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ENGINEERING DATA TRANSMITTAL

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1. EDT 602648

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2. To: (Receiving Organization) Distribution		3. From: (Originating Organization) Geosciences		4. Related EDT No.: n/a					
5. Proj./Prog./Dept./Div.: 200 West Area Carbon Tetrachloride Expedited Response Action		6. Cog. Engr.: V. J. Rohay		7. Purchase Order No.: n/a					
8. Originator Remarks: Please review and approve as indicated. Please provide comments by 2/18/94. THANK YOU.				9. Equip./Component No.: n/a					
				10. System/Bldg./Facility: n/a					
				12. Major Assm. Dwg. No.: n/a					
				13. Permit/Permit Application No.: n/a					
11. Receiver Remarks:				14. Required Response Date: 2/18/94					
15. DATA TRANSMITTED									
(A) Item No.	(B) Document/Drawing No.	(C) Sheet No.	(D) Rev. No.	(E) Title or Description of Data Transmitted	(F) Impact Level	(G) Reason for Trans- mittal	(H) Orig- inator Dispo- sition	(I) Receiv- er Dispo- sition	
1	WHC-SD-EN-AP-159		0	Wellfield Strategy and Recommendations for the 200 West Area Carbon Tetrachloride Expedited Response Action	4	1, 4/ 2	/		
16. KEY									
Impact Level (F)		Reason for Transmittal (G)			Disposition (H) & (I)				
1, 2, 3, or 4 (see MRP 5.43)		1. Approval 2. Release 3. Information 4. Review 5. Post-Review 6. Dist. (Receipt Acknow. Required)			1. Approved 2. Approved w/comment 3. Disapproved w/comment 4. Reviewed no/comment 5. Reviewed w/comment 6. Receipt acknowledged				
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1	/	Cog. Mgr. A. J. Knepp <i>A. J. Knepp</i> 3/28/94 H6-06				S. A. Driggers H6-04 4			
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18.		19.		20.		21. DOE APPROVAL (if required) Ltr. No.			
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BD-7400-172-2 (07/91) GEF097

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New or novel (patentable) subject matter? ☒ No ☐ Yes If "Yes", has disclosure been submitted by WHC or other company? ☐ No ☐ Yes Disclosure No(s).			Information received from others in confidence, such as proprietary data, trade secrets, and/or inventions? ☒ No ☐ Yes (Identify)		
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SUPPORTING DOCUMENT		1. Total Pages 158
2. Title Wellfield Strategy and Recommendations for the 200 West Area Carbon Tetrachloride Expedited Response Action		3. Number WHC-SD-EN-AP-159
		4. Rev No. 0
5. Key Words unsaturated zone, wellfield areas of influence, extraction strategies <div style="text-align: center; font-weight: bold; font-size: 1.2em;">APPROVED FOR PUBLIC RELEASE</div> <div style="text-align: center; font-style: italic;">5/16/94 JDS/13</div>		6. Author Name: V.J. Rohay <div style="text-align: center; font-style: italic;">V.J. Rohay 5/4/94</div> Signature Organization/Charge Code 81231/PU2BD
7. Abstract Rohay, V.J., and R.J. Cameron, 1994, <i>Wellfield Strategy and Recommendations for the 200 West Area Carbon Tetrachloride Expedited Response Action</i> , WHC-SD-EN-AP-159, Rev. 0, prepared by V.J. Rohay, Westinghouse Hanford Company, and R.J. Cameron, ENSERCH Environmental, for Westinghouse Hanford Company, Richland, Washington.		
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ACRONYMS

CPT	cone penetrometer
DNAPL	dense nonaqueous phase liquid
DOE	U.S. Department of Energy
Ecology	Washington State Department of Ecology
EPA	U.S. Environmental Protection Agency
ERA	Expedited Response Action
ppm _v	parts per million by volume
PFE	pneumatic fracturing extraction
RL	U.S. Department of Energy, Richland Field Office
SVOC	semivolatile organic compound
VES	vapor extraction system
VOC	volatile organic compound

Metric Conversion Chart

The following conversion chart is provided to the reader as a tool to aid in conversion.

Into Metric Units			Out of Metric Units		
<u>If You Know</u>	<u>Multiply By</u>	<u>To Get</u>	<u>If You Know</u>	<u>Multiply</u>	<u>To Get</u>
Length			Length		
inches	25.4	millimeters	millimeters	0.039	inches
inches	2.54	centimeters	centimeters	0.394	inches
feet	0.305	meters	meters	3.281	feet
yards	0.914	meters	meters	1.094	yards
miles	1.609	kilometers	kilometers	0.621	miles
Area			Area		
sq. inches	6.452	sq. centimeters	sq. centimeters	0.155	sq. inches
sq. feet	0.093	sq. meters	sq. meters	10.76	sq. feet
sq. yards	0.0836	sq. meters	sq. meters	1.196	sq. yards
sq. miles	2.6	sq. kilometers	sq. kilometers	0.4	sq. miles
acres	0.405	hectares	hectares	2.47	acres
Mass (weight)			Mass (weight)		
ounces	28.35	grams	grams	0.035	ounces
pounds	0.454	kilograms	kilograms	2.205	pounds
short ton	0.907	metric ton	metric ton	1.102	short ton
Volume			Volume		
teaspoons	5	milliliters	milliliters	0.033	fluid ounces
tablespoons	15	milliliters	liters	2.1	pints
fluid ounces	30	milliliters	liters	1.057	quarts
cups	0.24	liters	liters	0.264	gallons
pints	0.47	liters	cubic meters	35.315	cubic feet
quarts	0.95	liters	cubic meters	1.308	cubic yards
gallons	3.8	liters			
cubic feet	0.028	cubic meters			
cubic yards	0.765	cubic meters			
Temperature			Temperature		
Fahrenheit	subtract 32, then multiply by 5/9	Celsius	Celsius	multiply by 9/5, then add 32	Fahrenheit
Pressure			Pressure		
inches of H ₂ O	0.00246	atmospheres	atmospheres	406.5	inches of H ₂ O
inches of Hg	0.03332	atmospheres	atmospheres	30.005	inches of Hg

EXECUTIVE SUMMARY

Carbon tetrachloride was disposed to the soil column at several sites adjacent to the Hanford Site Z Plant (Plutonium Finishing Plant) during operations from 1955 through 1973. In 1990 a Carbon Tetrachloride Expedited Response Action (ERA) was initiated to mitigate the spread of this contamination in the subsurface. Under the auspices of this ERA, several active soil vapor extraction systems have been placed in operation since 1992 to remove the carbon tetrachloride by extracting contaminated soil gas.

Field investigations and vapor extraction operations have revealed the presence of carbon tetrachloride in the unsaturated zone soil gas at concentrations ranging from 1 to approximately 30,000 ppm_v. The unsaturated zone in the Z Plant area is approximately 65 m thick and is relatively permeable, with the exception of a lower permeability zone from 35 to 45 m depth. In general, higher concentrations of carbon tetrachloride have been observed overlying and within the lower permeability layers.

To meet the objectives of the ERA, it is necessary to remove as much carbon tetrachloride as possible from the unsaturated zone and to prevent or mitigate further migration of carbon tetrachloride to the groundwater. The strategy to meet these objectives requires trade-offs between the higher removal rates possible from the upper permeable zone, which is somewhat isolated from the groundwater, and the lower removal rates anticipated within and below the low permeability zone, which pose a greater threat to the groundwater.

Controlling airflow in the subsurface and understanding the location and movement of contaminated soil gas are essential for optimizing the extraction operations. Using wells in optimal locations and extracting soil gas from various intervals based on changing subsurface conditions will enhance the extraction operations.

The strategy for meeting the ERA objectives must be dynamic in nature to account for changing conditions as the extraction process proceeds. To maintain this strategy, it is recommended that during FY 1994:

- Twenty-six existing wells be modified, if feasible, to allow greater access to the subsurface using the vapor extraction systems.
- The wells and intervals utilized for extraction operations be carefully selected to maximize their areas of influence and recovery rates to meet the project objectives.
- The 500 ft³/min system be used to increase the overall extraction capacity and to provide the flexibility to extract over a greater area.
- Further numerical modeling be conducted to better understand the soil vapor extraction process and to suggest operational parameters.

- Short-term extraction tests be performed whenever soil gas is first extracted from a well and then at least quarterly during operation to provide information regarding the changing levels of carbon tetrachloride and its movement with time.
- Tracer gas testing be used to determine subsurface airflow pathways, rate of carbon tetrachloride transport, and areas of influence of the extraction wells.
- Downhole pressures be continuously recorded wherever possible in subsurface open intervals to monitor areas for influence caused by the soil vapor extraction operation.

In addition, it is recommended that, in the long term:

- Smaller capacity (e.g., 300 to 500 ft³/min) vapor extraction units be considered to increase the area affected by soil vapor extraction operations.
- Technologies having potential to enhance the soil vapor extraction operations, including pulsed versus continuous pumping, pneumatic fracturing, air injection, and surface seals, be investigated.
- Laboratory-scale testing be conducted to define the carbon tetrachloride sorption equilibrium for various soil types to aid the modeling and provide indications of total airflow required to remove the carbon tetrachloride from the subsurface.

The recommendations provided in this report represent a broad spectrum of possible wellfield activities that, if implemented, would enhance the VES operations. However, due to programmatic and budgetary constraints, it may not be possible to implement all of the recommendations at this time. These recommendations will be updated every six months to reflect additional operational data.

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1.0 INTRODUCTION

1.1 PURPOSE

On December 20, 1990, the U.S. Environmental Protection Agency (EPA) and the Washington State Department of Ecology (Ecology) requested the U.S. Department of Energy (DOE), Richland Field Office (RL) to proceed with the detailed planning, including nonintrusive field work, required to implement an Expedited Response Action (ERA) for removing carbon tetrachloride contamination in the unsaturated soils in the 200 West Area of the Hanford Site. The request was based on concerns that the carbon tetrachloride residing in the soils was continuing to spread to the groundwater and, if left unchecked, would significantly increase the area of groundwater contamination. The purpose of this ERA is to minimize carbon tetrachloride migration within the unsaturated zone beneath and away from the carbon tetrachloride disposal sites in the 200 West Area.

Based on the initial site investigations and on the engineering evaluation and cost assessment, the preferred alternative for removal of the carbon tetrachloride from the unsaturated zone was identified as soil vapor extraction followed by aboveground vapor collection on granular activated carbon (GAC) (DOE-RL 1991). In January 1992, the EPA and Ecology authorized DOE to initiate soil vapor extraction for cleanup of the carbon tetrachloride. The first active vapor extraction system (VES) began operating in February 1992.

This wellfield recommendations report was developed to provide guidance and recommend strategies to enhance the operation of the active soil VES used as part of the ERA. This report also describes pertinent site characteristics and discusses results of site-specific soil vapor extraction modeling. The development of this report was directed by the *FY93 Wellfield Enhancement Workplan* and the *FY94 Wellfield Optimization and Site Characterization Task Plan for the Carbon Tetrachloride ERA* (Rohay and Cameron 1992, Rohay 1994).

The recommendations provided in this report represent a broad spectrum of possible wellfield activities that, if implemented, would enhance the VES operations. However, due to programmatic and budgetary constraints, it may not be possible to implement all of the recommendations at this time. These recommendations will be updated every six months to reflect additional operational data.

1.2 VAPOR EXTRACTION SYSTEM OPERATIONS BACKGROUND

A pilot VES was tested at the 216-Z-1A Tile Field in April 1991 (DOE-RL 1991). Based upon the results of this testing and as part of the Carbon Tetrachloride ERA, a full-scale VES was installed and began operating at the tile field in February 1992. Extraction at two of the 216-Z-18 Crib wells with the same system was begun in the summer of 1992. This system originally had a design capacity of 500 ft³/min but was upgraded to 1,000 ft³/min in March 1993. Two VES units, one with 1,500 ft³/min capacity and one with 500 ft³/min capacity, began operating in March 1993 at the 216-Z-9 Trench. The

extracted carbon tetrachloride is collected on GAC contained in large steel canisters. All three systems were shut down on June 3, 1993, because of a GAC canister overheating incident at 216-Z-9 (WHC 1993a). The 1,000 ft³/min system resumed operation at the 216-Z-1A/18 Wellfield on November 15, 1993; the 1,500 ft³/min system resumed operation at the 216-Z-9 Wellfield on February 23, 1994.

2.0 SITE CHARACTERISTICS

This section provides a brief summary of site characteristics as background for this report. More detailed discussions of site characteristics are provided in Rohay et al. (1992), Piepho et al. (1993), Rohay et al. (1993), and Last and Rohay (1993).

2.1 DISPOSAL SITES AND CONSTITUENTS

In the 200 West Area, carbon tetrachloride was used at Z Plant (currently called the Plutonium Finishing Plant) primarily by the Recuplex Facility and the Plutonium Reclamation Facility (Figure 2-1). No other plant in the 200 West Area is known to have used carbon tetrachloride.

Carbon tetrachloride was used in mixtures with other organics to recover plutonium from aqueous streams at Z Plant. The chemical processes used to recover plutonium resulted in the production of actinide-bearing aqueous and organic waste liquids. The primary radionuclide components of these liquids were $^{239/240}\text{Pu}$ and ^{241}Am . The aqueous waste stream, characterized as high-salt aqueous waste, was primarily a concentrated nitrate solution with a pH of 1 (neutralized to a pH of 2.5 prior to discharge). The organic liquids discharged to the disposal sites consisted of carbon tetrachloride in mixtures with tributyl phosphate, dibutyl butyl phosphate, or lard oil.

Both aqueous and organic phases were discharged to the same liquid waste disposal sites. The organic wastes were periodically discharged batch-wise. The aqueous wastes were continuously discharged. The aqueous wastes were typically saturated with carbon tetrachloride (<1%) but account for <5% of the carbon tetrachloride discharged.

Degradation products of carbon tetrachloride include chloroform and methylene chloride. Breakdown products of tributyl phosphate include dibutyl phosphate, monobutyl phosphate, butanol, and butanone. In addition to the plutonium and americium, constituents of the aqueous waste streams discharged to the sites included aluminum, cadmium, calcium, chromium, fluoride, chloride, iron, iodine, magnesium, nickel, nitrate, rubidium, sodium, sulfate, sulfamate, cesium, cobalt, uranium, ruthenium, and strontium.

The primary known carbon tetrachloride disposal sites, all located near Z Plant, are the 216-Z-9 Trench, 216-Z-1A Tile Field; and 216-Z-18 Crib, known collectively as the Z-Crib Area (See Figure 2-1). The 216-Z-9 Trench was used from 1955 to 1962 to receive all organic and aqueous waste from the Recuplex Facility. Organic and aqueous waste from the Plutonium Reclamation Facility was discharged to the 216-Z-1A Tile Field from 1964 to 1969 and to the 216-Z-18 Crib from 1969 to 1973. Elevated levels of carbon tetrachloride in the soil gas emanating from wells and other monitoring points indicate that other locations in the general vicinity of the Z-Crib Area may have been used as carbon tetrachloride disposal sites (e.g., the 216-Z-12 Crib) or that carbon tetrachloride has migrated laterally. Direct discharge of carbon tetrachloride to the soil column was discontinued in 1973.

Estimates of the volumes and quantities of various liquids and contaminants discharged to the 216-Z-1A Tile Field, 216-Z-18 Crib, and 216-Z-9 Trench are summarized in Table 2-1.

Table 2-1. Soil Contaminant Inventory in the Z-Crib Area.

Contaminant	216-Z-9 Trench	216-Z-1A Tile Field	216-Z-18 Crib
Carbon tetrachloride (L)	83,000-300,000	170,000	110,000
Plutonium (kg)	106 ^a	57	23
Americium (kg)	2.5	1	≈0.4
Total liquid (L)	4.09 x 10 ⁶	5.2 x 10 ⁶	3.86 x 10 ⁶
Period of use	1955-1962	1964-1969	1969-1973

^a58 kg were later removed.

2.2 SITE HYDROGEOLOGY

The unsaturated zone underlying the Z Crib Area consists primarily of fluvial and glaciofluvial sediments. The sediments, from youngest to oldest, are as follows:

- Hanford formation--unconsolidated glaciofluvial gravels, sands, and silts deposited by Pleistocene cataclysmic flood waters.
- Early Palouse soil--silt and fine-grained sand
- Plio-Pleistocene unit--basaltic detritus and carbonate-rich paleosol, often referred to as the caliche layer
- Ringold Formation--a series of consolidated alluvial sands and gravels and overbank and lacustrine deposits of late Miocene to Pliocene age.

The unsaturated zone ranges in thickness across the 200 West Area from 58 to 82 m and beneath the carbon tetrachloride disposal sites from 60 to 66 m. Because the caliche layer is less permeable than the other units, it may temporarily divert or perch liquids and/or dense vapors. The top of this unit is approximately 40 m below ground surface. The topography of the caliche layer surface suggests that it locally forms a ridge that extends south-southwest beneath the three carbon tetrachloride disposal sites and may divert fluids laterally to the west-northwest.

Perched water was discovered in two locations during 1992-1993 drilling operations in the vicinity of the 216-Z-9 Trench. The water is perched on the top of the caliche layer. At well 299-W15-216, the perched zone is 10 to 20 ft thick, and at well 299-W15-220, the perched zone is 2 to 3 ft

thick. The water is presumably from the 216-Z-21 Crib, which is an active water discharge site.

2.3 EXTENT OF CONTAMINATION

Results of FY 1991 and FY 1992 characterization activities at the carbon tetrachloride site were used to refine the site conceptual model of the carbon tetrachloride behavior and distribution (Last and Rohay 1993). In this refined conceptual model, the highest concentrations of carbon tetrachloride are located in the vicinity of the 216-Z-9 Trench; concentrations in the vicinity of the 216-Z-1A Tile Field and 216-Z-18 Crib are typically one to two orders of magnitude lower. The conceptual model of carbon tetrachloride migration pathways and phase distribution is illustrated in Figure 2-2.

At the 216-Z-9 Trench, the carbon tetrachloride concentrations appear to be highest adjacent to and north of the disposal facility. The soil-gas survey results indicate that the highest near-surface soil-gas concentrations of carbon tetrachloride (72 ppm_v) and chloroform are located just north of the 216-Z-9 Trench. The highest subsurface carbon tetrachloride vapor concentrations (over 10,000 ppm_v) were measured in wells and deep soil-gas ports near the trench (Figure 2-3). The highest carbon tetrachloride concentrations (up to 37.8 ppm_v) detected in sediment samples were from a well drilled adjacent to the trench in 1992 (well 299-W15-217). Concentrations of carbon tetrachloride extracted from wells in the 216-Z-9 Wellfield have been as high as 28,500 ppm_v; concentrations extracted from wells in the 216-Z-1A/18 Wellfield during vapor extraction operations typically range from 200 to 1000 ppm_v.

Sediment and subsurface soil-gas samples indicate that the highest concentrations of carbon tetrachloride in the unsaturated zone are associated with the early Palouse soil and the top of the Plio-Pleistocene unit, located at a depth of approximately 35 to 40 m. The early Palouse soil is a fine-grained unit with high porosity, small pore-size distribution, and relatively low hydraulic conductivity; the Plio-Pleistocene unit is a calcium carbonate-cemented horizon with very low hydraulic conductivity. Numerical flow simulations appear to support the contention that the early Palouse soil is the primary repository for carbon tetrachloride and other volatile organic compounds (VOC). Sediment samples suggest that higher concentrations of VOC may also be associated with the capillary fringe zone, located within 3 to 6 m above the water table.

Total VOC vapor concentrations (found to consist predominantly of carbon tetrachloride) measured in existing boreholes and deep soil-gas ports suggest a correlation with barometric pressure changes. Air flow measurements in the boreholes indicate that barometric pressure fluctuations may constitute a significant release mechanism for VOC out of the unsaturated zone (through boreholes) into the atmosphere, and could account for 3% of the carbon tetrachloride inventory estimated to have been discharged to the soil column. Ambient soil-surface flux measurements suggest natural fluxes of carbon tetrachloride from the unsaturated zone on the order of 0.25 g/m²/yr, based on a rough estimate that 18% of the estimated discharged inventory may have been released to the atmosphere via natural flux from the soil surface.

Although carbon tetrachloride is typically the predominant VOC constituent in the extracted soil gas, characterization sampling at wellheads has demonstrated that other contaminants can be found at elevated concentrations. For instance, preliminary work at wells 299-W18-7 and 299-W18-248 showed concentrations of methylene chloride at concentrations around 80 ppm_v, which were higher than the carbon tetrachloride concentration during this sampling sequence. Soil-gas sampling from other wells has indicated chloroform as a high percentage of the VOC concentration. The soil-gas also contains naturally occurring radon.

Well construction and waste water disposal histories suggest that some of the older existing wells, including deep groundwater wells, had the potential to provide a vertical conduit for the downward migration of carbon tetrachloride and other contaminants directly to the unconfined aquifer. However, column pore volume estimates and numerical model simulations suggest that, at the 216-Z-9 Trench, it is likely the wastes reached the water table regardless of whether poorly sealed wells provided a preferential pathway.

Concentrations of dissolved carbon tetrachloride detected in the upper 10 m of the unconfined aquifer (as defined by the 10-p/b contour) have accounted for approximately 2% of the total carbon tetrachloride inventory (Rohay and Johnson 1991). The dissolved plume is estimated to cover an area of 13 km². It appears to be emanating from the area of the 216-Z-9 Trench and extending primarily to the northwest.

Sampling data from one well (299-W15-6) also suggest that carbon tetrachloride occurs deep within the aquifer, at least near the 216-Z-9 Trench, where dissolved carbon tetrachloride was detected 52 m below the water table. However, the well itself may have provided the preferential pathway for the vertically distributed contaminants.

An order-of-magnitude estimate of the 1990 inventory of carbon tetrachloride remaining in the subsurface was made using available groundwater concentration data, soil-gas concentration data, and well venting data (WHC 1993b). Total atmospheric losses are estimated to be 21%; the unsaturated zone inventory (in soil gas, soil moisture, and adsorbed phases) accounts for 12%; the dissolved phase in the aquifer is estimated as 2%; leaving 65% of the original carbon tetrachloride volume unaccounted for. However, the estimates did not consider pockets of residual saturation in the unsaturated zone, perched organic liquid on low-permeability lenses, or separate organic liquid phase present within the unconfined aquifer. Any or all of these forms of concentrated carbon tetrachloride may be present within the subsurface, but none have been positively identified. Based on high concentrations of carbon tetrachloride (≈30,000 ppm_v) in the extracted soil vapor from some of the wells at the 216-Z-9 Trench, it is assumed that a significant fraction of the carbon tetrachloride is present in the unsaturated soils as residual saturation.

Figure 2-1. Z-Crib Area.

VCJ\101493-A

Figure 2-2. Conceptual Model of Carbon Tetrachloride Migration Pathways and Phase Distribution.

H9106027.1

Figure 2-3. Maximum Carbon Tetrachloride Concentrations Measured in Baseline Monitoring Wells and Deep Soil-Gas Probe Network December 1991 - September 1992.
(from WHC 1993b)

3.0 WELLFIELD RECOMMENDATIONS FOR VAPOR EXTRACTION OF THE Z-CRIB AREA

The recommendations for the Z-Crib Area Wellfield are part of a strategy to improve the efficiency of the VES and to increase the potential for long-term success of the remediation effort. This section provides recommendations for enhancing operations with regard to wellfield areas of influence, soil vapor extraction numerical modeling, wellfield testing, and extraction strategies. These recommendations, which address both the FY 1994 and long-term timeframes, are intended as guidance for possible wellfield activities.

