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Wellfield Strategy and Recommendations for the 200 West Area Carbon Tetrachloride Expedited Response Action

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ACRONYMS

bgs	below ground surface
CPT	cone penetrometer
DCA	dichloroethane
DOE	U.S. Department of Energy
Ecology	Washington State Department of Ecology
EPA	U.S. Environmental Protection Agency
ERA	Expedited Response Action
FY	fiscal year
GAC	granular activated carbon
HEPA	high-efficiency particulate air
MIBK	methyl isobutyl ketone
ppm_v	parts per million by volume
PCE	tetrachloroethylene
PFE	pneumatic fracturing extraction
PSVE	passive soil vapor extraction
TCA	trichloroethane
TOC	top of casing
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

If You Know	*Multiply By*	To Get
Length		
inches	25.4	millimeters
inches	2.54	centimeters
feet	0.305	meters
yards	0.914	meters
miles	1.609	kilometers
Area		
sq. inches	6.452	sq. centimeters
sq. feet	0.093	sq. meters
sq. yards	0.0836	sq. meters
sq. miles	2.6	sq. kilometers
acres	0.405	hectares
Mass (weight)		
ounces	28.35	grams
pounds	0.454	kilograms
short ton	0.907	metric ton
Volume		
teaspoons	5	milliliters
tablespoons	15	milliliters
fluid ounces	30	milliliters
cups	0.24	liters
pints	0.47	liters
quarts	0.95	liters
gallons	3.8	liters
cubic feet	0.028	cubic meters
cubic yards	0.765	cubic meters
Temperature		
Fahrenheit	subtract 32, then multiply by 5/9	Celsius
Pressure		
inches of H_2O	0.00246	atmospheres
inches of Hg	0.03332	atmospheres

Out of Metric Units

If You Know	Multiply By	*To Get*
Length		
millimeters	0.039	inches
centimeters	0.394	inches
meters	3.281	feet
meters	1.094	yards
kilometers	0.621	miles
Area		
sq. centimeters	0.155	sq. inches
sq. meters	10.76	sq. feet
sq. meters	1.196	sq. yards
sq. kilometers	0.4	sq. miles
hectares	2.47	acres
Mass (weight)		
grams	0.035	ounces
kilograms	2.205	pounds
metric ton	1.102	short ton
Volume		
milliliters	0.033	fluid ounces
liters	2.1	pints
liters	1.057	quarts
liters	0.264	gallons
cubic meters	35.315	cubic feet
cubic meters	1.308	cubic yards
Temperature		
Celsius	multiply by 9/5, then add 32	Fahrenheit
Pressure		
atmospheres	406.5	inches of H_2O
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 unsaturatd zone. Under the auspices of this ERA, three 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 parts per million by volume (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 <u>and</u> 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:

- Continuous operation of all three vapor extraction systems be implemented
- Twenty-four existing wells be modified, if feasible, to allow greater access to the subsurface using the vapor extraction systems
- Up to fifteen new extraction wells be considered to provide complete coverage of the unsaturated zone within the primary carbon tetrachloride soil vapor plume
- Passive soil vapor extraction be considered at those wells with carbon tetrachloride concentrations less than 200 ppm_v
- Smaller capacity (e.g., 300 to 500 ft^3/min) vapor extraction units be considered to increase the area affected by soil vapor extraction operations
- Downhole pressures be continuously recorded wherever possible in subsurface open intervals to monitor areas for influence caused by the soil vapor extraction operation

- Characterization testing and sampling 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 to identify other volatile organic contaminants being extracted

- The Vapor Extraction System Characterization Unit be used to collect vacuum, flow, and carbon tetrachloride concentration data for wells within the plume but currently inaccessible to the active vapor extraction systems

- Tracer gas test data be evaluated to determine subsurface airflow pathways, rate of carbon tetrachloride transport, and areas of influence of the extraction wells

- 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

- Further numerical modeling be conducted to better understand the soil vapor extraction process and to suggest operational strategies and parameters.

The recommendations provided in this report represent a broad spectrum of possible wellfield activities that, if implemented, would enhance the vapor extraction system operations. These recommendations will be updated as necessary 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 Operations 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 analysis, 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 strategy and recommendations report was developed to provide guidance to enhance the operation of the soil VES used as part of the ERA. This report also describes pertinent site characteristics and discusses results of site-specific soil vapor extraction numerical 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. This report has been updated from the initial wellfield strategy and recommendations report issued in May 1994 as WHC-SD-EN-AP-159, Rev. 0 (Rohay and Cameron 1994). These recommendations will be updated as necessary 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 May 1992. This system originally had a design capacity of 500 ft^3/min but was upgraded to 1,000 ft^3/min in March 1993. Two VES units, one with 1,500-ft^3/min capacity and one with 500-ft^3/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 1993b). The 1,000-ft^3/min system resumed operation at the 216-Z-1A/18 wellfield on

November 15, 1993; the 1,500-ft^3/min system resumed operation at the 216-Z-9 wellfield on February 23, 1994; and the 500-ft^3/min system resumed operation at the 216-Z-18 wellfield on June 30, 1994.

1.3 TYPICAL SOIL VAPOR EXTRACTION PROJECT PROGRESSION

A typical soil vapor extraction project proceeds through various phases, including initial site characterization, pilot testing, full-scale operations, and targeted operations. These phases are briefly discussed below.

1.3.1 Initial Site Characterization

A site is identified where soils in the unsaturated zone are contaminated with volatile compounds. An extensive investigation of the subsurface is performed to identify contaminant concentrations and locations.

The applicability of the site for remediation using vapor extraction is made through consideration of the soil types and air permeability testing. The air permeability testing can be performed on the bench-scale or in the field and provides an indication of the achievable rates of flow in the subsurface.

This provides input to subsurface airflow modeling which yields an initial indication of the expected site-wide extraction flow rates, placement of open intervals in the subsurface, and the areas of influence of those open intervals.

1.3.2 Pilot Testing

Based on the information provided by the airflow modeling, a field pilot test is then performed giving actual site information on flow rates, extracted soil vapor contaminant and moisture concentrations, areas of influence, and the performance of aboveground extraction and treatment equipment. In conjunction with the field testing program, bench-scale studies using site soils is often performed to further delineate the extraction requirements of the site (e.g., ratio of extracted pore volumes to contaminant removal efficiency).

The information provided by the pilot testing and the bench-scale studies is then fed back into the airflow model to provide more refined predictions. This provides input for the design of the full-scale system, which includes the wellfield and the aboveground equipment.

1.3.3 Full-Scale System

The wellfield of the full-scale system includes the number, location, diameter, length, and open area of the subsurface open intervals required for extraction and the location of the subsurface monitoring points. The aboveground equipment includes soil vapor extraction machinery and treatment processes.

After the full-scale system is operating, frequent characterization and monitoring is performed that provides added input to the airflow modeling. This results in further refinement of the operational parameters based on contaminant extraction trends and other information. In addition to changes in the operational parameters, changes may be made to the design of the extraction system and the design of the wellfield.

1.3.4 Target Areas

As extraction operations proceed, the contaminant concentrations in the some of the subsurface zones are substantially reduced. Gradually, the emphasis of the extraction operations shifts to targeted areas of extraction, such as low-permeability zones. Continued operations provide the input on the targeted subsurface areas of focused extraction efforts. The data gathered during this effort, coupled with airflow modeling, provide estimates of the effectiveness of the extraction operations and the time period for which extraction operations must proceed. The extraction operations continue until desired cleanup levels are obtained.

1.4 CARBON TETRACHLORIDE ERA SOIL VAPOR EXTRACTION PROJECT PROGRESSION

The Carbon Tetrachloride ERA vapor extraction project at 200-ZP-2 Operable Unit has progressed along the same general lines as those described for a typical soil vapor extraction project. However, due to the size and complexity of the site and the expedited nature of the project, some variations from the typical approach have been taken. The various phases are described below.

1.4.1 Initial Site Characterization

The initial site characterization was conducted at the known primary carbon tetrachloride disposal sites in 1991. Additional site characterization activities have included areas further from the primary disposal sites. For example, such activities have identified the 216-Z-12 Crib as an area of elevated concentrations of carbon tetrachloride in the subsurface.

1.4.2 Pilot Testing

The pilot testing at the site first occurred in 1991 and provided the information necessary to design the first full-scale system. Subsequent pilot-testing has been performed at various locations at the site because of the addition of two full-scale systems and the new locations at which they operate.

The air permeability testing and initial airflow modeling, typically done as part of the initial characterization work, were performed as part of the pilot testing due to the expedited nature of the project. The bench-scale studies of the site soils for extraction efficiency is now being performed and the results will benefit the operations of the full-scale systems and help determine the operational parameters for the target zones. Additionally, the studies will help determine the levels of soil remediation reasonably achievable.

1.4.3 Full-Scale Systems

Three full-scale systems are in operation at the site. Further characterization, operational data, wellfield and laboratory testing, and airflow numerical modeling will determine the total extraction capacity required for the site. This may necessitate the addition of more full-scale systems.

1.4.4 Target Areas

Two target areas already identified are the zone above the groundwater and the zone around the caliche layer. Potentially, several more target areas in the subsurface will be identified. Studies to identify these areas and the operational parameters to address these areas will need to be performed.

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 and Johnson (1991), Rohay et al. (1992), Piepho et al. (1993), Rohay et al. (1993), Last and Rohay (1993), and Rohay et al. (1994).

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 waste streams at Z Plant. The chemical processes used to recover plutonium resulted in the production of actinide-bearing organic and aqueous waste liquids, which were discharged to the soil column at subsurface disposal facilities near Z Plant. The primary radionuclide components of these liquids were $^{239/240}$Pu and ^{241}Am. The organic liquids consisted of 50% to 85% by volume carbon tetrachloride mixed with either tributyl phosphate, dibutyl butyl phosphonate, or lard oil. These organic solutions made up only approximately 4% to 8% of the total volume of liquid wastes discharged to the soil column disposal facilities. The predominant wastes discharged were acidic, high-salt (sodium nitrate) aqueous wastes containing the organic mixtures in saturation amounts (< 1%). However, the aqueous wastes account for 5% of the carbon tetrachloride discharged.

Both aqueous and organic liquids were discharged to the same liquid waste disposal sites. The organic wastes were periodically discharged in small (100- to 200-L) batches. Thus, carbon tetrachloride was introduced to the unsaturated zone as an aqueous-phase and also as a dense, nonaqueous-phase liquid.

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, referred to collectively as the Z-Crib Area in this report (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. 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.

Figure 2-1. Z-Crib Area.

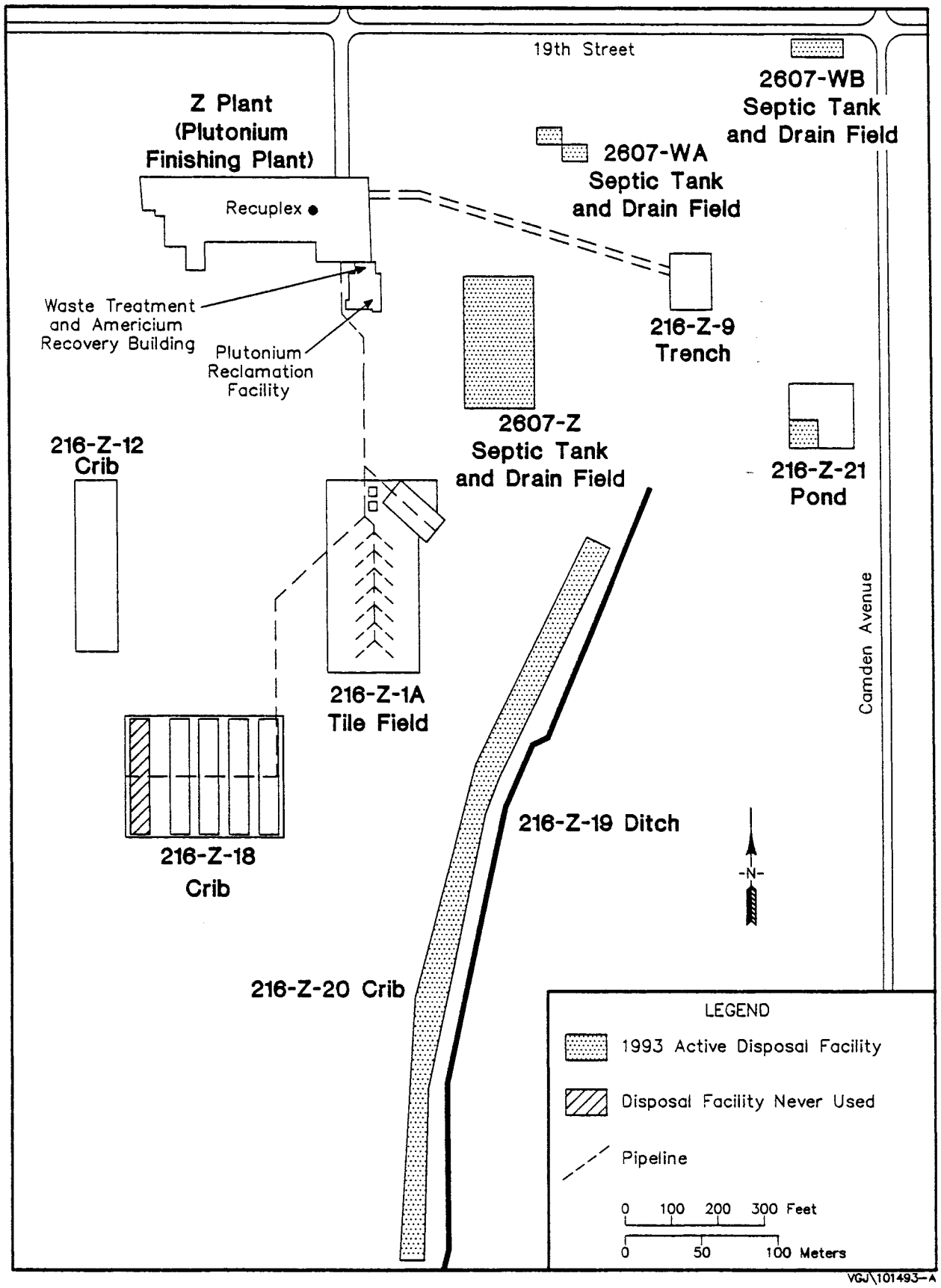


Table 2-1. Soil Contaminant Inventory in the Z-Crib Area.

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)	4.09×10^6	5.2×10^6	3.86×10^6
Period of use	1955-1962	1964-1969	1969-1973

[a]58 kg were later removed.

Three other sites in the vicinity of Z Plant probably received some carbon tetrachloride wastes: the 216-Z-12 Crib, the 216-Z-19 Ditch, and the 216-T-19 Crib (Figure 2-1; 216-T-19 is north of the area shown). The 216-Z-12 Crib received analytical and development laboratory waste from Z Plant from 1959 to 1973 and is estimated to have received a small volume of organics including carbon tetrachloride (Kasper 1981). The 216-Z-19 Ditch was used to convey process cooling water and steam condensate from Z Plant from 1971 to 1981; apparently, carbon tetrachloride was also occasionally or accidentally released to this ditch (Rohay and Johnson 1991). The 216-T-19 Crib received approximately 80 L of carbon tetrachloride between 1973 and 1976 in the overhead condensate discharged from the 242-T evaporator (Rohay et al. 1993).

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
- Plio-Pleistocene unit--in the Z-Crib Area, a fine sandy silt sequence overlying a carbonate-cemented gravel sequence (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.

Perched water was encountered in two locations during 1992-1993 drilling operations in the vicinity of the 216-Z-9 Trench. The water is perched in the Plio-Pleistocene unit. Perched water was observed at a depth of 28 to 33 m in well 299-W15-216 in 1992, and at a depth of 32.5 to 33.5 m in

well 299-W15-220 in 1993 (Rohay et al. 1992, 1993). The water is presumably from the 216-Z-21 Crib, which is an active water discharge site approximately 40 m southeast of well 299-W15-216 (Figure 2-1).

2.3 EXTENT OF CONTAMINATION

The following summary of the carbon tetrachloride contamination, which incorporates results of the fiscal year (FY) 1991 through FY 1993 characterization and wellfield activities, is taken from Rohay et al. (1994). Carbon tetrachloride is found throughout the 65-m-thick unsaturated zone underlying the three primary disposal facilities. Laterally, the highest concentrations of carbon tetrachloride are consistently 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. Vertically, the highest concentrations are associated with the fine-grained, relatively impermeable Hanford lower fine and Plio-Pleistocene units, located at depths of 35 to 40 m below ground surface. The conceptual model of carbon tetrachloride migration pathways and phase distribution is illustrated in Figure 2-2.

The highest near-surface vapor concentration of carbon tetrachloride measured during a soil-gas survey in 1992 was 72 parts per million by volume (ppm_v) just north of the 216-Z-9 Trench. Maximum vapor concentrations observed at wellheads and deep soil-gas probes, which were measured twice a week for 25 months (December 1991 through December 1993), exceeded 10,000 ppm_v total volatile organic compounds (VOCs) at monitoring locations above the Plio-Pleistocene unit and immediately north of the 216-Z-9 Trench (Figure 2-3). At similar locations above the Plio-Pleistocene unit in the 216-Z-1A/216-Z-18 area, maximum concentrations were an order of magnitude lower. However, maximum concentrations from monitoring ports below the Plio-Pleistocene unit were approximately 1,000 ppm_v in both areas (Figure 2-4). The highest carbon tetrachloride concentration in the sediment samples collected during drilling of 13 new wells in 1992 and 1993 was 37.8 ppm from the Hanford lower fine/Plio-Pleistocene interval at the 216-Z-9 Trench. In contrast, the highest carbon tetrachloride concentration in a sediment sample from the 216-Z-1A/216-Z-18 area was only 6.6 ppm, but was also associated with the Hanford lower fine/Plio-Pleistocene interval. The highest carbon tetrachloride concentrations in soil-gas samples collected with the SEAMIST (tradename of Eastman Cherrington Environmental, Santa Fe, New Mexico) soil-gas sampling system during drilling exceeded 10,000 ppm_v in wells at the 216-Z-9 Trench. Carbon tetrachloride concentrations in soil vapor extracted from wells using the vapor extraction systems have been as high as 28,500 ppm_v from intervals above the Plio-Pleistocene unit at the 216-Z-9 Trench. Extracted soil-gas concentrations from the 216-Z-1A/216-Z-18 wellfield are an order of magnitude lower.

Atmospheric pressure fluctuations appear to constitute a significant release mechanism for carbon tetrachloride vapor out of the unsaturated zone both through boreholes and through the soil surface. Based on continuous airflow measurements into and out of boreholes, average carbon tetrachloride concentrations in the vented air, and length of time each well was available as a pathway, an estimated 3% of the original carbon tetrachloride inventory has been lost to the atmosphere since 1955 through borehole venting. The calculated quantity of carbon tetrachloride lost to the atmosphere in 1990 from the soil/air interface, based on diffusion of the vapor phase from the water table to the ground surface, was estimated to be 0.15 $g/m^2/yr$ for the area overlying the groundwater plume. Measured soil flux rates in the vicinity of the 216-Z-9 Trench ranged from 0.0007 to 0.48 $g/m^2/yr$ in 1993. It is estimated that, between 1955 and 1990, 18% of the total carbon tetrachloride inventory was lost to the atmosphere through natural soil flux. Thus, a total of 21% of the carbon tetrachloride may have been released to the atmosphere.

