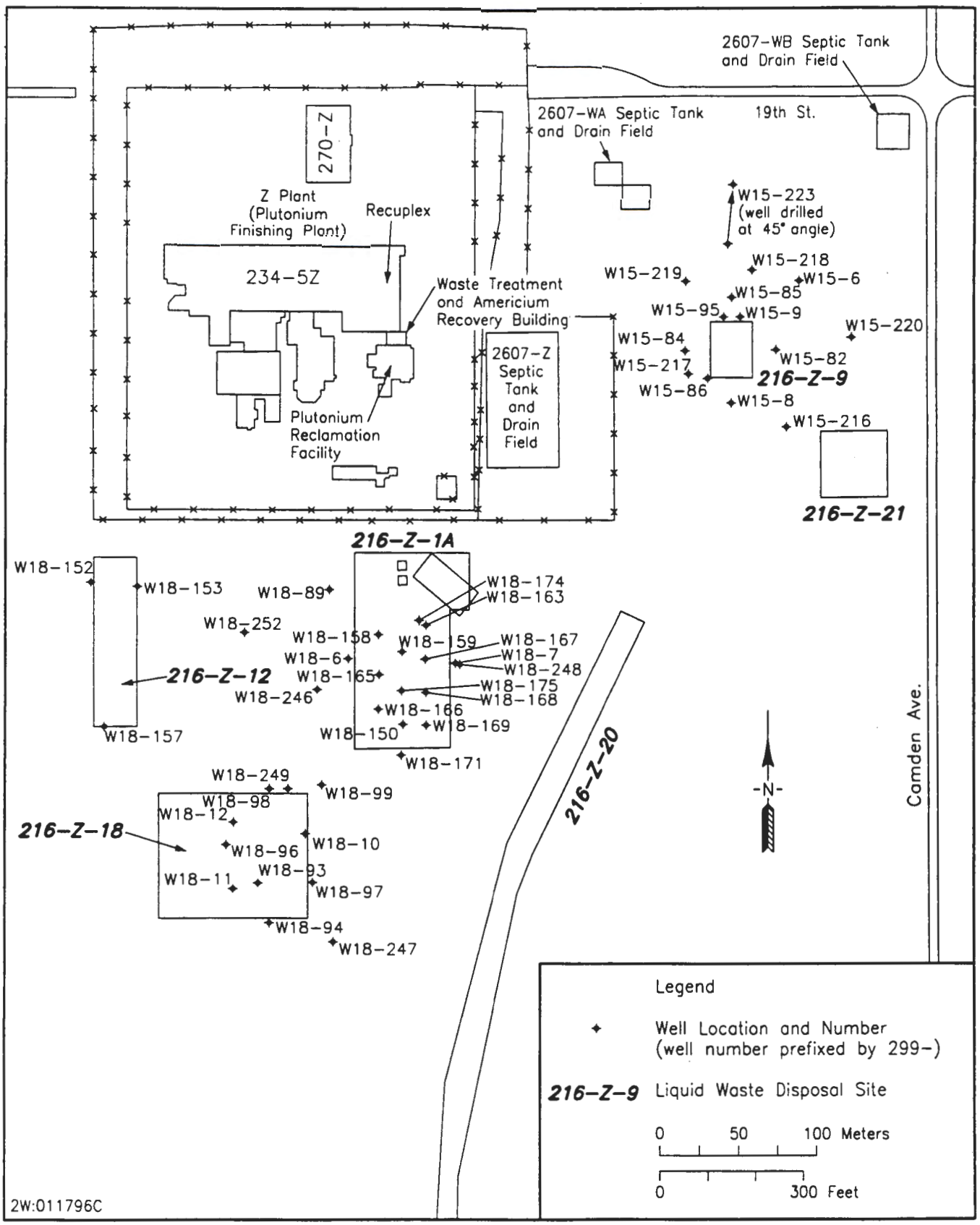
The 200-ZP-2 Operable Unit is located in the 200 West Area of the Hanford Site. The operable unit is a *Comprehensive Environmental Response, Compensation, and Liability Act of 1980* (CERCLA) past-practice unit as defined by the *Hanford Federal Facility Agreement and Consent Order* (Ecology et al. 1994). The U.S. Department of Energy has been conducting an expedited response action (ERA) to treat carbon tetrachloride contamination since 1992 at the operable unit at the direction of the U.S. Environmental Protection Agency (EPA) and the Washington State Department of Ecology.

Organic and aqueous wastes containing carbon tetrachloride were discharged to three principal disposal sites in the 200-ZP-2 Operable Unit: 216-Z-1A Tile Field, 216-Z-9 Trench, and 216-Z-18/-12 Cribs. An estimated 600 to 900 metric tons of carbon tetrachloride were discharged to these sites between 1955 and 1973 (DOE-RL 1991). No liquid organic waste was discharged to the waste management units after 1973. Carbon tetrachloride is the primary volatile organic compound (VOC) of concern in the operable unit. Other VOCs detected in trace quantities include methylene chloride, chloroform, methyl ethyl ketone, perchloroethylene (PCE), and trichloroethylene (TCE).

The 200-ZP-2 ERA currently uses a soil vapor extraction (SVE) system at each of the three principal disposal sites; the extraction wellfield configuration for each system is depicted in Figure 1. The SVE systems induce a vacuum into the vadose zone via the extraction wells, thus pulling organic-laden soil vapors to the surface for treatment. The 216-Z-9 Trench wellfield design consists of 14 extraction wells with 21 open intervals, and the SVE system has a 42-m^3/min (1,500-ft^3/min) capacity. The 216-Z-1A Tile Field wellfield design consists of 16 extraction wells with 21 open intervals, and the SVE system has a 28-m^3/min (1,000-ft^3/min) capacity. The 216-Z-18/-12 Cribs wellfield design consists of 16 extraction wells with 21 open intervals, and the SVE system has a 14-m^3/min (500-ft^3/min) capacity. All extracted soil vapors are passed through granular activated carbon (GAC) where the carbon tetrachloride and other trace VOCs are removed.