3.1 RECOMMENDATIONS REGARDING WELLFIELD AREAS OF INFLUENCE

The area of influence of a well describes the radial area surrounding the well through which vapor extraction is able to induce air flow. The effectiveness of vapor extraction to remediate the subsurface is thus dependent on establishing areas of influence of wells sufficient to address the areas of contamination. Controlling flow in the subsurface and understanding the location of concentrated zones of carbon tetrachloride are essential for optimizing the extraction process. General vapor extraction strategies are discussed in Appendix D.

3.1.1 Areas of Influence of Existing Wellfield Configuration

3.1.1.1 Problem. The areas of influence of the extraction well configuration must allow extraction access to the entire subsurface within the Z-Crib Area. The existing wellfield configuration does not provide this coverage.

3.1.1.2 Discussion. Tables 3-1 and 3-2 describe the existing wells with open intervals in the subsurface above and below the caliche, respectively. The existing wells in the Z-Crib Area are shown in Figure 3-1. Figures depicting the areas of influence of the existing wellfield configuration were developed based on vapor extraction operation times and open interval locations. Figures 3-2, 3-3, 3-4, and 3-5 provide a representation of the coverage of the Z-Crib Area by the existing wells. The areas of influence were approximated based on the following assumptions:

- The area of influence is a right circular cylinder. For wells with open intervals above the caliche, the cylinder extends from the caliche to the surface. For wells with open intervals below the caliche, the cylinder extends from the groundwater to the caliche. (The vertical lengths of these cylinders imply vertical permeabilities that are much greater than horizontal permeabilities. This not the case; horizontal permeability typically exceeds vertical permeability by a factor of 10. However, making these assumptions regarding the lengths of the cylinders is reasonable for this discussion. Future revisions to this report will better define the shapes of the areas of influence when specific field information is available. Also,

future revisions will include cross-sections of the subsurface that will address the horizontal areas of influence.)

- The soil vapor extraction operation is either intermittent or continuous as described below.
 - Intermittent operation (8-hours per day, 5-days per week) limits the area of influence because the influence must be reestablished every time extraction is restarted. The area of influence is estimated by determining the total volume of air extracted over 8 hours at the maximum flow assuming an effective soil porosity of 20%. Soil moisture can have a significant effect on the area of influence by limiting the airflow pathways. The area of influence will typically increase with time as preferential pathways are established due to removal of the moisture with the extracted soil gas.
 - Continuous operation assumes that the extraction operation continues long enough that an equilibrium is established and the maximum radius of influence is achieved. For a well with a maximum flow of 300 ft³/min at 120 in. H₂O vacuum, the radius of influence is assumed to be 100 ft (DOE-RL 1991, Appendix F). The radii of influence of the other wells are proportionate to flow.

To achieve the areas of influence shown in the figures simultaneously, the following rates of soil-gas extraction would be required. (Note: intermittent and continuous extraction *flow rates* are the same; the area of influence varies because intermittent operation requires re-establishing of the area of influence.)

216-Z-1A/18 Wellfield	Above the caliche	3,180 ft ³ /min
	Below the caliche	890 ft ³ /min
216-Z-12 Wellfield	Above the caliche	350 ft ³ /min
	Below the caliche	800 ft ³ /min
216-Z-9 Wellfield	Above the caliche	2,340 ft ³ /min
	Below the caliche	1,000 ft ³ /min

The total soil-gas extraction rate that would be required to achieve the areas of influence simultaneously is 8,560 ft³/min. This is far beyond the present extraction capacity of 3,000 ft³/min; however, it is not intended that all the wells be used at once. The wells used at any one time for extraction should be carefully selected so that interference is minimized. This interference is sometimes referred to as "shadowing," which means that the net effect on a zone influenced by two wells at the same time can be nearly zero because the zones of influence in two directions cancel each other.

3.1.1.3 Recommendation. It is recommended that the wellfield design team carefully select the wells and intervals used for extraction operations. The wellfield design team should consider the overall project objectives, the need to minimize area of influence interference, and the expected performance of each well based on characterization testing and past operating conditions.

It is recommended that during FY 1994 the 500 ft³/min system be used for extraction of wells in the 216-Z-12 Wellfield. Baseline monitoring has indicated that this section of the Z-Crib Area contains significant soil vapor contaminant concentrations (Figure 3-3). Extraction operations will help mitigate the migration of the soil vapor plume.

For the long term, it is recommended that additional smaller capacity VES units be considered to allow the existing wellfield to have a greater area of influence. These smaller VES units would allow more flexibility in placement over the wide areal extent of the Z-Crib Area. The extraction capacity per VES unit should be 300 to 500 ft³/min (at 120 in. H₂O vacuum), which would allow the VES units to be purchased "off-the-shelf" and would supply enough extraction capacity to effectively function with one or two wells. Incorporating several of these smaller units would greatly increase the flexibility and extraction capacity of the VES operations and would reduce the length of time until remediation is completed.

3.1.2 Areas of Influence of Modified Wellfield Configuration

3.1.2.1 Problem. The areas of influence depicted in Figures 3-2 through 3-5 indicate that the large areas where carbon tetrachloride is likely to reside (see Figure 3-3) cannot be addressed by the existing wellfield configuration. Modifications need to be made to the existing wellfield to increase the areas of influence.

3.1.2.2 Discussion. A modified wellfield configuration was developed to increase the area of influence of the VES operation. These well modifications (Tables 3-3 and 3-4) include adding perforated intervals to the existing wells and modifying existing perforations. A discussion regarding the selections of the wells and the intervals is included as Appendix E. The resulting modified wellfield configuration is described in Tables 3-5 and 3-6.

The modified areas of influence were approximated based on the same assumptions as described in Section 3.1.1. Figures 3-6, 3-7, 3-8, and 3-9 provide a representation of the coverage of the Z-Crib Area by the modified configuration.

The modified configuration allows overlapping of the areas of influence. This overlapping is necessary to have more than one well access an area of the subsurface, providing a greater opportunity for complete remediation. Overlapping is not the same as the "shadowing" previously discussed. Overlapping is achieved by extracting at different times from two open intervals that are in close proximity, allowing each area of influence to become fully developed. Shadowing occurs during simultaneous extraction from two open intervals in close proximity, resulting in a net canceling effect on the area between the open intervals.

It should be recognized that the areas of influence are shown in two-dimensions and the influence is assumed to extend from the caliche layer to the surface or from the groundwater to the caliche layer. In reality, the areas of influence may vary widely in shape and the vertical influence may be much less than assumed. Therefore, the overlapping shown in the figures may be quite different than will occur with actual site operations. It follows

that the actual areas of influence may not cover the Z-Crib Area as idealized by the figures. Future revisions of this report will address this topic more closely.

To achieve the areas of influence simultaneously as shown in Figures 3-6 through 3-9, the following rates of soil-gas extraction would be required. (Note: Intermittent and continuous extraction *flow rates* are the same; the area of influence varies because intermittent operation requires reestablishing the area of influence.)

216-Z-1A/18 Wellfield	Above the caliche	6,280 ft ³ /min
	Below the caliche	1,080 ft ³ /min
216-Z-12 Wellfield	Above the caliche	2,150 ft ³ /min
	Below the caliche	1,100 ft ³ /min
216-Z-9 Wellfield	Above the caliche	3,390 ft ³ /min
	Below the caliche	1,350 ft ³ /min

The total soil-gas extraction rate that would be required to achieve the areas of influence simultaneously is 15,350 ft³/min. As discussed previously, it is not intended that all the wells be used for extraction at one time; however, it is recommended as a long-range strategy that consideration be given to increasing the total extraction capacity from the present capacity of 3,000 ft³/min.

3.1.2.3 Recommendation. A modified wellfield configuration is recommended for FY 1994. These well modifications are listed in Tables 3-3 and 3-4. The resulting modified wellfield configuration is described in Tables 3-5 and 3-6.

Wells were prioritized for FY 1994 modification activities (Table 3-7). The prioritization of modification activities was based on the following assumptions:

- The primary objective of the ERA is to protect the groundwater from further contamination resulting from the migration of soil vapor from the unsaturated zone to the saturated zone. Therefore, the highest priority was placed on the modification of wells providing access to the area between the caliche layer and the water table.
- An additional objective of the ERA is to minimize the migration of contaminated vapor away from the Z-Crib Area. Therefore, a high priority was placed on modification of wells near the outer boundaries of the known soil vapor plume. In particular, wells in the 216-Z-12 Wellfield were given priority over others because of the relatively high soil vapor concentrations and the few wells with existing open intervals in the subsurface.
- Following protecting the groundwater and minimizing migration of the soil vapor away from the Z Crib Area, emphasis was placed on modification of wells in areas of high soil vapor contaminant concentrations. These modifications provide the ability to

extract more contaminant and to reduce the high-concentration sources from the subsurface.

- Some wells are to be perforated in intervals both above and below the caliche layer. For these wells, it was assumed that both intervals would be perforated while the perforating equipment was set up at the well. Therefore, wells, rather than specific intervals, have been prioritized for modification.
- Five wells in the 216-Z-9 Wellfield may be used for groundwater tracer tests. These wells are 299-W15-5, W15-6, W15-8, W15-9, and W15-84. It is assumed that these wells can be used for soil vapor extraction before and after these tests. Modification activities for these wells will be re-evaluated in the next update to this report.
- Well 299-W18-1 may soon be used for groundwater extraction during the 200-ZP-1 pump-and-treat tests. It is assumed that it may be used for vapor extraction before and after its use for groundwater extraction.
- Well 299-W18-24 is a *Resource Conservation and Recovery Act* (RCRA) well in the 216-Z-12 Wellfield that may be used for vapor extraction but may not be modified. Therefore, it will not be perforated to enhance the extraction of soil vapor. Groundwater samples are collected at this well every three months, so coordination must occur between its uses for soil vapor extraction and groundwater monitoring.

3.2 RECOMMENDATIONS REGARDING SOIL VAPOR EXTRACTION NUMERICAL MODELING

3.2.1 Problem

The volume of soil gas that must be extracted to remove most of the carbon tetrachloride from the unsaturated zone in the Z-Crib Area needs to be estimated. The time required for remediation can then be determined based on the planned equipment capacity.

3.2.2 Discussion

Numerical modeling of the soil vapor extraction process was conducted to estimate the carbon tetrachloride removal rate and provide information regarding the volume of extracted soil gas and the time required for remediation. This information is intended to provide guidance for the remediation efforts.

The numerical modeling was conducted using the HyperVentilate software package developed under a Federal Technology Transfer Act Cooperative Research and Development Agreement between the EPA and Shell Oil Company (EPA 1993). HyperVentilate is based on Johnson et al. (1990). Annotated data printouts

from the HyperVentilate program are provided in Appendix A. The modeling uses specific chemical characteristics of carbon tetrachloride, which are provided in Appendix B.

The complexities of predicting vapor extraction process efficiency are apparent when consideration is given to the many ill-defined or unknown system variables that are inherent to subsurface systems. The influence of airflow on carbon tetrachloride extraction from Z-Crib Area soils is not easily estimated. This is due to the complex interactions that define the vapor phase partitioning of carbon tetrachloride on the Z-Crib Area soils.

Modeling the effects of vapor extraction is also complicated by inconsistent soil inventory data. The inventory of carbon tetrachloride discharged to the Z-Crib Area based on historical records does not appear to match soil and soil-gas samples from this area (WHC 1993b). Records indicate that significantly more carbon tetrachloride was discharged than can be accounted for in the unsaturated zone based on available data. Possible explanations for this include erroneous records, greater evaporation and atmospheric dispersion than assumed, the presence of undetected separate phase carbon tetrachloride in the saturated or unsaturated zone, and/or natural or bio-degradation.

Soil that is saturated with liquid carbon tetrachloride will have an associated equilibrium soil-gas concentration of 120,000 ppm_v at 20 °C. As a rule-of-thumb, for soils saturated with an organic contaminant, standard soil vapor extraction will produce a gas stream containing 1/10 to 1/2 the expected concentration (EPA 1993). Therefore, vapor extraction concentrations greater than 12,000 ppm_v of carbon tetrachloride may indicate that the soil is saturated and a separate carbon tetrachloride phase is probably present near the extraction well.

Soil that is not saturated with carbon tetrachloride will have soil-gas concentrations related to the quantity of contaminant dissolved in the soil moisture and adsorbed to the solid soil matrix. This function (isotherm) can be complex but usually can be fitted empirically to one of several standard forms including linear, freundlich, or langmuir. A linear isotherm was used to determine a vapor phase partitioning coefficient (Appendix C).

This isotherm had the following form:

$$q_e (\mu\text{g/kg}) = 0.73 C_e (\text{ppm}_v). \quad (1)$$

where: q_e = solid phase concentration (mass of contaminant sorbed on soil particles plus mass dissolved in soil moisture per mass of soil)

C_e = vapor phase equilibrium concentration

The maximum soil-gas carbon tetrachloride concentrations found to date in the Z-Crib Area are 30,000 ppm_v at the 216-Z-9 Wellfield and 1,700 ppm_v at the 216-Z-1A/18 Wellfield. Subsurface inventories were calculated using these concentrations, the vapor phase partitioning coefficient, a contaminated depth of 20 m, and a contaminated area of 60,000 m² for the 216-Z-9 Wellfield and 240,000 m² for the combined 216-Z-1A/18 and 216-Z-12 Wellfields. These

calculations predict carbon tetrachloride inventories of 50,000 kg beneath the 216-Z-9 Wellfield surface and 10,000 kg beneath the combined 216-Z-1A/18 and 216-Z-12 Wellfield surface. However, disposal records indicate that 130,000 to 450,000 kg of carbon tetrachloride were discharged to the 216-Z-9 Trench and 440,000 kg were discharged to the 216-Z-1A Tile Field and 216-Z-18 Crib.

The discrepancy between the estimated amount of carbon tetrachloride discharged and the predicted remaining carbon tetrachloride inventory could be accounted for most easily if a separate carbon tetrachloride phase were present beneath each of the disposal sites. The soil-gas concentrations found to date indicate that a separate carbon tetrachloride phase is probably present in the unsaturated zone of the 216-Z-9 Wellfield and is being remediated by vapor extraction operations. If a separate phase is present within the 216-Z-1A/18 Wellfield, it is likely located in a low-permeability lens such as the early Palouse soil and the caliche layer. This has implications for vapor extraction operations because very high recovery rates can be expected from the 216-Z-9 Wellfield until the separate phase is removed. The extracted soil-gas concentrations will then decrease as the adsorbed carbon tetrachloride is removed. If a separate phase is located in a low-permeability lens in the combined 216-Z-1A/18 and 216-Z-12 Wellfields, the extracted soil-gas concentrations can be expected to stay nearly constant for an extended time period.

Extraction of soil gas from a region containing a low-permeability lens adds a diffusional constraint to the mass transfer. Soil gas in the subsurface will flow across the surface of, rather than through, a low-permeability lens such as the caliche layer. During extraction, carbon tetrachloride vapors in the lens must first diffuse through the low permeability lens to the flowing soil gas. As extraction proceeds, the carbon tetrachloride is removed from deeper into the low permeability lens, increasing the diffusional distance and thus decreasing the extraction rate. A dramatic decrease in extraction rate can be expected for operation when the majority of the carbon tetrachloride is present in a low-permeability lens (Figure 3-10). For example, from the time that extraction from the low-permeability lens begins, the extraction rate drops to 10% within 100 days and levels off at 5% within one year. The expected vapor extraction rate at the 216-Z-1A/18 Wellfield is near the flat portion of the curve.

Specific cleanup standards have not been established that determine when remediation is completed. However, for the purpose of modeling, the use of active vapor extraction operations will be necessary only until residual carbon tetrachloride has been reduced to the level at which passive vapor extraction operations are cost effective. As concluded in a separate study, passive vapor extraction becomes cost effective when the equilibrium concentration of carbon tetrachloride in the subsurface is reduced to less than 200 ppm_v. The present equilibrium concentration in the 216-Z-1A/18 Wellfield is in the range of several hundred to 1,000 ppm_v carbon tetrachloride.

Numerical modeling was used to provide an indication of the total volume of soil gas that must be extracted from the combined 216-Z-1A/18 and 216-Z-12 Wellfield and the 216-Z-9 Wellfield for remediation of the carbon

tetrachloride contamination. This modeling was based on the following assumptions:

- The residual inventory of carbon tetrachloride is 225,000 kg in both the 216-Z-9 Wellfield and the combined 216-Z-1A/18 and 216-Z-12 Wellfield.
- The extraction rate will be 1,500 std. ft³/min for 6,000 hours per year at each of the two sites (this represents a 68% total operating efficiency; the present 5-day per week, 8-hour per day operation provides about 24% operating efficiency).
- Extracted soil gas will average 600 ppm_v carbon tetrachloride from the combined 216-Z-1A/18 and 216-Z-12 Wellfield and 30,000 ppm_v carbon tetrachloride from the 216-Z-9 Wellfield.

Using these assumptions, 1.9×10^9 stdft³ of soil gas must be extracted from the combined 216-Z-1A/18 and 216-Z-12 Wellfield over 3.5 years to remove 225,000 kg of carbon tetrachloride. At the present 24% operating efficiency, as opposed to the assumed 68%, the time required for vapor extraction operations to achieve the same level of carbon tetrachloride recovery extends to 10 years.

Similarly, 4.0×10^7 stdft³ of soil gas must be extracted from the 216-Z-9 Wellfield over one month to remove 225,000 kg, assuming the extracted carbon tetrachloride concentration remains near 30,000 ppm_v.

Modeling was performed to predict flow rates from individual extraction wells. The parameters used for this modeling were an air permeability for the soils ranging from 2 to 15 darcy (DOE-RL 1991), a well diameter of 4 in., a radius of influence of 100 ft, and a screened interval of 15 ft. Flow rates predicted for well vacuums ranging from 5 to 120 in. H₂O are listed in Table 3-8.

Flow rates predicted for open intervals ranging from 10 to 20 ft long for a 4-in. diameter well under a vacuum of 120 in. H₂O are listed in Table 3-9. The flow rates given a vacuum of 120 in. H₂O, an open interval 15 ft long, and well diameters ranging from 4 to 8 in. diameter are listed in Table 3-10. These flow rates are used in the following sections to address the wellfield areas of influence.

3.2.3 Recommendations

It is recommended that the 500 ft³/min system be used during FY 1994 for extraction of wells in the 216-Z-12 Wellfield. For the long term, it is recommended that additional vapor extraction capacity be considered for the 216-Z-1A/18 and 216-Z-12 Wellfield in addition to the currently planned 1,500 stdft³/min capacity in this area. As identified in Section 3.1.2, the airflow rate required to impact the entire wellfield is 5,000 stdft³/min at the 216-Z-9 Wellfield and 11,000 stdft³/min at the combined 216-Z-1A/18 and 216-Z-12 Wellfield. Due to the larger contaminated area of the 216-Z-1A/18 and 216-Z-12 Wellfield, additional extraction capacity may be needed to create a wider area of influence using the existing wellfield.

It is also recommended for the long term that further laboratory-scale testing be performed to define the carbon tetrachloride sorption equilibria over a range of concentrations and Z-Crib Area soil types; determine the impacts of soil moisture/humidity on sorption capacity; and determine extraction efficiency as a function of soil type, airflow, and carbon tetrachloride concentration. This information would greatly aid the numerical modeling of the soil vapor extraction process. The modeling is important for determining optimum locations and depths for new wells, expected extraction rates, and duration of operations. This information will facilitate the most effective use of the available equipment.

It is important that the areas influenced by the extraction operations encompass all of the subsurface zones containing carbon tetrachloride contamination. According to Johnson et al. (1990), the area of influence is theoretically a right circular cylinder with the extraction well as the central axis. The magnitude of this influence is affected by many factors including soil porosity, permeability in relation to a source of unobstructed flow (such as the surface), total vacuum created by the extraction process, and duration of continuously applied vacuum. The area of influence is critical because it determines the area from which carbon tetrachloride vapor will be drawn to the well. As the extraction process continues, soil gas is affected farther and farther away from the well until an equilibrium is reached. As an example, the 80-hour soil vapor extraction pilot test performed in the 216-Z-1A Wellfield demonstrated an area of influence of about 100 ft radially from well 299-W18-171 at 10 in. Hg vacuum and a flow of about 300 ft³/min (DOE-RL 1991).

An understanding of the effective areas of influence created by multiple operating extraction intervals is essential for understanding the effective remediation zone in the subsurface. Assuming a right circular cylinder for the shape of the area of influence is acceptable until specific field information is obtained that better describes the shape of the influence. It is critical that better data for definition of the areas of influence be obtained because this information will be used to select locations for new extraction wells.

3.3 RECOMMENDATIONS REGARDING WELLFIELD TESTING

Wellfield testing will provide site-specific data on the characteristics of the Z-Crib Area subsurface. In particular, the characteristics regarding airflow need to be addressed. Understanding and controlling the airflow in the subsurface are essential to the success of the soil vapor extraction operations. The tests described in the following sections are recommended.

3.3.1 Characterization Testing and Characterization Sampling

3.3.1.1 Problem. Information regarding changes in extraction well flow characteristics and changes in VOC concentrations needs to be obtained on a routine basis to aid in understanding the dynamics of the wellfield and to provide information for developing operational enhancement strategies. Currently, this information is not being obtained on a routine basis.

3.3.1.2 Discussion. Characterization testing and characterization sampling are short-term tests that provide a snapshot of the conditions in the subsurface. This information is useful for understanding the operational parameters and directing changes in extraction strategy.

Characterization tests use the VES equipment to extract soil gas from a single open interval while measurements are made of the flow rate, vacuum, and carbon tetrachloride concentration. This is repeated for each open interval that can be reasonably connected to the equipment. Characterization sampling is performed in the same manner, except that the extracted soil gas is analyzed for the full spectrum of constituents. This is important for identification and quantification of unknown compounds, particularly those that may have adverse effects on health or equipment.

Both characterization testing and characterization sampling may be performed without significantly impacting full-scale VES operations by using equipment that measures the flow and vacuum from each discrete open interval and pulls a sample of soil gas for analysis. This may require the use of portable instruments at or near the wellhead before the flows from discrete open intervals are combined.

The results of the characterization testing and sampling will be used to provide insight into the changes in location and concentration of the carbon tetrachloride vapor plumes. The results of previous characterization testing in the 216-Z-1A/18 Wellfield and 216-Z-9 Wellfield are presented in Tables 3-11 and 3-12, respectively.

3.3.1.3 Recommendation. It is recommended that characterization testing and characterization sampling be performed whenever soil gas is first extracted from a well. Characterization tests should then be performed approximately every two weeks for the duration of the soil vapor extraction operations. Characterization sampling should be performed at least monthly for the duration of the soil vapor extraction operations. The performance of these tests is directed by *Design, Operation, and Monitoring of the Vapor Extraction System at the 216-Z-1A Tile Field* (Driggers 1994), which is included in the *FY94 Wellfield Optimization and Site Characterization Task Plan for the Carbon Tetrachloride ERA* (Rohay 1994).