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

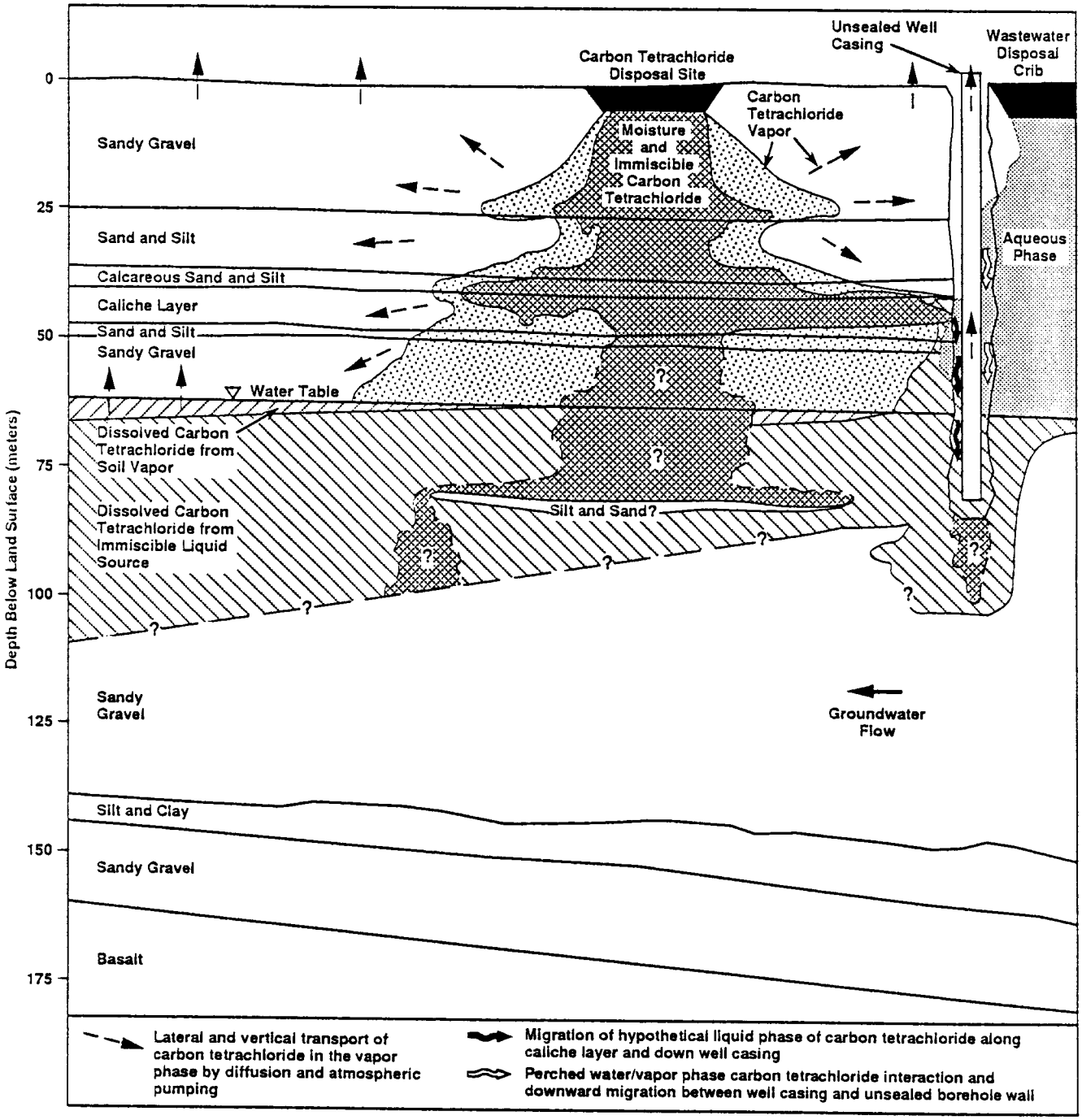


Figure 2-3. Maximum Carbon Tetrachloride Concentrations Recorded at Wells and Deep Soil-Gas Probes Open Above the Plio-Pleistocene Unit, December 1991 Through December 1993 (from Fancher 1994).

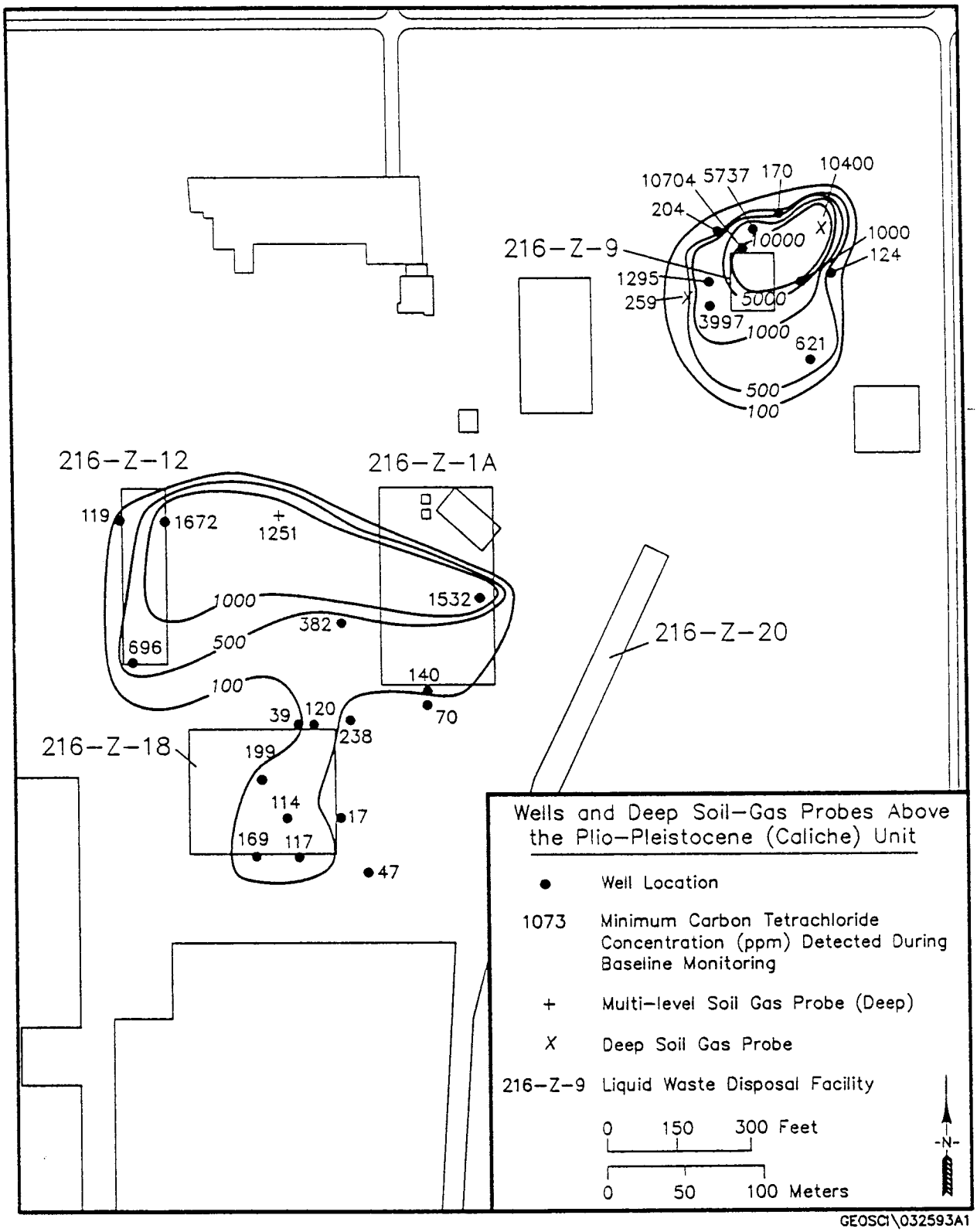
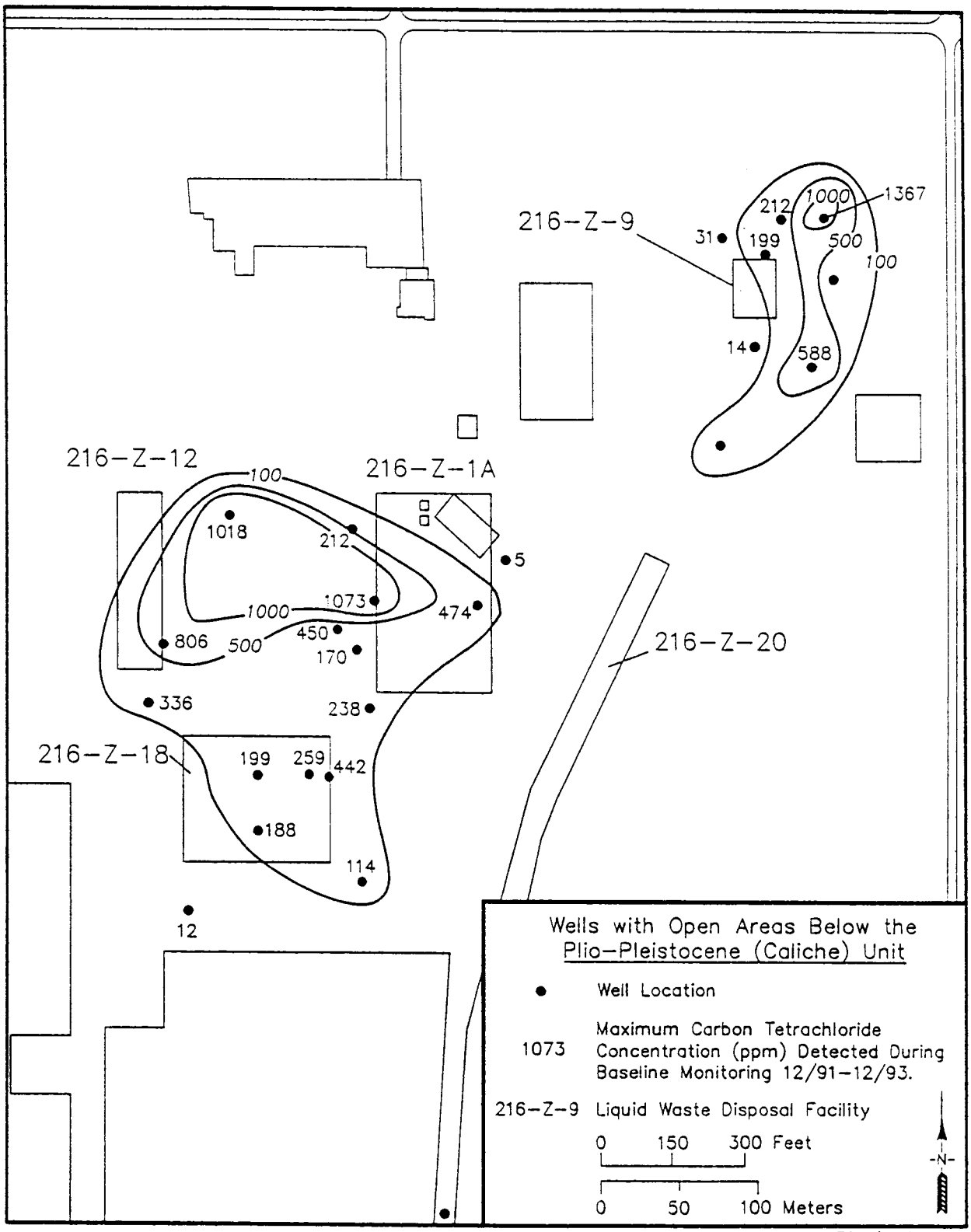


Figure 2-4. Maximum Carbon Tetrachloride Concentrations Recorded at Wells Open Below the Plio-Pleistocene Unit, December 1991 Through December 1993 (from Fancher 1994).



Carbon tetrachloride is typically the predominant VOC constituent in the extracted soil gas. Other VOCs detected, usually in minor amounts, include chloroform, methylene chloride, methyl ethyl ketone, tetrachloroethylene (PCE), 1,1,1-trichloroethane (TCA), 1,2-dichloroethane (DCA), and methyl isobutyl ketone (MIBK). However, characterization sampling at wellheads has demonstrated that co-contaminants can be found at elevated concentrations. For instance, soil-gas monitoring at well 299-W18-7 showed higher concentrations of methylene chloride than carbon tetrachloride. Soil-gas sampling from other wells has indicated chloroform can be 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.

The areal extent of the dissolved carbon tetrachloride groundwater plume has remained about 10 km^2 over the last 3 years. Concentrations of dissolved carbon tetrachloride detected in the groundwater have been estimated to account for approximately 2% of the original carbon tetrachloride inventory (Rohay and Johnson 1991). Concentrations of carbon tetrachloride in wells at the perimeter of the plume appear to be increasing, suggesting that the groundwater plume is migrating laterally to the north, west, and south. However, the centroid of the dissolved carbon tetrachloride plume appears to be stationary. The fact that the zone of highest concentrations (4,000 to 7,000 μg/L) includes the 216-Z-9 Trench, which has been inactive since 1962, suggests that the carbon tetrachloride discharged there has been providing a continuous source of contamination to the groundwater. The highest observed groundwater concentration is approximately 1% of the aqueous solubility of carbon tetrachloride.

Groundwater samples from one well indicate that there is deeply distributed carbon tetrachloride near the 216-Z-9 Trench (up to 5,800 μg/L at the top of the aquifer and 3,800 μg/L at 52 m beneath the water table). However, the well itself, which lacked an annular seal until 1987 and has a long perforated interval, may have provided the preferential pathway for the downward migration of contaminants. Nonaqueous-phase liquid carbon tetrachloride has not been observed in the saturated zone.

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 1993a). For these rough-order-of-magnitude estimates, it was assumed that 750,000 kg of carbon tetrachloride was discharged to the soil column between 1955 and 1973. Total atmospheric losses are estimated to be 21%; the unsaturated zone inventory (in soil gas, soil moisture, and adsorbed phases) accounts for 12%; and 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 nonaqueous-phase liquid residual saturation in the unsaturated zone, perched nonaqueous-phase liquid on low-permeability lenses, or separate nonaqueous-phase liquid present within the unconfined aquifer. Any or all of these forms of concentrated carbon tetrachloride may be present within the subsurface, although none has been observed. However, the high concentrations (approximately 25% of the saturated vapor concentration) extracted from the 216-Z-9 wellfield suggest the presence of carbon tetrachloride residual saturation, particularly associated with the Hanford lower fine and Plio-Pleistocene units. A portion of the inventory may have been biodegraded.

As of the end of September 1994, a total of 40,000 kg of carbon tetrachloride has been removed from the unsaturated zone using active vapor extraction.

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 modifications, soil vapor extraction numerical modeling, wellfield testing, and extraction strategies. These recommendations are intended as guidance for possible wellfield activities.

Recommendations regarding wellfield modifications address ways to increase subsurface access to the contaminated soil gas by the VESs. Increased access can be achieved by adding open intervals (through modifications to existing wells and/or installation of new wells); by expanding the effective radius of influence of existing open intervals (through continuous operation of the VES, air injection, and/or implementation of surface seals); by adding VES capacity (through implementation of passive vapor extraction, use of additional VES units, and/or intermittent pumping, which can increase the number of extraction wells per system); and by increasing the effective permeability of the subsurface to air flow (through air injection and/or pneumatic fracturing).

Recommendations regarding soil vapor extraction numerical modeling deal with the volume of soil gas which must be extracted and the time required to achieve a given level of remediation. The modeling is used as a tool to provide guidance on contaminant removal strategies, including efficient use of vapor extraction capacity, optimum locations and depths of open intervals and extraction rates and durations; and identification of critical wellfield system parameters (such as airflow pathways and carbon tetrachloride sorption equilibria); and relative vapor extraction efficiency.

Recommendations regarding wellfield testing are designed to measure the effectiveness of the wellfield modifications and enhancements and to provide input and calibration data to the numerical model. Wellfield testing provides site-specific data on extraction system operational parameters (such as identity of co-contaminants, changes in extraction well flows and concentrations, and determination of areas of influence), and subsurface contaminant vapor flow characteristics (such as airflow permeabilities and pathways, transport rates, and sorption equilibria).

These three types of activities are conducted iteratively. For example, wellfield testing monitors changes in extraction well soil-gas concentrations. These data are used to refine the numerical model; results of the modeling based on these new data are used to determine if and what wellfield modifications are needed; the effectiveness of modifications to the wellfield is evaluated using wellfield testing data. Such continual iteration is necessary to understand and optimize the dynamic wellfield system. The goal is enhanced vapor extraction operations to meet the ERA objectives of controlling carbon tetrachloride migration and removing mass.

3.1 RECOMMENDATIONS REGARDING WELLFIELD MODIFICATIONS

Controlling flow in the subsurface, establishing areas of influence of wells sufficient to address the areas of contamination, and understanding the location of concentrated zones of carbon tetrachloride are essential for optimizing removal of carbon tetrachloride using soil vapor extraction. Options for increasing contaminant removal include improving subsurface access to the contamination by modifying existing wells and/or installing new wells for vapor extraction and implementing strategies

to enhance the availability of the contaminant to the wells. General vapor extraction strategies are discussed in Appendix A.

3.1.1 Wellfield Configuration

3.1.1.1 Problem. 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 areas of influence of the extraction well configuration must allow extraction access to the entire contaminated 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.)

- The soil vapor extraction operation is either intermittent or continuous as described below.

  — Intermittent operation (8 h/day, 5 days/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 (8 to 12 hours) that an equilibrium is established and the maximum radius of influence is achieved. For a well with a maximum flow of 300 ft^3/min at 120 in. H_2O 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 measured or estimated flow.

The areas of influence depicted in Figures 3-2 through 3-5 indicate that the large areas where carbon tetrachloride is likely to reside (Figures 2-3 and 2-4) cannot be addressed by the existing wellfield configuration. Comparison of Figures 3-2 and 3-4 (intermittent operations) with Figures 3-3 and 3-5 (continuous operation) demonstrates the necessity of continuous soil vapor extraction operation for more effective carbon tetrachloride remediation.

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

Well	Open interval (ft below toc)	Casing diameter (in.)	Piezometer diameter (in.)	Observed flow (ft^3/min)	Observed vacuum (in. H_2O)
216-Z-1A/18 TILE FIELD					
299-W18-10	100-130	6	6	80	100
299-W18-11	100-130	6	6	33	101
299-W18-87 U M L	33-38 65-70 125-130	6	1.5 1.5 1.5	78 (combined)	127
299-W18-89	108-130	6	6	367	97
299-W18-93	63-77	6	6	170	100
299-W18-94	68-78	6	6	272	102
299-W18-96	122-132 bgs	2	2	256	100
299-W18-97	63-75	6	6	297	102
299-W18-98	66-77	6	6	265	101
299-W18-99	93-103	6	6	226	99
299-W18-150 U M L	65-70 85-90 113-118	6	1.5 1.5 1.5	20 17 53	121 116 127
299-W18-158 U M L	75-80 89-94 119-124	6	1.5 1.5 1.5	78 27 50	124 125 120
299-W18-159	113-120	6	6	39	97
299-W18-163 U M L	69.5-79.5 92.5-99.5 114.5-119.5	6	1.5 1.5 1.5	0 0 0	119 117 120
299-W18-165	122-127	6	6	4	122
299-W18-166	124-129	6	6	4	120
299-W18-167	89-119	8	8	20	87
299-W18-168	97-127	8	8	7	89
299-W18-169	96-126	8	8	0	90
299-W18-171 U M L	19.8-24.5 56-76 114.5-129.5	8	2 2 2	284 (combined)	88
299-W18-174	106-126 bgs	4	4	112	94
299-W18-175 U L	87-94 115-120	6	6 6	40 (combined)	88
299-W18-246 U	120-130 bgs	4	2	156	90
299-W18-247 U	199-129 bgs	4	2	150[a]	100[a]
299-W18-248	123-139 bgs	4	4	27	91
299-W18-249	122-137 bgs	4	4	476	85

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

Well	Open interval (ft below toc)	Casing diameter (in.)	Piezometer diameter (in.)	Observed flow (ft^3/min)	Observed vacuum (in. H_2O)
216-Z-1A/18 TILE FIELD (cont.)					
299-W18-252 U	113-133 bgs	4	2	236	95
CPT-2	34-37 bgs	1	1	65[b]	100[b]
CPT-4	90-103 bgs	1	1	40[b]	100[b]
CPT-20	71-84 bgs	1	1	40[b]	100[b]
216-Z-12 CRIB					
299-W18-152	88-118	8	8	150[a]	100[a]
299-W18-153	80-110	8	8	150[a]	100[a]
299-W18-157	80-110	8	8	150[a]	100[a]
CPT-10	94-107 bgs	1	1	40[b]	100[b]
216-Z-9 TRENCH					
299-W15-82	73-88 bgs	8	8	288	116
299-W15-84	75-90 bgs	8	8	440	101
299-W15-85	89-98 bgs	8	8	216	115
299-W15-95	70.5-98 bgs	8	8	63	99
299-W15-216 U	70-80 bgs	4	2	196	107
299-W15-217	106-121 bgs	4	4	158	114
299-W15-218 U	99-114 bgs	4	2	129	117
299-W15-219 U	87-102 bgs	4	2	124	113
299-W15-220 U	90-95 bgs	4	2	158	93
299-W15-223[c]	103-117 (vertical)	3.5	3.5	209	91
CPT-3	39-52 bgs	1	1	65[b]	100[b]
CPT-5	35-48 bgs	1	1	65[b]	100[b]
CPT-8	100-113 bgs	1	1	12	96
CPT-11	64-77 bgs	1	1	40[b]	100[b]
CPT-12	36-49 bgs	1	1	64	101
CPT-19	36-49 bgs	1	1	65[b]	100[b]
CPT-21	84-97 bgs	1	1	40[b]	100[b]

[a]Value estimated based on average observed flow (147 ft^3/min) and vacuum (103 in. H_2O) for 216-Z-1A/18/12 wells open above caliche (wells with flows ≤ 10 ft^3/min not included).

[b]Value estimated as follows:

CPT wells below 0- to 50-ft depth = 15 ft^3/min (based on CPT-8)
CPT wells below 50- to 100-ft depth = 40 ft^3/min
CPT wells below 100- to 150-ft depth = 65 ft^3/min (based on CPT-12).

[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.
U = upper, M = middle, L = lower.

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

Well	Open interval (ft below toc)	Casing diameter (in.)	Piezometer diameter (in.)	Observed flow (ft^3/min)	Observed vacuum (in. H_2O)
216-Z-1A/18 TILE FIELD					
299-W18-6	190-201	8	8	387	86
299-W18-7	190-203	8	8	222	85
299-W18-9	180-211	6	6	145[a]	100[a]
299-W18-10	150-214	6	6	80	100
299-W18-11	180-211	6	6	33	101
299-W18-12	190-211	6	6	145[a]	100[a]
299-W18-246 L	165-175 bgs	4	2	52	87
299-W18-247 L	162-172 bgs	4	2	145[a]	100[a]
299-W18-252 L	165-185 bgs	4	2	96	122
216-Z-12 CRIB					
299-W18-1	195-200	8	8	145[a]	100[a]
299-W18-2	200-208	8	8	145[a]	100[a]
299-W18-4	200-211	8	8	145[a]	100[a]
299-W18-5	195-211	8	8	145[a]	100[a]
299-W18-24	205-213	4	4	145[a]	100[a]
216-Z-9 TRENCH					
299-W15-5	173-217	8	8	115[b]	110[b]
299-W15-6	175-190	6	6	115[b]	110[b]
299-W15-9	186-189	8	8	115[b]	110[b]
299-W15-216 L	175-185 bgs	4	2	86	106
299-W15-218 L	180-195 bgs	4	2	104	110
299-W15-219 L	167-182 bgs	4	2	124	111
299-W15-220 L	155-170 bgs	4	2	149	104

[a]Value estimated based on average observed flow (145 ft^3/min) and vacuum (97 in. H_2O) for 216-Z-1A/18/12 wells open below caliche.