As the ERA has progressed over the past 5 years, carbon tetrachloride concentrations have decreased at the inlet of the SVE systems from a maximum of about 30,000 parts per million by volume (ppmv) to less than 50 ppmv. Although this is indicative of the effectiveness of the SVE systems, laboratory studies of carbon tetrachloride partitioning in Hanford soils (BHI 1996c) indicate that only about 15% of carbon tetrachloride in permeable soils can be removed using SVE technology. The remaining VOCs are believed to be adsorbed/fixed within the soil micropores. The studies also concluded that carbon tetrachloride removal from low-permeable soils is diffusion limited, i.e., SVE is ineffective in removing VOCs from low-permeable soils. These findings are substantiated by case studies from other SVE sites.

Figure 1. Location of Extraction and Monitoring Wells at the Carbon Tetrachloride Soil Vapor Extraction Sites.



1.1 PURPOSE AND SCOPE

The purpose of this study is to identify and perform a preliminary evaluation of technologies that may enhance the volatilization and thus the removal of carbon tetrachloride (and other VOCs) adsorbed to and within soil particles. Increasing the volatility of the organics increases organic concentrations in the extracted soil vapor and thus increases the rate of carbon tetrachloride removed by the SVE systems. This evaluation concentrates on soil-heating technologies because they can deliver the energy required to volatilize the organics and can be readily used in conjunction with existing SVE systems.

This evaluation is intended to provide information regarding soil-heating technologies including a summary of their implementation and effectiveness at other sites, their applicability and implementability to the 200-ZP-2 ERA site geologic formations, and general cost estimates (if known) for implementation. This information can then be used to make decisions to further pursue soil-heating-enhanced SVE at the ERA site.

Section 1.2 provides a brief explanation of applicable or relevant and appropriate requirement (ARAR) compliance; Section 2.0 provides descriptions of the ERA site geology and contamination; Section 3.0 discusses the selection and evaluation of the soil-heating technologies; and Section 4.0 provides the overall summary and conclusions.

1.2 COMPLIANCE WITH APPLICABLE OR RELEVANT AND APPROPRIATE REQUIREMENTS

ARARs reflect the requirements of federal and state environmental regulations that are applicable or relevant and appropriate. Section 121 of CERCLA and Superfund compliance requires that hazardous substance cleanup meets either "applicable" or "relevant and appropriate" requirements, but not necessarily both.

For the preliminary screening of technologies to enhance the volatility of carbon tetrachloride, it is assumed that ARAR compliance will be maintained at the SVE systems. ARARs for the SVE systems are identified in the *Design, Operations, and Maintenance of the Soil Vapor Extraction Systems for the 200 West Area Carbon Tetrachloride Expedited Response Action* (BHI 1996b).

2.0 SITE CHARACTERISTICS

2.1 SITE GEOLOGY

The vadose zone underlying the three principal carbon tetrachloride disposal sites consists of approximately 66 m (216 ft) of relatively permeable sand and gravel interrupted by a relatively low-permeability interval composed of silt and fine sand. Table 1 lists the geologic formations

constituting the vadose zone and their respective soil types, depths, permeabilities, and soil moisture content. Although the thickness of each geologic layer varies among disposal sites, the average values provided in Table 1 are used in this evaluation. In general, the moisture content of the gravel layers is the lowest and the moisture content of the Plio-Pleistocene layer is the highest.

Table 1. Characteristics of Geologic Units Underlying the Carbon Tetrachloride Disposal Sites.

Layer ID	Geologic Layer	Primary Material	Depth (m)	Permeability (m^2)	Field Moisture Content[a] (vol%)
H_{uf}	Hanford Upper Fine	Sand	0-6	1.6E-11 (permeable)	5.5
H_{uc}	Hanford Upper Coarse	Gravel	6-16	4.1E-10 (permeable)	4.6 - 5.7
H_f	Hanford Fine	Sand	16-30	1.6E-11 (permeable)	1.5 - 19.7
H_{lc}	Hanford Lower Coarse[b]	Gravel	30-34	3.3E-10 (permeable)	5.1 - 5.3
H_{lf}	Hanford Lower Fine[b]	Silt and Fine Sand	34-38	1.6E-12 (low permeability)	6.1 - 11.8
PP	Plio-Pleistocene (caliche)	Fine Sandy Silt/ Cemented Sandy Gravel	38-45	8.2E-13 (low permeability)	8.1 - 38.5
R_{ge}	Ringold Unit E	Gravel	45-66	1.3E-10 (permeable)	3.4 - 17.6

[a]Source: Wright et al. (1994).
[b]Not present at Z-9.

2.2 SITE CONTAMINATION

Carbon tetrachloride was found throughout the unsaturated zone underlying the three primary disposal sites during characterization activities in 1992 and 1993. Laterally, the highest concentrations of carbon tetrachloride were consistently located in the vicinity of the Z-9 site. Vertically, the highest concentrations were associated with the fine-grained, less permeable Hanford lower fine and Plio-Pleistocene layers (WHC 1994).

Initial carbon tetrachloride vapor concentrations measured at the SVE systems were 1,000 ppmv at the Z-1A and Z-18 sites in 1992 and 30,000 ppmv at the Z-9 site in 1993. Inlet concentrations of carbon tetrachloride to the SVE systems at all three sites have been declining since operations began. The relatively rapid decline in concentration followed by a longer period of slowly decreasing concentrations, as shown in Figure 2 for the Z-18 site, is typical of all three sites. Inlet carbon tetrachloride concentrations to all three SVE systems were less than 50 ppmv in June 1996.

2.3 SOIL VAPOR EXTRACTION WELLFIELD

Currently, 46 wells with 63 extraction intervals are available for vapor extraction. The layout of the wells is provided in Figure 1. Thirteen of these wells were drilled during 1992 and 1993 and completed as vapor extraction wells with stainless steel casing and screens; one well was drilled at a 45° incline. Other existing wells, drilled between 1954 and 1978 and completed with carbon steel casing, and were adapted for vapor extraction by perforating the well casing with mechanical or jet perforators. Seventeen wells have two screened or perforated open intervals isolated by downhole packers. Well diameters range from 6.4 to 20 cm (2.5 to 8 in.).