3.3.2 Permeability Testing

3.3.2.1 Problem. The permeability to airflow of the Z-Crib Area soils has not been fully established. This information is necessary for developing an understanding of the areas of influence and will significantly improve the accuracy of the soil vapor extraction numerical modeling process.

3.3.2.2 Discussion. The permeability to airflow of soils is a measure of the ability of vapors to flow through porous media and is perhaps the single most important parameter with respect to the success of soil venting (Pedersen and Curtis 1991). Air permeability less than $1 \times 10^{-10} \text{ cm}^2$ in the soil is considered unfavorable for soil vapor extraction (EPA 1991). For the Z-Crib Area, the air permeability is estimated to be 2.0×10^{-8} to $14.8 \times 10^{-8} \text{ cm}^2$ (2 to 15 darcy), based on testing performed at the 216-Z-1A Tile Field (DOE-RL 1991, Appendix F).

The orientation of zones of higher air permeability in the soil is another factor affecting the extraction of soil vapor. Under active vacuum, soil-gas flow is predominantly horizontal because the horizontal permeability is usually 3 to 10 times greater than vertical permeability.

For the Z-Crib Area, the interbedded horizons of fine-grained silts and sands, which generally have much lower air permeability than the coarse sands and gravels, serve to exaggerate this tendency of horizontal flow. This is an important factor regarding the control of the airflow in the subsurface.

A more detailed discussion of air permeability testing is presented in EPA (1991) and Pedersen and Curtis (1991).

3.3.2.3 Recommendation. It is recommended that an air extraction test be performed to determine the soil air permeability of the unsaturated zone between an extraction well and a pressure monitoring well. Following the test, the soil pressure data should be plotted as pressure decrease versus time. This information should be used for assessing areas of influence and to assist in the soil vapor monitoring.

3.3.3 Tracer Gas Testing

3.3.3.1 Problem. Understanding the transport of soil gas in the subsurface due to induced vacuum and/or naturally induced pressure gradients is necessary for improving the efficiency of soil vapor extraction operations. Empirical measurements of this transport are not presently available in the Z Crib Area.

3.3.3.2 Discussion. A tracer gas can be used to determine the subsurface airflow pathways, rate of transport of carbon tetrachloride vapor, and the areas of influence of the extraction wells. A known quantity of sulfur hexafluoride, a nontoxic inert gas that can be detected at the part per trillion levels, is injected into the subsurface at a known depth. The transport of this tracer is then determined with and without extraction of soil gas from nearby extraction wells by measuring the concentration of the tracer gas at subsurface monitoring ports and in the extracted soil gas. Tracer gas testing is planned for each of the two primary wellfields at some time during the operation of the VES at those sites in FY 1994. Tracer gas testing will be conducted by Washington State University for Westinghouse Hanford Company (WHC) on active extraction wells according to the tracer gas test plan (WHC 1993c) and the FY 1994 wellfield task plan (Rohay 1994).

3.3.3.3 Recommendation. It is recommended that the information gathered from the tracer gas tests be used to define more closely the horizontal radii of influence of extraction wells, the vertical influence, the air permeability, and the soil-gas flow patterns, and to provide qualitative and quantitative information regarding the transport of soil gas due to naturally induced pressure gradients. This information should also be included in the soil vapor extraction numerical modeling.

3.3.4 Downhole Pressure Monitoring

3.3.4.1 Problem. The pressures created in the subsurface need to be monitored to determine the areas of influence of the extraction wells. This is the most direct means of determining the subsurface areas that are being addressed by the soil vapor extraction operations. Currently, downhole pressures are not being monitored in the open intervals throughout the wellfields.

3.3.4.2 Discussion. The areas of influence of the extraction wells can be determined by the measurement of the pressures in the subsurface. The open intervals of the wells are the conduits to the subsurface allowing this monitoring. Pressure transducers placed at the wellheads in sealed wells provide a means of measuring subsurface pressure at the surface.

Both the barometric pressure changes and the induced vacuum will have an effect on the pressure measurements in the soil. It is necessary that the effects of barometric pressure changes be understood for each open interval so that the net effect of the induced vacuum can be calculated. A net induced effect of approximately 1/2 in. of water vacuum is generally considered to be the threshold point at which the subsurface is within the area of influence of the soil vapor extraction process.

3.3.4.3 Recommendation. It is recommended that downhole pressures in each of the open intervals be monitored to collect data on the effects of barometric pressure at the well open intervals and the effects of the induced vacuum created by the VES operations.

During FY 1994, downhole pressures should be monitored on the open intervals of wells in the Z-Crib Area wherever feasible. The monitoring should be collected using pressure transducers and recorded on data loggers; the data should be provided to the wellfield design team on a routine basis for analysis. This monitoring will provide a specific measure of the areas of influence created by the VES operations.

3.3.5 Vapor Extraction Efficiency Study

3.3.5.1 Problem. The total amount of soil gas that must be removed from the subsurface and the time it takes to remove carbon tetrachloride from the various Z-Crib Area soils are presently gross estimates. Obtaining empirical information will significantly improve the accuracy of these important parameters.

3.3.5.2 Discussion. Wellfield and laboratory testing (as detailed in Appendix C) that defines the carbon tetrachloride sorption equilibrium over a range of concentrations and Z-Crib Area soil types would provide data for (1) determining the impact of soil moisture/humidity on sorption capacity, (2) determining the extraction efficiency as a function of soil type, airflow, and carbon tetrachloride concentration, (3) defining the effects of a lower permeability layer on extraction efficiency, (4) defining the field capacity of Hanford Site soils, (5) defining liquid, soil, and gas phase equilibrium, and (6) providing information for better carbon tetrachloride inventory estimates. This information would substantially aid the numerical modeling of

the soil vapor extraction process and would provide empirical information regarding projected cleanup times and total volume of air removal required.

3.3.5.3 Recommendation. It is recommended for the long term that wellfield and laboratory-scale testing, which define the carbon tetrachloride sorption equilibrium over a range of concentrations and Z-Crib Area soil types, be performed.

3.4 RECOMMENDATIONS REGARDING EXTRACTION STRATEGIES

This section describes some of the overall strategies for vapor extraction operations from the various parts of the Z-Crib Area. A general discussion of vapor extraction strategies is presented in Appendix D.

Specific wells to be used for extraction are not addressed in this section. The selection of potential well locations and extraction rates is determined using multiple factors that can vary significantly between the planned 6-month updates to this report. For this reason, it is strongly recommended that characterization testing be performed every 2 weeks and characterization sampling be performed every month during periods of full-scale extraction operations. The results of the testing should be communicated to the wellfield design team for decisions regarding necessary changes to the extraction parameters and extraction locations.

An understanding of the nature of soil vapor extraction operations, subsurface vapor flow, and full characterization of the extracted soil gas is essential for safe and continuing operations of the VES. It is necessary that operating parameters be frequently measured during all extraction operations, and the characterization of the soil gas from all the wells is an essential element in gaining an understanding of the flow and contaminant characteristics of the site. This information will lead to improved long-term operations and enhanced extraction of carbon tetrachloride.

3.4.1 Recommendations for Extraction from the 216-Z-1A/18 Wellfield

3.4.1.1 Operational Data Summary. Operation of the VES on nine wells at the 216-Z-1A Tile Field has produced extracted soil vapor concentrations generally ranging from 100 to 800 ppm_v carbon tetrachloride. The typical extraction flow rates range from 20 to 300 ft³/min per extraction well. The extracted soil vapor concentrations from two wells in the 216-Z-18 Crib have been a few hundred ppm_v carbon tetrachloride. Characterization testing data from June 1993 are presented in Table 3-11. The extent of the horizontal influence of the vacuum placed upon each of the extraction wells is in the range of 100 ft, established during the pilot testing of the VES (DOE-RL 1991, Appendix F).

The VES that has operated at the 216-Z-1A/18 Wellfield recorded 33 separate data points including temperatures, pressures, flow rates, humidity, carbon tetrachloride concentrations, alpha and beta radiation, and radon concentrations. However, most of the carbon tetrachloride concentration data logged by the data acquisition system are suspect due to a lack of instrument signal conditioning.

Generally, the soil vapor extraction operation in the 216-Z-1A/18 Wellfield has been rather predictable. The concentrations of carbon tetrachloride in the extracted soil gas have typically fallen from 500-1000 ppm_v to 200-500 ppm_v over several months of intermittent operation. Future revisions of this report will more closely address the operational experience and data.

3.4.1.2 Recommendations. Because the carbon tetrachloride plume appears to be of roughly the same magnitude throughout the 216-Z-1A/18 Wellfield, there are no specific plumes that must be kept intact. It is recommended that the full capacity of the extraction equipment be used to address the greatest possible volume of subsurface soil gas, including the low-permeability lenses. It is recommended that flow across the zones of low permeability be established to begin the removal of carbon tetrachloride from these lenses. The concentration of carbon tetrachloride removed from these lenses will be significantly lower than from other regions of the subsurface; however, delaying this removal will ultimately extend the overall length of the remediation effort. The removal of the carbon tetrachloride from the zones of low permeability will become a diffusion-rate limited process taking much longer than the removal of carbon tetrachloride from the highly permeable zones.

As vapor extraction operations proceed, carbon tetrachloride concentrations in the area will be reduced. Eventually, specific zones in the subsurface may require individual attention to complete removal of the carbon tetrachloride. Further investigation and analysis will determine the usefulness and applicability of air injection wells and the potential benefits of pneumatic fracturing for the low-permeability zones.

Extraction below the caliche is recommended to address the unsaturated soils near the groundwater, thus reducing the migration of carbon tetrachloride vapor to the groundwater.

It is recommended that future operational data be recorded and presented in a form that facilitates trend analyses and indicates expected operating parameters.

It is anticipated that the VES system will be used at full flow or vacuum capacity (1,000 ft³/min at 10 in. Hg) for the duration of the remedial activities in the 216-Z-1A/18 Wellfield.

3.4.2 Recommendations for Extraction from the 216-Z-12 Crib Area

3.4.2.1 Operational Data Summary. A vapor extraction system has not been operated at the 216-Z-12 Wellfield.

3.4.2.2 Recommendations. Characterization testing and characterization sampling of the extraction wells in the 216-Z-12 Crib area should be performed prior to full-scale VES operations. This testing will provide an indication of equilibrium concentrations at the open intervals in the subsurface and will also provide information for optimizing the removal of carbon tetrachloride from the subsurface through definition of extraction locations and flow rates.

It is assumed that the VES that will operate at the 216-Z-12 Crib area will have an extraction capability of 500 ft³/min at 10 in. Hg vacuum.

3.4.3 Recommendations for Extraction from the 216-Z-9 Trench Area

3.4.3.1 Operational Data Summary. Full-scale extraction operations have not been performed in the 216-Z-9 Wellfield. However, characterization testing was conducted at several wells in spring 1993. As shown in Table 3-12, the concentrations of carbon tetrachloride in the extracted soil vapor from wells in the 216-Z-9 Wellfield range from 77 to 28,500 ppm_v. In approximately 50 hours of characterization testing, more than 1,500 lb of carbon tetrachloride has been removed from the subsurface in this area, an average of about 30 lb/hr.

3.4.3.2 Recommendations. Information is yet to be gained that will aid in the selection of potential extraction wells because the VES has not yet operated in a full-production mode at the 216-Z-9 Trench. The initial characterization tests have clearly demonstrated that the carbon tetrachloride concentrations at this site far exceed those found anywhere else in the Z-Crib Area. This offers the greatest potential for removal of carbon tetrachloride from the subsurface relative to the amount of soil gas extracted.

The high concentrations of carbon tetrachloride are expected to diminish rapidly when full-scale VES operations begin. Based on 30,000 ppm_v carbon tetrachloride (the approximate maximum value measured during extraction operation at this site) extracted 24 hours per day at 1,500 ft³/min, all of the carbon tetrachloride known to have been discharged to the 216-Z-9 Trench would be extracted in less than 40 days. However, due to the nature of the soil-gas movement, site logistics, and contaminant behavior, it is probable that the extracted vapor concentration will drop relatively rapidly (over a period of several days or weeks) to a level where actual removal of the residual carbon tetrachloride from the site will take several years.

It is recommended that extraction operations be performed to remove the greatest mass of carbon tetrachloride from the subsurface while keeping the high concentration plume intact. This entails pulling from only those wells that are very high in carbon tetrachloride concentration, even if they provide relatively low flow. Once the plume is pulled apart, it will take more extracted soil gas to remove the same volume of carbon tetrachloride. The best strategy is to keep the high concentration plume together and extract soil gas until the plume diminishes to concentrations in the range of the outlying wells.

A reduction in extracted vapor concentration does not automatically translate to a significant reduction in the residual carbon tetrachloride concentration. At high flow rates past the residual contamination in the subsurface; the vapor concentration will quickly diminish because of the diffusion limitations previously discussed. Frequent characterization tests targeted at gaining an understanding of the equilibrium concentrations in the subsurface over time should be performed. This is important because of the need to keep the high concentration contaminant plume intact for extraction.

As the high concentration contaminant plume is diminished, a broader array of wells in the 216-Z-9 Trench area can be utilized for extraction. Further investigation and analysis will determine the usefulness and applicability of air injection wells and the potential benefits of pneumatic fracturing. It is anticipated that as the number of extraction wells increases, the use of the system at full capacity of 1,500 ft³/min at 10 in. Hg vacuum will be realized.

3.4.4 Extraction Enhancement Strategies

Several strategies have been developed to enhance the soil vapor extraction process. These strategies are described in detail in the following sections.

3.4.4.1 Pulsed Versus Continuous Pumping. When the VOC concentration in the soil gas has been reduced significantly from its initial concentration, the remedial process generally becomes diffusion rate limited. According to Hutzler et al. (1991), several studies have indicated that intermittent venting (i.e., periodic pumping or pulsed pumping) from individual wells is probably more efficient in terms of mass VOC extracted per unit of energy expended. This is especially true when extracting from soils where mass transfer is limited by the rate at which chemicals diffuse out of immobile air and water. Optimal operation of a VES may involve using extraction wells for short time periods to allow for liquid and gas diffusion and to change airflow patterns in the subsurface region that is targeted. However, in work performed by Armstrong and Frind (1992), pulse pumping appeared no more effective than continuous pumping.

It has not yet been determined whether pulsed or continuous pumping will be the most cost-effective mechanism for removing VOC in the Z-Crib Area. Testing may be necessary to make a decision. A further investigation of these extraction approaches is recommended for the long term.

3.4.4.2 Pneumatic Fracturing. Hasbach (1993) reports on an emerging technology that may improve the effectiveness of soil vapor extraction in regions of low permeability through the use of pneumatic fracturing extraction (PFE). The PFE technology involves injecting high-pressure air into the ground at controlled pressure and flow rates to fracture and/or aerate the contaminated zones. For the particular site discussed, an increase of greater than 700% VOC removal was achieved through the use of PFE technology. Prefracture airflow compared to postfracture results showed that airflow increased from 0.5 ft³/min to 75 ft³/min.

In the Z-Crib Area, silty lenses and the caliche layer are regions of low permeability where remedial activities may benefit from PFE. It is recommended that further investigation into this technology be performed for its potential application to the low-permeability lenses at the Z Crib Area for the long term.

3.4.4.3 Air Injection. Controlling airflow in the subsurface is essential to the success of a vapor extraction project. Performing air injection allows some control of the airflow pathways so that certain subsurface regions can be

targeted. Air injection also provides a mechanism for increasing the total flow within the subsurface to sweep away the contaminants more efficiently.

Air injection involves injecting air into one or more open intervals while simultaneously extracting from one or more open intervals. Air injection is typically performed in one of three ways: (1) the air is forced into the open interval with a blower, (2) the air is allowed to flow in naturally without the aid of a blower, and (3) the air is heated and forced into the open interval where the higher temperature can increase the volatilization of the VOC.

Careful planning and execution are necessary for air injection to produce the desired results. If performed improperly, air injection can be detrimental to the goal of remediation of a site. As pointed out by Rainwater et al. (1988), air injection has been used to induce airflow and enhance evaporation of volatile liquids from porous media, but it is possible that the air pressure gradients could induce flow away from the extraction points.

It is recommended that further investigations be performed and consideration be given to the applicability and predicted effectiveness of air injection for the long-term remediation of the Z-Crib Area.

3.4.4.4 Surface Seals. Seals such as plastic, asphalt, or clay may be placed over the soil surface to impede air flow. Surface seals such as these have been used in conjunction with vapor extraction operations to reduce the short-circuiting of the airflow pathway from the surface to the open interval in the subsurface. This effectively enlarges the radius of influence of each open interval, improving the performance of the extraction system.

In the Z-Crib Area, most of the extraction is performed from 60 to 200 ft below the surface. This may be too deep for surface seals to exhibit a noticeable effect. According to Pedersen and Curtis (1991) and Johnson et al. (1990), the effects of a surface seal are reduced when the open interval is greater than 25 ft below the surface.

A different purpose may also be served by surface seals. The loss of carbon tetrachloride to the atmosphere from the surface of the Z-Crib Area (WHC 1993b) may become recognized as an exposure pathway of concern. Surface seals may be used to reduce this atmospheric loss, if necessary.

Figure 3-1. Z-Crib Area Wells.

Figure 3-3. Areas of Influence in Wells with Open Intervals Above Caliche--Existing Configuration (Continuous Operation).

ABOVE-EX.DWG revised on 3/8/94 by RMMS

Figure 3-4. Areas of Influence in Wells with Open Intervals Below Caliche--Existing Configuration (Intermittent Operation).

BELOW-EX.DWG revised on 3/5/94 by RMMS

Figure 3-5. Areas of Influence in Wells with Open Intervals Below Caliche--Existing Configuration (Continuous Operation).

BELOW-EX.DWG revised on 3/8/94 by RMMS

Figure 3-6. Areas of Influence in Wells with Open Intervals Above Caliche--Modified Configuration (Intermittent Operation).

ABOVE-MODWG revised on 3/13/94 by RWMS

Figure 3-8. Areas of Influence in Wells with Open Intervals
Below Caliche--Modified Configuration (Intermittent Operation).

BELOW-MO.DWG revised on 3/13/94 by RMMS

Figure 3-9. Areas of Influence in Wells with Open Intervals Below Caliche--Modified Configuration (Continuous Operation).

BELOW-MO.DWG revised on 3/13/94 by RMMS

Figure 3-10. Vapor Extraction From a Low-Permeability Lens.

Table 3-1. Z-Crib Area Wells With Open Intervals Above the Caliche (Existing Configuration). (Sheet 1 of 4)

Well	Open interval (ft below toc)	Casing diameter (in.)	Piezometer diameter (in.)	Maximum flow (ft ³ /min)
216-Z-1A/18 TILE FIELD				
299-W18-87	A 33-38 B 65-70 C 125-130	6	1.5 1.5 1.5	120 (combined) ^a
299-W18-93	63-77	6	6	100 ^b
299-W18-94	68-78	6	6	150 ^b
299-W18-96	122-132 bgs	2	2	100 ^b
299-W18-97	63-75	6	6	300 ^a
299-W18-98	66-77	6	6	100 ^b
299-W18-99	93-103	6	6	90 ^b
299-W18-150	A 65-70 B 85-90 C 113-118	6	1.5 1.5 1.5	32 ^a 28 ^a 84 ^a
299-W18-158	A 75-80 B 89-94 C 119-124	6	1.5 1.5 1.5	40 ^a 40 ^a Leak
299-W18-159	113-120	6	6	70 ^a
299-W18-163	A 69.5-79.5 B 92.5-99.5 C 114.5-119.5	6	1.5 1.5 1.5	11 ^a 10 ^a 8 ^a
299-W18-165	122-127	6	6	40 ^b

Table 3-1. Z-Crib Area Wells With Open Intervals Above the Caliche
(Existing Configuration). (Sheet 2 of 4)

Well	Open interval (ft below toc)	Casing diameter (in.)	Piezometer diameter (in.)	Maximum flow (ft ³ /min)
216-Z-1A/18 TILE FIELD (cont.)				
299-W18-166	124-129	6	6	16 ^a
299-W18-167	114-119	8	8	40 ^b
299-W18-168	118-123	8	8	30 ^a
299-W18-171	A 20-25 B 57-77 C 115-130	8	2 2 2	300(combined) ^a
299-W18-174	106-126 bgs	4	4	300 ^b
299-W18-175	A 87-94 B 115-120	6	6 6	90 (combined) ^a
299-W18-246	A 120-130 bgs	4	2	200 ^b
299-W18-247	A 119-129 bgs	4	2	200 ^b
299-W18-248	123-139 bgs	4	4	250 ^b
299-W18-249	122-137 bgs	4	4	300 ^b
CPT-2	34-37 bgs	1	1	70 ^b
CPT-20	71-84 bgs	1	1	60 ^b

Table 3-1. Z-Crib Area Wells With Open Intervals Above the Caliche
(Existing Configuration). (Sheet 3 of 4)

Well	Open interval (ft below toc)	Casing diameter (in.)	Piezometer diameter (in.)	Maximum flow (ft ³ /min)
216-Z-12 CRIB				
299-W18-252	A 113-133 bgs	4	2	250 ^b
CPT-4	90-103 bgs	1	1	50 ^b
CPT-10	94-107 bgs	1	1	50 ^b

Table 3-1. Z-Crib Area Wells With Open Intervals Above the Caliche (Existing Configuration). (Sheet 4 of 4)

Well	Open interval (ft below toc)	Casing diameter (in.)	Piezometer diameter (in.)	Maximum flow (ft ³ /min)
216-Z-9 TRENCH				
299-W15-82	73-88 bgs	8	8	250 ^a
299-W15-84	75-90 bgs	8	8	75 ^a
299-W15-85	83-98 bgs	8	8	75 ^a
299-W15-95	83-98 bgs	8	8	80 ^b
299-W15-216	A 70-80 bgs	4	2	150 ^a
299-W15-217	106-121 bgs	4	4	170 ^a
299-W15-218	A 99-114 bgs	4	2	250 ^b
299-W15-219	A 87-102 bgs	4	2	250 ^b
299-W15-220	A 80-95 bgs	4	2	250 ^b
299-W15-223 ^c	103-117 (vertical)	3.5	3.5	250 ^b
CPT-3	39-52 bgs	1	1	170 ^b
CPT-5	35-48 bgs	1	1	70 ^b
CPT-8	100-113 bgs	1	1	50 ^b
CPT-11	64-77 bgs	1	1	60 ^b
CPT-12	36-49 bgs	1	1	70 ^a
CPT-19	36-49 bgs	1	1	70 ^b
CPT-21	84-97 bgs	1	1	50 ^b

^a measured value^b estimated value^c Well 299-W15-223 is a 45° angle well and the length of the screened interval is 20 ft

toc = top of casing

bgs = below ground surface

Table 3-2. Z-Crib Area Wells With Open Intervals Below the Caliche
(Existing Configuration). (Sheet 1 of 2)

Well	Open interval (ft below toc)	Casing diameter (in.)	Piezometer diameter (in.)	Maximum flow (ft ³ /min)
216-Z-1A/18 TILE FIELD				
299-W18-6	190-201	8	8	150 ^b
299-W18-7	190-203	8	8	150 ^b
299-W18-9	180-211	6	6	100 ^b
299-W18-10	180-211	6	6	80 ^a
299-W18-11	180-211	6	6	100 ^b
299-W18-12	190-211	6	6	80 ^b
299-W18-246	165-175 bgs	4	2	150 ^b
299-W18-247	162-172 bgs	4	2	80 ^b
216-Z-12 CRIB				
299-W18-1	195-200	8	8	150 ^b
299-W18-2	200-208	8	8	100 ^b
299-W18-4	200-211	8	8	100 ^b
299-W18-5	195-211	8	8	150 ^b
299-W18-24	205-213	4	4	100 ^b
299-W18-252	165-185 bgs	4	2	200 ^b