[b]Value estimated based on average observed flow (116 ft^3/min) and vacuum (108 in. H_2O) for 216-Z-9 wells open below caliche.

toc = top of casing.

bgs = below ground surface.

L = lower.

Figure 3-1. Z-Crib Area Wells.

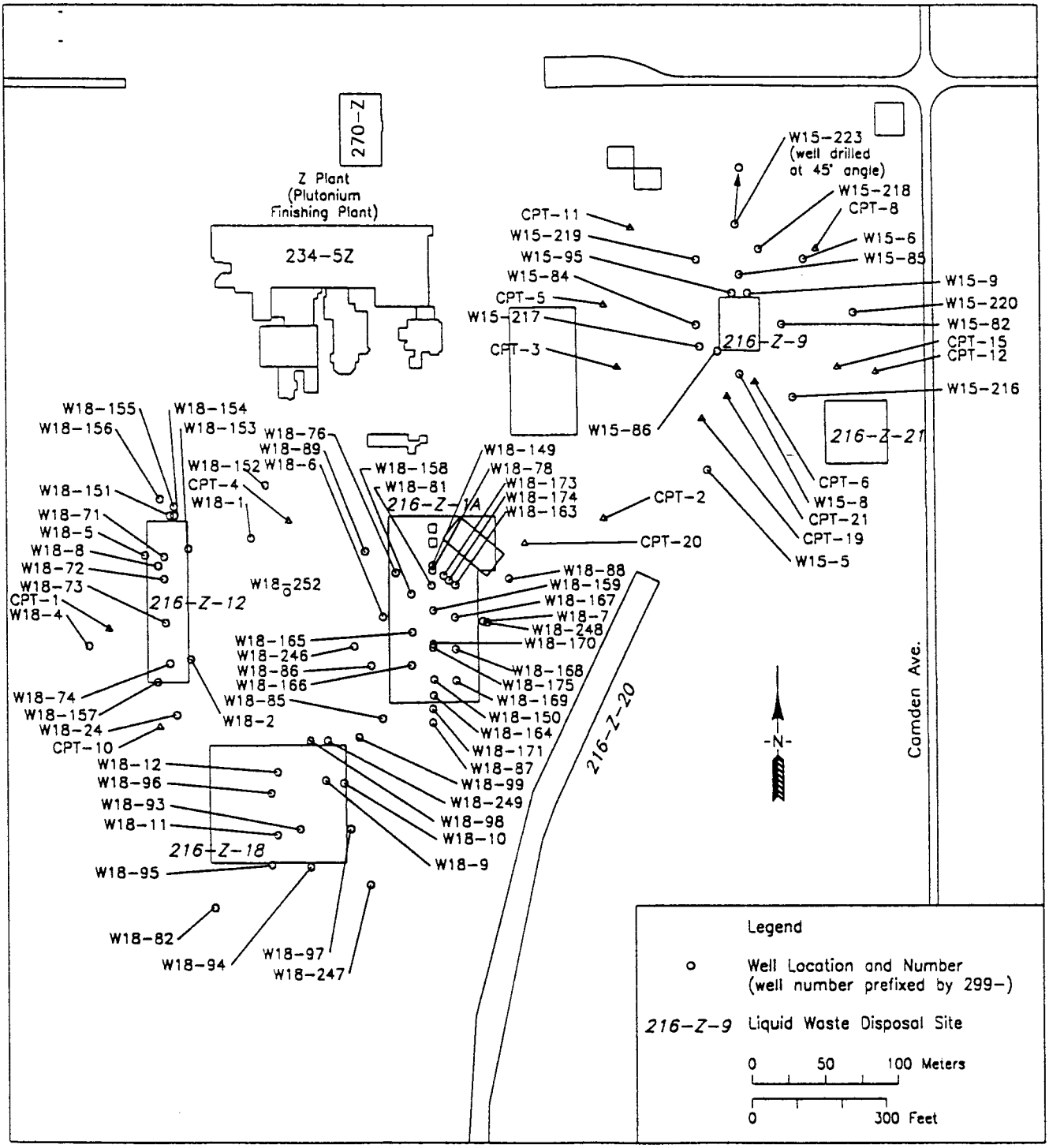


Figure 3-2. Areas of Influence in Wells with Open Intervals Above the Caliche--Existing Configuration (Intermittent Operation).

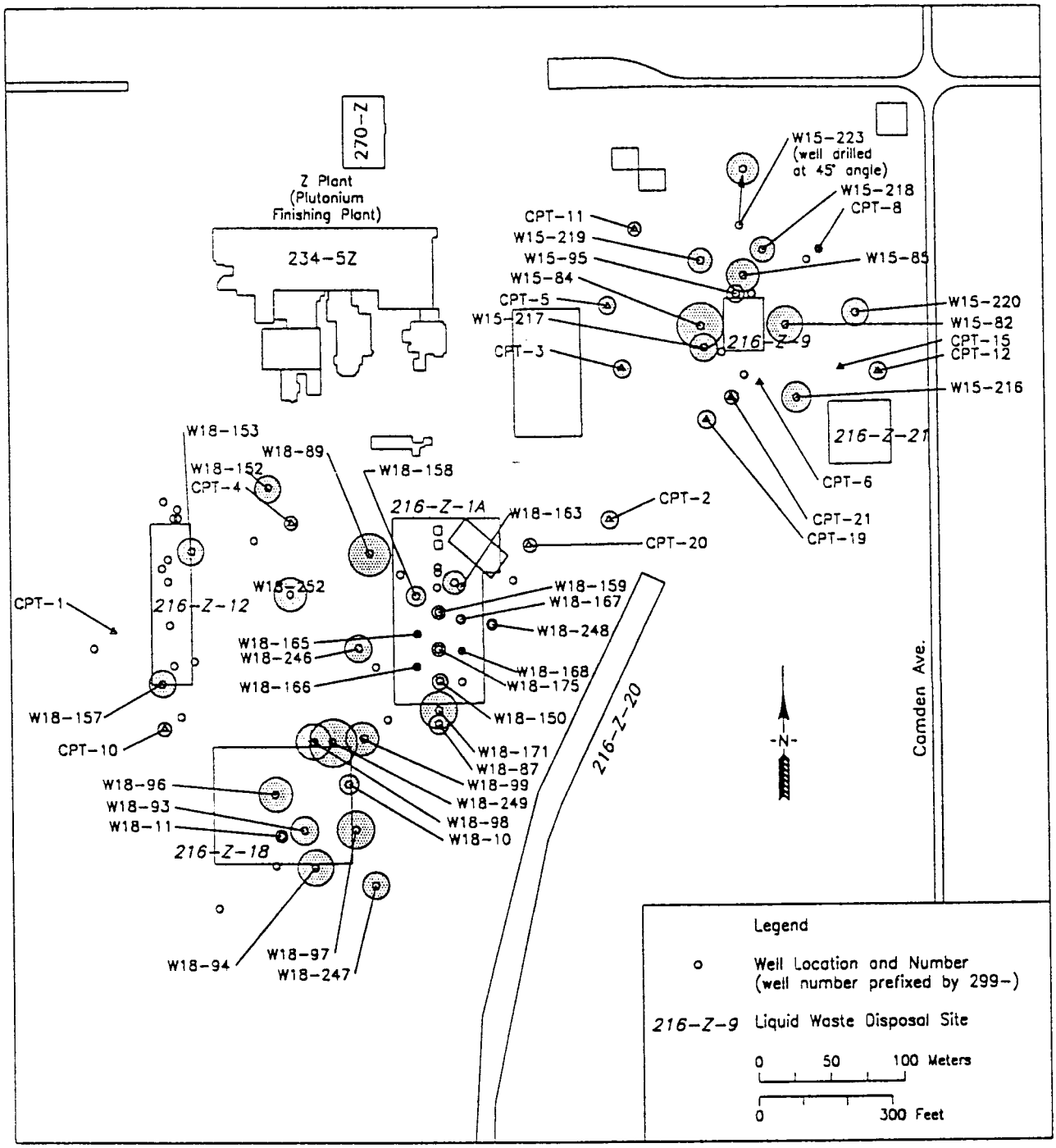


Figure 3-3. Areas of Influence in Wells with Open Intervals Above Caliche--Existing Configuration (Continuous Operation).

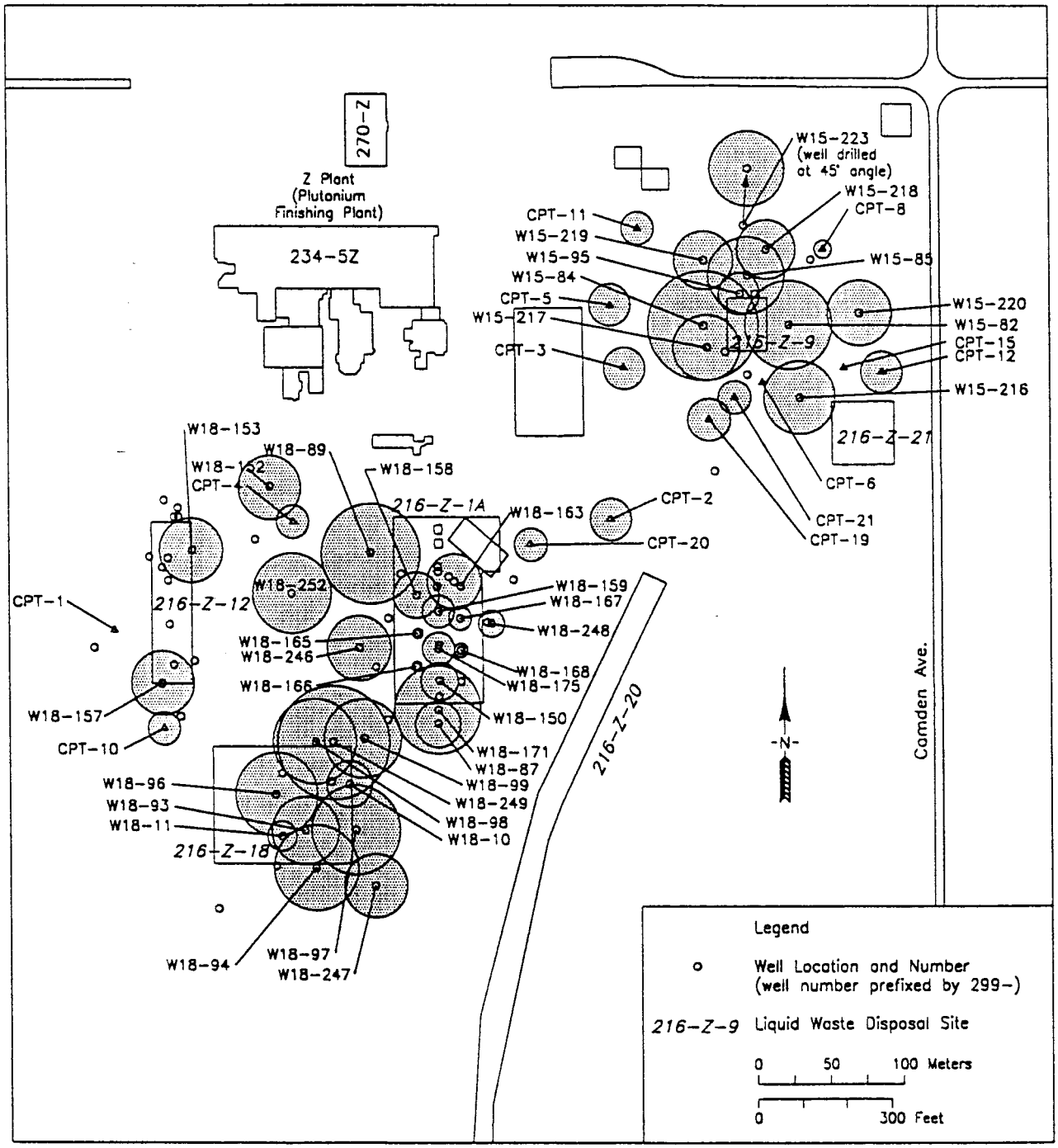


Figure 3-4. Areas of Influence in Wells with Open Intervals Below Caliche--Existing Configuration (Intermittent Operation).

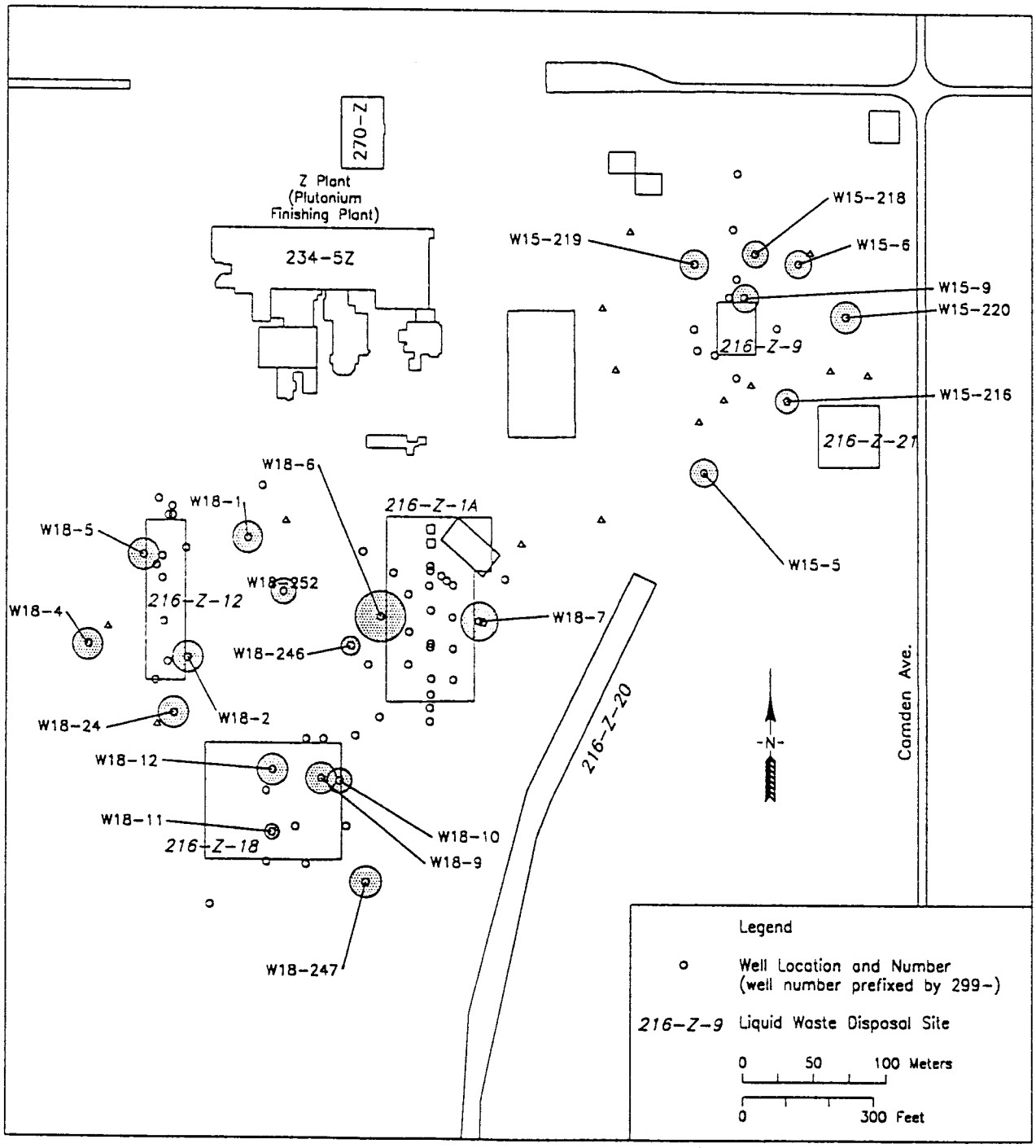
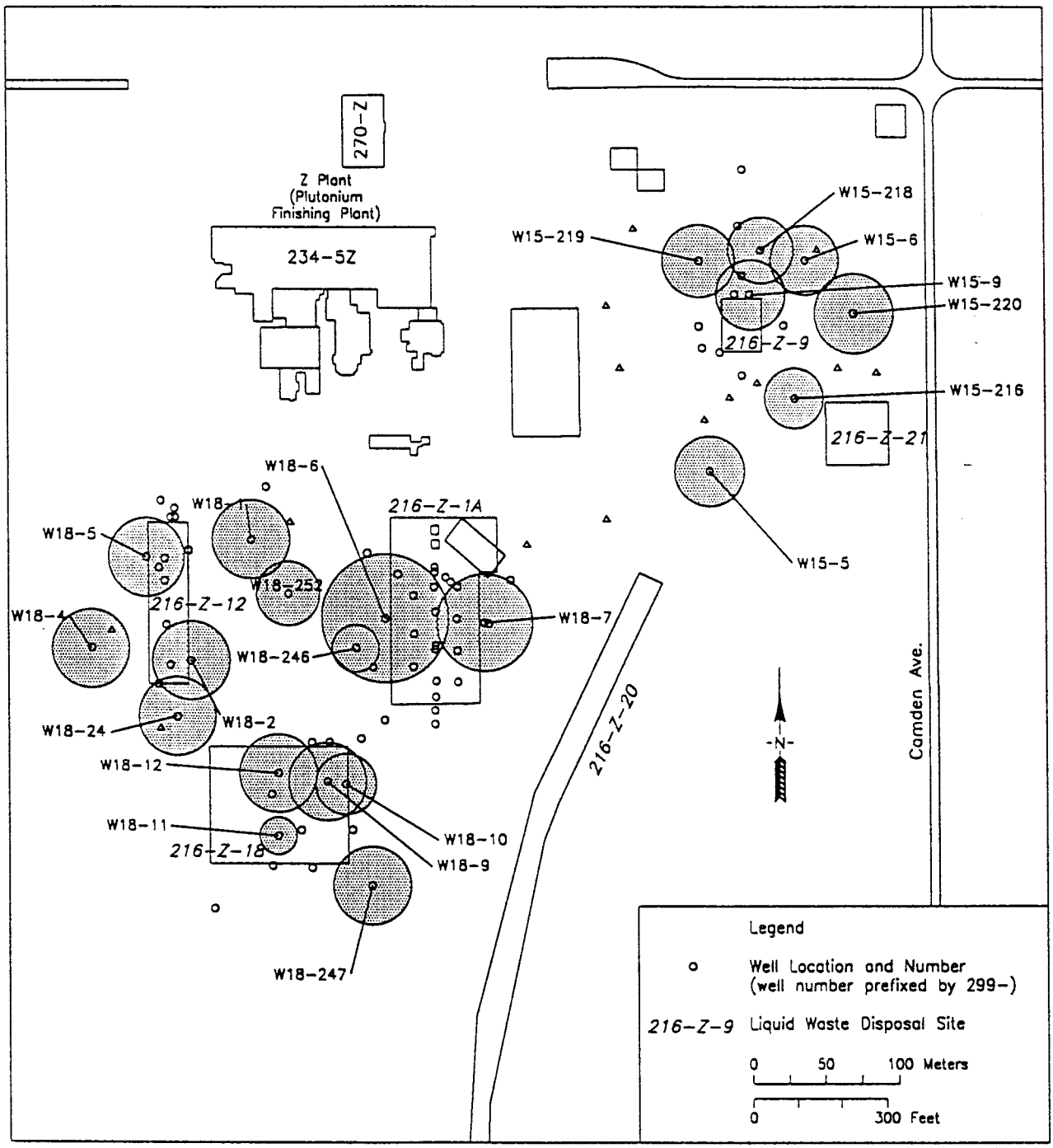


Figure 3-5. Areas of Influence in Wells with Open Intervals Below Caliche--Existing Configuration (Continuous Operation).



A modified wellfield configuration was developed to increase the area of influence of the VES operation. Improvements to the wellfield configuration include modifications to existing wells and the addition of new vapor extraction wells.

The modifications to existing wells include adding perforated intervals and modifying existing perforated intervals (Tables 3-3 and 3-4). The areas of influence of the modified wellfield configuration are depicted in Figures 3-6, 3-7, 3-8, and 3-9. The resulting modified wellfield configuration is described in Tables 3-5 and 3-6. The wells were prioritized for modification as indicated in Table 3-7. A discussion regarding the selections of the wells and the intervals is included as Appendix B.

A list of 15 proposed new soil vapor extraction wells is given in Table 3-8. These new wells are located to provide nearly complete extraction coverage of the unsaturated zone beneath the 216-Z-9 Trench, 216-Z-1A Tile Field, 216-Z-18 Crib, and 216-Z-12 Crib. The area identified for extraction coverage is based on the carbon tetrachloride vapor concentrations observed during 25 months of baseline monitoring (Fancher 1994) and shown in Figures 2-3 and 2-4. The locations of the proposed new wells, and the additional coverage they will provide, are indicated in Figures 3-10 and 3-11, which were constructed assuming that all of the modifications to existing wells are completed and that VES operations are continuous. The radii of influence assigned to the new wells were 100 ft for intervals open above the caliche and 125 ft for intervals open below the caliche, assuming continuous VES operations, 300 ft^3/min extraction flow rates, and 4-in.-diameter well completions similar to those of vapor extraction wells installed in FY 1993 (Rohay et al. 1993). The proposed new wells are numbered in approximate order of priority (Table 3-8).