Each SVE system extracts simultaneously from multiple wells and thus may extract from several geologic layers. Depths, lengths, and associated geologic layers of the open interval(s) for each well are provided in Table 2. No open intervals occur in the uppermost two geologic layers, the Hanford upper fine and Hanford upper coarse; however, the extraction wells open in underlying layers effectively pull air vertically through these layers.

Based on numerical airflow modeling, the areal extent of SVE influence at the 216-Z-9 and 216-Z-1A/216-Z-18/216-Z-12 wellfields is estimated to be 28,000 m^2 (310,000 ft^2) and 86,000 m^2 (920,000 ft^2), respectively (BHI 1996a). Assuming the average depth to groundwater is 66 m (216 ft) (Table 1), the total volume of soil encompassed by the extraction well network is 7,500,000 m^3 (9,800,000 yd^3).

The volumes of permeable and low-permeability soils potentially influenced by SVE systems operation are provided in Table 3. For this evaluation, the low-permeability geologic layers are assumed to be the Hanford lower fine and the Plio-Pleistocene.

2.4 EFFECTIVENESS OF CURRENT SOIL VAPOR EXTRACTION OPERATIONS

The open interval of many extraction wells encompasses both permeable and low-permeability geologic layers (see Table 2), such that soil vapor flow in a permeable layer is induced directly above and/or below the contaminated, low-permeability silty (Hanford lower fine) and caliche layers (Plio-Pleistocene). This sweeping process across the surface of the low-permeability layers maximizes volatilization and diffusion of organics into the permeable layer and flow field

Figure 2. Carbon Tetrachloride Concentrations Measured at the 500-ft^3/min Soil Vapor Extractions System, June 1994 - June 1995.

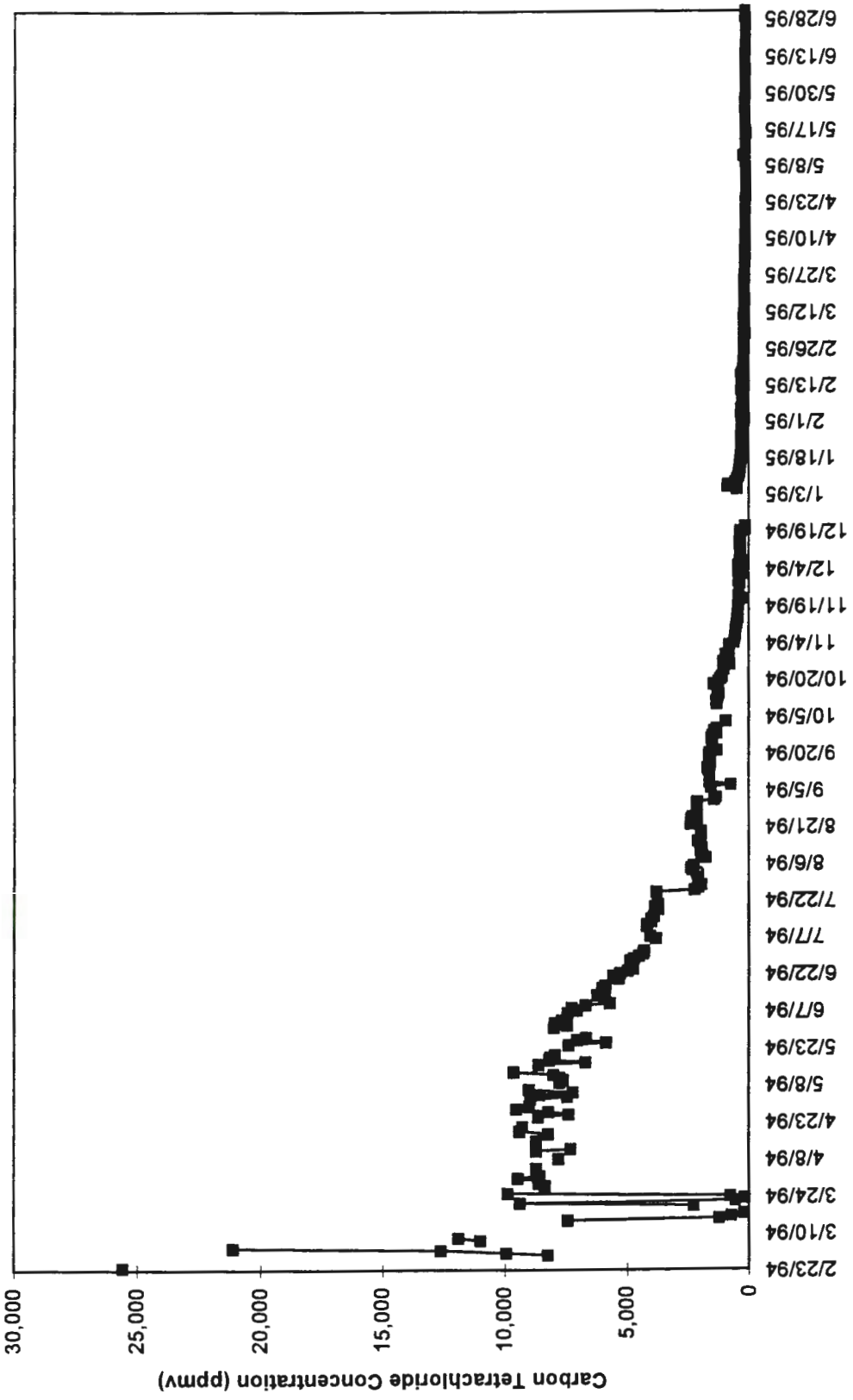


Table 2. Depths, Lengths, and Associated Geologic Layers of Open Well Intervals.