Table 3-2. Z-Crib Area Wells With Open Intervals Below the Caliche
(Existing Configuration). (Sheet 2 of 2)

Well	Open interval (ft below toc)	Casing diameter (in.)	Piezometer diameter (in.)	Maximum flow (ft ³ /min)
216-Z-9 TRENCH				
299-W15-5	173-217	8	8	150 ^b
299-W15-6	175-190	6	6	150 ^b
299-W15-9	186-189	8	8	100 ^b
299-W15-216	175-185 bgs	4	2	150 ^a
299-W15-218	180-195 bgs	4	2	150 ^b
299-W15-219	167-182 bgs	4	2	150 ^b
299-W15-220	155-170 bgs	4	2	150 ^b

^a measured value
^b estimated value
 toc = top of casing
 bgs = below ground surface

Table 3-3. Wells to be Modified for Extraction Above the Caliche. (Sheet 1 of 2)

Well	Casing diameter (in.)	Present open interval (ft below toc)	Perforate (ft below toc)	Modified open interval (ft below toc)	Present Flow (ft ³ /min)	Modified Flow (ft ³ /min)
216-Z-1A/18 TILE FIELD						
299-W18-6	8	None	100-130	100-130	NA	200 ^b
299-W18-10	6	None	100-130	100-130	NA	300 ^b
299-W18-11	6	None	100-130	100-130	NA	300 ^b
299-W18-89	6	None	100-130	100-130	NA	300 ^b
299-W18-158	6	A 75-80 B 89-94 C 119-124	80-89	A 70-94 B 119-124	40 ^a 40 ^a Leak	150 ^b 40 ^a
299-W18-159	6	113-120	90-113	90-120	70 ^a	300 ^b
299-W18-163	6	A 69.5-79.5 B 92.5-99.5 C 114.5-119.5	54.5-79.5 92.5-119.5	A 54.5-79.5 B 92.5-119.5	11 ^a 18 ^a	300 ^b 300 ^b
299-W18-165	6	122-127	97-122	97-127	40 ^b	300 ^b
299-W18-166	6	124-129	99-124	99-129	16 ^a	300 ^b
299-W18-167	8	114-119	89-114	89-119	40 ^b	300 ^b
299-W18-169	8	None	102-132	102-132	NA	300 ^b

Table 3-3. Wells to be Modified for Extraction Above the Caliche. (Sheet 2 of 2)

Well	Casing diameter (in.)	Present open interval (ft below toc)	Perforate (ft below toc)	Modified open interval (ft below toc)	Present Flow (ft ³ /min)	Modified Flow (ft ³ /min)
216-Z-12 CRIB						
299-W18-1	8	None	100-130	100-130	NA	300 ^b
299-W18-2	8	None	100-130	100-130	NA	300 ^b
299-W18-4	8	None	100-130	100-130	NA	300 ^b
299-W18-152	8	None	88-118	88-118	NA	300 ^b
299-W18-153	8	None	80-110	80-110	NA	300 ^b
299-W18-157	8	None	80-110	80-110	NA	300 ^b
216-Z-9 TRENCH						
299-W15-6	6	None	75-100	75-100	NA	200 ^b
299-W15-8	8	None	90-115	90-115	NA	200 ^b
299-W15-9	8	None	90-115	90-115	NA	200 ^b
299-W15-84	8	75-90 bgs	90-100 bgs	75-100 bgs	75 ^a	200 ^b
299-W15-86	8	None	110-140	110-140	NA	250 ^b
299-W15-95	8	83-98 bgs	73-83 bgs	73-98 bgs	80 ^b	250 ^b

^a measured value

^b estimated value

toc = top of casing

bgs = below ground surface

Table 3-4. Wells to be Modified for Extraction Below the Caliche.

Well	Casing diameter (in.)	Present open interval (ft below toc)	Perforate (ft below toc)	Modified open interval (ft below toc)	Present Flow (ft ³ /min)	Modified Flow (ft ³ /min)
216-Z-1A/18 TILE FIELD						
299-W18-7	8	190-203	180-190	180-203	150 ^b	250 ^b
299-W18-10	6	180-211	170-180	170-211	80 ^a	150 ^b
299-W18-12	6	190-211	180-190	180-211	80 ^b	100 ^b
216-Z-12 CRIB						
299-W18-1	8	195-200	175-195	175-200	150 ^b	200 ^b
299-W18-2	8	200-208	183-200	183-208	100 ^b	200 ^b
299-W18-4	8	200-211	186-200	186-211	100 ^b	200 ^b
299-W18-5	8	195-211	186-195	186-211	150 ^b	200 ^b
216-Z-9 TRENCH						
299-W15-6	6	175-190	160-190	160-190	150 ^b	200 ^b
299-W15-8	8	None	167-197	167-197	NA	200 ^b
299-W15-9	8	186-189	164-186	164-189	100 ^b	200 ^b

^a measured value^b estimated value

toc = top of casing

bgs = below ground surface

Table 3-5. Z-Crib Area Wells With Open Intervals Above the Caliche
(Modified Configuration). (Sheet 1 of 5)

Well	Open interval (ft below toc)	Casing diameter (in.)	Piezometer diameter (in.)	Maximum flow (ft ³ /min)
216-Z-1A/18 TILE FIELD				
299-W18-6	A 100-130	8	2	200 ^b
299-W18-10	A 100-130	6	2	300 ^b
299-W18-11	A 100-130	6	2	300 ^b
299-W18-87	A 33-38 B 65-70 C 125-130	6	1.5 1.5 1.5	120 (combined) ^a
299-W18-89	100-130	6	6	300 ^b
299-W18-93	130-140	6	6	100 ^b
299-W18-94	103-118	6	6	150 ^b
299-W18-96	122-132 bgs	6	6	100 ^b
299-W18-97	60-72	6	6	300 ^a
299-W18-98	68-78	6	6	100 ^b
299-W18-99	90-100	6	6	90 ^b
299-W18-150	(A) 65-90 (B) 113-118	6	1.5 1.5	32 ^a 84 ^a
299-W18-158	(A) 75-94 (B) 119-124	6	1.5 1.5	200 ^a Leak
299-W18-159	90-120	6	6	300 ^b
299-W18-163	A 54.5-79.5 B 92.5-119.5	6	1.5 1.5	300 ^b 300 ^b

Table 3-5. Z-Crib Area Wells With Open Intervals Above the Caliche
(Modified Configuration). (Sheet 2 of 5)

Well	Open interval (ft below toc)	Casing diameter (in.)	Piezometer diameter (in.)	Maximum flow (ft ³ /min)
216-Z-1A/18 TILE FIELD (cont.)				
299-W18-165	97-127	6	6	300 ^b
299-W18-166	99-129	6	6	300 ^b
299-W18-167	89-119	8	8	300 ^b
299-W18-168	118-123	8	8	30 ^a
299-W18-169	102-132	8	8	300 ^b
299-W18-171	A 20-25 B 57-77 C 115-130	8	2 2 2	300 (combined) ^a
299-W18-174	106-126 bgs	4	4	300 ^b
299-W18-175	A 87-94 B 115-120	6	6 6	90 (combined) ^a
299-W18-246	A 120-130 bgs	4	2	200 ^b
299-W18-247	A 119-129 bgs	4	2	200 ^b
299-W18-248	123-139 bgs	4	4	250 ^b
299-W18-249	122-137 bgs	4	4	300 ^b
CPT-2	34-47 bgs	1	1	70 ^b
CPT-20	71-84 bgs	1	1	60 ^b

Table 3-5. Z-Crib Area Wells With Open Intervals Above the Caliche
(Modified Configuration). (Sheet 3 of 5)

Well	Open interval (ft below toc)	Casing diameter (in.)	Piezometer diameter (in.)	Maximum flow (ft ³ /min)
216-Z-12 CRIB				
299-W18-1	A 100-130	8	2	300 ^b
299-W18-2	A 100-130	8	2	300 ^b
299-W18-4	A 100-130	8	2	300 ^b
299-W18-152	88-118	8	8	300 ^b
299-W18-153	80-110	8	8	300 ^b
299-W18-157	80-110	8	8	300 ^b
299-W18-252	A 113-133 bgs	4	2	250 ^b
CPT-4	90-103 bgs	1	1	50 ^b
CPT-10	94-107 bgs	1	1	50 ^b

Table 3-5. Z-Crib Area Wells With Open Intervals Above the Caliche
(Modified Configuration). (Sheet 4 of 5)

Well	Open interval (ft below toc)	Casing diameter (in.)	Piezometer diameter (in.)	Maximum flow (ft ³ /min)
216-Z-9 TRENCH				
299-W15-6	A 75-100	6	2	200 ^b
299-W15-8	A 90-115	8	2	200 ^b
299-W15-9	A 90-115	8	2	200 ^b
299-W15-82	73-88 bgs	8	8	250 ^a
299-W15-84	75-100 bgs	8	8	200 ^b
299-W15-85	83-98 bgs	8	8	75 ^a
299-W15-86	110-140	8	8	250 ^b
299-W15-95	73-98 bgs	8	8	250 ^b
299-W15-216	A 70-80 bgs	4	2	150 ^a
299-W15-217	106-121 bgs	4	4	70 ^a
299-W15-218	A 99-114 bgs	4	2	250 ^b
299-W15-219	A 87-102 bgs	4	2	250 ^b
299-W15-220	A 80-95 bgs	4	2	250 ^b

Table 3-5. Z-Crib Area Wells With Open Intervals Above the Caliche
(Modified Configuration). (Sheet 5 of 5)

Well	Open interval (ft below toc)	Casing diameter (in.)	Piezometer diameter (in.)	Maximum flow (ft ³ /min)
216-Z-9 TRENCH (cont.)				
299-W15-223 ^c	103-117 bgs	3.5	3.5	250 ^b
CPT-3	39-52 bgs	1	1	170 ^b
CPT-5	35-48 bgs	1	1	70 ^b
CPT-8	100-113 bgs	1	1	50 ^b
CPT-11	64-77 bgs	1	1	60 ^b
CPT-12	36-49 bgs	1	1	70 ^a
CPT-19	36-49 bgs	1	1	70 ^b
CPT-21	84-97 bgs	1	1	50 ^b

^a measured value^b estimated value^c Well 299-W15-223 is a 45° angle well and the length of screened interval is 20 ft.

toc = top of casing

bgs = below ground surface

Table 3-6. Z-Crib Area Wells With Open Intervals Below the Caliche
(Modified Configuration). (Sheet 1 of 2)

Well	Open interval (ft below toc)	Casing diameter (in.)	Piezometer diameter (in.)	Maximum flow (ft ³ /min)
216-Z-1A/18 TILE FIELD				
299-W18-6	B 190-201	8	2	150 ^b
299-W18-7	180-203	8	8	250 ^b
299-W18-9	180-211	6	6	100 ^b
299-W18-10	B 170-211	6	2	150 ^b
299-W18-11	B 180-211	6	2	100 ^b
299-W18-12	180-211	6	6	100 ^b
299-W18-246	B 165-175 bgs	4	2	150 ^b
299-W18-247	B 162-172 bgs	4	2	80 ^b
216-Z-12 CRIB				
299-W18-1	B 175-200	8	2	200 ^b
299-W18-2	B 183-208	8	2	200 ^b
299-W18-4	B 186-211	8	2	200 ^b
299-W18-5	186-211	8	8	200 ^b
299-W18-24	205-213	4	4	100 ^b
299-W18-252	165-185 bgs	4	2	200 ^b

Table 3-6. Z-Crib Area Wells With Open Intervals Below the Caliche
(Modified Configuration). (Sheet 2 of 2)

Well	Open interval (ft below toc)	Casing diameter (in.)	Piezometer diameter (in.)	Maximum flow (ft ³ /min)
216-Z-9 TRENCH				
299-W15-5	173-217	8	8	150 ^b
299-W15-6	B 160-190	6	2	200 ^b
299-W15-8	B 167-197	8	2	200 ^b
299-W15-9	B 164-189	8	2	200 ^b
299-W15-216	B 175-185 bgs	4	2	150 ^a
299-W15-218	B 180-195 bgs	4	2	150 ^b
299-W15-219	B 167-182 bgs	4	2	150 ^b
299-W15-220	B 155-170 bgs	4	2	150 ^b

^a measured value^b estimated value

toc = top of casing

bgs = below ground surface

Table 3-7. Prioritization of Well Modification Activities.

Well Prioritization	Well Identification	Perforation Above Caliche (ft below toc)	Perforation Below Caliche (ft below toc)
1	299-W18-4	100-130	186-200
2	299-W18-5		186-195
3	299-W18-2	100-130	183-200
4	299-W18-7		180-190
5	299-W18-12		180-190
6	299-W18-10	100-130	170-180
7	299-W18-152	88-118	
8	299-W18-89	100-130	
9	299-W18-11	100-130	
10	299-W18-157	80-110	
11	299-W18-153	80-110	
12	299-W15-95	73-83 bgs	
13	299-W15-84	90-100 bgs	
14	299-W15-86	110-140 bgs	
15	299-W18-169	96-126	
16	299-W18-167	89-114	
17	299-W18-166	99-124	
18	299-W18-165	97-122	
19	299-W18-6	100-130	
20	299-W18-158	80-89	
21	299-W18-159	90-113	
22	299-W18-163	54.5-79.5 92.5-119.5	
23	299-W15-6	75-100	160-190
24	299-W15-8	90-115	167-197
25	299-W15-9	90-115	164-186
26	299-W18-1	100-130	185-195

toc = top of casing
bgs = below ground surface

Table 3-8. Predicted Flow Rates for Various Well Vacuums.

Well Vacuum in. H ₂ O	Flow Rate in a Single Well (stdft ³ /min)	
	2 darcy	15 darcy
5	1.3	9.7
10	2.6	19.3
20	5.1	38.0
40	9.9	74.1
60	14.4	108.3
100	22.8	171.0
120	26.6	199.4

Table 3-9. Predicted Flow Rates for Various Well Open Interval Lengths in a 4-in. Diameter Well (Vacuum at 120 in. H₂O).

Open Interval Length (ft)	Flow Rate from Single Well (stdft ³ /min)	
	2 darcy Permeability	15 darcy Permeability
10	17.7	132.9
15	26.6	199.4
20	35.4	265.8

Table 3-10. Predicted Flow Rates for Various Well Diameters With a 15-ft-long Open Interval (Vacuum at 120 in. H₂O).

Well Diameter (in.)	Flow Rate from Single Well (stdft ³ /min)	
	2 darcy Permeability	15 darcy Permeability
4	26.6	199.4
6	28.4	212.9
8	29.8	223.6

Table 3-11. Results of 216-Z-1A/18 Tile Field Characterization Tests.

DATE	WELL INTERVAL	VACUUM (in. H ₂ O)	FLOW (stdft ³ /min)	CCl ₄ CONCENTRATION (ppm _v)	CCl ₄ lb/hr
06/01/93	299-W18-175	132	68	475	0.83
06/01/93	299-W18-150 A ^(a)	131	32	33	0.03
06/01/93	299-W18-150 B ^(b)	132	28	219/157 ^(d)	0.16/0.11
06/01/93	299-W18-150 C ^(c)	132	84	215	0.46
06/01/93	299-W18-166	130	16	5/82	0.002/0.03
06/01/93	299-W18-158 A	31	64 leak	2	0.003
06/01/93	299-W18-158 B	131	40	86	0.09
06/01/93	299-W18-158 C	131	40	108/144 ^(d)	0.11/0.15
06/01/93	299-W18-159	132	72	298	0.55
06/01/93	299-W18-168	139	27	131/212 ^(d)	0.09/0.15
06/01/93	299-W18-163 A	141	11	2	0.0005
06/01/93	299-W18-163 B	130	10	2	0.0005
06/01/93	299-W18-163 C	124	8	5	0.001
06/01/93	299-W18-87 C	130	120	75	0.23
06/01/93	299-W18-171 C	130	296	325	2.5
06/01/93	299-W18-97	134	312	23	0.18
06/01/93	299-W18-10	130	80	147/221 ^(d)	0.30/0.45

(a) Upper interval

(b) Middle interval

(c) Lower interval

(d) Dual concentration values denote measurements taken at two different times during testing.

Table 3-12. Results of 216-Z-9 Trench Characterization Testing.
(based on average of measured values recorded in logbook)

DATE	WELL INTERVAL	VACUUM (in. H ₂ O)	FLOW (stdft ³ /min)	CCl ₄ CONCENTRATION (ppm _v)	CCl ₄ lb/hr
Before Perforation					
03/31/93	299-W15-82	128	23	1,333	0.8
04/14/93	299-W15-95	unknown	22	5,660	3.2
After Perforation					
04/28/93	299-W15-82 ^(a)	116	203	22,350	117
04/28/93	299-W15-95 ^(b)	118	34	10,700	9.3
04/29/93	299-W15-84 ^(c)	102	75	8,475	16
04/30/93	299-W15-85 ^(d)	85	205	15,950	84
05/04/93	299-W15-217 ^(e)	56	75	13,474	26
05/05/93	299-W15-217 ^(e)	130	157	17,975	73
05/10/93	299-W15-217 ^(e)	119	186	24,367	116
05/11/93	299-W15-217 ^(e)	102	173	23,933	106
05/27/93	CPT-12 ^(f)	101	64	78	0.1
06/03/93	299-W15-82 ^(a)	69	253	28,500	18

- (a) Perforated from 73-88 ft bgs
- (b) Perforated from 83-98 ft bgs
- (c) Perforated from 75-90 ft bgs
- (d) Perforated from 83-98 ft bgs
- (e) Screened from 106-121 ft bgs
- (f) Drilled interval from 36-49 ft bgs

4.0 CONCLUSIONS AND SUMMARY OF RECOMMENDATIONS

4.1 CONCLUSIONS

The following subsections are brief summaries of the conclusions detailed in Chapter 3.0.

4.1.1 Required Volume of Extracted Soil Gas

To remove 225,000 kg of carbon tetrachloride from the combined 216-Z-1A/18 and 216-Z-12 Wellfield, at least 1.9×10^9 ft³ of soil gas must be removed from the subsurface. To remove 225,000 kg of carbon tetrachloride from the 216-Z-9 Wellfield, at least 4.0×10^7 ft³ of soil gas must be removed from the subsurface. The difference in extracted soil-gas volume between the two sites is due to the areal extent of the sites and the order of magnitude difference in concentrations.

4.1.2 Length of Extraction Time Required for Remediation

Assuming continuous operation (68% operating efficiency), it will take over 3.5 years to remove the 225,000 kg from the combined 216-Z-1A/18 and 216-Z-12 Wellfield. At the present 24% operating efficiency, it will take over 10 years to reach the same carbon tetrachloride recovery levels.

Assuming the extracted soil-gas carbon tetrachloride concentration in the 216-Z-9 Wellfield remained approximately 30,000 ppm_v, it would take slightly longer than one month to remove 225,000 kg of carbon tetrachloride. The likely scenario is that the concentrations will fall off appreciably and the estimated time for removal of the carbon tetrachloride is closer to that for the combined 216-Z-1A/18 and 216-Z-12 Wellfield.

4.2 SPECIFIC RECOMMENDATIONS

The following subsections are brief summaries of the specific recommendations detailed in Chapter 3.0.

4.2.1 Modify Wells to Allow Greater Access to the Subsurface

Twenty-six existing wells in the Z-Crib Area should be modified, if feasible, to increase the areas of influence of the VES to allow access to the entire subsurface area. The wells recommended for modification are detailed in Tables 3-3 and 3-4; the prioritized list of wells recommended for modification is presented in Table 3-7. A discussion centering around the strategy used for the recommended wellfield modifications is provided in Appendix E.

4.2.2 Increase Extraction Capacity

The 500 ft³/min system should be used for extraction of wells in the 216-Z-12 Wellfield to help mitigate the migration of the soil vapor plume.

For the longer term, additional smaller VES units should be considered to increase the extraction capacity to allow soil gas to be extracted from a larger area of the subsurface at one time. Smaller VES units allow more flexibility in placement over the wide areal extent of the Z-Crib Area. The extraction capacity per VES unit should be 300 to 500 ft³/min, which would allow the VES units to be purchased "off-the-shelf" and would supply enough extraction capacity to effectively function at one or two wells. Incorporating several of these smaller units would greatly increase the flexibility and extraction capacity of the VES operations and would reduce the length of time until remediation is completed.

4.2.3 Additional Numerical Modeling of the Extraction Process

Further numerical modeling of the soil vapor extraction process is essential to the long-term success of the extraction operations in the Z-Crib Area. Numerical modeling of the airflow provides an understanding of the extraction process and the airflow pathways, helps validate the soil permeabilities, provides an indication of the areas of influence of the extraction wells, and provides an indication of the length of time that extraction operations must be performed.

4.2.4 Characterization Testing and Characterization Sampling

Characterization testing and characterization sampling should initially be performed whenever soil gas is first extracted from a well and then again approximately every two weeks for the duration of the soil vapor extraction operations. The results of the tests should be used to provide insight into the changes of location and concentration of the carbon tetrachloride vapor plumes and the consequent effect on extraction strategy.

4.2.5 Tracer Gas Testing

Tracer gas testing should be used to determine the subsurface airflow pathways, rate of carbon tetrachloride vapor transport, and areas of influence of the extraction wells. Tracer gas testing should be performed at various locations throughout the Z-Crib Area.

4.2.6 Downhole Pressure Monitoring

Downhole pressures in each of the open intervals should be monitored to collect data on the effects of barometric pressure at the well open intervals and the effects of induced vacuum created by the VES operations. This will provide specific information regarding the areas of influence of the extraction wells.

4.2.7 Technologies Requiring Further Investigation

For the longer term, extraction enhancement technologies should be further investigated for potential enhancement of the extraction operations throughout the Z-Crib Area. These technologies include pulsed versus continuous pumping, pneumatic fracturing, air injection, and surface seals.

4.2.8 Vapor Extraction Efficiency Study

For the longer term, wellfield and laboratory-scale testing that define the carbon tetrachloride sorption equilibrium over a range of concentrations and Z-Crib Area soil types should be performed. This will provide specific information for various Z-Crib Area soils regarding the amount of soil gas that must be extracted from the subsurface to remove the carbon tetrachloride and the amount of time it takes to remove the carbon tetrachloride.

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APPENDIX A
VAPOR EXTRACTION NUMERICAL MODELING

The numerical modeling of the soil vapor extraction process was conducted using the HyperVentilate software package developed under a Federal Technology Transfer Act Cooperative Research and Development Agreement between the U.S. Environmental Protection Agency (EPA) and Shell Oil Company. HyperVentilate is based on Johnson et al. (1990).

The modeling was conducted to estimate the carbon tetrachloride removal rate and provide information regarding the volume of extracted soil gas and the extraction time required to remediate the Z-Crib Area. This information is intended to provide guidance for the remediation efforts.

The following annotated printouts from HyperVentilate are intended to provide the reader a better understanding of the HyperVentilate software and the modeling performed for this report.