Priorities were assigned for modifications to existing wells and installation of new wells as indicated in Table 3-9. The prioritization was based on the following assumptions.

1. 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 providing access to the area between the caliche layer and the water table in areas with the highest carbon tetrachloride concentrations. Contamination located in these areas has the shortest pathway to the unconfined aquifer.

2. As additional protection of the groundwater, the second highest priority was placed on providing access to areas of high carbon tetrachloride concentrations. The highest concentrations are found above the caliche layer beneath the 216-Z-9 Trench. These high levels likely are the result of nonaqueous-phase residual saturation and as such may pose a significant risk to further contamination of the unconfined aquifer.

3. The third priority is placed on providing access to areas of high soil vapor contaminant concentrations above the caliche in the areas around 216-Z-1A, 216-Z-18, and 216-Z-12 to reduce the high-concentration sources from the subsurface.

4. An additional objective of the ERA is to minimize migration of contaminated vapor away from the Z-Crib Area. Therefore, emphasis was placed on subsurface access above and below the caliche near the outer boundaries of the known soil vapor plume. In particular, wells west of the 216-Z-12 wellfield were given priority because of the relatively high soil vapor concentrations in the 216-Z-12 vicinity and the few wells with existing open intervals.

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

Well	Casing diameter (in.)	Present open interval (ft below toc)	Perforate (ft below toc)	Modified open interval (ft below toc)	Observed 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	150[a]
299-W18-10	6	100-130	100-130[b]	100-130	80	150[a]
299-W18-11	6	100-130	100-130[b]	100-130	33	150[a]
299-W18-150 U	6	65-70	65-90	65-90	20	150[a]
M		85-90			17	
L		113-119		113-119	53	53[a]
299-W18-158 U	6	75-80	80-89	75-94	78	150[a]
M		89-94			27	
L		119-124		119-124	50	50
299-W18-159	6	113-120	90-120[b]	90-120	39	150[a]
299-W18-163 U	6	69.5-79.5	54.5-79.5	54.5-79.5	0	150[a]
M		92.5-99.5			0	
L		114.5-119.5	92.5-119.5	92.5-119.5	0	150[a]
299-W18-165	6	122-127	97-127[b]	97-127	4	150[a]
299-W18-166	6	124-129	99-129[b]	99-129	4	150[a]
299-W18-167	8	89-119	89-119	89-119	20	150[a]
299-W18-168	8	97-127	97-127	97-127	7	150[a]
299-W18-169	8	96-126	96-126[b]	96-126	0	150[a]
299-W18-175 U	6	87-94	90-120	90-120	40	
L		115-120			(combined)	150[a]
216-Z-12 CRIB						
299-W18-1	8	None	100-130	100-130	NA	150[a]
299-W18-2	8	None	100-130	100-130	NA	150[a]
299-W18-4	8	None	100-130	100-130	NA	150[a]
216-Z-9 TRENCH						
299-W15-6	6	None	75-100	75-100	NA	200[c]
299-W15-8	8	None	90-115	90-115	NA	200[c]
299-W15-9	8	None	90-115	90-115	NA	200[c]
299-W15-86	8	None	110-140	110-140	NA	200[c]
299-W15-95	8	70.5-98 bgs	73-98 bgs[b]	73-98 bgs	63	200[c]

[a]Value estimated based on average observed flow (147 ft^3/min) and vacuum (103 in. H_2O) for 216-Z-1A/18/12 wells open above caliche.

[b]Present interval to be re-perforated.

[c]Value estimated based on average observed flow (198 ft^3/min) and vacuum (107 in. H_2O) for 216-Z-9 wells open above caliche.

toc = top of casing.

bgs = below ground surface.

U = upper, M = middle, L = lower.

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)	Observed flow (ft^3/min)	Modified flow (ft^3/min)
216-Z-1A/18 TILE FIELD						
299-W18-7	8	190-203	175-190	175-203	222	300[a]
299-W18-12	6	190-211	180-190	180-211	145[b]	145[b,c]
216-Z-12 CRIB						
299-W18-1	8	195-200	175-195	175-200	145[b]	145[b,c]
299-W18-2	8	200-208	183-200	183-208	145[b]	145[b,c]
299-W18-4	8	200-211	186-200	186-211	145[b]	145[b,c]
299-W18-5	8	195-211	186-195	186-211	145[b]	145[b,c]
216-Z-9 TRENCH						
299-W15-6	6	175-190	160-190[d]	160-190	115[e]	115[e,c]
299-W15-8	8	None	167-197	167-197	NA	115[e,c]
299-W15-9	8	186-189	164-189[d]	164-189	115[e]	115[e,c]

[a]Value estimated based on 300 ft^3/min reference flow.

[b]Value estimated based on average observed flow (145 ft^3/min) and vacuum (97 in. H_2O) for 216-Z-1A/18/12 wells open below caliche.

[c]Estimates of observed and modified flows are listed as the same.

[d]Present interval to be re-perforated.

[e]Value estimated based on average observed flow (116 ft^3/min) and vacuum (108 in. H_2O) for 216-Z-9 wells open below caliche.

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

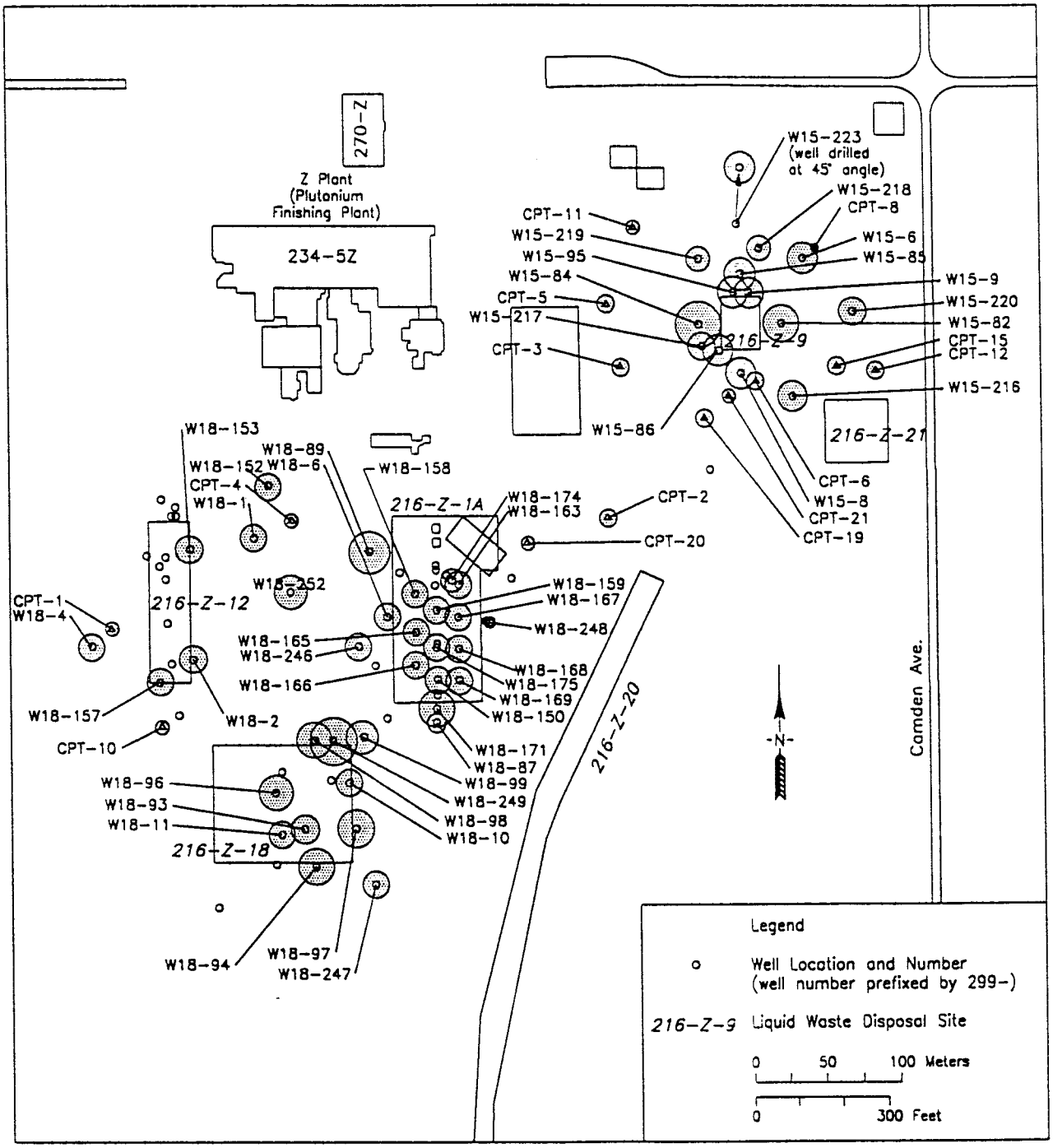


Figure 3-7. Areas of Influence in Wells with Open Intervals Above Caliche--Modified Configuration (Continuous Operation).

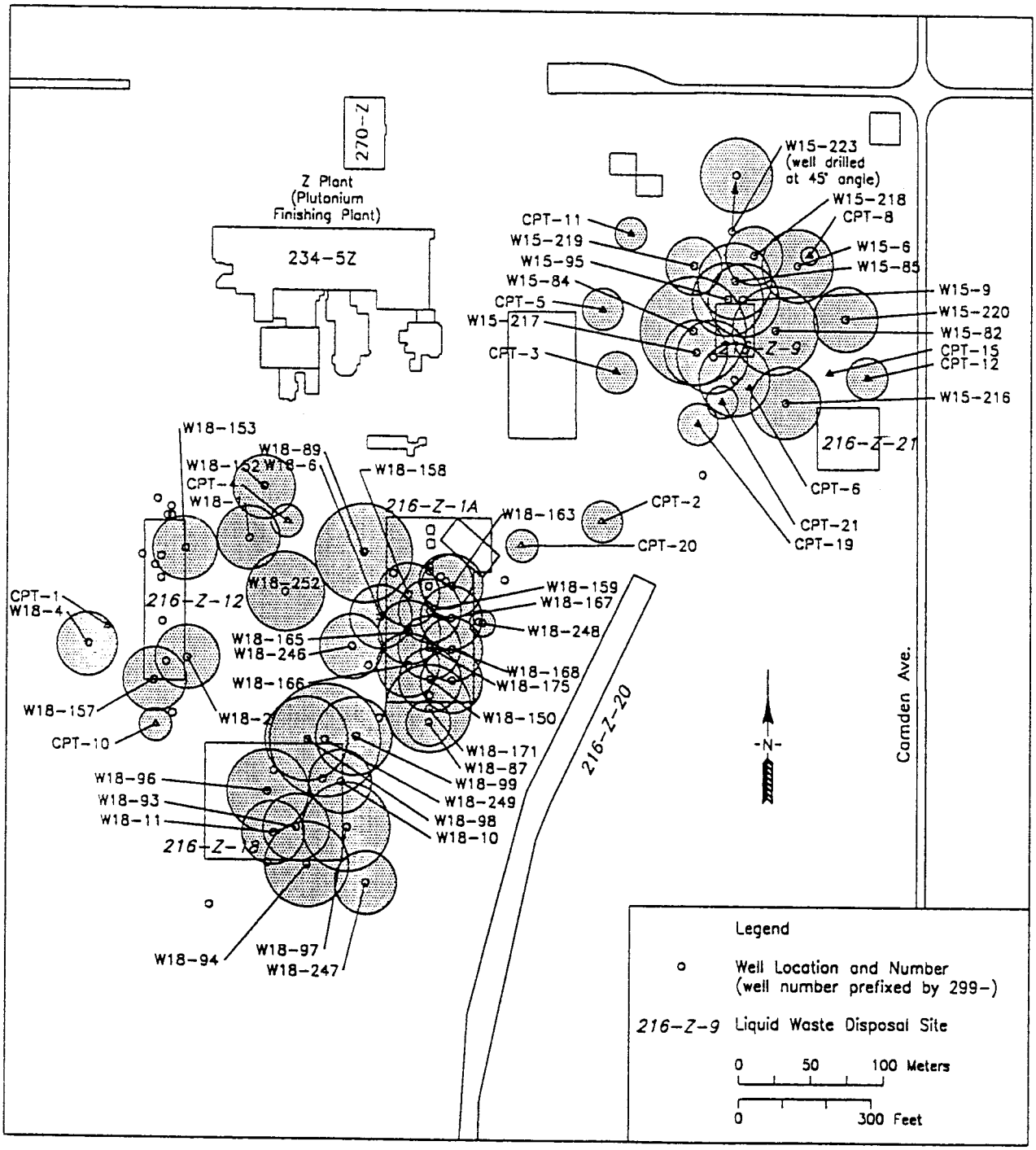


Figure 3-8. Areas of Influence in Wells with Open Intervals Below Caliche--Modified Configuration (Intermittent Operation).

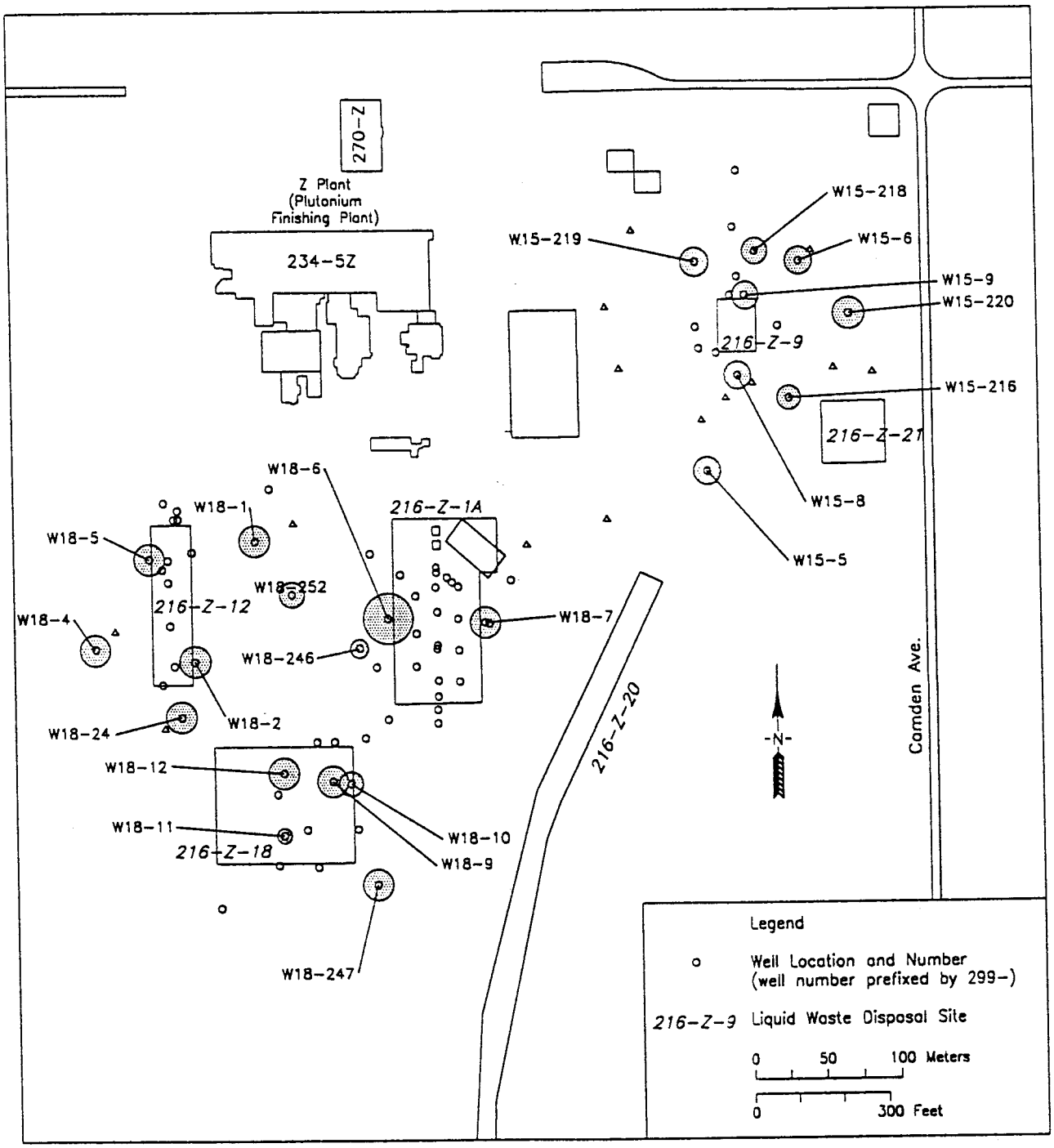


Figure 3-9. Areas of Influence in Wells with Open Intervals Below Caliche--Modified Configuration (Continuous Operation).

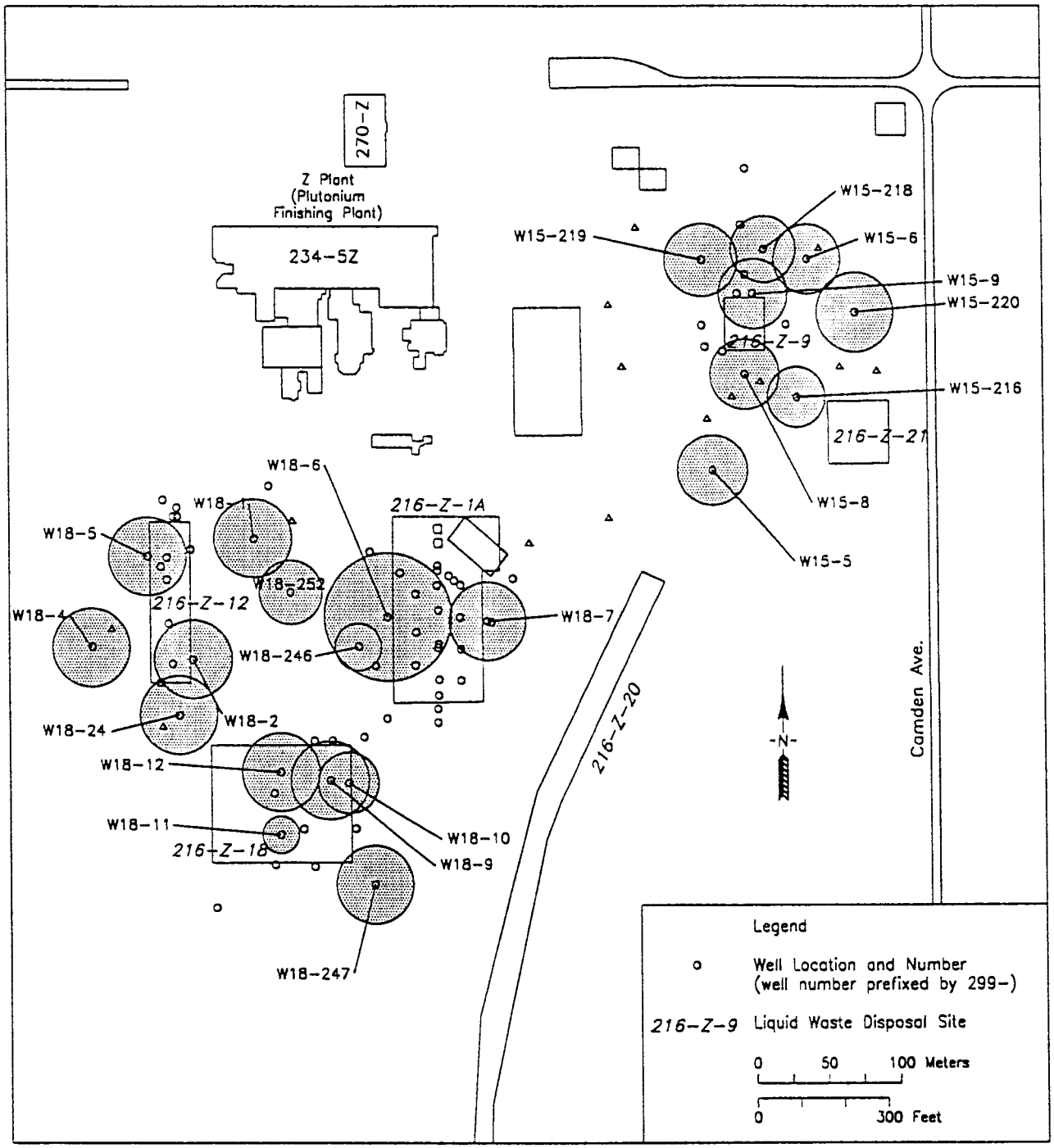


Table 3-5. Z-Crib Area Wells with Open Intervals Above the Caliche (Modified Configuration). (sheet 1 of 3)