Well No.	Top of Interval (m bgs)	Bottom of Interval (m bgs)	Length of Screen (m)	Screen in Layer Hf (m)	Screen in Layer Hlc (m)	Screen in Layer Hlf (m)	Screen in Layer PP (m)	Screen in Layer Rge (m)
W15-6U	21.0	28.6	7.6	7.62				
W15-6L	46.9	57.9	11.0					10.97
W15-8U	28.3	34.4	6.1	6.10				
W15-8L	50.3	59.4	9.1					9.14
W15-9U	26.8	34.4	7.6	5.79			1.83	
W15-9L	49.4	57.6	8.2					8.23
W15-82	22.9	27.4	4.6	4.57				
W15-84	22.9	27.4	4.6	4.57				
W15-85	25.3	29.9	4.6	4.57				
W15-86	32.6	41.8	9.1	1.52			3.05	4.57
W15-95	22.2	29.9	7.6	7.62				
W15-216U	21.3	24.4	3.0	3.05				
W15-216L	53.3	56.4	3.0					3.05
W15-217	32.3	36.9	4.6	2.44			2.13	
W15-218U	30.2	34.7	4.6	2.44			2.13	
W15-218L	55.2	59.7	4.6					4.57
W15-219U	26.5	31.1	4.6	4.57				
W15-219L	50.9	55.5	4.6					4.57
W15-220U	24.4	29.0	4.6	4.57				
W15-220L	47.2	51.8	4.6					4.57
W15-223	31.4	35.7	4.3	2.13			2.13	
W18-6U	29.0	38.1	9.1		7.92		1.22	
W18-6L	57.9	63.4	5.5					5.49
W18-7	51.5	63.4	4.6					10.06
W18-10U	29.6	38.7	9.1	0.61	8.53			
W18-10L	44.8	64.3	19.5				3.66	15.85
W18-11U	29.6	38.7	9.1	3.66	5.49			
W18-11L	54.9	64.9	10.1					10.06
W18-12	54.3	64.9	10.7					10.67
W18-89	32.0	38.7	6.7		6.71			
W18-93	18.3	22.6	4.3	4.27				
W18-94	19.8	22.9	3.0	3.05				
W18-96	37.2	40.2	3.0		1.83	0.91	0.30	
W18-97	18.3	21.9	3.7	3.66				
W18-98	19.2	22.6	3.4	3.35				
W18-99	27.4	30.5	3.0	3.05				
W18-150U	18.9	26.5	7.6	7.62				
W18-150L	33.5	35.1	1.5		0.61	0.91		
W18-152	26.2	35.4	9.1	7.31	1.83			
W18-153	22.9	32.0	9.1	9.14				
W18-157	23.8	32.9	9.1	9.14				
W18-158U	21.9	28.0	6.1	6.10				
W18-158L	35.7	37.2	1.5		0.30		1.22	
W18-159	27.1	36.3	9.1		4.27	4.88		
W18-163U	16.2	23.8	7.6	7.62				
W18-163L	27.4	35.7	8.2		4.57	3.66		
W18-165	28.6	37.8	9.1	0.91	4.27	3.66	0.30	
W18-166	29.3	38.4	9.1	3.05	3.05	2.44	0.61	
W18-167	26.2	35.4	9.1	0.91	3.05	5.18	0.91	
W18-168	28.6	37.8	9.1	1.52	0.30	5.79	1.52	
W18-169	28.3	37.5	9.1		3.05	6.10		
W18-171U	16.5	22.6	6.1	6.10				
W18-171L	34.1	38.7	4.6		4.27	0.30		
W18-174	32.6	38.7	6.1		1.83	2.13	2.13	
W18-175	26.5	35.7	9.1		0.30	8.84		
W18-246U	36.6	39.6	3.0		3.05			
W18-246L	50.3	53.3	3.0					3.05
W18-247U	36.3	39.3	3.0		1.22	1.83		
W18-247L	49.4	52.4	3.0					3.05
W18-248	37.8	42.4	4.6			0.61	3.96	
W18-249	37.2	41.8	4.6		1.52	1.22	1.83	
W18-252U	34.4	40.5	6.1		3.66		2.44	
W18-252L	50.3	56.4	6.1					6.10

bgs = below ground surface

Table 3. Volumes of Permeable and Less Permeable Soils Under Extraction.

216-Z-1A/216-Z-18		216-Z-9	
Permeable m^3 (yd^3)	Less Permeable m^3 (yd^3)	Permeable m^3 (yd^3)	Less permeable m^3 (yd^3)
4,663,100 (6,100,000)	917,330 (1,200,000)	1,681,770 (2,200,000)	198,750 (260,000)
Total Permeable = 6,344,880 m^3 (8,300,000 yd^3)			
Total Less Permeable = 1,146,660 m^3 (1,500,000 yd^3)			

induced by the SVE system(s). The open interval of other extraction wells encompasses one or more relatively permeable layers; thus, organic-laden soils in these layers are in direct contact with the flow field.

Laboratory studies were conducted to estimate reasonably achievable carbon tetrachloride soil concentration levels at the 200-ZP-2 ERA site using SVE (BHI 1996c). One set of experiments was designed to simulate airflow through a permeable layer overlying a carbon tetrachloride-saturated, low-permeability layer; the other set of experiments simulated airflow directly through a carbon tetrachloride-saturated permeable layer. The experiments used soil from the 200-ZP-2 ERA site to most effectively reproduce site-specific conditions.

The desorption experiments conducted by passing air through a permeable layer overlying a carbon tetrachloride-saturated low-permeability layer resulted in final carbon tetrachloride concentrations in the low-permeability layer as high as 42,000 mg/kg (BHI 1996c). These experiments, which provided the best possible contact between the flow field and the surface of the contaminated low-permeability layer, indicate that ambient-temperature SVE is ineffective in removing a substantial mass of carbon tetrachloride from low-permeability layers. That is, SVE does not appear to substantially increase the diffusion of carbon tetrachloride vapors from the low-permeability layer to the flow field. This conclusion supports the potential for soil-heating technologies to greatly enhance carbon tetrachloride volatilization and subsequent removal from geologic layers with relatively low permeabilities.