Flowrate Estimation:

☐ Medium Sand
☐ Fine Sand
☐ Silty Sand
☐ Clayey Silts
☒ Input Your Own Permeability Range

Permeability Range (darcy)

to

Well Radius in

Radius of Influence ft

Interval Thickness* ft

--> Calculate Flowrate Ranges <--

* thickness of screened interval, or permeable zone (whichever is smaller).

1) Choose Soil Type, or
Optional - Enter your own permeability values (darcy)
 2) Enter Well Radius (in)
 3) Enter Radius of Influence (ft) & Interval Thickness*
 4) Optional - Enter your own well vacuum (406" = max)
 5) Click button to calculate Predicted Flowrate Ranges

Predicted Flowrate Ranges

Well Vacuum P_w (in H_2O)	Flowrate (SCFM) (single well)
5	1.29 to 9.69
10	2.57 to 19.25
20	5.07 to 38.03
40	9.88 to 74.14
60	14.44 to 109.33
120	26.59 to 199.41
100	22.80 to 170.96

4

About Soils (& Unit Conversions) 8 Info about Calculation

Permeability Range

DOE/RL (1991), Appendix F gave permeabilities for Well 299-W18-171 (216-Z-1A) ranging from 2 to 15 darcy for the three screened intervals of this well. These same values were used for modeling.

Well Radius and Interval Thickness

All of the recently installed extraction wells have a radius of 2 in. and a screened interval of 10 to 20 ft. An average of 15 ft was used.

Radius of Influence

DOE/RL (1991), Appendix F estimated a radius of influence for 299-W18-171 of 250 ft at 100 in H_2O vacuum and 300 stdft³/min flow. A conservative 100 ft was used for modeling.

Flowrate Estimation:

☐ Medium Sand
☐ Fine Sand
☐ Silty Sand
☐ Clayey Silts
☒ Input Your Own Permeability Range

Permeability Range (darcy)

2 to 15

Well Radius 2 in

Radius of Influence 100 ft

Interval Thickness* 10 ft

--> Calculate Flowrate Ranges <--

* thickness of screened interval, or permeable zone (whichever is smaller).

About Soils (& Unit Conversions)

1) Choose Soil Type, or
 Optional - Enter your own permeability values (darcy)
 2) Enter Well Radius (in)
 3) Enter Radius of Influence (ft) & Interval Thickness*
 4) Optional - Enter your own well vacuum (406" = max)
 5) Click button to calculate Predicted Flowrate Ranges

Predicted Flowrate Ranges

Well Vacuum P_w (in H ₂ O)	Flowrate (SCFM) (single well)
5	0.86 to 6.46
10	1.71 to 12.84
20	3.38 to 25.35
40	6.59 to 49.42
60	9.63 to 72.22
120	17.72 to 132.94
100	15.20 to 113.98

4

Info about Calculation

Interval Thickness

This shows the impact on flow rates of reducing the interval thickness to 10 ft.

Flowrate Estimation:

☐ Medium Sand
☐ Fine Sand
☐ Silty Sand
☐ Clayey Silts
☒ Input Your Own Permeability Range

Permeability Range (darcy)

2

 to

15

Well Radius

2

 in
Radius of Influence

100

 ft
Interval Thickness*

20

 ft

--> Calculate Flowrate Ranges <--

* thickness of screened interval, or permeable zone (whichever is smaller).

1) Choose Soil Type, or
Optional - Enter your own permeability values (darcy)
2) Enter Well Radius (in)
3) Enter Radius of Influence (ft) & Interval Thickness*
4) Optional - Enter your own well vacuum (406" = max)
5) Click button to calculate Predicted Flowrate Ranges

Predicted Flowrate Ranges

Well Vacuum P_w (in H_2O)	Flowrate (SCFM) (single well)
5	1.72 to 12.91
10	3.42 to 25.67
20	6.76 to 50.70
40	13.18 to 98.85
60	19.26 to 144.44
120	35.45 to 265.87
100	30.39 to 227.95

About Soils (& Unit Conversions)

8

Info about Calculation

Interval Thickness

This shows the impact on flow rates of increasing the interval thickness to 20 ft.

H16

Help: Compound List

User Specified Composition

Enter Data Mode Set All to 0

#	Compound Name	Mass Fraction	Molecular Weight (g)	Vapor Pressure (atm) 20 °C
59	n-dodecane	0.00	170.3	0.0004
60	naphthalene	0.00	128.2	0.00014
61	n-hexylbenzene	0.00	162.3	0.0001
62	methyl-naphthalene	0.00	142.2	0.00005
63	tetrachloromethane	0.00	153.84	0.12
64	1% tetrachloromethane	0.00	153.84	0.0012
65	0.5% tetrachloromethane	1.00	153.84	0.0006
66	25% tetrachloromethane	0.00	153.84	0.03

Directions for Use of Table

1) Type in Mass Fraction Values and use the arrow keys, & the program will increment you to the next line (above or below)

1.00000 = Sum of Mass Fractions

Sum

How Do I Measure a Distribution? Return to Vapor Conc. Estimation Card Print Lists

Vapor Concentration

Four entries were made for carbon tetrachloride (tetrachloromethane):

100% tetrachloromethane ≈	120,000 ppm _v
25% tetrachloromethane ≈	30,000 ppm _v
1% tetrachloromethane ≈	1,200 ppm _v
0.5% tetrachloromethane ≈	600 ppm _v

The average soil-gas concentration measured during extraction at 216-Z-1A was 570 ppm_v tetrachloromethane; therefore 0.5% tetrachloromethane was assumed for modeling of the 216-Z-1A Tile Field/216-Z-18 Crib/216-Z-12 Crib area. A concentration of 25% tetrachloromethane (30,000 ppm_v) was used for modeling of the 216-Z-9 Crib area.

Vapor Concentration Estimation - Calculation			
1	Type in Temperature (C) (hit <return>)	<input type="text" value="20"/>	
2	Click to Enter Composition of Contaminant or Choose one of the Default Distributions	☒ Enter Distribution ☐ "Fresh" Gasoline ☐ "Weathered" Gasoline	
3	Click to View Distributions, (optional)	<input type="button" value="View Distributions"/>	
4	Click to Perform Calculations	☒ Perform Calculations	
Results:		Sum of Mass Fractions	<input type="text" value="1.00000"/>
		Calc. Vapor Pressure	<input type="text" value="0.00060"/> atm
		Calc. Vapor Concentration	<input type="text" value="3.83716"/> mg/l
<div> <input type="button" value="How Do I Measure a Distribution?"/> <input type="button" value="←"/> <input type="button" value="10"/> <input type="button" value="→"/> <input type="button" value="About Calculation"/> <input type="button" value="Print Card"/> </div>			

216-Z-1A MODEL:**Temperature**

DOE-RL (1991) lists the soil temperature at 15 to 20 °C. An average temperature of 20 °C was assumed.

Composition

CCl₄, 0.5% of saturation.

Vapor Concentration

3.84 mg/L $\approx$ 600 ppm_v.

Maximum Removal Rate

Maximum Removal Rate Estimates

select your unit/preference below

☐ (lb/d)
☒ (kg/d)

These are "maximum removal rates", and should only be used as screening estimates to determine if venting is even feasible at a given site. Continue on to the next card to assess if these rates are acceptable...

Flow Rate Estimates		Flow Rate Estimates		Flow Rate Estimates		Flow Rate Estimates	
Temperature (C)	Soil Type	Soil Permeability Range (darcy)	Well Radius (m)	Radius of Influence (ft)	Contaminant Type	Removable Zone Thickness (ft)	
20	User Defined	2	2	100	User Defined	15	
20	User Defined	2	2	100	User Defined	15	

5	10	20	40	60	120	100
1.29	2.57	5.07	9.88	14.44	26.59	22.80
to	to	to	to	to	to	to
9.69	19.25	38.03	74.14	108.33	199.41	170.96

0.20	0.41	0.83	1.71	2.65	5.90	4.73
to	to	to	to	to	to	to
1.54	3.09	6.26	12.87	19.88	44.26	35.47

E_w - Well

Vacuum

(in H₂O)

Flow Rate Estimates

[SCFM]

(single well)

Max. Removal Rate Estimates

[kg/d]

(single well)

Is Soil Venting Appropriate?

At this point, you compare the maximum possible removal rate with your desired removal rate.

If the maximum removal rate does not exceed your desired removal rate, then soil venting is not likely to meet your needs, and you should consider another treatment technology, or make your needs more realistic.

In the next cards, we will refine the removal rate estimates, in order to decide if venting can achieve your objectives.

1 Enter Estimated Spill Mass ☒ kg ☐ lb

2 Enter Desired Remediation Time days

3

Single Vertical Well Results

Desired Removal Rate:	<input type="text" value="300"/>	[kg/d]
Gauge Vacuum (in H ₂ O):	<input type="text" value="120"/>	[in H ₂ O]
Min Flowrate @ 120in H ₂ O	<input type="text" value="26.59"/>	[SCFM]
Max Flowrate @ 120in H ₂ O	<input type="text" value="199.41"/>	[SCFM]
Max. Est. Removal Rate:		
(lower estimate) - per well	<input type="text" value="5.90"/>	[kg/d]
(upper estimate) - per well	<input type="text" value="44.26"/>	[kg/d]

← 13 →

216-Z-1A MODEL:**Spill Mass**

A combined 450,000 kg (DOE-RL 1991) of carbon tetrachloride was discharged to the 216-Z-1A Tile Field and 216-Z-18 Crib. It was assumed that 50% has evaporated and/or moved into the aquifer and is unavailable for vapor extraction.

To obtain reasonable estimates, a remediation time of 750 days was assumed. This is equal to 3 years at a 68% total operating efficiency (TOE).

Results

The desired removal rate is 300 kg/day. The maximum removal rate per well is 6 to 44 kg/day depending on soil permeability.

① -> Import Data <-

Saturated Vapor Concentration at time=0 .3837E-01 [mg/L]

FIRST PRESS THE IMPORT DATA BUTTON!

Min Volume to Remove >90% of Initial Residual 234.55 [L-air/g-residual]

These are the results for the contaminant type that you have specified. All of this

Temperature (°C): 20

Contaminant Type: User Defined

Qr/M(0) L-air/ g-residual	Vapor Conc. [% Initial]	Residual Level [% Initial]	BP #1 Residual [% total]	BP #2 Residual [% total]	BP #3 Residual [% total]	BP #4 Residual [% total]	BP #5 Residual [% total]
.00	100.00	100.00	.00	100.00	.00	.00	.00
13.03	100.00	95.00	.00	100.00	.00	.00	.00
26.06	100.00	90.00	.00	100.00	.00	.00	.00
39.09	100.00	85.00	.00	100.00	.00	.00	.00
52.12	100.00	80.00	.00	100.00	.00	.00	.00
65.15	100.00	75.00	.00	100.00	.00	.00	.00
78.18	100.00	70.00	.00	100.00	.00	.00	.00
91.21	100.00	65.00	.00	100.00	.00	.00	.00

17

Print Card

216-Z-1A MODEL:

Air/Residual Ratio

The calculated minimum volume of air to remove <90% of the initial residual contamination is 234.55 L-air/g-residual.

Therefore an inventory of 225,000 kg would require the extraction of 5.3×10^{10} L (1.9×10^9 ft³) of soil gas at 600 ppm_v to remediate. This is equivalent to operating a 1,500 stdft³/min soil vapor extraction system continuously for 3.5 years assuming a 68% TOE.

Is Venting Appropriate?

This is a complete summary of the data and results. Based upon these numbers, a "minimum number of wells" has been calculated, which should give you some indication of how appropriate venting is for your application. Note that this is the number of wells if circumstances are ideal, which they rarely are.

The next card discusses some of the conditions that may limit the effectiveness

Temperature (°C):	20
Contaminant Type:	User Defined
Soil Type:	User Defined
Well Radius (in):	2
Est. Radius of Influence (ft):	100
Permeable Zone Thickness (ft):	15
Flowrate per Well (120" Vac) (SCFM)	26.59
Flowrate per Well (120" Vac) (SCFM)	199.41
Min. Vol. of Air (L/g-residual):	234.55
Estimated Spill Mass:	225000 kg
Desired Remediation Time (days):	750

Minimum # of Wells Based on Your Input Parameters

6.10 < 45.75

18

216-Z-1A MODEL:

Assuming an average vapor concentration of 600 ppm_v, 6 to 46 wells around 216-Z-1A Tile Field, 216-Z-18 Crib, and 216-Z-12 Crib must be extracted simultaneously to remove 225,000 kg of carbon tetrachloride in 3 years.

Vapor Concentration Estimation - Calculation			
1	Type in Temperature (C) (hit <return>)	20	
2	Click to Enter Composition of Contaminant or Choose one of the Default Distributions	☒ Enter Distribution ☐ "Fresh" Gasoline ☐ "Weathered" Gasoline	
3	Click to View Distributions, (optional)	View Distributions	
4	Click to Perform Calculations	Perform Calculations	
Results:		Sum of Mass Fractions	1.00000
		Calc. Vapor Pressure	0.03000 atm
		Calc. Vapor Concentration	191.85793 mg/l
<div> How Do I Measure a Distribution? ← 10 → About Calculation Print Card </div>			

216-Z-9 MODEL:**Temperature**

DOE-RL (1991) lists the soil temperature at 15 to 22 °C. An average temperature of 20 °C was assumed.

Composition

CCl₄, 25% of saturation.

Vapor Concentration

192 mg/L ≈ 30,000 ppm_v.

Maximum Removal Rate Estimates

select your unit preference below

☐ [lb/d]
☒ [kg/d]

Note:
 These are "maximum removal rates", and should only be used as screening estimates to determine if venting is even feasible at a given site. Continue on to the next card to assess if these rates are acceptable.

Temperature (C)
 Soil Type
 Soil Permeability Range (darcy) to
 Well Radius (in)
 Radius of Influence (ft)
 Contaminant Type
 Permeable Zone Thickness (ft)

P_w - Well Vacuum (in H ₂ O)	Flowrate Estimates (SCFM) (single well)		Max. Removal Rate Estimates [kg/d] (single well)	
5	1.29	to 9.69	10.22	to 76.76
10	2.57	to 19.25	20.61	to 154.41
20	5.07	to 38.03	41.72	to 312.94
40	9.88	to 74.14	85.73	to 643.34
60	14.44	to 108.33	132.53	to 994.23
120	26.59	to 199.41	295.09	to 2213.01
100	22.80	to 170.96	236.54	to 1773.60

12 Print Card

216-Z-19 MODEL:

Maximum Removal Rate

The estimated flow rates and the concentration entered earlier are used to calculate the removal rate.

Is Soil Venting Appropriate?

At this point, you compare the maximum possible removal rate with your desired removal rate.

If the maximum removal rate does not exceed your desired removal rate, then soil venting is not likely to meet your needs, and you should consider another treatment technology, or make your needs more realistic.

In the next cards, we will refine the removal rate estimates, in order to decide if venting can achieve your objectives.

1 Enter Estimated Spill Mass ☒ kg ☐ lb

2 Enter Desired Remediation Time days

3

Single Vertical Well Results

Desired Removal Rate:	<input type="text" value="300"/>	[kg/d]
Gauge Vacuum (in H ₂ O):	<input type="text" value="120"/>	[in H ₂ O]
Min Flowrate @ 120 in H ₂ O	<input type="text" value="26.59"/>	[SCFM]
Max Flowrate @ 120 in H ₂ O	<input type="text" value="199.41"/>	[SCFM]
Max. Est. Removal Rate:		
(lower estimate) - per well	<input type="text" value="295.09"/>	[kg/d]
(upper estimate) - per well	<input type="text" value="2213.01"/>	[kg/d]

← 13 →

216-Z-9 MODEL:**Spill Mass**

130,000 to 450,000 kg (DOE-RL 1991) of carbon tetrachloride was discharged to the 216-Z-9 Trench. It was assumed that 50% has evaporated and/or moved into the aquifer and is unavailable for vapor extraction.

To obtain reasonable estimates, a remediation time of 750 days was assumed. This is equal to three years at a 68% TOE.

Results

The desired removal rate is 300 kg/day. The maximum removal rate per well is 295 to 2,213 kg/day depending on soil permeability.

① → Import Data ←

FIRST PRESSTHE IMPORT DATA
BUTTON!

These are the results for the contaminant
type that you have specified. All of this

Saturated Vapor
Concentration at time=0: **.1919E+03** [mg/L]

Min Volume to Remove
>90% of Initial Residual: **4.69** [L-air/g-resi-
dual]

Temperature (°C): **20**

Contaminant Type: **User Defined**

Q/M(0) L-air/ g-residual	Vapor Conc. [% Initial]	Residual Level [% Initial]	BP #1 Residual [% total]	BP #2 Residual [% total]	BP #3 Residual [% total]	BP #4 Residual [% total]	BP #5 Residual [% total]
.00	100.00	100.00	.00	100.00	.00	.00	.00
.26	100.00	95.00	.00	100.00	.00	.00	.00
.52	100.00	90.00	.00	100.00	.00	.00	.00
.78	100.00	85.00	.00	100.00	.00	.00	.00
1.04	100.00	80.00	.00	100.00	.00	.00	.00
1.30	100.00	75.00	.00	100.00	.00	.00	.00
1.56	100.00	70.00	.00	100.00	.00	.00	.00
1.82	100.00	65.00	.00	100.00	.00	.00	.00

← 17 → Print Card

216-Z-9 MODEL:**Air/Residual Ratio**

The calculated minimum volume of air to remove >90% of the initial residual contamination is 4.69 L-air/g-residual.

Therefore, an inventory of 225,000 kg would require the extraction of 1.1×10^9 L (3.7×10^7 ft³) of soil gas at 30,000 ppm_v to remediate. This is equivalent to operating a 1,500 stdft³/min soil vapor extraction system continuously for one month assuming a 68% TOE.

Is Venting Appropriate?

This is a complete summary of the data and results. Based upon these numbers, a "minimum number of wells" has been calculated, which should give you some indication of how appropriate venting is for your application. Note that this is the number of wells if circumstances are ideal which they rarely are.

The next card discusses some of the conditions that may limit the effectiveness

Temperature (°C):	20
Contaminant Type:	User Defined
Soil Type:	User Defined
Well Radius (in):	2
Est. Radius of Influence (ft):	100
Permeable Zone Thickness (ft):	15
Flowrate per Well (120" Vac) (SCFM)	26.59
Flowrate per Well (120" Vac) (SCFM)	199.41
Min. Vol. of Air (L/g-residual):	4.69
Estimated Spill Mass:	225000 kg
Desired Remediation Time (days):	750

Minimum # of Wells Based on Your Input Parameters

0.12 < 0.91

18

216-Z-9 MODEL:

Assuming an average vapor concentration of 30,000 ppm_v, one well around the 216-Z-9 Trench must be extracted continuously to remove 225,000 kg of carbon tetrachloride in three years.

H25

Help: 6c) Low Permeability Lenses

In the situation depicted above, vapor flows past, rather than through the contaminated soil zone, such as might be the case for a contaminated clay lens surrounded by sandy soils. In this case vapor diffusion through the clay to the flowing vapor limits the removal rate (the removal rate actually becomes independent of total vapor flowrate at high flowrates). The maximum removal rate in this case occurs when the vapor flow is fast enough to maintain a low

Show Me Equations
Return
Let's Do a Calculation

The following pages present results of modeling extraction from a low-permeability lens such as the caliche layer found in the Plio-Pleistocene Unit.

Help: 6c) Low Permeability Lenses - Equations

$$R_{est} = \pi (R_2^2 - R_1^2) \sqrt{\frac{C_{est} D^{eff} C_{soil} \rho_{soil}}{2 t}}$$

$$\delta = \sqrt{\frac{C_{est} D^{eff} t}{C_{soil} \rho_{soil}}}$$

where:

- R_{est} = estimated removal rate [mg/d]
- δ = thickness of "dried-out" zone [m]
- R_1 = defines region in which contamination is present [m]
- R_2 = defines region in which contamination is present [m]
- C_{est} = estimated saturated vapor concentration [mg/m³]
- D^{eff} = effective soil vapor diffusion coefficient [m²/d]
- C_{soil} = initial residual level of contaminant in soil [mg/kg]
- ρ_{soil} = soil bulk density [kg/m³]
- t = time [d]

Derivations for these equations are given in Johnson, et al - "A Practical Approach to the Design, Operation and Monitoring of In Situ Soil Venting Systems" - 1990.

These Equations are valid for single-component contaminants; removal rates for mixtures probably will be lower, due to composition changes and liquid-phase diffusional resistances.

[Let's Do a Calculation](#)

[Return](#)

H26

AIM

Association for Information and Image Management

1100 Wayne Avenue, Suite 1100
Silver Spring, Maryland 20910
301/587-8202

Centimeter

Inches

MANUFACTURED TO AIM STANDARDS
BY APPLIED IMAGE, INC.

2 of 2

Help: Low Permeability Lenses - Calculation

① Process Variables:
(input values)

2 venting well radius [in]
 900 radial width of contaminated zone [ft]
 310 residual contaminant level [mg/kg]

② Contaminant Properties:

153.840058 contaminant molecular weight [g/mole]
 0.456 contaminant vapor pressure [mm Hg]
 20 temperature [C]
☐ use values already input from Card 10

Just enter values into the appropriate fields, then click on the "Calculate" button.

③ --> Calculate <--

Time (days)	Removal Rate (kg/d)	δ (m)
1	2837.400	0.048
7	1072.436	0.128
30	518.036	0.265
60	366.307	0.375
120	259.018	0.530
180	211.487	0.650
240	183.153	0.750
360	149.544	0.919
540	122.102	1.125
720	105.744	1.299
1080	86.339	1.591

Return H30

Venting Well Radius

Radius of the well is 2 in.

Radial Width of Contaminated Zone

The radius of a circle with an area enclosing the soil vapor plume around 216-Z-1A Tile Field, 216-Z-18 Crib, and 216-Z-12 Crib (Figure 2-2) is 900 ft.

Residual Contaminant Level

A residual contaminant level of 310 mg/kg of tetrachloromethane was used. This concentration, if representative of the early Palouse and Plio-Pleistocene formations, would result in an inventory of ~200,000 kilograms tetrachloromethane in the area of 216-Z-1A Tile Field, 216-Z-18 Crib, and 216-Z-12 Crib.

Contaminant Vapor Pressure

The vapor pressure equivalent to 0.5% tetrachloromethane is 0.456 mm Hg.

Help: Low Permeability Lenses - Calculation

① Process Variables:
(input values)

2 venting well radius [in]
450 radial width of contaminated zone [ft]
1250 residual contaminant level [mg/kg]

② Contaminant Properties:

153.840002 contaminant molecular weight [g/mole]
22.8 contaminant vapor pressure [mm Hg]
20 temperature (C)
☐ use values already input from Card 10

Just enter values into the appropriate fields, then click on the "Calculate" button.

③ --> Calculate <--

Time (days)	Removal Rate (kg/d)	δ (m)
1	1424.409	0.024
7	538.376	0.064
30	260.060	0.132
60	183.890	0.187
120	130.030	0.264
180	106.169	0.324
240	91.945	0.374
360	75.073	0.458
540	61.297	0.560
720	53.085	0.647
1080	43.343	0.792

Return H30

Venting Well Radius

Radius of the well is 2 in.

Radial Width of Contaminated Zone

The radius of a circle with an area enclosing the soil vapor plume around 216-Z-9 Crib (Figure 2-2) is 450 ft.