Well		Open interval (ft below toc)	Casing diameter (in.)	Piezometer diameter (in.)	Observed flow (ft^3/min)
216-Z-1A/18 TILE FIELD					
299-W18-6	U	100-130	8	2	150[a]
299-W18-10	U	100-130	6	2	150[a]
299-W18-11	U	100-130	6	2	150[b]
299-W18-87	U M L	32.5-38.1 64.7-67.9 124.4-129.3	6	1.5 1.5 1.5	78 (combined)
299-W18-89		108-130	6	6	367
299-W18-93		63-77	6	6	170
299-W18-94		68-78	6	6	272
299-W18-96		122-132 bgs	6	6	256
299-W18-97		63-75	6	6	297
299-W18-98		66-77	6	6	265
299-W18-99		93-103	6	6	226
299-W18-150	U L	65-90 113-119	6	1.5 1.5	150[a] 53
299-W18-158	U L	75-94 119-124	6	1.5 1.5	150[a] 50
299-W18-159		90-120	6	6	150[a]
299-W18-163	U L	54.5-79.5 92.5-119.5	6	1.5 1.5	150[a] 150[a]
218-W18-165		97-127	6	6	150[a]
299-W18-166		99-129	6	6	150[a]
299-W18-167		89-119	8	8	150[a]
299-W18-168		97-127	8	8	150[a]
299-W18-169		96-126	8	8	150[a]
299-W18-171	U M L	19.8-24.5 56-76 114.5-129.5	8	2 2 2	284 (combined)
299-W18-174		106-126 bgs	4	4	112
299-W18-175		90-120	6	6	150[a]
299-W18-246	U	120-130 bgs	4	2	156

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

Well	Open interval (ft below toc)	Casing diameter (in.)	Piezometer diameter (in.)	Oserved flow (ft^3/min)
216-Z-1A/18 TILE FIELD (cont.)				
299-W18-247 U	119-129 bgs	4	2	150[a]
299-W18-248	123-139 bgs	4	4	27
299-W18-249	122-137 bgs	4	4	476
299-W18-252	113-133 bgs	4	2	236
CPT-2	34-47 bgs	1	1	65[b]
CPT-4	90-103 bgs	1	1	40[b]
CPT-20	71-84 bgs	1	1	40[b]
216-Z-12 CRIB				
299-W18-1	100-130	8	2	150[a]
299-W18-2	100-130	8	2	150[a]
299-W18-4	100-130	8	2	150[a]
299-W18-152	88-118	8	8	150[a]
299-W18-153	80-110	8	8	150[a]
299-W18-157	80-110	8	8	150[a]
CPT-10	94-107 bgs	1	1	40[b]
216-Z-9 TRENCH				
299-W15-6	75-100	6	2	200[c]
299-W15-8	90-115	8	2	200[c]
299-W15-9	90-115	8	2	200[c]
299-W15-82	73-88 bgs	8	8	288
299-W15-84	75-90 bgs	8	8	440
299-W15-85	83-98 bgs	8	8	216
299-W15-86	110-140	8	8	200[c]
299-W15-95	73-98 bgs	8	8	200[c]
299-W15-216 U	70-80 bgs	4	2	196
299-W15-217	106-121 bgs	4	4	158
299-W15-218 U	99-114 bgs	4	2	129
299-W15-219 U	87-102 bgs	4	2	124

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

Well	Open interval (ft below toc)	Casing diameter (in.)	Piezometer diameter (in.)	Oserved flow (ft^3/min)
216-Z-9 TRENCH (cont.)				
299-W15-220 U	80-95 bgs	4	2	158
299-W15-223[d]	103-117 bgs	3.5	3.5	209
CPT-3	39-52 bgs	1	1	65[b]
CPT-5	35-48 bgs	1	1	65[b]
CPT-8A	100-113 bgs	1	1	12
CPT-11	64-77 bgs	1	1	40[b]
CPT-12	36-49 bgs	1	1	64
CPT-19	36-49 bgs	1	1	65[b]
CPT-21	84-97 bgs	1	1	40[b]

[a]Value estimated based on average observed flow (147 ft^3/min) and vacuum (103 in. H_2O) for 216-Z-1A/18/12 wells open above caliche.

[b]Value estimated as follows:

CPT wells below 0- to 50-ft depth = 15 ft^3/min (based on CPT-8)
CPT wells below 50- to 100-ft depth = 40 ft^3/min
CPT wells below 100- to 150-ft depth = 65 ft^3/min (based on CPT-12)

[c]Value estimated based on average observed flow (198 ft^3/min) and vacuum (107 in. H_2O) for 216-Z-9 wells open above caliche.

[d]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.
U = upper, M = middle, L = lower.

Table 3-6. Z-Crib Area Wells with Open Intervals Below the Caliche (Modified Configuration).

Well		Open interval (ft below toc)	Casing diameter (in.)	Piezometer diameter (in.)	Observed flow (ft^3/min)
216-Z-1A/18 TILE FIELD					
299-W18-6	L	190-201	8	2	387
299-W18-7		175-203	8	8	300[a]
299-W18-9		180-211	6	6	145[b]
299-W18-10	L	150-214	6	2	80
299-W18-11	L	180-211	6	2	33
299-W18-12		180-211	6	6	145[b]
299-W18-246	L	165-175 bgs	4	2	52
299-W18-247	L	162-172 bgs	4	2	145[b]
299-W18-252	L	165-185 bgs	4	2	96
216-Z-12 CRIB					
299-W18-1		175-200	8	2	145[b]
299-W18-2		183-208	8	2	145[b]
299-W18-4		186-211	8	2	145[b]
299-W18-5		186-211	8	8	145[b]
299-W18-24		205-213	4	4	145[b]
299-W15-5		173-217	8	8	115[c]
299-W15-6	L	160-190	6	2	115[c]
299-W15-8	L	167-197	8	2	115[c]
299-W15-9	L	164-189	8	2	115[c]
299-W15-216	L	175-185 bgs	4	2	86
299-W15-218	L	180-195 bgs	4	2	104
299-W15-219	L	167-182 bgs	4	2	124
299-W15-220	L	155-170 bgs	4	2	149

[a]Value estimated based on 300 ft^3/min reference flow.

[b]Value estimated based on average observed flow (145 ft^3/min) and vacuum (97 in. H_2O) for 216-Z-1A/18/12 wells open below caliche.

[c]Value estimated based on average observed flow (116 ft^3/min) and vacuum (108 in. H_2O) for 216-Z-9 wells open below caliche.

toc = top of casing.

bgs = below ground surface.

L = lower.

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-W15-9	90-115	164-189
2	299-W15-8	90-115	167-197
3	299-W15-6	75-100	160-190
4	299-W15-86	110-140	
5	299-W15-95	73-98 bgs	
6	299-W18-7		175-190
7	299-W18-12		180-190
8	299-W18-166	99-129	
9	299-W18-169	96-126	
10	299-W18-165	97-127	
11	299-W18-163	54.5-79.5 92.5-119.5	
12	299-W18-168	97-127	
13	299-W18-158	80-89	
14	299-W18-167	89-119	
15	299-W18-6	100-130	
16	299-W18-159	90-120	
17	299-W18-175	90-120	
18	299-W18-150	65-90	
19	299-W18-11	100-130	
20	299-W18-10	100-130	
	299-W18-1[a]	100-130	175-195
	299-W18-2[a]	100-130	183-200
	299-W18-4[a]	100-130	186-200
	299-W18-5[a]		186-195

[a]Wells currently in use for 200-ZP-1 groundwater pump-and-treat testing.
toc = top of casing.

Table 3-8. Proposed New Vapor Extraction Wells.

Well number and priority	East/West coordinates (m)	North/South coordinates (m)	Approximate depth of screened interval (ft below toc)
1	566711	135706	U 110-140 L 170-200
2	566795	135696	U 110-140 L 170-200
3	566806	135595	U 110-140 L 170-200
4	566852	135671	U 110-140 L 170-200
5	566688	135631	U 110-140 L 170-200
6	566703	135571	U 110-140 L 170-200
7	566402	135418	U 110-140 L 170-200
8	566479	135456	U 110-140 L 170-200
9	566427	135385	U 110-140 L 170-200
10	566464	135381	U 110-140 L 170-200
11	566766	135527	U 110-140 L 170-200
12	566423	135339	U 110-140 L 170-200
13	566517	135332	U 110-140 L 170-200
14	566347	135424	U 110-140 L 170-200
15	566397	135299	U 110-140 L 170-200

toc = top of casing.
U = upper, L = lower.

Figure 3-10. Areas of Influence in Proposed New Vapor Extraction Wells with Open Intervals Above Caliche--Modified Configuration (Continuous Operation).

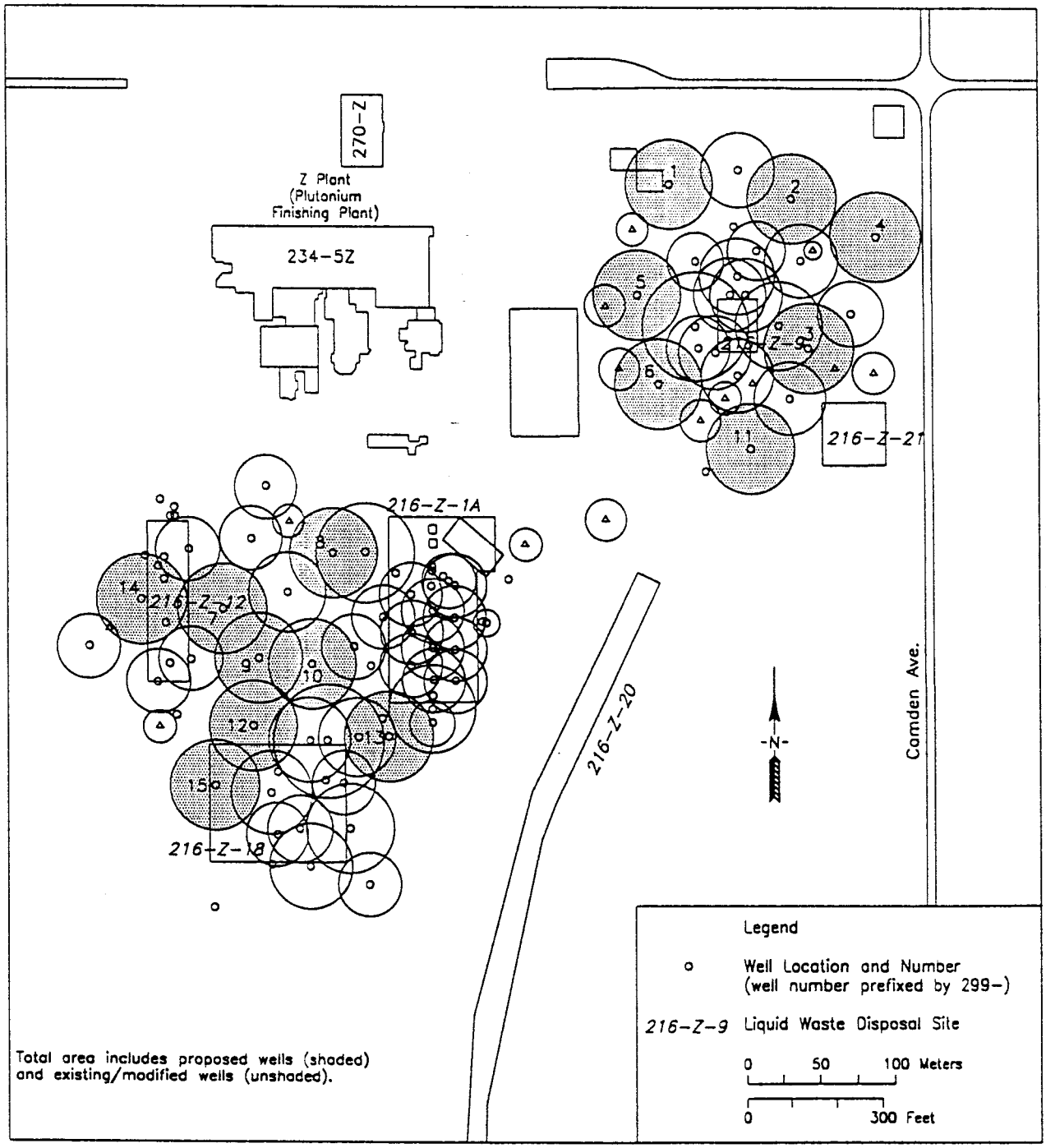


Figure 3-11. Areas of Influence in Proposed New Vapor Extraction Wells with Open Intervals Below Caliche--Modified Configuration (Continuous Operation).

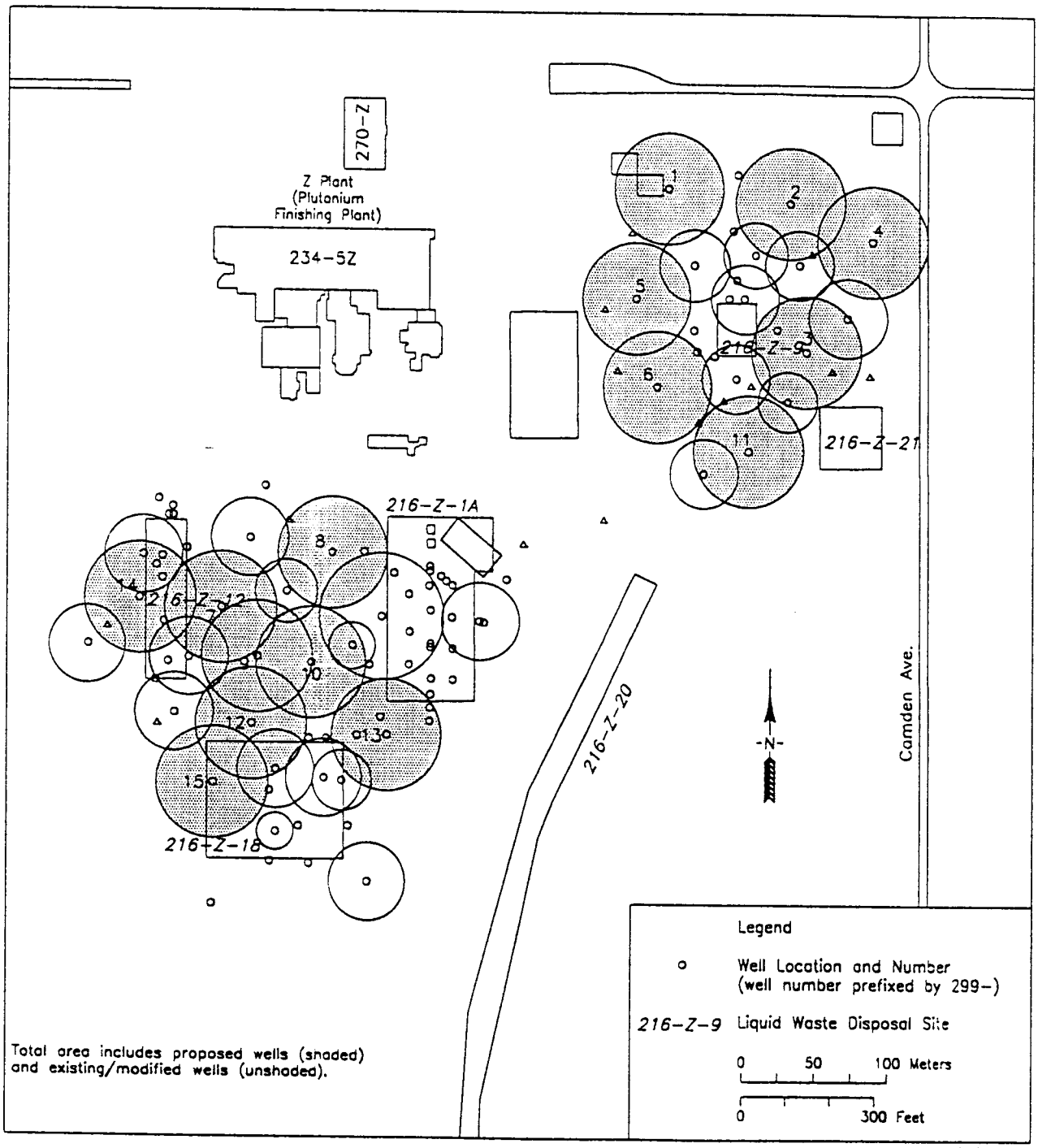


Table 3-9. Prioritization of New and Modified Extraction Wells.

Priority	Extraction target zone	New well prioritization no.	Total no. new screened intervals	Modified well prioritization no.	Total no. new perforated intervals
1	Between caliche and water table in core of known plume, emphasizing areas of highest contaminant concentrations first	1-11, 12-13	13	1-3, 6-7	5
2	Above the caliche beneath 216-Z-9	1-6, 11	7	1-3, 4-5	5
3	Above the caliche in 216-Z-1A/216-Z-181/216-Z-12 wellfields	7-10, 12-13	5	8-20	14
4	Above and below the caliche at perimeter of known plume	14, 15	4	NA[a]	0

[a]Modification of wells 299-W18-1, 299-W18-2, 299-W18-4, and 299-W18-5 above and/or below the caliche would provide seven open intervals in the 216-Z-12 area. These wells are currently in use for 200-ZP-1 groundwater pump-and-treat testing.

5. Some wells are to be perforated or screened in intervals both above and below the caliche layer. For these wells, it was assumed that both intervals would be perforated or screened at the same time. Therefore, wells, rather than specific intervals, have been prioritized.

The modified wellfield 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 achieved by extracting at different times from two open intervals that are in close proximity, allowing each area of influence to become fully developed. A different phenomenon known as 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.

The estimated areas of influence for continuous vapor extraction are given in Table 3-10 for existing, modified, and new proposed wellfield configurations.

Table 3-10. Existing Vapor Extraction Areas of Influence.

Wellfield configuration/ operation		Area of influence (ft^2)	
		Above caliche	Below caliche
Existing	Continuous	542,271	424,526
	Intermittent	117,485	73,851
Modified	Continuous	638,283	431,746
	Intermittent	169,794	74,836
Proposed new	Continuous	936,583	931,768

As seen in Table 3-10, implementing continuous VES operations would increase the existing area of coverage by 362% or 420,000 ft^2 above the caliche and by 475% or 350,000 ft^2 below the caliche. The modified wellfield configuration would increase the area of coverage by 18% or 96,000 ft^2 above the caliche and by 2% or 7,200 ft^2 below the caliche for continuous operations. Similarly, the proposed wellfield including new wells increase the area of coverage by 47% or 300,000 ft^2 above and 116% or 500,000 ft^2 below the caliche, compared to the existing wellfield. [NOTE: The increase in area of coverage below the caliche layer after modification appears to be small because, pending results of characterization testing, the flow rates estimated for most of the existing and modified wells were the same (Table 3-4).]

3.1.1.3 Recommendation. It is recommended that continuous vapor extraction operations be implemented at the 216-Z-9 wellfield to increase the effective area of influence of existing extraction intervals. (Continuous operations have already been implemented at the 216-Z-1A and 216-Z-18 wellfields.) A modified wellfield configuration is also recommended to increase access to the known contaminant plume. Existing wells selected for perforation are prioritized in Table 3-5; proposed new vapor extraction wells are prioritized in Table 3-6.

It is recognized that several simplifying assumptions were used in assessing the coverage provided by the current wellfield and determining the locations for modified and new open intervals. It is further recognized that extensive resources may be required for installation of new wells. Therefore, it is recommended that these enhancements to the current wellfield configuration be implemented in phases as part of the iterative process which permits collection and analysis of data to identify optimal new open interval locations and extraction rates.

Existing wells have been periodically evaluated and mechanically perforated to provide open intervals since inception of the vapor extraction pilot test in 1991. Use of this existing resource is a relatively cost-effective way to increase the coverage, and it is recommended that these modifications be made

during FY 1995. Most of the wells to be modified were selected to increase observed flow rates or to lengthen existing open intervals (Tables 3-3 and 3-4 and Appendix B). It is apparent from observed flow rates that the mechanical perforator may not always be an effective way to cut through the steel well casings. In addition, several wells have multiple casing strings that cannot be cut with a mechanical perforator. As an alternative, it is recommended that an explosion-based perforator be used to modify these wells.

Identification of new wells to complete the wellfield coverage is intended to provide an initial estimate of the need for additional intervals, based on current operations. The new wells are prioritized to provide guidance for a phased installation. However, it is also recommended that the extraction enhancement strategies described in Section 3.1.4 be considered for alternative ways to effectively increase the wellfield coverage.

3.1.2 Passive Soil Vapor Extraction

3.1.2.1 Problem. In areas where carbon tetrachloride concentrations are low, active vapor extraction may no longer be the most cost-effective extraction method for removing the contaminants from the unsaturated zone. Passive soil vapor extraction (PSVE) appears to be viable as an extraction process that can complement active vapor extraction under certain conditions.

3.1.2.2 Passive Soil Vapor Extraction. Passive soil vapor extraction is proposed as part of a dynamic wellfield strategy that will optimize removal of carbon tetrachloride (Rohay 1994). A PSVE system utilizes the natural movement of air in the soil to carry VOCs from the unsaturated zone to the surface. Each well with an open area in the subsurface will naturally "breathe," i.e., inhale ambient air from the surface and exhale soil gas. This passive breathing results from pressure differentials that occur between the soil pressure near the open interval of a well and atmospheric pressure. No energy input is required, thus the system is passive.