The desorption experiments that passed air through a column of permeable silty sand resulted in an overall carbon tetrachloride removal of only about 10%, thus yielding a final carbon tetrachloride soil concentration of about 7 to 3,000 mg/kg (Storey 1996). These experiments, which provided virtually ideal contact between the flow field and the contaminated permeable soils, indicate that SVE using ambient temperatures will not effectively remove all carbon tetrachloride from permeable soils. This conclusion supports the potential for soil-heating technologies, if implemented, to significantly increase the mass of carbon tetrachloride extracted by SVE.

3.0 IDENTIFICATION AND EVALUATION OF APPLICABLE TECHNOLOGIES

A literature search was conducted to identify soil-heating technologies with the potential to deliver sufficient energy to increase vadose zone soil temperatures such that carbon tetrachloride volatilization will be enhanced. Reports from the EPA (1995a, 1995b), Pacific Northwest National Laboratory (PNNL) (Bergsman et al. 1993), the *Hazardous Waste Consultant* (HWC 1994), and HAZMACOM '94 (Beyke 1994) were the primary literature sources for the technology identification. The following soil-heating technologies were identified for evaluation:

- Hot air injection
- Steam injection
- Six-phase soil heating
- Radio-frequency (RF) heating.

3.1 APPLICABILITY OF SOIL HEATING

The volatility (vapor pressure) of organics increases with increasing temperature. By increasing the temperature of the contaminated soils, adsorbed or liquid carbon tetrachloride is converted to the vapor phase. In the vapor phase, the VOCs diffuse or are pulled through the permeable soils to merge with the flow field induced by the SVE systems where they are subsequently transported to the surface for treatment.

Dong and Bozzelli (Wilson and Clarke 1994) performed bench-scale desorption studies on organic contaminants in soil matrices. Their results estimated a minimum allowable temperature (MAT) to effect relatively complete desorption of specific contaminants. To determine the MATs, soil samples were saturated with a known mass of the organic contaminant and heated in an ex situ reactor for 1 hour at a preselected temperature. The soil samples were then analyzed to assess the extent of contaminant desorption. The experiment was repeated several times at different temperatures on a given soil matrix until the MAT for efficient contaminant desorption was attained. Table 4 lists the MAT and associated desorption efficiency for carbon tetrachloride, chloroform, and methylene chloride. From this study, the MAT for effective carbon tetrachloride desorption was estimated at 80 °C (176 °F) for 99.1% removal. The methods used by Dong and Bozzelli included (1) using disturbed soils that likely differ from the undisturbed 200-ZP-2 ERA site-specific soils and (2) baking the soils to very high temperatures to remove moisture prior to spiking the soils and running the desorption tests. Because the MAT was not estimated based on 200-ZP-2 ERA site-specific soils, and because dry soils have a higher affinity for adsorbing organics (due to the absence of water in the soil micropores), the MAT of 80 °C (176 °F) for effective desorption of carbon tetrachloride may differ from actual in situ applications at the 200-ZP-2 ERA site.

Table 4. Thermal Desorption Removal Efficiencies for Organics from Soil at Minimum Allowable Temperature.

Contaminant	Boiling Point °C (°F)	Minimum Allowable Temperature °C (°F)	Removal (%)
Carbon Tetrachloride	77 (170)	80 (176)	99.1
Chloroform	61.7 (145)	120 (248)	97.4
Methylene Chloride	40 (104)	100 (212)	97.3

The soil-heating technologies identified for this evaluation use a medium (air or steam) to transport thermal energy, or electrical/electromagnetic energy, to increase the temperature of VOC-laden soils. The vaporized water and contaminant front condenses as it migrates to cooler soils ahead of the heated soil front. As the heated soil front continues to move away from its energy source, the total mass of desorbed water and organic will steadily increase and thus the mass of the condensed water/organic front will increase. To minimize the accumulation of condensed organic/water, careful consideration must be given to the power/capacity of the SVE system(s) and the placement of the injection and extraction wells to provide optimum transport of the organic/water-laden vapor to the surface for treatment.

If the extraction well radius-of-influence does not overlap the heated soil front, organic/water-laden vapors produced via soil heating will not be captured and the organics/water will condense on cooler soils with no net gain in contaminant removal. This dilemma may potentially transport the contamination to previously clean soils and/or to groundwater. Similarly, if the extraction well radius-of-influence overlaps the heated soil front, but the respective flow field velocity is low, the organic/water-laden soil vapor may condense on the soils between the extraction well and heated soil front. Therefore, extraction well placement must be such that a relatively high-velocity flow field induced by the SVE systems encompasses the heated soil front. In this manner, the mass of condensate can be minimized and the effective use of the energy source maximized.

According to a recent article in the *Hazardous Waste Consultant*, soil heating can produce the following effects (HWC 1994):

- A doubling of the contaminant vapor pressure for every 14 °C (25 °F) increase in soil temperature. This equates to the doubling of the contaminant concentrations in the extracted soil vapor and thus a two-fold increase in the extraction rate

- Reduced soil moisture, thus improved soil air porosity.

The article also states that soil heating is most cost effective under the following circumstances:

- When ambient-temperature SVE operation would require more than 8 months
- When the contaminant is concentrated in a small area rather than dissipated throughout a larger area
- When remediation of soils must be accomplished within a specific time interval.

The actual relationship between temperature and contaminant removal (i.e., MAT) has not been established for 200-ZP-2 ERA site-specific soils, and this information is key to an effective evaluation of soil-heating technologies. Additional laboratory efforts and/or field demonstrations would be necessary to determine the MAT for carbon tetrachloride desorption from each geologic layer at the ERA site. Furthermore, the volatilization of carbon tetrachloride via soil heating may result in volatilization of other VOCs (and semi-VOCs) not currently addressed (e.g., tributyl phosphate) at 200-ZP-2. This potential requires further evaluation as it could result in modification to the current SVE systems operating parameters and/or the treatment systems.

Each of the applicable soil-heating technologies is described in more detail in the following sections.

3.2 HOT AIR INJECTION

3.2.1 Technology Description

Hot air injection requires the heating of ambient air to temperatures between 316 °C (600 °F) and 427 °C (800 °F) followed by injection of the hot air into the subsurface. The hot air may be injected into a single injection well or a network of injection wells. An electric heater or fuel burner may be used to heat the air. Generally, burners are generally more cost effective for larger applications than electric heaters. The injection and extraction wells must be designed to withstand the high temperatures of the hot air being delivered to the subsurface.