Residual Contaminant Level

A residual contaminant level of 1,250 mg/kg of tetrachloromethane was used. This concentration, if representative of the early Palouse and Plio-Pleistocene formations, would result in an inventory of ~200,000 kilograms tetrachloromethane in the area of 216-Z-9 Crib.

Contaminant Vapor Pressure

The vapor pressure equivalent to 0.5% tetrachloromethane is 22.8 mm Hg.

Help: 6a) Dilution Effects [Bypassing]

The figure above depicts the case where some vapors "bypass" zones of contamination, and therefore the vapors removed from the extraction well represent a mixture of the vapors obtained from both contaminated and clean vapor flowpaths. One can roughly judge the amount of bypassing by the well placement, screening, and contaminant distribution. Generally, observed vapor concentrations are roughly 10 - 50% of the ideal saturated concentrations. To account for this in the modelling, therefore, multiply the number of wells on card 18 by a factor of 2 to 10 and removal rates (and vapor concentrations) by a factor of 0.10 to 0.50 (10% to 50%).

Return

H23

NOTE:

Generally, observed vapor concentrations are roughly 10 to 50% of the ideal saturated concentrations.

Help: 6a) Dilution Effects [Bypassing]

by a factor of 2 to 10, and removal rates (and vapor concentrations) by a factor of 0.10 to 0.50 (10% to 50% efficiency factor).

This information may also have been obtained during an air permeability test, when soil gas concentrations at vadose monitoring installations, and extraction well concentrations are compared

Return

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APPENDIX B
CARBON TETRACHLORIDE CHEMICAL CHARACTERISTICS

Raoult's Law - A physical law which describes the relationship between the vapor pressure of a component over a solution, the vapor pressure of the same component over pure liquid, and the mole fraction of the component in the solution. The component is the solvent portion of the solution. Raoult's law is generally valid for components with a mole fraction near 1. For an ideal solution:

$$P = (X)(P^{\circ}) \quad (1)$$

Where:

P = vapor pressure of the component over the solution
 X = mole fraction of the component in the solution
 P[°] = vapor pressure of the pure component

Henry's Law - A physical law which describes the relationship between vapor pressure of a component over a solution and the mole fraction of the component in the solution. Henry's law is generally valid for dilute solutions in which the component mole fraction is near 0. For an ideal solution:

$$P = (X)(H_c) \quad (2)$$

Where:

$$H_c = \text{Henry's Constant, unitless} \quad (3)$$

The Henry's Law constant is temperature dependent. This correlation for carbon tetrachloride is as follows (Munz, C., and P.V. Roberts, 1987, *Journal of AWWA Research and Technology*, May 1987, pp. 62-69):

$$\log H_c = 5.853 - 1718/T[K] \quad (4)$$

A temperature of 20 °C (293 K) was used in the body of the report and is representative of soil-gas venting from wells in the vicinity of the 216-Z-9 Trench.

Table B-1. Carbon Tetrachloride Chemical Properties.

PROPERTY	VALUE
Molecular Weight	153.82
Melting Point	-23 °C
Boiling Point	76.8 °C
Vapor Pressure (@ 20 °C)	112 mm Hg
Solubility in Water (@ 20 °C)	800 mg/L
Log Octanol/Water Coefficient	2.73
Henry's Law Constant (@ 20 °C)	0.976
Specific Gravity (@ 25 °C)	1.588

APPENDIX C
VAPOR PHASE PARTITIONING COEFFICIENT DETERMINATION

WHC-SD-EN-AP-159, Rev. 0

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1.0 INTRODUCTION

One of the primary challenges of predicting the fate of carbon tetrachloride in the subsurface is to define the vapor phase partitioning coefficient (K_v) accurately for the soils of interest. This coefficient can be used in an isotherm expression (Equation 1) to determine the solid phase sorbed concentration of carbon tetrachloride given the equilibrium vapor phase concentration. Determination of the sorbed and vapor concentrations is critical for estimating carbon tetrachloride atmospheric losses and residual inventory at the 200 West Area of the Hanford Site.

$$q_e = K_v C_e \quad (1)$$

where: q_e = solid phase concentration (mass of contaminant sorbed on soil particles plus mass dissolved in soil moisture per mass of soil)
 K_v = equilibrium partition coefficient
 C_e = gas phase equilibrium concentration.

The coefficient K_v is calculated for linear isotherm traces and is dependent upon a variety of system conditions (soil moisture, relative humidity, physical and chemical soil characteristics, temperature, etc.). Consequently, it is not typically available in the literature. Due to the system specific conditions that define K_v , it was decided to estimate K_v under field conditions.

2.0 LABORATORY TESTING

2.1 BACKGROUND

The experimental procedure initially developed to estimate carbon tetrachloride vapor phase sorption involved the testing of soil samples at a Washington State University laboratory. These samples were collected during the drilling of Wells 299-W15-220 and 299-W18-252 during FY 1993 in the 200 West Area.

A static headspace analysis procedure was developed that is detailed in the following discussion. This procedure was developed because it would theoretically afford a relatively efficient method of defining K_v using field soil samples under actual field soil moisture, relative humidity, and temperature conditions.

Thirty-three individual soil samples were collected at eleven depths (three samples per depth) from Well 299-W15-220, east of the 216-Z-9 Trench. Sample collection was initiated at the 90- to 95-ft interval, and collection proceeded at approximately 10-ft intervals to termination at the 190- to 195-ft interval. Of the 33 soil samples collected from Well 299-W15-220, three (all at 95-ft depth) had detectable concentrations of carbon tetrachloride. Two of the four samples collected from Well 299-W18-252, west of the 216-Z-1A Tile Field, had detectable carbon tetrachloride concentrations. The relatively low number of samples with detectable carbon tetrachloride was an apparent result of the combined effect of collecting a small mass of soil and low solid phase (sorbed)

carbon tetrachloride concentrations. Consequently, it was not possible to define equilibrium solid and gas-phase sorption using the samples as received from the field. Based on these results, a carbon tetrachloride addition protocol was developed that involved spiking selected samples with a known mass of carbon tetrachloride. The procedure employed is presented in the following section.

2.2 METHODOLOGY

Eight samples were selected for the carbon tetrachloride sorption experiments that involved the addition of carbon tetrachloride. Three samples were collected from the 95-ft interval and three from the 125-ft interval (Well 299-W15-220). Two samples were collected from Well 299-W18-252 at 177 ft. Selection of these sample sets allowed for sorption experiments to be carried out on a sandy gravel and sandy silt. In addition to the sample bottles containing soil, three blank bottles (containing no soil) were used and carried through all the experimental procedures to verify the sample recovery. All experiments were carried out in the original collection bottles (120 mL septum bottles).

Carbon Tetrachloride Addition. Each bottle was spiked with 1 μL of liquid carbon tetrachloride and allowed to equilibrate at 18 $^{\circ}\text{C}$ for three days. Following equilibration, the vapor phase was analyzed for carbon tetrachloride using a gas chromatograph that was calibrated using vapor phase carbon tetrachloride standards.

Concentration Calculations. The total mass of carbon tetrachloride in each bottle was then determined by maintaining the bottles at 96 $^{\circ}\text{C}$ for two hours and quantifying the carbon tetrachloride vapor phase concentration (Voice 1993). The concentration measured at 96 $^{\circ}\text{C}$ was corrected for the loss of carbon tetrachloride that resulted from the analysis at 18 $^{\circ}\text{C}$ (Equation 2) and the total mass sorbed to the soil was then calculated using Equation 3. Equation 3 solves for the mass of contaminant sorbed per mass of soil.

$$C_{adj} = C_{96} + \frac{V_s}{V_b} C_{18} \quad (2)$$

where:

- C_{adj} = adjusted concentration (ppm_v)
- C_{96} = concentration measured at 96 $^{\circ}\text{C}$ (ppm_v)
- C_{18} = concentration measured at 18 $^{\circ}\text{C}$ (ppm_v)
- V_s = sample volume withdrawn to determine concentration at 18 $^{\circ}\text{C}$ (4mL)
- V_b = vapor phase volume in bottle

Equation (3):

$$q_e = \frac{V_b (C_{adj} - C_{18}) (M.W.)}{m (V_m)} \quad (3)$$

where:

- q_e = Solid phase concentration ($\mu\text{g}/\text{kg}$)
- V_b = vapor phase volume in bottle (L)
- m = soil mass (kg)

M.W. = molecular weight of carbon tetrachloride, 154 g/mole
 V_m = molar volume, 22.4 L/mole

Sorption isotherms were then developed by plotting values of q_e and C_e .

2.3 RESULTS AND DISCUSSION

Two points should be made from the data presented in Table C-2. The first is that the concentrations at 18 °C and 96 °C in the blank bottles are consistent, indicating that no detectable losses of carbon tetrachloride occurred throughout the analytical procedures. The value for q_e for bottle CEE37 is negative, a physical impossibility and a result of a leak in the septum during the heating procedure. This leak was visually observed and noted during the analysis procedure. The septum type for bottles CEE34 and CEE37 differed from those septa used on the remainder of the bottles. As a result of the observed leak, bottles CEE34 and CEE37 were not used in subsequent isotherm development and data analysis.

The second point is that the data in Figures C-1 and C-2 indicate a maximum solid phase carbon tetrachloride concentration of approximately 3500 $\mu\text{g/g}$ at a vapor phase equilibrium concentration of ~16,000 $\mu\text{g/L}$ (2,693 ppm @ 18 °C, 700 mm Hg). The data from each set of samples have been approximated with a linear line of best fit. The slopes of the lines fitting each data set are not significantly different. Similarity in sorption data between the two sample sets is evidenced by Figure C-3, where the data from both sets of samples are combined. The slope for the line of best fit for the combined data is 0.63 and for Figures C-1 and C-2 is 0.67 and 0.55, respectively. It should be noted that the intercept of the line of best fit is not zero. This indicates that over a full range of equilibrium vapor phase concentrations, the sorption isotherm is nonlinear. As a result, a linear partitioning coefficient, K_v , cannot be determined.

2.4 FUTURE WORK

These data are a preliminary indication of solid sorption capacity over a relatively narrow carbon tetrachloride vapor phase concentration range. An ideal outcome would have been that the intercept was close to zero for the line of best fit. Since this was not the case, a wider range of vapor phase concentrations should be studied to define the isotherm shape. Additional equilibrium studies should involve the use of larger soil samples.

Visual observation of the soil samples indicated a range of soil moistures. If soil moisture is shown to vary at the site, isotherm data could be collected at varying soil moisture levels.

This study yielded valuable information that can be used for future planned efforts with respect to the removal of residual carbon tetrachloride from the unsaturated zone. Although this study was preliminary in scope, the results indicate that solid phase concentrations of carbon tetrachloride could be significantly less than was assumed for the carbon tetrachloride residual inventory calculations (WHC 1993). This highlights the system-specific nature of vapor phase partitioning and the necessity to determine partitioning under conditions that closely approximate those found in the field.

The low vapor phase partitioning also points out the necessity to modify the experimental protocol used to determine gas phase equilibrium. This is a result of the difficulty encountered in measuring small changes in vapor concentration. This modification would involve the development of a continuous flow protocol, rather than the batch protocol used previously. It is fortuitous that the continuous flow apparatus could be used for both equilibrium data development and gas phase extraction data development.

Additional primary objectives of the laboratory-scale extraction tests are as follows:

- Define the effects of a lower permeability layer (e.g., a clay lens) on extraction efficiency. This would be particularly applicable to the caliche layer that may contain significant quantities of carbon tetrachloride. Even though the partitioning onto the solid phase is probably small, the permeability of the layer would decrease extraction efficiency as a result of diffusion limitations.
- Define the carbon tetrachloride field capacity of Hanford Site soils.
- Define liquid (groundwater), soil, and gas phase equilibria and the degree to which vapor extraction impacts contaminated groundwater; that is, how fast does the equilibrium shift as the vapor concentration is reduced over the groundwater during soil vapor extraction.
- Provide vapor partitioning and equilibria information to help assess the efficiency of passive vapor extraction.

The proposed study would be closely related to the tracer gas investigation currently in progress. Both projects would result in compatible and mutually beneficial information. The tracer gas experiments could be extremely useful in the proposed laboratory-scale investigation. It should be possible to define the diffusion characteristics of different soil materials using tracer techniques. The information gained could then be applied to the field investigation to further elucidate those findings.

3.0 BOREHOLE SAMPLE DATA

Some sample data exist (Rohay et al. 1993) in which borehole soil and soil-gas concentrations are available. These data are given in Table C-1 and are plotted in Figure C-4 along with the WSU laboratory data from Table C-2.

These data show more scatter than the WSU laboratory data but also cover a broader concentration range. Because the data appear linear with a y-intercept near zero, a linear isotherm was assumed and the y-intercept was forced to zero. A linear regression was found to have a slope of 0.73 and R^2 value of 0.835, indicating a fairly good fit. The resulting linear isotherm is represented by the following equation:

$$Q_g (\mu g/kg) = 0.73 C_g (ppm_v) . \quad (4)$$

Table C-1. Well Sample Carbon Tetrachloride Data.

WELL #	DEPTH (ft)	CCl ₄ CONCENTRATION IN SOIL GAS (ppm) ⁽¹⁾	CCl ₄ CONCENTRATION IN SOIL (ppb) ⁽²⁾
W18-96	87.0	8.1	93.0
	101.0	8.3	127.0
	122.0	98.1	111.0
W18-252	49.0	1.7	20.0
	86.0	16.3	30.0
	123.0	5.2	10.0
	138.0	36.4	307.0
	159.0	1,419.6	205.0
	186.0	8.9	159.0
	202.0	169.7	130.0
W15-218	60.0	45.4	354.0
	92.0	102.9	810.0
	112.0	16,660.0	15,794.0
	112.0	20,910.0	15,794.0
	127.0	29.8	25.0
	140.0	10.2	244.0
	140.0	7.9	244.0
	159.0	155.0	37.0
	179.0	778.6	50.0
	190.0	10,380.0	25.0
W15-220	51.0	853.7	1,052.0
	90.0	1,511.6	1,132.0
	115.0	633.0	25.0
	142.0	149.0	20.0
	142.0	167.2	20.0
	160.0	108.4	15.0
	182.0	49.4	20.0
	182.0	50.2	20.0

NOTES:

- (1) Field gas sample, analyzed by GC/ECD.
 (2) Soil sample preserved in methanol, analyzed by GC.

Table C-2. Measured and Calculated Data for the Determination of Carbon Tetrachloride Vapor Phase Sorption Equilibria.

Bottle No.	gas vol (mL)	soil mass (g)	C, 18° (ppm)	C 96° (ppm)	adj C 96° (ppm) ⁴	adj C 96° (μg/L)	C, 18° (μg/L)	q _e (μg/Kg)
CEE10 ¹	106.430	37.870	2143	2149	2229	13155	12644	1435
CEE11 ¹	100.250	52.450	2740	2914	3023	17838	16167	3195
CEE12 ¹	113.040	22.500	2392	2323	2407	14206	14113	463
CEE34 ²	108.780	33.470	2464	2598	2688	15863	14538	4307
CEE37 ²	118.690	7.150	2358	2220	2299	13567	13913	-5733
CEE13 ³	106.430	31.820	2450	2445	2537	14969	14455	1718
CEE14 ³	112.890	17.870	2434	2410	2496	14728	14361	2320
CEE15 ³	97.050	51.220	2802	2997	3112	18364	16532	3471
blank 1	121.010	0	2263	2069	2218	13090	13352	---
blank 2	121.250	0	2127	2008	2148	12676	12550	---
blank 3	122.250	0	2460	2259	2419	14278	14514	---

- 1 Samples collected from the 125 ft interval (299-W15-220): Sandy gravel, 40% gravel, cobbles to 2 in. diameter, 80% felsics, 20% basalt.
- 2 Samples collected from 175 ft (299-W18-252)
- 3 Samples collected from 95 ft interval (299-W15-220): Sandy silt interbeds
- 4 Concentration adjusted for the removal of 4 mL of sample during 18 °C analysis.

Figure C.1. Equilibrium Carbon Tetrachloride Sorption Isotherm for Sandy Silt Soil.

Figure C-2. Equilibrium Sorption Isotherm for Sandy Gravel Soil.

Figure C-3. Equilibrium Sorption Isotherm for Data From Both Sandy Silt and Sandy Gravel Soil Samples.

Figure C-4. Soil Gas Isotherm.

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APPENDIX D
GENERAL VAPOR EXTRACTION STRATEGIES

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1.0 GENERAL EXTRACTION STRATEGIES

1.1 STRATEGY FOR WELLFIELD DESIGN

A wellfield for soil vapor extraction typically consists of vertical extraction wells and monitoring wells. The wells have one or more open intervals that provide access for airflow in the subsurface. The extraction wells are connected at the surface to a vacuum pump that pulls the soil vapors from the subsurface. The monitoring wells are utilized for measuring the vacuum achieved at different locations in the wellfield, which helps in determining the radius of influence of the extraction system.

For an effective wellfield design, it is essential that the horizontal and vertical extent of contamination is known. The horizontal extent of contamination dictates the necessary radius of influence of the extraction system. The vertical extent of contamination determines the different levels in the subsurface that must be included in the extraction process.

The horizontal radius of influence of the extraction system is a function of the number of extraction wells, the vacuum/flow relationship, the horizontal air permeability of the soil, and time. As an extraction system operates over time, the soil pores farther away from the extraction wells become evacuated and the radius of influence of the system increases. An area of subsurface is generally considered to be within the radius of influence when the extraction system places the soils under greater than 0.5 in. H₂O vacuum.

It is critical that the design of the wellfield be such that control of the airflows in the subsurface is maintained. This is because control of the subsurface airflow ultimately dictates the effectiveness of the remediation. Control of the airflow is achieved through proper placement of the wells and the open intervals in the wells, the ability to manipulate the extraction rate from each open interval, and the selective introduction of injected air through open intervals to the subsurface.

1.1.1 Open Intervals and Wells

The open intervals in wells provide the access to the subsurface through which the vapor extraction process takes place. The open intervals must be large enough to allow significant airflow to optimize the remediation, but small enough to provide a discrete extraction segment for targeting regions within the subsurface. The open intervals must also provide means for sampling soil gas and monitoring induced vacuum. The open intervals in the subsurface may be provided through vertical wells, cone penetrometer (CPT) wells, or angled/horizontal wells.

It is essential that there are enough wells, spaced appropriately, with open intervals in the needed regions, to provide complete extraction and monitoring coverage of the entire Z-Crib Area. The locations of these wells and open intervals are currently being determined.

The majority of wells in the 200 West Area are vertical wells drilled using the cable tool drilling technology. New vapor extraction wells installed during 1992 and 1993 are completed with either one screened interval above the caliche

zone or with two screened intervals, one above and one below the caliche zone. The screened intervals are selected based on observations during drilling of the geology and contaminant concentrations. A packer is emplaced in the dual-screened wells to isolate the two zones. Most of the wells are completed with 4-in.-diameter stainless steel casing. The cable tool drilling technology for vertical wells can achieve the required depths within the unsaturated and saturated zones and allow some flexibility in choosing screened intervals. However, the costs must be carefully weighed against the benefits derived. According to the Government Accounting Office, the average cost between May and December 1991 to install vertical wells at the Hanford Site in areas that are contaminated by hazardous and/or radioactive materials and also require chemical sampling was \$2,069/ft (GAO 1993).

The CPT wells are a promising lower cost alternative for partial fulfillment of the capabilities of vertical wells. Although detailed cost information is not available, the CPT wells cost in the range of \$100 to \$300/ft to install at the Hanford Site. The CPT well is a 1-in. inside diameter rod that is pushed down into the subsurface until it reaches the desired depth or refusal. The wells can be outfitted with holes drilled into the rod in the interval to be open in the subsurface. Several CPT wells have been installed in the Z-Crib Area in this manner (Richterich 1993). Testing of one CPT well for functioning as an extraction well produced about 60 ft³/min flow at 9.5 in. Hg vacuum. Although this is considerably less flow than some of the 4-in. diameter vertical wells, it is adequate to provide a useful function for controlling flow in the subsurface. This same type of well can also be used for air injection, tracer gas injection, and monitoring of induced vacuum in the subsurface. One limitation to the use of the CPT to install vapor extraction wells is that the maximum depth it has reached in the Z-Crib area is less than 120 ft (i.e., above the caliche) (Richterich 1993). It is recommended that consideration be given to implementation of this technology where applicable.

One angled well was installed on the north side of the 216-Z-9 Trench Area using the sonic drilling technology in 1993. It was drilled at a 45° angle under a parking lot into an area that is believed to have high concentrations of carbon tetrachloride. The ability to angle under the parking lot allowed access to an area that may have been much more difficult to remediate without the direct extraction capability of an open interval. It is recommended that more consideration be given to the utilization of angled wells and horizontal wells.

1.1.2 Vacuum Monitoring Wells

The VES functions by inducing a vacuum in the subsurface. To determine those areas of the subsurface that are under vacuum and thus are being remediated, it is necessary to monitor the vacuum at outlying wells. However, it has been documented that wells sealed to ambient air will also be influenced by barometric pressure waves transmitting through the subsurface (Rohay et al. 1993). Therefore, it is necessary to understand the effects that changes in the barometric pressure relative to changes in the induced vacuum have on each monitoring well. The wellfield at the 216-Z-1A Tile Field is currently outfitted with pressure transducers to provide information regarding these effects. Wherever feasible, pressure transducers should be added to all of the wells in the Z-Crib Area that may be used as vacuum monitoring wells.

1.2 STRATEGY FOR SUBSURFACE AIRFLOW

The typical strategy for soil vapor extraction is to maximize the mass flux of the contamination out of the subsurface. The maximum venting efficiency is obtained when airflow is maintained through areas of contamination.

If the extraction system is configured so that the air flows past a contaminated zone rather than through it, the rate of contaminant removal is controlled by the rate of diffusion of vapors into the zone being actively vented. In this situation, there may be a high initial rate of removal. However, as the soil vapors in equilibrium are extracted, the rate of removal quickly falls to a diffusion controlled rate.

The volume of soils in the unsaturated zone of the Z-Crib Area is too large to put all the soils under extraction at one time. The total capacity of the present extraction units is about 3,000 ft³/min at 137 in. H₂O vacuum, which is sufficient to address the soils underlying the three disposal sites. However, the Z-Crib Area encompasses a volume of soils much larger than the disposal sites only. It is thus necessary to extract only from those areas that best meet the purpose of the expedited response action (ERA).

The purpose of the ERA is to prevent, or at least minimize, further migration of the carbon tetrachloride contamination from the unsaturated soils to uncontaminated areas (DOE-RL 1991). This does not necessarily mean it is essential to remove the greatest amount of carbon tetrachloride in the least amount of time. It does mean that those areas surrounding the carbon tetrachloride vapor plume must be addressed by the vapor extraction pumping. This may or may not result in insignificant levels of carbon tetrachloride removed from the subsurface. However, removing large quantities of carbon tetrachloride does contribute to the overall reduction in potential carbon tetrachloride migration by reducing the source.

During the initial stages of extraction, while carbon tetrachloride is in equilibrium or near equilibrium concentrations in the subsurface, extraction over a wide area probably best addresses the purpose of the ERA by reducing the overall concentration of carbon tetrachloride in the subsurface. As the process becomes volatilization-rate limited and diffusion-rate limited, more specific regions within the subsurface must be addressed.