The concept of using this natural air flow as the driving force for a remediation system has been tested on a small scale by the wellhead monitoring systems placed on wells within the Z-Crib Area. Based on the data gathered from these stations, PSVE appears viable as a technology that can augment active vapor extraction (WHC 1994). Demonstrations of PSVE are scheduled for September through December 1994. If these demonstrations are successful, multiple PSVE systems could be utilized on extraction wells that are located outside the area of influence of an active VES and that have carbon tetrachloride concentrations of 200 ppm_v or less (WHC 1994). Table 3-11 lists some of the existing extraction wells that are good candidates for PSVE in approximate order of priority. In most cases these wells were selected based on the vapor concentrations measured during the baseline monitoring program (Fancher 1994). When additional characterization data become available, the well priorities should be reviewed. Additional extraction wells should be considered for PSVE as the extracted soil-gas concentrations drop and stay below 200 ppm_v of carbon tetrachloride. Some near-surface soil flux surveys indicate that a soil vapor plume may extend to the north of the 216-Z-9 Trench (Rohay et al. 1994). Wells in this area should also be characterized for possible use of PSVE systems.

Table 3-11. Proposed Passive Soil Vapor Extraction Wells.

Well interval	Expected carbon tetrachloride concentrations (ppm_v)
Below the Caliche	
299-W18-247L	100
299-W18-11	200
Above the Caliche	
299-W18-247U	50
299-W18-94	100
299-W18-97	50
CPT-2	50
CPT-20	50
CPT-10	200

The minimum components for a PSVE system are an appropriately sized GAC canister and piping or hoses to direct the soil gas from the well to the canister. Additional elements that may be included are a check valve, a blast gate valve, a flow enhancement device, and a high-efficiency particulate air (HEPA) filter. These elements are shown in Figure 3-12.

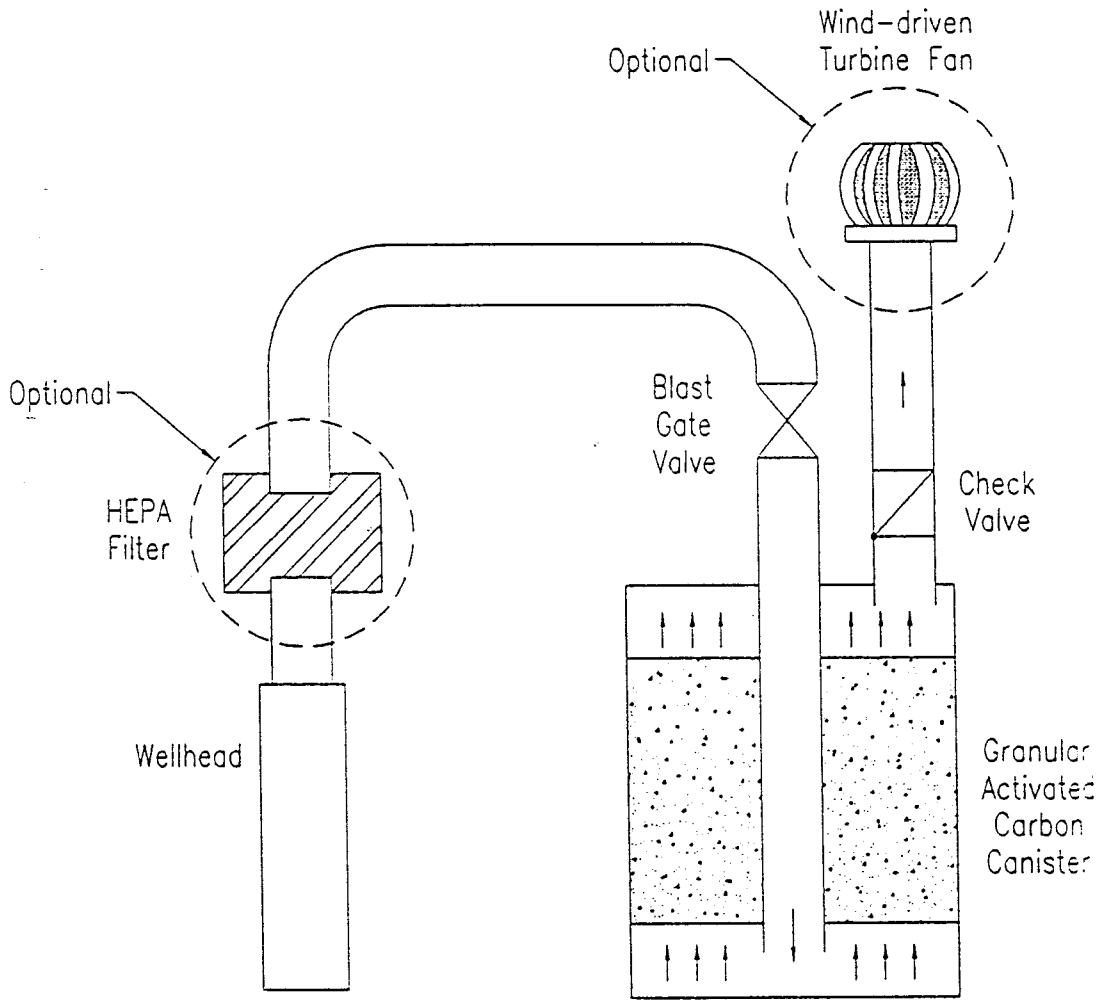
The check valve is used to limit the flow of air into the well. Without such a valve, during the periods when the atmospheric pressure is greater than the soil pressure, air will flow back into the well. While this does not compromise the integrity of the system, the introduction of ambient air to the soil has the effect of pushing the contaminated vapor away from the well. This can result in lower concentrations of VOCs being drawn from the soil when the pressure reverses. Including a check valve in the PSVE system increases the concentration of VOCs extracted.

The blast gate valve is used to seal off the well during installation and maintenance of the PSVE system.

The enhancement device may be any device, mechanical or otherwise, that passively increases the vacuum on the well, thereby increasing the volume of air extracted. There are a number of possible devices available. Purely mechanical devices include a venturi tube, a turbine, and a tornado, all of which operate using wind power. Other devices include motorized fans or pumps that may be operated using batteries and solar panels.

The HEPA filter is used to protect the PSVE system and the environment from particulate radionuclides that may be extracted from the well. It is not considered to be a necessary part of the PSVE system and should only be used if it is determined that there is a reasonable potential for the presence of particulate radionuclides.

Figure 3-12. Passive Soil Vapor Extraction System Conceptual Design.



3.1.2.3 Recommendation. It is recommended that, pending successful field demonstration, PSVE systems be considered to extract contaminated soil gas from wells with relatively low concentrations of carbon tetrachloride. Existing wells selected for PSVE are approximately prioritized in Table 3-11.

3.1.3 Expanded Soil Vapor Extraction System Capacity

3.1.3.1 Problem. The volume of contaminated subsurface within the Z-Crib Area that can be addressed simultaneously with the existing vapor extraction capacity is limited. In addition, some wells in contaminated areas are effectively inaccessible to the existing VES systems.

3.1.3.2 Discussion. To achieve the areas of influence simultaneously for the existing wellfield (Figures 3-2 to 3-5) or the proposed modified wellfield (Figures 3-10 and 3-11), the following rates of soil vapor extraction would be required. (NOTE: Intermittent and continuous extraction flow rates are the same; the area of influence varies because the intermittent operation requires reestablishing the area of influence each time.)

	Existing Wellfield	Flow rates (ft^3/min)	Modified Wellfield (Existing and New Wells)	Flow rates (ft^3/min)
216-Z-1A/18 Tile Field	Above the caliche	3,700	Above the caliche	6,900
	Below the caliche	1,300	Below the caliche	2,900
216-Z-12 Crib	Above the caliche	800	Above the caliche	2,100
	Below the caliche	700	Below the caliche	1,600
216-Z-9 Trench	Above the caliche	2,300	Above the caliche	5,400
	Below the caliche	800	Below the caliche	3,000
	Total	9,600		21,900

The total soil-gas extraction rate that would be required to achieve the areas of influence simultaneously is 9,600 ft^3/min and 21,900 ft^3/min for the existing and modified wellfield, respectively. This is far beyond the present extraction capacity of 3,000 ft^3/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 different directions cancel each other.

3.1.3.3 Recommendation. It is recommended that the extraction capacity be increased to expand the volume of unsaturated soils from which soil vapor can be extracted at any given time. This increased capacity could be in smaller VES units that 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 ft^3/min, which would allow the VES unit to be purchased "off-the-shelf" and would supply enough extraction capacity to effectively extract from one or two wells each. 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.

In addition, use of PSVE systems on wells with low contaminant concentrations would make additional active VES capacity available (Section 3.1.2). Similarly, use of an intermittent pumping

strategy for wells with diffusion-rate-limited concentrations would increase the number of wells that could be addressed by the active VESs (Section 3.1.4.2).

3.1.4 Extraction Enhancement Strategies

3.1.4.1 Problem. Availability of carbon tetrachloride that is primarily contained within low-permeability layers is diffusion-limited. Enhancement of the active soil vapor extraction process may be required to maintain efficient remediation. Several strategies are described in the following sections.

3.1.4.2 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 of 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.

3.1.4.3 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 ft^3/min to 75 ft^3/min.

In the Z-Crib Area, silty lenses and the caliche layer are regions of low permeability where remedial activities may benefit from PFE.

3.1.4.4 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.

3.1.4.5 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 1993a) may become recognized as an exposure pathway of concern. Surface seals may be used to reduce this atmospheric loss, if necessary.

3.1.4.6 Recommendation. It is recommended that further investigations into the applicability and predicted effectiveness of various vapor extraction enhancement strategies be conducted in anticipation of eventual reduced efficiency of active vapor extraction operations.

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 C. The modeling uses specific chemical characteristics of carbon tetrachloride, which are provided in Appendix D.

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 in 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 1993a). 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 nonaqueous-phase liquid carbon tetrachloride in the saturated or unsaturated zone, and/or natural or biodegradation.

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 one-tenth to one-half 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 nonaqueous-phase liquid 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 langmiur. A linear isotherm was used to determine a vapor phase partitioning coefficient (Appendix E).

This isotherm had the following form:

$$C_s\ (\mu g/kg) = 0.73\ C_v\ (ppm_v). \qquad (1)$$

where:

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

C_v = 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 interval 20 m thick, and a contaminated area of 60,000 m^2 for the 216-Z-9 wellfield and 240,000 m^2 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 nonaqueous-phase liquid carbon tetrachloride were present beneath each of the disposal sites. The soil-gas concentrations found to date indicate that nonaqueous-phase liquid carbon tetrachloride is probably present in the unsaturated zone of the 216-Z-9 wellfield and is being remediated by vapor extraction operations. If a nonaqueous-phase liquid is present within the 216-Z-1A/18 wellfield, it is likely located in a low-permeability lens such as the Hanford lower fine and Plio-Pleistocene units. This has implications for vapor extraction operations because very high recovery rates can be expected from the 216-Z-9 wellfield until the nonaqueous-phase liquid is removed. The extracted soil-gas concentrations will then decrease as the adsorbed carbon tetrachloride is removed. If nonaqueous-phase liquid 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 3-13). 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 1 year. The expected vapor extraction rate at the 216-Z-1A/18 wellfield is near the flat portion of the curve.

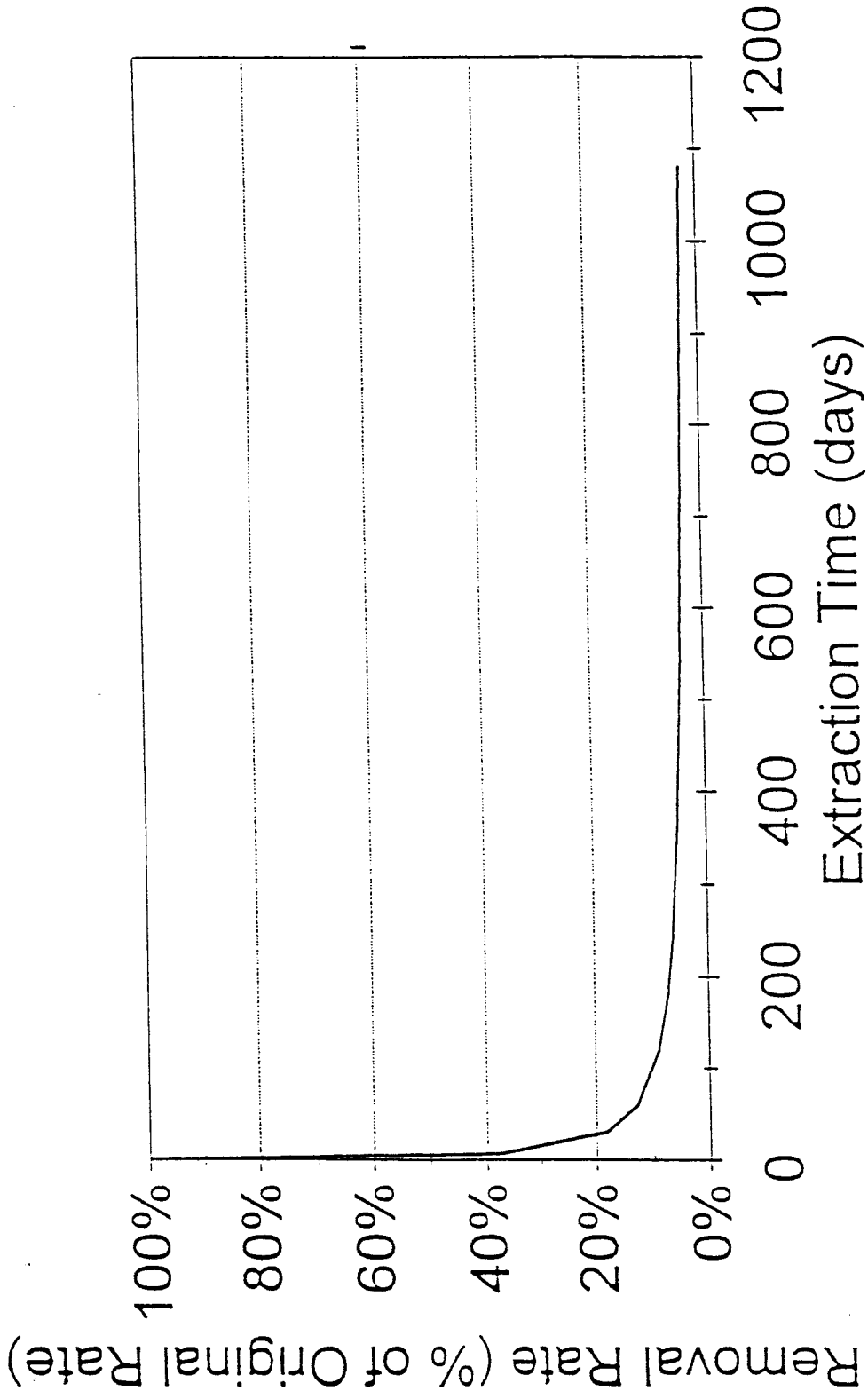
Specific cleanup standards have not been established that determine when remediation is completed. However, for the purpose of modeling, the use of active vapor extraction operations is assumed to be necessary only until residual carbon tetrachloride has been reduced to the level at which PSVE operations are cost effective. As concluded in a separate study, PSVE becomes cost effective when the equilibrium concentration of carbon tetrachloride in the subsurface is reduced to less than 200 ppm_v (WHC 1994). 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 $stdft^3$/min for 6,000 h/year at each of the two sites (this represents a 68% total operating efficiency; the present 5-day/week, 8-h/day operation at 216-Z-9 provides about 24% operating efficiency).

Figure 3-13. Vapor Extraction from a Low-Permeability Lens.



- 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 x 10^9 $stdft^3$ 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 a 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 x 10^7 $stdft^3$ of soil gas must be extracted from the 216-Z-9 wellfield over 1 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. H_2O are listed in Table 3-12.

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. H_2O are listed in Table 3-13. The flow rates given a vacuum of 120 in. H_2O, an open interval 15 ft long, and well diameters ranging from 4 to 8 in. diameter are listed in Table 3-14. These flow rates were used in the preceding sections to address the wellfield areas of influence.

3.2.3 Recommendations

Based on the time required to remediate the 216-Z-1A/18 and 216-Z-12 wellfields, 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-$stdft^3$/min capacity in this area. As identified in Section 3.1.3, the airflow rate required to impact the entire existing wellfield is 3,100 $stdft^3$/min at the 216-Z-9 wellfield and 6,500 $stdft^3$/min at the combined 216-Z-1A/18 and 216-Z-12 wellfield. Because of 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. In addition, it is recommended that the 500-ft^3/min system be used for extraction of wells in the 216-Z-12 wellfield where carbon tetrachloride soil-gas concentrations are higher than at 216-Z-18 (Fancher 1994).

It is also recommended 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

Table 3-12. Predicted Flow Rates for Various Well Vacuums.

Well vacuum in. H_2O	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 3-13. Predicted Flow Rates for Various Well Open Interval Lengths in a 4-in.-Diameter Well (Vacuum at 120 in. H_2O).

Open interval length (ft)	Flow rate from a 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 3-14. Predicted Flow Rates for Various Well Diameters with a 15-ft-Long Open Interval (Vacuum at 120 in. H_2O).

Well diameter (in.)	Flow rate from a 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

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 120 in. H_2O vacuum and a flow of about 300 ft^3/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.

Additional numerical modeling is recommended to simulate the wellfield airflow dynamics and vapor transport, rather than the individual well areas of influence and flow rates. The ability to simulate the wellfield responses under different airflow rates and pumping scenarios would be extremely advantageous for optimizing extraction capacity and extraction well placement. Two new numerical modeling codes that appear to include these capabilities are AIR3D, which predicts airflow paths and rates in a three-dimensional unsaturated zone, and VAPOR3D, which uses the flow predictions and multispecies chemical data to predict chemical transport (Joss 1993a, 1993b). These codes are anticipated to be released very soon in the public domain by the U.S. Geological Survey.

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 critical 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. For example, testing following the GAC overheating incident at 216-Z-9 in June 1993 indicated that heat of

adsorption alone at 28,500 ppm_v was insufficient to cause the observed paint discoloration (WHC 1993b). As a result, it was recommended that the soil gas be more fully characterized for other compounds that could contribute to overheating.

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 extracts 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 wellfield, 216-Z-18 wellfield, and 216-Z-9 wellfield are presented in Tables 3-15, 3-16, and 3-17, respectively.

Data from these tables have been used to develop the graphical representations of carbon tetrachloride concentrations over time in extracted soil gas. Concentration is believed to be more appropriate than contaminant flux as an indicator of subsurface characteristics. Flux is a dependent variable (a function of concentration and flow rate). Characterization of these areas with respect to flux will likely reflect variations in pumping parameters, and will provide little insight into subsurface contaminant profiles.

Analysis of 216-Z-1A Tile Field Data: Characterization data from wells 299-W18-150L, 299-W18-158L, 299-W18-168, and 299-W18-171 which have open intervals above the caliche are shown in Figure 3-14. The first three of these wells showed an increase in carbon tetrachloride concentrations after the extended VES shutdown (June 3 - November 15, 1993). Operation of the VES since November 1993 has resulted in a trend to decreasing concentrations that now are at levels near or below those seen in June 1993. This indicates that prior to the shutdown, extracted soil vapors were not at equilibrium and that pulsed VES operation, where extraction wells are used alternatingly, should be investigated to optimize extraction at this wellfield. It is recommended that the extraction wells be alternated weekly or biweekly.

Characterization data from wells open below the Plio-Pleistocene caliche layer indicate that carbon tetrachloride concentrations in the extracted soil gas have been increasing in May and June 1994 (Figure 3-15). This suggests that extraction from the lower interval is pulling in the plume and removing carbon tetrachloride from the zone closer to the water table.

Analysis of 216-Z-9 Trench Data: The carbon tetrachloride profile for four wells within the 216-Z-9 Trench area are shown in Figure 3-16. Full-scale extraction operations had not begun at the 216-Z-9 wellfield prior to the beginning of the extended VES shutdown in June 1993. A general trend of decreasing concentrations is apparent for the four wells since restart of VES operations in February 1994. Based on these data, trends with respect to individual wells can be analyzed. For example, 12 discrete samples were collected at well 299-W15-217. Of these, three sets of data were collected on consecutive days (Table 3-17). Concentration of these consecutive samples does not significantly decrease. This may indicate that the contaminant source is greater than the gas volume pumped throughout the extraction duration. It is unlikely that equilibration of soil gas could occur within a 24-hour period. This basic trend can be seen for wells 299-W15-82 and 299-W15-84. Consecutive measurements were not collected at well 299-W15-95.