The heated ambient air will have a very low relative humidity as it is injected into the ground. As this hot, dry air passes through the soil, it volatilizes the organic constituents and water adsorbed/fixed to the soil; this dry, remediated soil nearly reaches the temperature of the injected air, while soils farther away from the injection well are significantly cooler. The air will tend to follow paths of least resistance; thus, the most permeable areas will be heated most effectively. With continued hot air injection and SVE system operation, the region of remediated soil expands towards the extraction well(s).

Extraction wells are placed strategically such that the perimeter of the radius of influence created by the SVE systems overlaps the zone influenced by the injected hot air. In this manner, the "hot" front is guided towards the extraction well. By adjusting the overlap of the zones of influence, the amount of condensed water and organic vapors at the heated soil front can be

controlled. That is, the closer the extraction well is to the injection well, the less accumulation of condensed water and organic vapors at the heated soil front.

3.2.2 Applicability to 200-ZP-2 Operable Unit

Implementation to date of the hot air injection technology has mainly involved sites with shallow contamination and relatively small volumes of soil to be remediated. The technology relies on sufficient soil permeability to allow the heated air to flow through the soils and contact the contaminated media. In theory, this technology should work effectively on the permeable geologic formations at the 200-ZP-2 sites. However, the large volume and greater depth of contamination in the operable unit poses an uncertainty that cannot be evaluated based on the available literature. Although this technology has not been used in environmental remediation at the depths found in the 200-ZP-2 Operable Unit, soil-heating techniques are routinely used in the petroleum industry at much greater depths to enhance oil recovery.

Uncertainties as to the applicability of hot air injection to permeable geologic formations include the following.

- The existing injection/extraction well designs require detailed evaluations to address effects of corrosion and thermal expansion.

- Injection and extraction well spacing is dependent on permeabilities and thus will differ for different geologic formations. Well spacing is also dependent on the volume of soil to be treated, the depth of contamination, and the soil moisture content.

- The effectiveness of hot air injection given the heterogeneity (nonideal conditions) of the permeable soils is not known. Without uniform contact between the heating medium and the contaminated soils, remediation of the targeted permeable layers will not be totally effective.

- The full extent and effect of the condensed water and organic front is uncertain, and thus the need for additional injection and extraction wells cannot be easily determined. Additionally, the mass of the condensed front needs to be evaluated to ensure migration of contaminants to groundwater does not occur.

- The MAT for 200-ZP-2 ERA soils is not known, and the potential for volatilization of co-contaminants must be evaluated.

- The desiccation of soils, in consideration of contamination depth and soil volume, may cause subsidence of the vadose zone.

The hot air injection technology is not considered effective for the low-permeability formations because insufficient airflow would limit heated air contact with the contaminated soils. Lower permeability soils lack flow pathways necessary for hot air (or steam injection) to be effective in heating soils and thus in enhancing volatilization. The WSU study (BHI 1996c) results confirm

that the rate of contaminant transport through low-permeability soils is extremely slow and will greatly limit the remediation of these soils.

The cost of implementing hot air injection for the permeable geologic formations at the 200-ZP-2 ERA site depends on (1) the suitability of existing wells for injection and extraction, (2) the size of the contaminated area to be remediated, (3) the MAT for effective desorption, and (4) the amount of energy required to meet remediation goals. No cost data for this technology were found in the literature.

3.3 STEAM INJECTION

3.3.1 Technology Description

Steam injection processes are designed to remove VOCs using steam at approximately 121 °C (250 °F) and 103 kPa (15 lb/in^2) to provide heat and pressure within the targeted zones. Steam is generated in a boiler system and injected at or below the targeted contaminated soils through an injection well or series of injection wells. The steam heats the soil mass at the injection interval to temperatures from 66 °C (150 °F) to 121 °C (250 °F) and is drawn towards the SVE well(s). As with hot air injection, the injection and extraction wells must be strategically placed to direct the flow of vaporized organic and water to the extraction wells. Well spacing is dependent on the SVE system capacity, the permeability of the soil in the treatment area, the depth and volume of contaminated soil, soil moisture content, and the concentration of contaminants. By adjusting the placement of the injection and extraction wells, the mass of condensed water and contaminant vapors can be controlled.

The following characteristics are desirable for effective steam injection applications.

- The soil must have moderate to high permeability. Soil heating via steam injection is dependent on thorough and uniform steam-soil contact.
- The subsurface geology should provide a confining layer below the target zone to prevent downward movement of contaminants associated with steam condensate.
- A low-permeability surface layer may be needed for shallow applications to prevent steam and heat loss to the atmosphere.

Steam injection offers an advantage over hot air injection in that steam delivers significantly more energy per mass than hot air: 9 kW per foot of screened interval compared to 1 kW per foot for hot air injection and lower operating cost per BTU (HWC 1994). Drawbacks to steam heating are related to the condensing of the steam and desorbed contaminant, which can result in the relocation of contaminants to the soils at the edge of the heated region and/or transport to groundwater.

3.3.2 Summary of Testing

Steam injection has been successfully tested in soils to a depth of approximately 12 m (40 ft) by Hughes Environmental on a contaminated area of 9,290 m^2 (2.3 acres, 100,000 ft^2) (EPA 1995a). The test was conducted in permeable sands with a treated volume of 72,675 m^3 (95,000 yd^3). The demonstration was conducted at the Rainbow Disposal Site in Huntington Beach, California, where an estimated 265,000 to 511,000 L (70,000 to 135,000 gal) of diesel was spilled. Roughly 60,000 L (16,000 gal) (12% to 24% of the spilled volume) of the diesel was recovered during the demonstration at a cost of $46/$yd^3$. The literature states that the Hughes site is the largest application of this technology ever attempted in terms of volume of soil treated.