The execution of this strategy will not result in the removal of the greatest amount of carbon tetrachloride in the least amount of time. It will result in some carbon tetrachloride removal and achievement of the ERA purpose. It will also contribute to the long-term remediation of the unsaturated soils of the Z-Crib Area.

1.3 STRATEGY FOR RATE OF EXTRACTION

Typical soil vapor extraction proceeds as follows.

- The system begins extracting soil vapor from the subsurface and the contaminant level in the extracted vapor slowly rises after a few hours or days. This is because the extraction well is not placed exactly in the highest zone of contamination. After a period of operation, the center of the plume tends to get pulled to the

extraction well and the contaminant level in the extracted soil vapor reaches its maximum.

- After operating for a few days to a few weeks, the resistance to flow drops and the same flow rate can be achieved with a lower vacuum. This is a result of moisture removal from the subsurface and the opening of preferential pathways for flow.
- After operating for a few days to a few months, the contaminant level in the extracted vapor has fallen off to a slight fraction of its maximum level. This is caused by the relatively fast advective extraction of VOCs from the regions of higher permeability soils. The regions of lower permeability soils do not get much airflow, resulting in a diffusion-rate limited extraction process.
- At this point in a typical operation, extraction processes are terminated and the subsurface is considered remediated. However, a restart of the operation a few weeks to a few months later demonstrates extracted vapor concentrations approaching that of the original level. This is due to the re-establishment of the equilibrium concentrations because of diffusion and advection.
- Because of this re-elevated contaminant level phenomenon, two basic strategies have emerged. One strategy involves "periodic pumping" of different wells, changing wells each time the extracted vapor concentration falls off to some established level. The other strategy is continual pumping of the extraction wells, with the extraction rate for each well tied to its extracted vapor concentration. Either of these strategies can be used to eventually achieve the remediation objectives for the subsurface.

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APPENDIX E
DISCUSSION REGARDING WELLFIELD MODIFICATIONS

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1.0 DISCUSSION REGARDING WELLFIELD MODIFICATIONS

This discussion centers around the strategy utilized for the recommended wellfield modifications. The objectives for modifying the existing wellfield are to (1) increase the ability to control flow in the subsurface, (2) provide increased coverage of the subsurface areas requiring extraction of VOC, (3) allow an increase in the rate of soil-gas extraction, thus reducing the total time for site remediation, (4) increase the number of subsurface monitoring locations, and (5) improve the potential of the wellfield to be used effectively for the full-term remediation of the site.

For this phase of modifications, changes were considered only to existing wells in the Z-Crib Area (Figure 3-1). The modifications consist of increases in the length of open intervals. The installation of new wells was not considered, though it is clear from the figures showing the areas of influence (Figures 3-2 through 3-9) that new wells may eventually be required to allow extraction from zones unattainable with existing wells, particularly those zones below the caliche layer.

Maximizing flow from each of the extraction wells is an important consideration for improving the effectiveness of the VES operations. However, it should be noted that in attempting to increase the flow through a well by increasing the length of the open interval, there is a trade-off with the loss of control of flow in the subsurface. The longer the open interval, the less capable the well is of providing extraction or injection at a specific horizon. This is a problem when control of the flow in the subsurface is necessary to address a specific layer, such as a low-permeability zone.

The ability to control flow and understand soil-gas movement are dependent upon access to the subsurface through wells with open intervals. Tables 3-1 and 3-2 describe the existing wells with open intervals in the subsurface above and below the caliche, respectively. The column in the tables listing maximum flow gives the actual measured values (where available) or an estimated maximum flow based on well construction, known stratigraphy, and mechanical impedance to flow.

The area of influence is a function of the flow from a well. To a point, increasing the flow from a well increases the area of influence of the well, thus effecting an increased zone of remediation.

Many factors have a bearing on the maximum flow from a well. Some of these factors include length of well open interval, percent of well casing open, permeability of the formation, and mechanical impedances to flow (e.g., pressure drop due to small-diameter pipe). Table E-1 shows the maximum flow at 10 in. Hg vacuum through various pipe diameters as a function of pipe length. This table points out the limitations to flow that exist due to the size of some of the nested piezometers (typically 1.5 or 2-in. diameter) and the CPT wells (1-in. diameter). For instance, regardless of the length of screened interval and the permeability of the formation, a 1.5-in. diameter piezometer will not allow flow of over 200 ft³/min.

This trade-off between maximizing flow and controlling flow in discrete intervals must be embraced in the context of site-specific stratigraphy and known soil-gas extraction capabilities. Greatly simplified, the Z-Crib Area subsurface is made up of zones of varying permeability consisting of gravels, sands, and

silts down to groundwater, which is about 200 ft below land surface. At about 120 to 130 ft below land surface, the caliche layer forms a relatively impermeable zone. These horizons and varying permeabilities present a challenge to extracting the VOC effectively from all the soils. They also greatly affect the extraction flow rates, zones from which soil gas is most effectively removed, and areas of influence.

Site operational data (Tables 3-11 and 3-12) demonstrate the wide range of extraction flow rates from wells, not necessarily as a function of open interval length. This makes it very difficult to establish a rate of flow per length of open interval. Two examples from a characterization test illustrate this point: (1) Well 229-W18-150 upper interval (65 to 70 ft below top of casing [toc]; 5 ft open interval) had a flow rate of 32 ft³/min at 131 in. H₂O vacuum and the lower interval (113 to 118 ft below toc; 5 ft open interval) had a flow rate of 84 ft³/min at 132 in. H₂O vacuum. (2) Well 299-W18-10 (open interval 180 to 211 ft below toc; 31 ft long) had a flow rate of 80 ft³/min at 130 in. H₂O vacuum and Well 299-W18-97 (open interval 60 to 72 ft below toc; 12 ft long) had a flow rate of 312 ft³/min at 134 in. H₂O vacuum.

The differences in the flow rates can primarily be assigned to differences in the permeabilities of the soils in the vicinity of the two open intervals (though the actual percentage of open area resulting from casing perforation is an unknown and potentially significant factor). Tables 3-8, 3-9, and 3-10 show the effects on flow rate as a function of soil permeability, length of open interval, and diameter of well.

It is evident that a rate of flow per length of open interval is difficult to establish for the wells in the Z-Crib Area. However, it is possible to establish an open interval length that can be reasonably expected to provide adequate flow given the constraints of varying permeabilities and controlling flow in the subsurface. That length has been determined to be 30 ft.

The 30-ft-long open interval was derived from consideration of many factors, including the operational data and the typical widths of soil horizons. This length should not be viewed as an absolute, but as a reasonable length to use toward wellfield optimization. Operational data obtained after modification of the existing wellfield will provide direction for future wellfield modification recommendations.

The following section of this appendix describes the recommended modifications of the existing wellfield, including changes to specific wells and open intervals and provides the reasoning for the selections.

2.0 WELLS TO BE MODIFIED FOR EXTRACTION

The selections of specific existing wells and open intervals for modifications were made with consideration of several factors, including (1) maximizing flow rate while controlling flow in the subsurface, (2) locating open intervals to function effectively with extraction from low-permeability layers, and (3) protecting the groundwater from VOC-laden soil gas.

Tables 3-1 and 3-2 describe the existing wellfield. Figures 3-2, 3-3, 3-4, and 3-5 show the areas of influence of the existing wellfield (see Section 3.1 for a discussion of the areas of influence). It is clear from the figures that some relatively large areas cannot be addressed by the existing wellfield.

The recommended modifications to the existing wellfield are described in Tables 3-3 and 3-4. Tables 3-5 and 3-6 describe the wellfield after modifications. The predicted areas of influence of the wellfield following modification are shown in Figures 3-6, 3-7, 3-8, and 3-9.

The following sections discuss the recommended modifications to specific wells and open intervals, provide reasoning for the selections, and describe some of the construction detail required because of the modifications.

Note: For Sections 2.1 through 2.6, the following nomenclature is used:

Ø = casing diameter, inches
 dtb = present depth to bottom of well, feet below top of casing
 poi = present open interval(s), feet below top of casing

Depths referenced to ground surface are followed by "bgs" (below ground surface).

2.1 WELLS IN THE 216-Z-1A/18 WELLFIELD ABOVE THE CALICHE

Well 299-W18-6 (Ø = 8; dtb = 200; poi = 190-201)

- Selected to provide coverage of area not otherwise accessible.
- Perforate from 100 to 130 ft below toc for present extraction and future focus on caliche layer.
- Predicted maximum flow from interval is 200 ft³/min.
- Also to be used for extraction below the caliche. A 2-in. Ø piezometer with packer should be used to provide access to this open interval.

Well 299-W18-7 (Ø = 8; dtb = 207; poi = 190-203)

- Not selected for use because adequate coverage of area exists based on present extraction strategies.

Well 299-W18-9 ($\varnothing$ = 6; dtb = 217; poi = 180-211)

- Not selected for use because adequate coverage of area exists based on present extraction strategies.

Well 299-W18-10 ($\varnothing$ = 6; dtb = 212; poi = 180-211)

- Selected to provide coverage of area not otherwise accessible.
- Perforate from 100 to 130 ft below toc for present extraction and future focus on caliche layer.
- Predicted maximum flow from interval is 300 ft³/min.
- Also to be used for extraction below the caliche. A 2-in. $\varnothing$ piezometer with packer should be used to provide access at the surface for both open intervals.

Well 299-W18-11 ($\varnothing$ = 6; dtb = 211; poi = 180-211)

- Selected to provide coverage of area not otherwise accessible.
- Perforate from 100 to 130 ft below toc for present extraction and future focus on caliche layer.
- Predicted maximum flow from interval is 300 ft³/min.
- Also to be used for extraction below the caliche. A 2-in. $\varnothing$ piezometer with packer should be used to provide access at the surface for both open intervals.

Well 299-W18-12 ($\varnothing$ = 6; dtb = 214; poi = 190-211)

- Not selected for use because adequate coverage of area exists based on present extraction strategies.

Well 299-W18-76 ($\varnothing$ = 6; dtb = 19; poi = none)

- Not selected for use because depth to bottom of well is too shallow to be useful based on present extraction strategies.
- Located in area without adequate coverage and may be selected for future use.

Well 299-W18-78 ($\varnothing$ = 6; dtb = 17; poi = none)

- Not selected for use because depth to bottom of well is too shallow to be useful based on present extraction strategies.

- Located in area without adequate coverage and may be selected for future use.

Well 299-W18-81 ($\emptyset$ = 6; dtb = 41; poi = none)

- Not selected for use because depth to bottom of well is too shallow to be useful based on present extraction strategies.
- Located in area without adequate coverage and may be selected for future use.

Well 299-W18-82 ($\emptyset$ = 6; dtb = 146; poi = none)

- Not selected for use because coverage in this area is not required based on present extraction strategies.

Well 299-W18-85 ($\emptyset$ = 6; dtb = 148; poi = none)

- Located in area without adequate coverage and may be selected for future use.

Well 299-W18-86 ($\emptyset$ = 6; dtb = 147; poi = none)

- Not selected for use because adequate coverage of area exists based on present extraction strategies.

Well 299-W18-87 ($\emptyset$ = 6; dtb = 148; poi = 33-38, 65-70, & 125-130)

- Present configuration of well provides adequate extraction capabilities based on present extraction strategies.

Well 299-W18-88 ($\emptyset$ = 6; dtb = 150; poi = none)

- Located in area without adequate coverage and may be selected for future use.

Well 299-W18-89 ($\emptyset$ = 6; dtb = 150; poi = none)

- Selected to provide coverage of area not otherwise accessible.
- Perforate from 100 to 130 ft below toc for present extraction and future focus on caliche layer.
- Predicted maximum flow from interval is 300 ft³/min.
- Only interval to be used, so extraction pipe will remain 6-in $\emptyset$.

Well 299-W18-93 ($\emptyset$ = 6; dtb = 138; poi = 63-77)

- Present configuration of well provides adequate extraction capabilities based on present extraction strategies.

Well 299-W18-94 ($\emptyset$ = 6; dtb = 83; poi = 68-78)

- Present configuration of well provides adequate extraction capabilities based on present extraction strategies.

Well 299-W18-95 ($\emptyset$ = 6; dtb = 77; poi = none)

- Not selected for use because coverage in this area is not required based on present extraction strategies.

Well 299-W18-96 ($\emptyset$ = 2; dtb = 132 bgs; poi = 122-132 bgs)

- Present configuration of well provides adequate extraction capabilities based on present extraction strategies.

Well 299-W18-97 ($\emptyset$ = 6; dtb = 82; poi = 63-75)

- Present configuration of well provides adequate extraction capabilities based on present extraction strategies.

Well 299-W18-98 ($\emptyset$ = 6; dtb = 75; poi = 66-77)

- Present configuration of well provides adequate extraction capabilities based on present extraction strategies.

Well 299-W18-99 ($\emptyset$ = 3; dtb = 129; poi = 93-103)

- Present configuration of well provides adequate extraction capabilities based on present extraction strategies.

Well 299-W18-149 ($\emptyset$ = 6; dtb = 75; poi = none)

- Located in area without adequate coverage and may be selected for future use.

Well 299-W18-150 ($\emptyset$ = 6; dtb = 128; poi = 65-70, 85-90, & 113-118)

- Present configuration of well provides adequate extraction capabilities based on present extraction strategies.

Well 299-W18-158 ($\emptyset$ = 6; dtb = 131; poi = 75-80, 89-94, & 119-124)

- Selected to provide coverage of area not otherwise accessible.
- Perforate from 80 to 89 ft below toc to connect two present open intervals to increase flow rate.
- Predicted maximum flow from new interval is 150 ft³/min.
- A 1.5-in. Ø piezometer with packer should be used to provide access at the surface for both open intervals.

Well 299-W18-159 (Ø = 6; dtb = 130; poi = 113-120)

- Selected to provide improved coverage of area.
- Perforate from 90 to 113 ft below toc to lengthen present open interval to flow rate.
- Predicted maximum flow from new interval is 300 ft³/min.
- Only interval to be used, so extraction pipe will remain 6-in. Ø.

Well 299-W18-163 (Ø = 8; dtb = 163; poi = 69.5-79.5, 92.5-99.5, & 114.5-119.5)

- Selected to provide improved coverage of area.
- Perforate from 54.5 to 79.5 and 92.5 to 119.5 ft below toc to lengthen the upper interval and combine the two lower intervals.
- Perforating includes reperforation of existing intervals to improve flow.
- A 2-in. piezometer with packer should be used to provide access at the surface for both open intervals.
- Predicted maximum flow from each interval is 300 ft³/min.

Well 299-W18-164 (Ø = 6; dtb = 146; poi = none)

- Not selected for use because adequate coverage of area exists based on present extraction strategies.

Well 299-W18-165 (Ø = 6; dtb = 128; poi = 122-127)

- Selected to provide coverage of area not otherwise accessible.
- Perforate from 97 to 122 ft below toc to increase perforated interval from 5 to 25 ft.
- Predicted maximum flow from interval is 300 ft³/min.
- Only interval to be used, so extraction pipe will remain 6-in Ø.

Well 299-W18-166 ($\varnothing$ = 6; dtb = 137; poi = 124-129)

- Selected to provide more complete coverage of critical area.
- Perforate from 99 to 124 ft below toc to increase perforated interval from 5 to 25 ft.
- Predicted maximum flow from interval is 300 ft³/min.
- Only interval to be used, so extraction pipe will remain 6-in $\varnothing$.

Well 299-W18-167 ($\varnothing$ = 8; dtb = 8; poi = 114-119)

- Selected to provide coverage of area not otherwise accessible.
- Perforate from 89 to 114 ft below toc to increase perforated interval from 5 to 30 ft.
- Predicted maximum flow from interval is 300 ft³/min.
- Only interval to be used, so extraction pipe will remain 8-in $\varnothing$.

Well 299-W18-168 ($\varnothing$ = 8; dtb = 131; poi = 118-123)

- Present configuration of well provides adequate extraction capabilities based on present extraction strategies.

Well 299-W18-169 ($\varnothing$ = 8; dtb = 132; poi = none)

- Selected to provide coverage of area not otherwise accessible.
- Perforate from 102 to 132 ft below toc for present extraction and future focus on caliche layer.
- Predicted maximum flow from interval is 300 ft³/min.
- Only interval to be used, so extraction pipe will remain 8-in $\varnothing$.

Well 299-W18-170 ($\varnothing$ = 6; dtb = 30; poi = none)

- Not selected for use because depth to bottom of well is too shallow to be useful based on present extraction strategies.

Well 299-W18-171 ($\varnothing$ = 8; dtb = 127; poi = 20-25, 57-77, & 115-130)

- Present configuration of well provides adequate extraction capabilities based on present extraction strategies.

Well 299-W18-173 ($\emptyset$ = 8; dtb = 51; poi = none)

Not selected for use because depth to bottom of well is too shallow to be useful based on present extraction strategies.

Well 299-W18-174 ($\emptyset$ = 4; dtb = 126 bgs; poi = 106-126 bgs)

Not selected for use because depth to bottom of well is too shallow to be useful based on present extraction strategies.

Well 299-W18-175 ($\emptyset$ = 6; dtb = 130; poi = 87-94 & 115-120)

Present configuration of well provides adequate extraction capabilities based on present extraction strategies.

Well 299-W18-246 ($\emptyset$ = 4; dtb = 175 bgs; poi = 120-130 & 165-175 bgs)

Present configuration of well provides adequate extraction capabilities based on present extraction strategies.

Well 299-W18-247 ($\emptyset$ = 4; dtb = 172 bgs; poi = 119-129 & 162-172 bgs)

Present configuration of well provides adequate extraction capabilities based on present extraction strategies.

Well 299-W18-248 ($\emptyset$ = 4; dtb = 139 bgs; poi = 123-139 bgs)

Present configuration of well provides adequate extraction capabilities based on present extraction strategies.

Well 299-W18-249 ($\emptyset$ = 4; dtb = 137 bgs; poi = 122-137 bgs)

Present configuration of well provides adequate extraction capabilities based on present extraction strategies.

CPT-2 ($\emptyset$ = 1; dtb = 37 bgs; poi = 34-37 bgs)

There is no available technology for modifying cone penetrometer wells.

CPT-20 ($\emptyset$ = 1; dtb = 84 bgs; poi = 71-84 bgs)

There is no available technology for modifying cone penetrometer wells.

2.2 WELLS IN THE 216-Z-12 WELLFIELD ABOVE THE CALICHE

Well 299-W18-1 ($\varnothing = 8$; dtb = 381; poi = 195-210)

- Selected to provide coverage of area not otherwise accessible.
- Perforate from 100 to 130 ft below toc for present extraction and future focus on caliche layer.
- Predicted maximum flow from interval is 300 ft³/min.
- Also to be used for extraction below the caliche. A 2-in. $\varnothing$ piezometer with packer should be used to provide access at the surface for both open intervals.

Well 299-W18-2 ($\varnothing = 8$; dtb = 244; poi = 200-208)

- Selected to provide coverage of area not otherwise accessible.
- Perforate from 100 to 130 ft below toc for present extraction and future focus on caliche layer.
- Predicted maximum flow from interval is 300 ft³/min.
- Also to be used for extraction below the caliche. A 2-in. $\varnothing$ piezometer with packer should be used to provide access at the surface for both open intervals.

Well 299-W18-4 ($\varnothing = 8$; dtb = 246; poi = 200-211)

- Selected to provide coverage of area not otherwise accessible.
- Perforate from 100 to 130 ft below toc for present extraction and future focus on caliche layer.
- Predicted maximum flow from interval is 300 ft³/min.
- Also to be used for extraction below the caliche. A 2-in. $\varnothing$ piezometer with packer should be used to provide access at the surface for both open intervals.

Well 299-W18-5 ($\varnothing = 8$; dtb = 272; poi = 195-211)

- Located in area without adequate coverage and may be selected for future use.

Well 299-W18-8 ($\varnothing = 6$; dtb = 77; poi = none)

- Located in area without adequate coverage and may be selected for future use.

Well 299-W18-24 ($\emptyset$ = 4; dtb = 235; poi = 205-213)

- Not selected for use because other uses of well, regulatory limitations, or physical restriction prevent use.

Well 299-W18-71 ($\emptyset$ = 6; dtb = 20; poi = none)

- Not selected for use because depth to bottom of well is too shallow to be useful based on present extraction strategies.

Well 299-W18-72 ($\emptyset$ = 6; dtb = 20; poi = none)

- Not selected for use because depth to bottom of well is too shallow to be useful based on present extraction strategies.

Well 299-W18-73 ($\emptyset$ = 6; dtb = 15; poi = none)

- Not selected for use because depth to bottom of well is too shallow to be useful based on present extraction strategies.

Well 299-W18-74 ($\emptyset$ = 6; dtb = 18; poi = none)

- Not selected for use because depth to bottom of well is too shallow to be useful based on present extraction strategies.

Well 299-W18-151 ($\emptyset$ = 10; dtb = 15; poi = none)

- Not selected for use because depth to bottom of well is too shallow to be useful based on present extraction strategies.

Well 299-W18-152 ($\emptyset$ = 8; dtb = 118; poi = none)

- Selected to provide coverage of area not otherwise accessible.
- Perforate from 88 to 118 ft below toc for present extraction.
- Predicted maximum flow from interval is 300 ft³/min.
- Only interval to be used, so extraction pipe will remain 8-in $\emptyset$.

Well 299-W18-153 ($\emptyset$ = 8; dtb = 110; poi = none)

- Selected to provide coverage of area not otherwise accessible.
- Perforate from 80 to 110 ft below toc for present extraction.
- Predicted maximum flow from interval is 300 ft³/min.

Only interval to be used, so extraction pipe will remain 8-in Ø.

Well 299-W18-154 (Ø = 10; dtb = 17; poi = none)

Not selected for use because depth to bottom of well is too shallow to be useful based on present extraction strategies.

Well 299-W18-155 (Ø = 10; dtb = 17; poi = none)

Not selected for use because depth to bottom of well is too shallow to be useful based on present extraction strategies.

Well 299-W18-156 (Ø = 10; dtb = 25; poi = none)

Not selected for use because depth to bottom of well is too shallow to be useful based on present extraction strategies.

Well 299-W18-157 (Ø = 8; dtb = 110; poi = none)

- Selected to provide coverage of area not otherwise accessible.
- Perforate from 80 to 110 ft below toc for present extraction.
- Predicted maximum flow from interval is 300 ft³/min.
- Only interval to be used, so extraction pipe will remain 8-in Ø.

Well 299-W18-252 (Ø = 4; dtb = 185 bgs; poi = 113-133 & 165-185 bgs)

- Present configuration of well provides adequate extraction capabilities based on present extraction strategies.

CPT-4 (Ø = 1; dtb = 103 bgs; poi = 90-103 bgs)

- There is no available technology for modifying cone penetrometer wells.

CPT-10 (Ø = 1; dtb = 107 bgs; poi = 94-107 bgs)

- There is no available technology for modifying cone penetrometer wells.

2.3 WELLS IN THE 216-Z-9 WELLFIELD ABOVE THE CALICHE

Well 299-W15-5 (Ø = 8; dtb = 599; poi = 173-217)

Not selected for use because other uses of well, regulatory limitations, or physical restriction prevent use.