Table 3-15. 216-Z-1A Tile Field, September 1992 Through June 1994. (sheet 1 of 2)

Date	Well and interval	Vacuum (in. H_2O)	Flow (stdft^3/min)	Carbon tetrachloride (ppm_v)	Carbon tetrachloride flux (lb/h)	$CHCl_3$ (ppm_v)	CH_2Cl_2 (ppm_v)	MEK (ppm_v)
5/2/94	299-W18-6	89	370	304	2.89	0	4	0
6/20/94	299-W18-6	86	387	525	5.22	0	7	0
5/6/94	299-W18-7	96	217	209	1.16	0	3	0
6/21/94	299-W18-7	85	222	388	2.21	0	6	0
6/2/93	299-W18-87	130	120	75	0.23			
11/16/93	299-W18-87	127	78	55	0.11	0.1	0.33	0
7/26/94	299-W18-89	97	367	496	4.68	0	6	0
6/1/93	299-W18-150L	132	84	219	0.47			
11/15/93	299-W18-150L	129	50	243	0.31	0.14	2.7	1.1
11/15/93	299-W18-150L[a]	129	50			0.6	6.67	
4/15/94	299-W18-150L	127	53	150	0.20	0.367		0.167
6/1/93	299-W18-150M	132	28	157	0.11			
4/18/94	299-W18-150M	116	17	180	0.08	0		0.9
6/1/93	299-W18-150U	131	32	35	0.03			
4/18/94	299-W18-150U	121	20	181	0.09	0		1.3
9/22/92	299-W18-158L[b]	91	45	500	0.58			
6/1/93	299-W18-158L	131	40	144	0.15			
11/15/93	299-W18-158L	124	26	394	0.26	3.8	3.6	0.8
4/18/94	299-W18-158L	120	50	192	0.25	0.87		0.53
6/1/93	299-W18-158M	131	40	91	0.09			
4/18/94	299-W18-158M	125	27	106	0.07	0.56		0.82
6/1/93	299-W18-158U[c]	31	64	2	0.00			
4/18/94	299-W18-158U	124	78	38	0.08	0.4		0.48
9/22/92	299-W18-159[b]	100	57	580	0.85			
6/1/93	299-W18-159	132	72	307	0.57			
4/15/94	299-W18-159	127	38	243	0.24	0.743		0.359
6/20/94	299-W18-159	97	39	238	0.24			
9/22/92	299-W18-163L[b]	80	26	140	0.09			
6/1/93	299-W18-163L	124	8	5	0.00			
11/15/93	299-W18-163L	128	0					
4/18/94	299-W18-163L	120	0					
6/2/93	299-W18-163M	130	10	2	0.00			
4/18/94	299-W18-163M	117	0					
6/2/93	299-W18-163U	141	11	2	0.00			
4/18/94	299-W18-163U	119	0					
4/20/94	299-W18-165	122	4	140	0.01			
6/1/93	299-W18-166	130	16	82	0.03			
11/16/93	299-W18-166	128	3	70	0.01	0.34	0.65	0
4/18/94	299-W18-166	120	4	148	0.02	0.74		0.82
4/20/94	299-W18-167	120	58	180	0.27			
6/21/94	299-W18-167	87	20	191	0.10	0	3	0
10/6/92	299-W18-168[b]	100	10	670	0.17			
6/1/93	299-W18-168	139	27	212	0.15			
11/16/93	299-W18-168	129	13	371	0.12	3.6	5	0.3
11/16/93	299-W18-168[a]	129	13				1.48	
4/18/94	299-W18-168	120	14	108	0.04	0		0.62
6/20/94	299-W18-168	89	7					

Table 3-15. 216-Z-1A Tile Field, September 1992 Through June 1994. (sheet 2 of 2)

Date	Well and interval	Vacuum (in. H_2O)	Flow (stdft^3/min)	Carbon tetrachloride (ppm_v)	Carbon tetrachloride flux (lb/h)	$CHCl_3$ (ppm_v)	CH_2Cl_2 (ppm_v)	MEK (ppm_v)
6/21/94	299-W18-169	90	0					
6/2/93	299-W18-171	130	296	329	2.50			
11/16/93	299-W18-171	108	249	52	0.33	0	0.8	0
4/15/94	299-W18-171	123	325	50	0.42	0		0.128
6/20/94	299-W18-171	88	284	8	0.06	0	1	0
4/21/94	299-W18-174	120	124	199	0.63	0	4	0
6/20/94	299-W18-174	94	112	227	0.65	1	4	0
9/22/92	299-W18-175[b]	90	60	605	0.93			
6/1/93	299-W18-175	132	68	490	0.86			
4/15/94	299-W18-175	124	33	576	0.49	0		1.6
6/20/94	299-W18-175	88	40	494	0.51	0	12	1
4/20/94	299-W18-246L	121	59	162	0.25	0.673	0.817	0.06
4/20/94	299-W18-246L	71	43	169	0.19	0.283	0.2	0
6/21/94	299-W18-246L	87	52	236	0.32	0	2	0
4/19/94	299-W18-246U	117	192	271	1.34	0.189		0.437
6/21/94	299-W18-246U	90	156	125	0.50	0	3	0
4/21/94	299-W18-248	120	30	142	0.11	0	1	0
6/21/94	299-W18-248	91	27	301	0.21	1	4	1

[a]Gas chromatograph analysis.
[b]Odyssey analysis.
[c]Leaking.
$CHCl_3$ = Chloroform.
CH_2Cl_2 = Methylene chloride.
MEK = Methylethyl ketone.
U = Upper.
M = Middle.
L = Lower.

Table 3-16. 216-Z-18 Crib, June 1993 Through June 1994.

Date	Well and interval	Vacuum (in. H_2O)	Flow (stdft^3/min)	Carbon tetrachloride (ppm$_v$)	Carbon tetrachloride flux (lb/h)	$CHCl_3$ (ppm$_v$)	CH_2Cl_2 (ppm$_v$)	MEK (ppm$_v$)
6/2/93	299-W18-10	130	80	221	0.45			
11/16/93	299-W18-10	130	46	342	0.40	4.7	6	0.8
4/15/94	299-W18-10	124	49	267	0.34	0.035		0.206
7/26/94	299-W18-10	100	80	149	0.31	1.26	0.95	0.76
7/14/94	299-W18-11	101	33	54	0.05	0	1.02	1.82
7/14/94	299-W18-93	100	170	26	0.11	0	1.76	0.98
7/25/94	299-W18-94	102	272	22	0.15	0	1.32	0.84
7/13/94	299-W18-96	100	256	103	0.68	0.7		0.3
6/2/93	299-W18-97	134	312	23	0.18			
11/16/93	299-W18-97	128		95		0	0	0
4/15/94	299-W18-97	129	258	48	0.32	0.453		0.149
7/26/94	299-W18-97	102	297	12	0.09	0	1.89	0.68
7/12/94	299-W18-98	126	328	38	0.32	1.51	1.72	0.11
7/12/94	299-W18-98	101	265	39	0.27	0	3.84	0.54
6/30/94	299-W18-99	99	226	106	0.62	0.32	1.64	0.31
7/11/94	299-W18-249	85	476	108	1.32	0.041	1.67	0.46
3/7/94	299-W18-252L	122	96	618	1.52	4.3	6.03	0.176
1/5/94	299-W18-252U	92	148	97	0.37	0.568	1.22	0.236
1/6/94	299-W18-252U	127	236	527	3.19	3.59	5.75	0.085
1/20/94	299-W18-252U	127	235	500	3.02			
3/10/94	299-W18-252U	57	186					
3/10/94	299-W18-252U	74	206					
3/10/94	299-W18-252U	95	233					
3/10/94	299-W18-252U	114	257	547	3.61			
3/10/94	299-W18-252U	131	269					
5/16/94	299-W18-252U	97	235	368	2.22	0	0	0
5/17/94	299-W18-252U	96	239	440	2.70	0	4	0
5/18/94	299-W18-252U	96	232	395	2.35	0	4	0
5/19/94	299-W18-252U	95	236	404	2.45	0	4	0

$CHCl_3$ = Chloroform.
CH_2Cl_2 = Methylene chloride.
MEK = Methylethyl ketone.
U = Upper.
L = Lower.

Table 3-17. 216-Z-9 Trench, April 1993 Through June 1994. (sheet 1 of 2)

Date	Well and interval	Vacuum (in. H_2O)	Flow (stdft^3/min)	Carbon tetra-chloride (ppm$_v$)	Carbon tetra-chloride flux (lb/h)	$CHCl_3$ (ppm$_v$)	CH_2Cl_2 (ppm$_v$)	MEK (ppm$_v$)	1,1,1-TCA (ppm$_v$)	PCE (ppm$_v$)	Other (ppm$_v$)
3/31/93	299-W15-82[a,b]	128	23	11,848	7.00						
4/1/93	299-W15-82[a,c]		55	8,208	11.60						
4/12/93	299-W15-82[a,c]			6,101							
4/28/93	299-W15-82	26	70	26,000	46.75						
6/3/93	299-W15-82	69	254	28,500	185.94						
2/23/94	299-W15-82	13	51	23,000	30.13	113	114	3.9			
2/23/94	299-W15-82[b]	13	51			16.1	24.6		3.2	6.3	1.5[d]
2/24/94	299-W15-82	13	48	25,300	31.19	106	139	4.1			
2/24/94	299-W15-82[b]	13	48			25	25		1.2	5.9	5.6[d]
5/10/94	299-W15-82	20		20,300		102	115	2.4			
5/11/94	299-W15-82	21		19,800		99.2	118	2.75			
6/1/94	299-W15-82	46		11,700		69.8	74.7	2			
6/10/94	299-W15-82	100		8,040		68.3	61.6	2			
9/6/94	299-W15-82	116	288	5,240	38.76	56.3	28.8	1.3			
4/2/93	299-W15-84[a]	128	0								
4/29/93	299-W15-84	20	75	8,475	16.33						
3/1/94	299-W15-84	65	323	8,230	68.28	51.7	58.8	1.64			
3/1/94	299-W15-84[b]	65	323			32.8	6		6.9	1.8	
3/1/94	299-W15-84	40	97	7,100	17.69	43.6	51.5	1.42			
3/1/94	299-W15-84[b]	40	97			46.7	5.3		2.8	3.1	
3/2/94	299-W15-84	40	206	9,910	52.44	57.4	69.2	2.2			
3/2/94	299-W15-84[b]	40	206			64.8	6.8		3.9	4.9	
5/10/94	299-W15-84	20		17,200		83.3	100	2			
5/11/94	299-W15-84	21		16,300		79.3	100	3			
6/1/94	299-W15-84	46		5,010		31.7	37.8	1.86			
6/10/94	299-W15-84	100		4,470		37.5	38.7	2			
9/6/94	299-W15-84	101	440	444	5.02	7.4	6.9	0.5			
4/2/93	299-W15-85[a]	130	0								
4/5/93	299-W15-85[a]	123	0								
4/30/93	299-W15-85	17	75	16,700	32.17						
3/3/94	299-W15-85	92	230	10,400	61.44	60.3	55.3	1.26			
3/3/94	299-W15-85[b]	92	230			16.1	5.5		2.3	2.4	
3/3/94	299-W15-85	62	96	12,600	31.07	59.1	76.6	2.2			
3/3/94	299-W15-85[b]	62	96			12.9	6.4		2.7	2.8	
9/6/94	299-W15-85	115	216	256	1.42	4.8	1	0.3			
4/5/93	299-W15-95[a]	123	0								
4/13/93	299-W15-95[a,c]		20	14,320	7.36						
4/14/93	299-W15-95[a,c]		20	6,240	3.21						
4/28/93	299-W15-95	118	34	10,700	9.34						
3/8/94	299-W15-95	105	21	11,900	6.42	60.9	67.3	1.6			
3/8/94	299-W15-95[b]	105	21			12.6	4.6		1.6	2.5	
5/18/94	299-W15-95	103	74	8,740	16.61	44.9	49.6	0			
6/1/94	299-W15-95	46		4,530		21.9	30.3	0.6			
6/10/94	299-W15-95	100		2,110		14.1	18.4	1.3			
9/6/94	299-W15-95	99	63	444	0.72	6.4	5.3	0.4			
3/17/94	299-W15-216L	106	86	878	1.94	3.9	6.9	0.68			
3/17/94	299-W15-216L[b]	106	86			0.2	0.1		<0.1	0.1	
3/18/94	299-W15-216U	107	196	1,410	7.10	9.16	8.81	0			
3/18/94	299-W15-216U[b]	107	196			4.4	0.2		0.1	0.5	
5/4/93	299-W15-217	62	75	18,200	35.06						
5/5/93	299-W15-217	130	157	23,800	95.98						
5/10/93	299-W15-217	119	186	23,000	109.89						
5/11/93	299-W15-217	95	178	25,500	116.59						

Table 3-17. 216-Z-9 Trench, April 1993 Through June 1994. (sheet 2 of 2)

Date	Well and interval	Vacuum (in. H_2O)	Flow (stdft³/min)	Carbon tetra-chloride (ppmv)	Carbon tetra-chloride flux (lb/h)	$CHCl_3$ (ppmv)	CH_2Cl_2 (ppmv)	MEK (ppmv)	1,1,1-TCA (ppmv)	PCE (ppmv)	Other (ppmv)
3/4/94	299-W15-217	28	40	15,500	15.93	76	88.9	2.85			
3/4/94	299-W15-217[b]	28	40			15.1	3.5		6.4	5.9	
3/4/94	299-W15-217	41	75	16,300	31.40	74.4	96.7	3.88			
3/4/94	299-W15-217[b]	41	75			24.7	3.7		6	6	
3/4/94	299-W15-217	61	95	20,300	49.54	93.2	112	3.94			
3/4/94	299-W15-217[b]	61	95			18.5	3		8.3	5.5	
3/4/94	299-W15-217	73	100	21,400	54.97	104	122	3.74			
3/4/94	299-W15-217[b]	73	100			17.3	2.9		7.7	5.9	
5/10/94	299-W15-217	20		7,070		44.5	47.1	1.9			
5/11/94	299-W15-217	21		7,000		42.9	48.4	1.8			
6/1/94	299-W15-217	46		10,600		60.3	67.1	2.13			
6/10/94	299-W15-217	100		6,800		59.1	53.5	1.7			
9/6/94	299-W15-217	114	158	1,420	5.76	20.6	11	0.8			
3/24/94	299-W15-218L	99	153	808	3.18	4.91	7.41	0.303			
3/24/94	299-W15-218L[b]	99	153			1.2	<0.1		<0.1	0.2	0.2[e]
9/7/94	299-W15-218L	110	104	595	1.59	8.8	8.8	0.5			
3/25/94	299-W15-218U	99	98	14,800	37.26	65.2	82.7	0			
3/25/94	299-W15-218U[b]	99	98			12	0.7		0.7	4.1	2.4[e]
9/7/94	299-W15-218U	117	129	424	1.40	7.6	4.2	0.1			
3/21/94	299-W15-219L	112	133	2,360	8.06	13.3	20.1	0.256			
3/21/94	299-W15-219L[b]	112	133			3.2	0.1			0.3	0.6[e]
9/7/94	299-W15-219L	111	124	450	1.43	6.4	8	0.3			
3/22/94	299-W15-219U	109	153	9,710	38.16	42.2	59.1	0			
3/22/94	299-W15-219U[b]	109	153			6.8	0.2		0.2	1.5	2.1[e]
9/7/94	299-W15-219U	113	124	490	1.56	8.4	7	0.3			
3/23/94	299-W15-220L	104	149	589	2.25	3	3.76	0.32			
3/23/94	299-W15-220L[b]	104	149			0.3	<0.1		<0.1	0.1	0.1[e]
3/23/94	299-W15-220U	93	158	2,740	11.12	13.3	19.6	0			
3/23/94	299-W15-220U[b]	93	158			1	<0.1		<0.1	0.2	1[e]
3/16/94	299-W15-223	91	209	1,500	8.05	8.4	11.3	0.08			
3/16/94	299-W15-223[b]	91	209			2.1	0.1		<0.1	0.1	
6/3/93	CPT-8	96	12	54	0.00						
5/27/93	CPT-12	101	64	74	0.00	3.4					

[a]Before perforating well casing.
[b]Gas chromatograph analysis.
[c]Odyssey analysis.
[d]Benzene.
[e]Methyl isobutyl ketone (MIBK).

$CHCl_3$ = Chloroform.
CH_2Cl_2 = Methylene chloride.
MEK = Methyl ethyl ketone.
1,1,1-TCA = 1,1,1-Trichloroethane.
PCE = Tetrachloroethylene.

Figure 3-14. Carbon Tetrachloride Concentrations in Soil Gas Extracted from Intervals Above the Plio-Pleistocene Caliche Layer at the 216-Z-1A Tile Field.

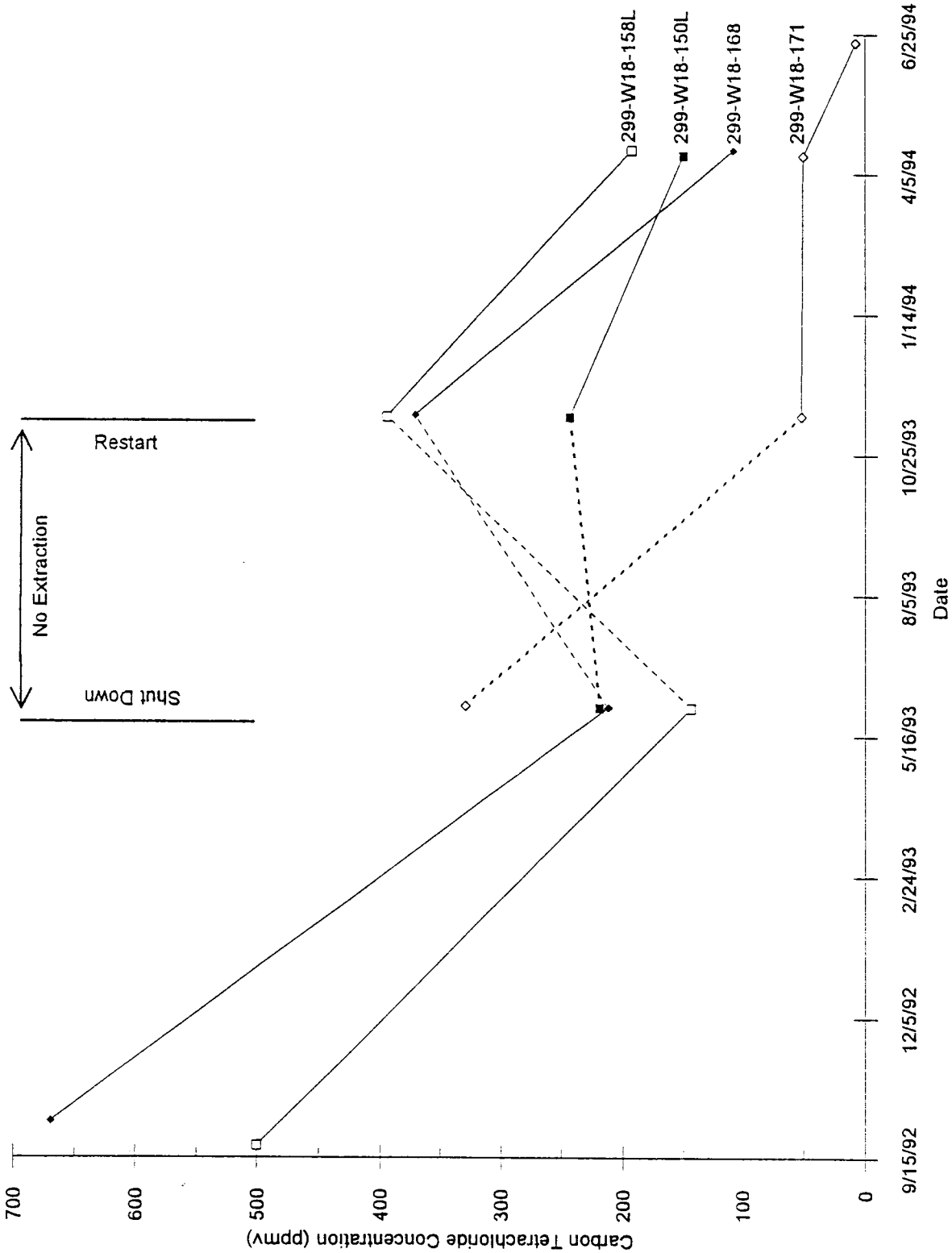


Figure 3-15. Carbon Tetrachloride Concentrations in Soil Gas Extracted from Intervals Below the Plio-Pleistocene Caliche Layer at the 216-Z-1A Tile Field.