A demonstration project at Solvent Service, Inc. in San Jose, California, was conducted using steam injection to treat 96 m^3 (125 yd^3) of soils contaminated with xylenes, ethylbenzene, 1,2-dichlorobenzene, 1,1,1-trichloroethane, TCE, tetrachloroethene, and acetone. The treatment depth was 6 m (20 ft). The project resulted in the removal of 245 kg (540 lb) of contaminants over 6 days with steam injection of 113 kg/h (250 lb/h) at 41 kPa (6 lb/in^2) (Smith and Hinchee 1993).

During small-scale field testing of this technology by Nunno (Smith and Hinchee 1993), removal of benzene, toluene, ethylbenzene, and xylene compounds, which are similar in volatility to carbon tetrachloride, was recorded at 99.5% in permeable sand.

3.3.3 Applicability to 200-ZP-2 Operable Unit

Similar to the hot air injection, steam injection has generally been applied to sites with relatively small volumes of contaminated soil with contamination depths of only 12 m (40 ft). Application of the technology to the scale of the ERA site has not been attempted. The volume and depth of contaminated soils at the 200-ZP-2 ERA site pose uncertainties as to the feasibility of implementing steam injection, and thus field testing may be warranted. As with hot air injection, this technology would be effective only on permeable soil formations. The suitability of existing injection/extraction wells would have to be evaluated to determine the need for additional borings or special construction requirements. The potential to drive contaminants to groundwater requires further evaluation. The effectiveness of steam injection given the heterogeneity of the soils also requires further consideration.

Steam can be generated from boilers, either electric or gas; however, significant quantities of steam may be available from the 200 Area steam power plant. The use of onsite steam should result in reduced costs for the implementation of steam injection.

3.4 SIX-PHASE SOIL HEATING

3.4.1 Technology Description

Six-phase soil heating is currently being developed by PNNL as a cleanup methos for VOC and semi-VOC contaminated soils. Six electrodes are placed in a hexagonal array, with an extraction well connected to a vacuum blower placed in the center of the array. Three-phase electrical power is converted to six-phase electrical power with transformers and applied through electrodes installed into the subsurface to the contaminated soils. A liquid electrolyte, usually sodium chloride, is continuously added to the soil column to stimulate conductivity. The resistive dissipation of the energy imparted on the soils from the electrodes causes the soil particles to heat. As the soils heat, soil moisture and VOCs volatilize and migrate towards the extraction well due to diffusion and/or the pressure gradient induced by the SVE system. The volatilized contamination and associated water vapor are withdrawn through the extraction well where the water is condensed and the VOC contamination is adsorbed onto GAC.

Six-phase soil heating can be applied to both permeable and low-permeability soils. However, contaminant transport through low-permeability soils is much slower than that from permeable soils. Volatilization of the water and organics in the low-permeability soils may create more interconnected pore space, thus aiding air flow through the zone.

3.4.2 Summary of Testing

Testing of this technology has been performed at the Hanford Site in sandy soils and at Savannah River Site in very low-permeability clay soils. The PNNL demonstration of this technology at the Hanford Site used six electrodes emitting 30 to 35 kW of power driven to a depth of 3 m (10 ft). The soil volume heated was 89 m^3 (116 yd^3). Operational problems included high resistances in the desiccated soils and fouling of power cables due to copper losses associated with high amperage. The test objective at Hanford was to demonstrate the heating capabilities of the technique; no contaminants were treated (Bergsman et al. 1993).

The demonstration at Savannah River treated 400 m^3 (500 yd^3) of low-permeability clay soils contaminated with PCE and TCE. Electrodes were placed in a hexagonal array in a 9-m- (30-ft) diameter circular area. Electrical contact between the electrodes and the soil column occurred between 7 and 13 m (23 and 44 ft) below ground surface. Soil-heating operations were performed for approximately one month. Soil temperatures within the hexagonal electrode array reached slightly above 100 °C (212 °F); soil temperatures measured outside the array reached approximately 50 °C (122 °F). Median PCE removal efficiency from within the electrode array was measured at 99.7%, and removal efficiency for soils outside the array where the soil temperatures reached approximately 50 °C (122 °F) was 93%. The TCE removal efficiencies were equivalent to PCE removal efficiencies (Gauglitz and Bergsman 1994).

3.4.3 Applicability to 200-ZP-2 Operable Unit

The current development status of this technology makes the application at the operable unit very uncertain. This technology has been demonstrated on relatively small soil volumes, up to 400 m^3 (500 yd^3). Implementation of this technology on a scale comparable to the remediation of the permeable soils within the ERA target zone has not been attempted. This technology is still in a developmental stage.

The depth of the contamination at 200-ZP-2 Operable Unit creates another significant uncertainty, both in terms of effectiveness and implementability. The technology has been demonstrated at depths to 13 m (44 ft); however, treatment of the permeable zones at 200-ZP-2 would require treatment to depths of up to 66 m (216 ft).

This process should be more effective in comparison to hot air or steam injection in low-permeability soils. Six-phase soil heating uses an electric field to heat the soils from within. Inherent soil moisture and soil particles absorb the energy from the electric field and are heated. The absence of substantial flow pathways through low-permeability soils will decrease the ease of removal of vapor-phase contamination via SVE operations. The WSU study results indicate that very little contaminant diffusion occurs through the low-permeability layers at ambient subsurface temperatures. However, heating the low-permeability layers uniformly should promote rapid diffusion of volatilized contaminants through the low-permeability soils to the flow zone induced by the SVE systems. Additionally, volatilization of soil moisture and organic contaminants may create additional or larger pore spaces, or at least free up the pore spaces within the low-permeability zones to aid the effectiveness of the SVE systems in extracting contaminated vapors through these layers.

Further evaluation of this technology would include consideration of the suitability and spacing of existing wells and/or additional wells and placement of the electrodes at the depths required in the 200-ZP-2 Operable Unit.

3.5 RADIO-FREQUENCY HEATING

3.5.1 Technology Description

Radio-frequency heating technologies use energy from RF waves to heat soils in situ. Heating is accomplished by applying a high-frequency, alternating-current electric field to the contaminated soils from a series of antennas installed via borings. Polar molecules, such as water, absorb electromagnetic energy, causing them to heat due to increased vibratory and rotational motion. This phenomenon of absorbing electromagnetic energy and transforming the energy from kinetic to thermal energy is called dielectric heating and is the principal process used by microwave ovens for cooking food.