Well 299-W15-6 ($\varnothing$ = 6; dtb = 304; poi = 175-190)

- Selected to provide coverage of area not otherwise accessible.
- Perforate from 75 to 100 ft below toc for present extraction.
- Predicted maximum flow from interval is 200 ft³/min.
- Also to be used for extraction below the caliche. A 2-in. $\varnothing$ piezometer with packer should be used to provide access at the surface for both open intervals.

Well 299-W15-8 ($\varnothing$ = 8; dtb = 203; poi = none)

- Selected to provide coverage of area not otherwise accessible.
- Perforate from 90 to 115 ft below toc for present extraction.
- Predicted maximum flow from interval is 200 ft³/min.
- Also to be used for extraction below the caliche. A 2-in. $\varnothing$ piezometer with packer should be used to provide access at the surface for both open intervals.

Well 299-W15-9 ($\varnothing$ = 8; dtb = 191; poi = 186-189)

- Selected to provide coverage of area not otherwise accessible.
- Perforate from 90 to 115 ft below toc for present extraction.
- Predicted maximum flow from interval is 200 ft³/min.
- Also to be used for extraction below the caliche. A 2-in. $\varnothing$ piezometer with packer should be used to provide access at the surface for both open intervals.

Well 299-W15-82 ($\varnothing$ = 8; dtb = 98 bgs; poi = 73-88 bgs)

- Present configuration of well provides adequate extraction capabilities based on present extraction strategies.

Well 299-W15-84 ($\varnothing$ = 8; dtb = 106 bgs; poi = 75-90 bgs)

- Selected to provide coverage of area not otherwise accessible.
- Perforate from 90 to 100 ft below toc to extend open interval from 15 to 25 ft.

- Predicted maximum flow from interval is 200 ft³/min.
- Only interval to be used, so extraction pipe will remain 8-in Ø.

Well 299-W15-85 (Ø = 8; dtb = 103 bgs; poi = 83-98 bgs)

- Present configuration of well provides adequate extraction capabilities based on present extraction strategies.

Well 299-W15-86 (Ø = 8; dtb = 140; poi = none)

- Selected to provide coverage of area not otherwise accessible.
- Perforate from 110 to 140 ft below toc for present extraction and future focus on caliche layer.
- Predicted maximum flow from interval is 250 ft³/min.
- Only interval to be used, so extraction pipe will remain 8-in Ø.

Well 299-W15-95 (Ø = 8; dtb = 100 bgs; poi = 83-98 bgs)

- Selected to provide coverage of area not otherwise accessible.
- Perforate from 73 to 83 ft below toc to increase open interval from 15 to 25 ft.
- Predicted maximum flow from interval is 250 ft³/min.
- Only interval to be used, so extraction pipe will remain 8-in Ø.

Well 299-W15-216 (Ø = 4; dtb = 184 bgs; poi = 70-80 & 175-185 bgs)

- Present configuration of well provides adequate extraction capabilities based on present extraction strategies.

Well 299-W15-217 (Ø = 4; dtb = 122 bgs; poi = 106-121 bgs)

- Present configuration of well provides adequate extraction capabilities based on present extraction strategies.

Well 299-W15-218 (Ø = 4; dtb = 196 bgs; poi = 99-114 & 180-195 bgs)

- Present configuration of well provides adequate extraction capabilities based on present extraction strategies.

Well 299-W15-219 (Ø = 4; dtb = 182 bgs; poi = 87-102 & 167-182 bgs)

Present configuration of well provides adequate extraction capabilities based on present extraction strategies.

Well 299-W15-220 ($\varnothing$ = 4; dtb = 185 bgs; poi = 80-95 & 155-170 bgs)

Present configuration of well provides adequate extraction capabilities based on present extraction strategies.

Well 299-W15-223 (45° well; $\varnothing$ = 3.5; dtb = 117 vertical bgs; poi = 103-117 vertical ft bgs [20 ft long])

Present configuration of well provides adequate extraction capabilities based on present extraction strategies.

CPT-3 ($\varnothing$ = 1; dtb = 52 bgs; poi = 39-52 bgs)

There is no available technology for modifying cone penetrometer wells.

CPT-5 ($\varnothing$ = 1; dtb = 48 bgs; poi = 35-48 bgs)

There is no available technology for modifying cone penetrometer wells.

CPT-8 ($\varnothing$ = 1; dtb = 113 bgs; poi = 100-113 bgs)

There is no available technology for modifying cone penetrometer wells.

CPT-11 ($\varnothing$ = 1; dtb = 77 bgs; poi = 64-77 bgs)

There is no available technology for modifying cone penetrometer wells.

CPT-12 ($\varnothing$ = 1; dtb = 49 bgs; poi = 36-49 bgs)

There is no available technology for modifying cone penetrometer wells.

CPT-19 ($\varnothing$ = 1; dtb = 49 bgs; poi = 36-49 bgs)

There is no available technology for modifying cone penetrometer wells.

CPT-21 ($\varnothing$ = 1; dtb = 97 bgs; poi = 84-97 bgs)

- There is no available technology for modifying cone penetrometer wells.

2.4 WELLS IN THE 216-Z-1A/18 WELLFIELD BELOW THE CALICHE

Well 299-W18-6 ($\emptyset$ = 8; dtb = 200; poi = 190-201)

- Present configuration of well provides adequate extraction capabilities based on present extraction strategies.

Well 299-W18-7 ($\emptyset$ = 8; dtb = 207; poi = 190-203)

- Selected to provide coverage of area not otherwise accessible.
- Perforate from 180 to 190 ft below toc to increase open interval from 13 to 23 ft.
- Predicted maximum flow from interval is 250 ft³/min.
- Only interval to be used, so extraction pipe will remain 8-in $\emptyset$.

Well 299-W18-9 ($\emptyset$ = 6; dtb = 217; poi = 180-211)

- Present configuration of well provides adequate extraction capabilities based on present extraction strategies.

Well 299-W18-10 ($\emptyset$ = 6; dtb = 212; poi = 180-211)

- Selected to provide coverage of area not otherwise accessible.
- Perforate from 170 to 180 ft below toc to increase the open interval from 31 to 41 ft to increase the flow.
- Predicted maximum flow from interval is 150 ft³/min (from 80 ft³/min).
- Also to be used for extraction above the caliche. A 2-in. $\emptyset$ piezometer with packer should be used to provide access at the surface for both open intervals.

Well 299-W18-11 ($\emptyset$ = 6; dtb = 211; poi = 180-211)

- Present configuration of well provides adequate extraction capabilities based on present extraction strategies.

Well 299-W18-12 ($\emptyset$ = 6; dtb = 214; poi = 190-211)

- Selected to provide coverage of area not otherwise accessible.

- Perforate from 180 to 190 ft below toc to increase open interval from 21 to 31 ft.
- Predicted maximum flow from interval is 100 ft³/min.
- Only interval to be used, so extraction pipe will remain 6-in Ø.

Well 299-W18-76 (Ø = 6; dtb = 19; poi = none)

- Not selected for use because depth to bottom of well is too shallow to be useful based on present extraction strategies.

Well 299-W18-78 (Ø = 6; dtb = 17; poi = none)

- Not selected for use because depth to bottom of well is too shallow to be useful based on present extraction strategies.

Well 299-W18-81 (Ø = 6; dtb = 41; poi = none)

- Not selected for use because depth to bottom of well is too shallow to be useful based on present extraction strategies.

Well 299-W18-82 (Ø = 6; dtb = 146; poi = none)

- Not selected for use because depth to bottom of well is too shallow to be useful based on present extraction strategies.

Well 299-W18-85 (Ø = 6; dtb = 148; poi = none)

- Not selected for use because depth to bottom of well is too shallow to be useful based on present extraction strategies.

Well 299-W18-86 (Ø = 6; dtb = 147; poi = none)

- Not selected for use because depth to bottom of well is too shallow to be useful based on present extraction strategies.

Well 299-W18-87 (Ø = 6; dtb = 148; poi = 33-38, 65-70, & 125-130)

- Not selected for use because depth to bottom of well is too shallow to be useful based on present extraction strategies.

Well 299-W18-88 (Ø = 6; dtb = 150; poi = none)

- Not selected for use because depth to bottom of well is too shallow to be useful based on present extraction strategies.

Well 299-W18-89 ($\emptyset$ = 6; dtb = 150; poi = none)

- Not selected for use because depth to bottom of well is too shallow to be useful based on present extraction strategies.

Well 299-W18-93 ($\emptyset$ = 6; dtb = 138; poi = 63-77)

- Not selected for use because depth to bottom of well is too shallow to be useful based on present extraction strategies.

Well 299-W18-94 ($\emptyset$ = 6; dtb = 83; poi = 68-78)

- Not selected for use because depth to bottom of well is too shallow to be useful based on present extraction strategies.

Well 299-W18-95 ($\emptyset$ = 6; dtb = 77; poi = none)

- Not selected for use because depth to bottom of well is too shallow to be useful based on present extraction strategies.

Well 299-W18-96 ($\emptyset$ = 2; dtb = 132 bgs; poi = 122-132 bgs)

- Not selected for use because depth to bottom of well is too shallow to be useful based on present extraction strategies.

Well 299-W18-97 ($\emptyset$ = 6; dtb = 82; poi = 63-75)

- Not selected for use because depth to bottom of well is too shallow to be useful based on present extraction strategies.

Well 299-W18-98 ($\emptyset$ = 6; dtb = 75; poi = 66-77)

- Not selected for use because depth to bottom of well is too shallow to be useful based on present extraction strategies.

Well 299-W18-99 ($\emptyset$ = 3; dtb = 129; poi = 93-103)

- Not selected for use because depth to bottom of well is too shallow to be useful based on present extraction strategies.

Well 299-W18-149 ($\emptyset$ = 6; dtb = 75; poi = none)

- Not selected for use because depth to bottom of well is too shallow to be useful based on present extraction strategies.

Well 299-W18-150 ($\emptyset$ = 6; dtb = 128; poi = none)

- Not selected for use because depth to bottom of well is too shallow to be useful based on present extraction strategies.

Well 299-W18-158 ($\emptyset$ = 6; dtb = 131; poi = 75-80, 89-94, & 119-124)

- Not selected for use because depth to bottom of well is too shallow to be useful based on present extraction strategies.

Well 299-W18-159 ($\emptyset$ = 6; dtb = 130; poi = 113-120)

- Not selected for use because depth to bottom of well is too shallow to be useful based on present extraction strategies.

Well 299-W18-163 ($\emptyset$ = 8; dtb = 163; poi = 69.5-79.5, 92.5-99.5, & 114.5-119.5)

- Located in area without adequate coverage an may be selected for future use.

Well 299-W18-164 ($\emptyset$ = 6; dtb = 146; poi = none)

- Not selected for use because depth to bottom of well is too shallow to be useful based on present extraction strategies.

Well 299-W18-165 ($\emptyset$ = 6; dtb = 128; poi = 122-127)

- Not selected for use because depth to bottom of well is too shallow to be useful based on present extraction strategies.

Well 299-W18-166 ($\emptyset$ = 6; dtb = 137; poi = 124-129)

- Not selected for use because depth to bottom of well is too shallow to be useful based on present extraction strategies.

Well 299-W18-167 ($\emptyset$ = 8; dtb = 8; poi = 114-119)

- Not selected for use because depth to bottom of well is too shallow to be useful based on present extraction strategies.

Well 299-W18-168 ($\emptyset$ = 8; dtb = 131; poi = 118-123)

- Not selected for use because depth to bottom of well is too shallow to be useful based on present extraction strategies.

Well 299-W18-169 ($\emptyset$ = 8; dtb = 132; poi = none)

Not selected for use because depth to bottom of well is too shallow to be useful based on present extraction strategies.

Well 299-W18-170 ($\emptyset$ = 6; dtb = 30; poi = none)

Not selected for use because depth to bottom of well is too shallow to be useful based on present extraction strategies.

Well 299-W18-171 ($\emptyset$ = 8, dtb = 127; poi = 20-25, 57-77, & 115-130)

Not selected for use because depth to bottom of well is too shallow to be useful based on present extraction strategies.

Well 299-W18-173 ($\emptyset$ = 8; dtb = 51; poi = none)

Not selected for use because depth to bottom of well is too shallow to be useful based on present extraction strategies.

Well 299-W18-174 ($\emptyset$ = 4; dtb = 126 bgs; poi = 106-126 bgs)

Not selected for use because depth to bottom of well is too shallow to be useful based on present extraction strategies.

Well 299-W18-175 ($\emptyset$ = 6; dtb = 130; poi = 87-94 & 115-120)

Not selected for use because depth to bottom of well is too shallow to be useful based on present extraction strategies.

Well 299-W18-246 ($\emptyset$ = 4; dtb = 175 bgs; poi = 120-130 & 165-175 bgs)

Present configuration of well provides adequate extraction capabilities based on present extraction strategies.

Well 299-W18-247 ($\emptyset$ = 4; dtb = 172 bgs; poi = 119-129 & 162-172 bgs)

Present configuration of well provides adequate extraction capabilities based on present extraction strategies.

Well 299-W18-248 ($\emptyset$ = 4; dtb = 139 bgs; poi = 123-139 bgs)

Not selected for use because depth to bottom of well is too shallow to be useful based on present extraction strategies.

Well 299-W18-249 ($\emptyset$ = 4; dtb = 137 bgs; poi = 122-137 bgs)

- Not selected for use because depth to bottom of well is too shallow to be useful based on present extraction strategies.

CPT-2 ($\emptyset$ = 1; dtb = 37 bgs; poi = 34-37 bgs)

- There is no available technology for modifying cone penetrometer wells.

CPT-20 ($\emptyset$ = 1; dtb = 84 bgs; poi = 71-84 bgs)

- There is no available technology for modifying cone penetrometer wells.

2.5 WELLS IN THE 216-Z-12 WELLFIELD BELOW THE CALICHE

Well 299-W18-1 ($\emptyset$ = 8; dtb = 381; poi = 195-210)

- Selected to provide coverage of area not otherwise accessible.
- Perforate from 185 to 195 ft below toc to increase open interval from 5 to 25 ft.
- Predicted maximum flow from interval is 200 ft³/min.
- Also to be used for extraction above the caliche. A 2-in. $\emptyset$ piezometer with packer should be used to provide access at the surface for both open intervals.

Well 299-W18-2 ($\emptyset$ = 8; dtb = 244; poi = 200-208)

- Selected to provide coverage of area not otherwise accessible.
- Perforate from 183 to 200 ft below toc to increase open interval from 8 to 25 ft.
- Predicted maximum flow from interval is 200 ft³/min.
- Also to be used for extraction above the caliche. A 2-in. $\emptyset$ piezometer with packer should be used to provide access at the surface for both open intervals.

Well 299-W18-4 ($\emptyset$ = 8; dtb = 246; poi = 200-211)

- Selected to provide coverage of area not otherwise accessible.
- Perforate from 186 to 200 ft below toc to increase open interval from 11 to 25 ft.
- Predicted maximum flow from interval is 200 ft³/min.

- Also to be used for extraction above the caliche. A 2-in. Ø piezometer with packer should be used to provide access at the surface for both open intervals.

Well 299-W18-5 (Ø = 8; dtb = 272; poi = 195-211)

- Selected to provide coverage of area not otherwise accessible.
- Perforate from 186 to 195 ft below toc to increase open interval from 16 to 25 ft.
- Predicted maximum flow from interval is 200 ft³/min.
- Only interval to be used, so extraction pipe will remain 8-in Ø.

Well 299-W18-8 (Ø = 6; dtb = 77; poi = none)

- Not selected for use because depth to bottom of well is too shallow to be useful based on present extraction strategies.

Well 299-W18-24 (Ø = 4; dtb = 235; poi = 205-213)

- Selected for use "as is" due to other uses of well, regulatory limitations, or physical restrictions.

Well 299-W18-71 (Ø = 6; dtb = 20, poi = none)

- Not selected for use because depth to bottom of well is too shallow to be useful based on present extraction strategies.

Well 299-W18-72 (Ø = 6; dtb = 20; poi = none)

- Not selected for use because depth to bottom of well is too shallow to be useful based on present extraction strategies.

Well 299-W18-73 (Ø = 6; dtb = 15; poi = none)

- Not selected for use because depth to bottom of well is too shallow to be useful based on present extraction strategies.

Well 299-W18-74 (Ø = 6; dtb = 18; poi = none)

- Not selected for use because depth to bottom of well is too shallow to be useful based on present extraction strategies.

Well 299-W18-151 (Ø = 10; dtb = 15; poi = none)

- Not selected for use because depth to bottom of well is too shallow to be useful based on present extraction strategies.

Well 299-W18-152 ($\emptyset$ = 8; dtb = 118; poi = none)

- Not selected for use because depth to bottom of well is too shallow to be useful based on present extraction strategies.

Well 299-W18-153 ($\emptyset$ = 8; dtb = 110; poi = none)

- Not selected for use because depth to bottom of well is too shallow to be useful based on present extraction strategies.

Well 299-W18-154 ($\emptyset$ = 10; dtb = 17; poi = none)

- Not selected for use because depth to bottom of well is too shallow to be useful based on present extraction strategies.

Well 299-W18-155 ($\emptyset$ = 10; dtb = 17; poi = none)

- Not selected for use because depth to bottom of well is too shallow to be useful based on present extraction strategies.

Well 299-W18-156 ($\emptyset$ = 10; dtb = 25; poi = none)

- Not selected for use because depth to bottom of well is too shallow to be useful based on present extraction strategies.

Well 299-W18-157 ($\emptyset$ = 8; dtb = 110; poi = none)

- Not selected for use because depth to bottom of well is too shallow to be useful based on present extraction strategies.

Well 299-W18-252 ($\emptyset$ = 4; dtb = 185 bgs; poi = 113-133 & 165-185 bgs)

- Present configuration of well provides adequate extraction capabilities based on present extraction strategies.

CPT-4 ($\emptyset$ = 1; dtb = 103 bgs; poi = 90-103 bgs)

- There is no available technology for modifying cone penetrometer wells.

CPT-10 ($\emptyset$ = 1; dtb = 107 bgs; poi = 94-107 bgs)

- There is no available technology for modifying cone penetrometer wells.

2.6 WELLS IN THE 216-Z-9 WELLFIELD BELOW THE CALICHE

Well 299-W15-5 ($\varnothing$ = 8; dtb = 599; poi = 173-217)

- Selected for use "as is" due to other uses of well, regulatory limitations, or physical restrictions.

Well 299-W15-6 ($\varnothing$ = 6; dtb = 304; poi = 175-190)

- Selected to provide coverage of area not otherwise accessible.
- Perforate from 160 to 190 ft below toc to increase open interval from 15 to 30 ft.
- Predicted maximum flow from interval is 200 ft³/min.
- Also to be used for extraction above the caliche. A 2-in. $\varnothing$ piezometer with packer should be used to provide access at the surface for both open intervals.

Well 299-W15-8 ($\varnothing$ = 8; dtb = 203; poi = none)

- Selected to provide coverage of area not otherwise accessible.
- Perforate from 167 to 197 ft below toc for protection of groundwater.
- Predicted maximum flow from interval is 200 ft³/min.
- Also to be used for extraction above the caliche. A 2-in. $\varnothing$ piezometer with packer should be used to provide access at the surface for both open intervals.

Well 299-W15-9 ($\varnothing$ = 8; dtb = 191; poi = 186-189)

- Selected to provide coverage of area not otherwise accessible.
- Perforate from 164 to 186 ft below toc to increase open interval from 3 to 25 ft.
- Predicted maximum flow from interval is 200 ft³/min.
- Also to be used for extraction above the caliche. A 2-in. $\varnothing$ piezometer with packer should be used to provide access at the surface for both open intervals.

Well 299-W15-82 ($\varnothing$ = 8; dtb = 98 bgs; poi = 73-88 bgs)

- Not selected for use because depth to bottom of well is too shallow to be useful based on present extraction strategies.

Well 299-W15-84 ($\varnothing$ = 8; dtb = 106 bgs; poi = 75-90 bgs)

Not selected for use because depth to bottom of well is too shallow to be useful based on present extraction strategies.

Well 299-W15-85 ($\varnothing$ = 8; dtb = 103 bgs; poi = 83-98 bgs)

Not selected for use because depth to bottom of well is too shallow to be useful based on present extraction strategies.

Well 299-W15-86 ($\varnothing$ = 8; dtb = 140; poi = none)

Not selected for use because depth to bottom of well is too shallow to be useful based on present extraction strategies.

Well 299-W15-95 ($\varnothing$ = 8; dtb = 100 bgs; poi = 83-98 bgs)

Not selected for use because depth to bottom of well is too shallow to be useful based on present extraction strategies.

Well 299-W15-216 ($\varnothing$ = 4; dtb = 185 bgs; poi = 70-80 & 175-185 bgs)

Present configuration of well provides adequate extraction capabilities based on present extraction strategies.

Well 299-W15-217 ($\varnothing$ = 4; dtb = 122 bgs; poi = 106-121 bgs)

Not selected for use because depth to bottom of well is too shallow to be useful based on present extraction strategies.

Well 299-W15-218 ($\varnothing$ = 4; dtb = 196 bgs; poi = 99-114 & 180-195 bgs)

Present configuration of well provides adequate extraction capabilities based on present extraction strategies.

Well 299-W15-219 ($\varnothing$ = 4; dtb = 182 bgs; poi = 87-102 & 167-182 bgs)

Present configuration of well provides adequate extraction capabilities based on present extraction strategies.

Well 299-W15-220 ($\varnothing$ = 4; dtb = 185 bgs; poi = 80-95 & 155-170 bgs)

Present configuration of well provides adequate extraction capabilities based on present extraction strategies.

Well 299-W15-223 (45° well; $\varnothing$ = 3.5; dtb = 117 vertical bgs; poi = 103-117 vertical ft bgs [20 ft long])

- Not selected for use because depth to bottom of well is too shallow to be useful based on present extraction strategies.

CPT-3 ($\emptyset$ = 1; dtb = 52 bgs; poi = 39-52 bgs)

- There is no available technology for modifying cone penetrometer wells.

CPT-5 ($\emptyset$ = 1; dtb = 48 bgs; poi = 35-48 bgs)

- There is no available technology for modifying cone penetrometer wells.

CPT-8 ($\emptyset$ = 1; dtb = 113 bgs; poi = 100-113 bgs)

- There is no available technology for modifying cone penetrometer wells.

CPT-11 ($\emptyset$ = 1; dtb = 77 bgs; poi = 64-77 bgs)

- There is no available technology for modifying cone penetrometer wells.

CPT-12 ($\emptyset$ = 1; dtb = 49 bgs; poi = 36-49 bgs)

- There is no available technology for modifying cone penetrometer wells.

CPT-19 ($\emptyset$ = 1; dtb = 49 bgs; poi = 36-49 bgs)

- There is no available technology for modifying cone penetrometer wells.

CPT-21 ($\emptyset$ = 1; dtb = 97 bgs; poi = 84-97 bgs)

- There is no available technology for modifying cone penetrometer wells.

Table E-1. Maximum Flow at 10 in. Hg Column Pressure Drop.

Pipe Length (ft)	Pipe Diameter (in.)						
	1	1.5	2	2.5	3	3.5	4
50	70	193	397	693	1,094	1,608	2,245
100	50	137	281	490	773	1,137	1,587
150	41	112	229	400	631	928	1,296
200	35	97	198	347	547	804	1,122
250	31	86	179	310	489	719	1,004
300	29	79	162	283	446	656	916

**DATE
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8/15/94

END