As with all soil-heating technologies, the soil near the antennas becomes dry and very hot. As the soil dries, the resistance to RF waves decreases, allowing the heated soil front to move

outward, volatizing soil moisture and VOC contamination. The volatized contaminants and associated water vapor are transported toward the extraction wells due to the pressure gradient induced by the SVE system. They are delivered to the treatment system via the extraction well network where the water is removed and the VOCs are adsorbed in GAC canisters.

3.5.2 Summary of Testing

This technology was tested by KAI Technologies, Inc. at Kelly Air Force Base in San Antonio, Texas, in 1994 on an estimated 85 m^3 (111 yd^3) of contaminated soils. The treatment depth was 6 m (20 ft), and the contaminants included total petroleum hydrocarbon, VOCs, and mainly, semi-VOCs. The demonstration project resulted in a 29% recovery and did not meet the projected contaminant removal levels (EPA 1995b). Inefficiencies caused by extraction well screened intervals prevented both isolation of the remediation zone and effective monitoring of the volatilization and removal of the contaminants. Costs associated with this demonstration project were approximately $286/ton without the SVE system. Assuming a soil density of 3,000 lb/ton, the treatment unit cost would be about $429/$yd^3$.

KAI Technologies, Inc. encountered operational difficulties due to frequent disruptions in power supply to the electrodes. Also, borehole liners had to be cooled occasionally, further disrupting the heating process. As with other soil-heating processes, disruptions in heating can cause nonuniform heating and incomplete remediation.

At the Volk Air National Guard Base RF heating demonstration at Camp Douglas, Wisconsin, 98% of VOCs and 94% of semi-VOCs were removed after 8 days of heating with a 30-kW power source (Smith and Hinchee 1993). The volume of soil treated during the Volk demonstration was approximately 17 m^3 (22 yd^3) at a treatment depth of 1.8 to 2.4 m (6 to 8 ft) below ground surface. The site was contaminated with 190,000 L (50,000 gal) of jet fuel with 4,000 ppm of total petroleum hydrocarbon. Cost estimates for the project were about $100/$yd^3$.

RF heating is capable of heating the soil to higher temperatures and at a faster rate than six-phase soil heating. During the Savannah River demonstration of six-phase soil heating, 25 days of heating were necessary to heat soils between 66 to 100 °C (150 to 212 °F). During the Volk demonstration of RF heating, 2 days of heating were necessary to heat soils to 100 °C (212 °F) and 12.5 days were necessary to heat soils to 149 °C (300 °F).

3.5.3 Applicability to the 200-ZP-2 Operable Unit

The size of the contaminated area and the depth of treatment are principal uncertainties for application of this technology at the operable unit. To date, field demonstrations of the technology have been confined to small sites and shallow depths. As with six-phase soil heating, the RF heating technology has a greater potential to enhance recovery of the carbon tetrachloride in the low-permeability layers relative to hot air and steam injection technologies.

Very little field-scale demonstration of this technology has been performed. However, based on the similarities in heating mechanism to six-phase soil heating, this technology may be applicable for the remediation of Hanford low-permeability soils.

4.0 SUMMARY AND CONCLUSIONS

Available information from the literature indicates that in situ heating of VOC-contaminated soils is capable of enhancing removal of adsorbed organics and organics fixed within soil micropores. The literature data indicate that recoveries of more than 90% of VOCs from soils are possible. If such recoveries could be achieved, they would represent a substantial enhancement over the existing ambient-temperature SVE system, which laboratory tests on Hanford Site soils have shown is capable of removing only about 10% of the adsorbed carbon tetrachloride from the permeable soil layers and even lower recoveries from the low-permeability layers. However, specific tests of soil heating for Hanford soils have not been performed, and therefore the relationship of recoverable VOC to soil temperature (MAT) needs to be verified in laboratory experiments as a first step. Knowledge of this relationship is critical to a more rigorous technical and cost evaluation of SVE enhancement technologies.

Available literature data indicate that soil-heating technologies have been successfully tested and/or applied full scale at other sites for in situ removal of vadose zone organics. However, most of the testing/applications have been limited to relatively shallow applications [<15-m (<50-ft) depth], and the scale of the systems have been relatively small. Extrapolation of the experiences at other sites to a Hanford application poses large technical and cost uncertainties, primarily because of the much greater depths and the larger volumes of soil that require remediation at Hanford. Reducing these uncertainties would require substantial efforts in field treatability/demonstration testing before a full-scale system could be confidently applied.

Of the four technologies evaluated, hot air and steam injection are judged as potentially the most practical and cost effective for application to the permeable soil layers. Although neither technology has been widely applied for site remediation, both have been extensively used in the petroleum industry to enhance oil recovery. As applied to Hanford for soil remediation, the principal uncertainties of these techniques relate to (1) the ability to obtain uniform flow of heating media in the subsurface and (2) the potential for condensation of organic-contaminated liquids that could potentially migrate to groundwater. These two uncertainties feed into the uncertainty of injection and extraction well placement.

For application to the low-permeability soil layers, it appears that electrical and RF heating may be more effective in removing VOCs than hot air or steam because these techniques are not dependent on the permeability of the soil for distribution of the heating media. However, implementability of either technology at Hanford is highly uncertain, and the costs are very speculative because of the greater depths and volumes of contamination. If it is feasible to implement these systems at the required depths, the costs would likely be quite high. A rigorous

evaluation of these technologies would require more detailed, site-specific technical evaluation and testing.

A more rigorous evaluation of the soil-heating technologies would require further studies to refine the technical information and costs. Limited laboratory studies should first be performed to establish the relationship between soil temperature and time on the recovery of VOCs. More rigorous engineering and cost evaluations should then be conducted to more thoroughly assess each of the heating technologies. This analysis would require more detailed vendor information, conceptual designs of each system, and more detailed cost estimates. Based on this information, the most technically viable and cost-effective technology would then be field tested to further demonstrate technical viability and costs.

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