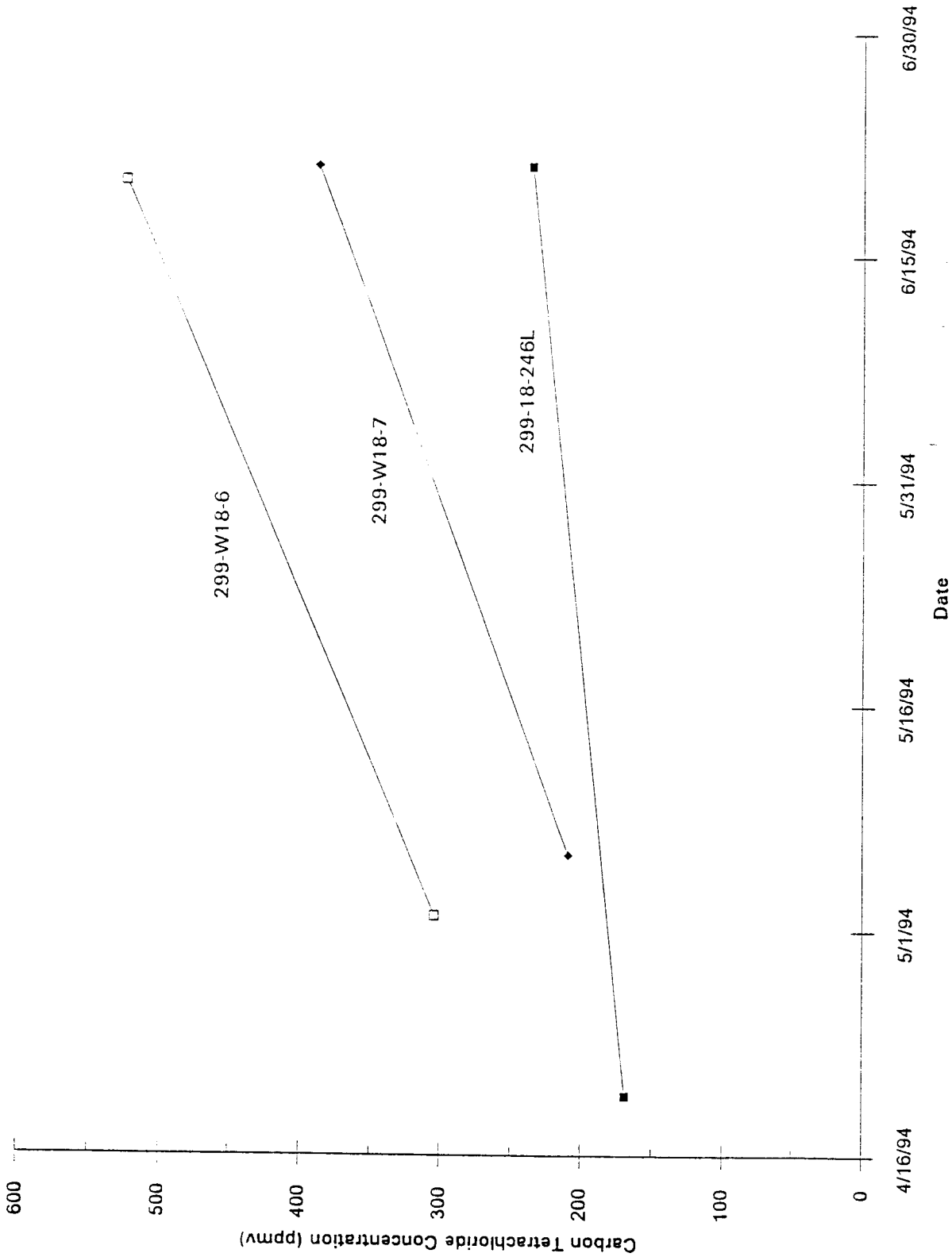
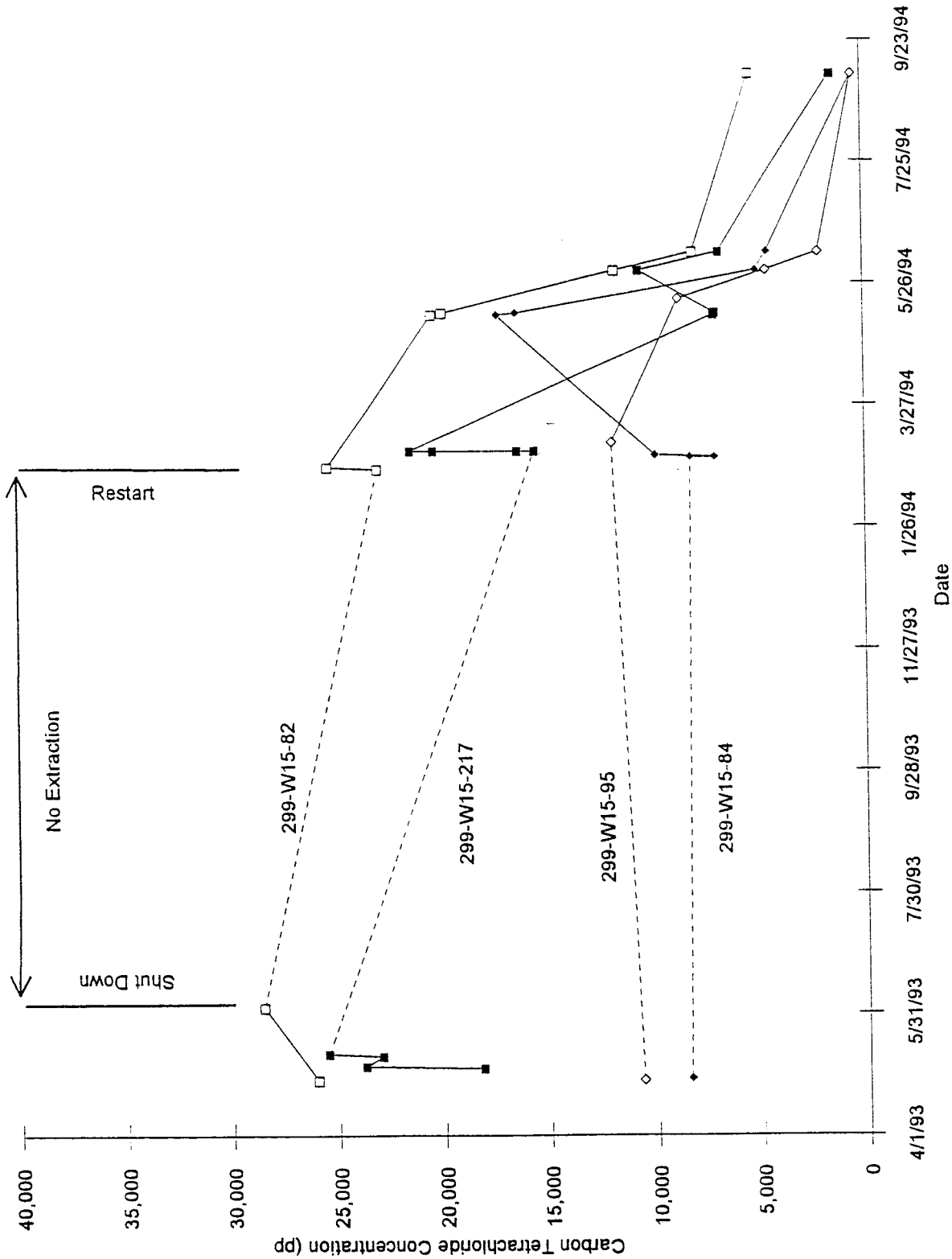


Figure 3-16. Carbon Tetrachloride Concentrations in Extracted Soil Gas at 216-Z-9 Trench Wells.



Analysis of 216-Z-18 Crib Data: Only wells 299-W18-252U, 299-W18-97, and 299-W18-10 have sufficient data to trend. In general, well 299-W18-252U carbon tetrachloride concentrations have averaged approximately 500 ppm_v (Figure 3-17). Well 299-W18-97, however, appears to show a trend to decreasing carbon tetrachloride concentrations. Well 299-W18-10 concentrations increased after the extended VES shutdown (June 3, 1993 - November 15, 1993), and now show a trend to decreasing contamination (Figure 3-18).

A vapor extraction test was performed on the upper interval of well 299-W18-252 on January 20, 1994 (Appendix F). A vacuum of 127 in. H_2O was applied by the VES, resulting in a vacuum of 70 in. H_2O at the wellhead and a flow of 230 to 240 $stdft^3/min$. Pressures were measured at the subsurface monitoring points installed at the CPT-4 array north of well 299-W18-252 (Appendix F). A profile view of the well and subsurface monitoring points and the vacuums measured during the test are also included in Appendix F. These vacuums have been corrected for the effects of barometric pressure. The barometric pressure and the subsurface differential pressure at 11 points were measured and recorded every 15 minutes. Based on the corrected subsurface vacuum readings, the radius of influence is estimated to be 125 ft.

During this test, differential pressures were also monitored at three stainless steel tubes strapped to the well casing during completion. One tube is open to the soil above the upper screened interval, which is above the Plio-Pleistocene caliche layer; one above the lower screened interval, below the Plio-Pleistocene caliche layer; and one below the lower screened interval. During the extraction tests from the upper screened interval, no vacuum response was detected from the two tubes open below the caliche (Appendix F).

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 2 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 1×10^{-10} 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 14.8×10^{-8} cm^2 (2 to 15 darcy), based on testing performed at the 216-Z-1A Tile Field (DOE-RL 1991, Appendix F).

Figure 3-17. Carbon Tetrachloride Concentrations in Soil Gas Extracted from Intervals Above the Plio-Pleistocene Caliche Layer at the 216-Z-18 Tile Field.

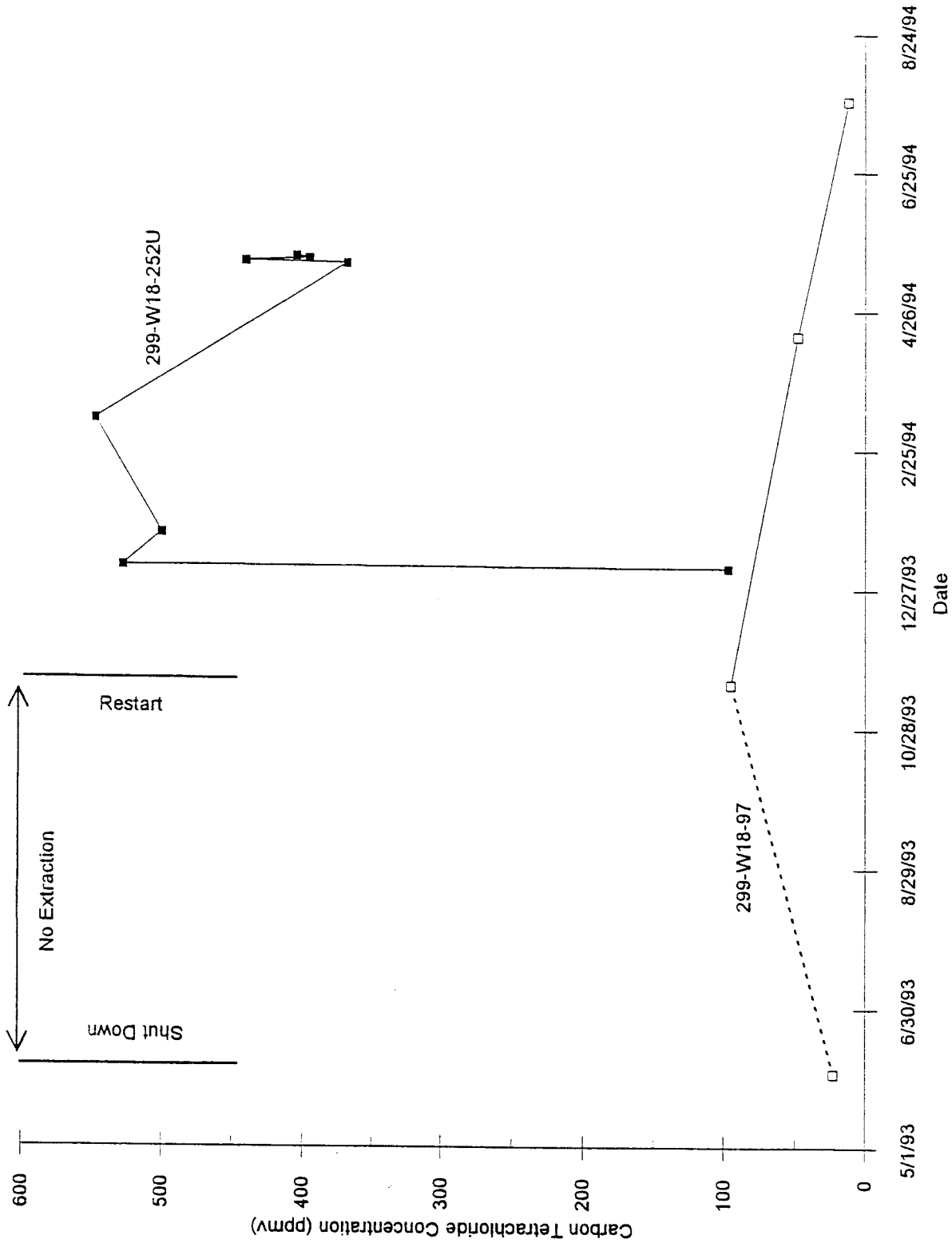
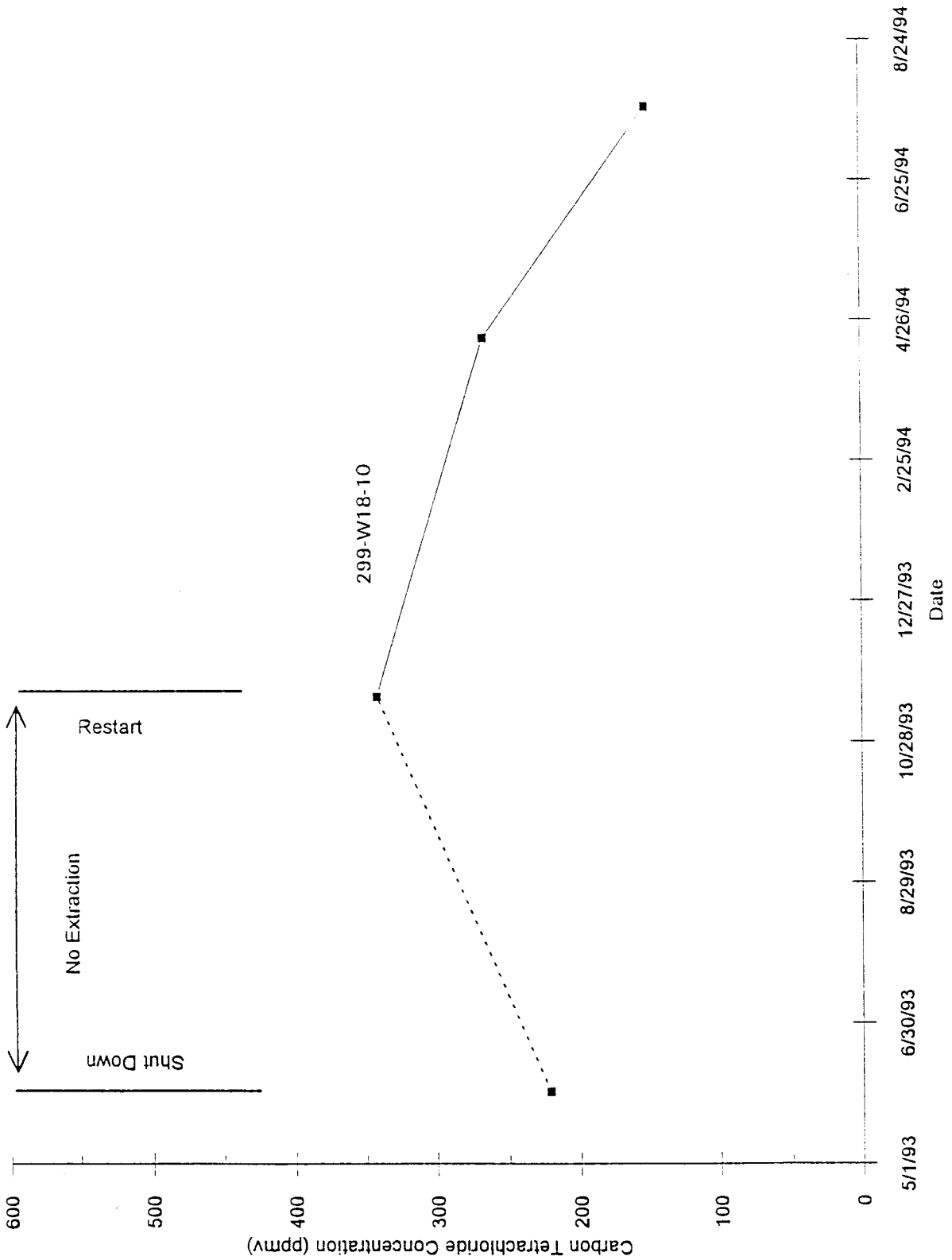


Figure 3-18. Carbon Tetrachloride Concentration in Soil Gas Extracted from Intervals Below the Plio-Pleistocene Caliche Layer at the 216-Z-18 Tile Field.



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. An air extraction test was performed at well 299-W18-252U (Appendix F). Following the test, the soil pressure data were plotted as pressure decrease versus time and used for assessing the area of influence and to assist in the soil vapor monitoring. It is recommended that additional analysis of the data be conducted to determine the soil air permeability of the unsaturated zone between the extraction well and the pressure monitoring probes. It is also recommended that additional permeability testing be conducted, particularly in the 216-Z-9 wellfield.

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 was conducted at each of the two primary wellfields during the operation of the VES at those sites in FY 1994. Tracer gas testing is being conducted by Washington State University for IT Hanford Company on active extraction wells according to the tracer gas test plan (WHC 1993c) and the FY 1994 wellfield task plan (Rohay 1994). The final report analyzing this testing will be available by December 31, 1994.

3.3.3.3 Recommendation. It is recommended that the information gathered from the tracer gas tests be evaluated 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 downhole pressures in the monitoring wells. 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. H_2O 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. Downhole pressures should be monitored at both primary wellfields. 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 E) 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 200 West Area 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 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 A.

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 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 extracted soil-gas characteristics are essential for safe and continuing operations of the VES. It is necessary that operating parameters be frequently measured during all extraction operations and that the soil gas from all the wells be fully characterized to gain 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.

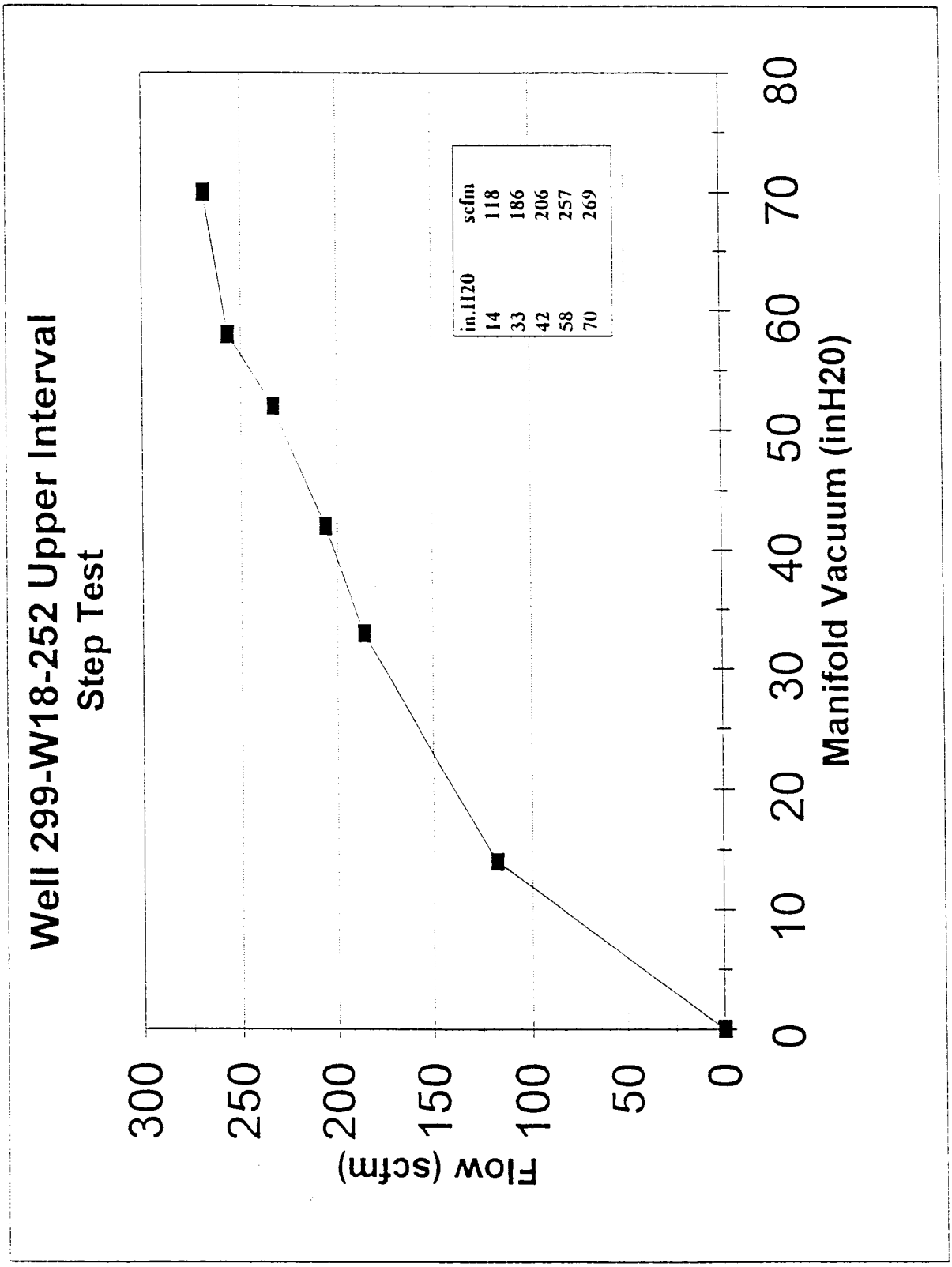
3.4.1 Recommendations for Extraction from the 216-Z-1A/18 Wellfield

3.4.1.1 Operational Data Summary. Operation of the VES on 22 wells at the 216-Z-1A Tile Field has produced extracted soil vapor concentrations generally ranging from 50 to 500 ppm_v carbon tetrachloride. The typical extraction flow rates range from 20 to 300 ft^3/min per extraction well. The extracted soil vapor concentrations from nine wells in the 216-Z-18 Crib have been from 20 to 100 ppm_v carbon tetrachloride. Characterization testing data are summarized in Tables 3-15 and 3-16. The extent of the horizontal influence of the vacuum placed upon each of the extraction wells above the caliche layer is in the range of 100 to 125 ft, established during the pilot testing of the VES at well 299-W18-171 and a characterization test at well 299-W18-252U (DOE-RL 1991, Appendix F). The increase in flow rate with increasing applied vacuum was measured at the upper interval of well 299-W18-252 in the 216-Z-1A/18 wellfield on March 10, 1994 (Figure 3-19). The maximum flow approaches 300 ft^3/min.

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 500-1,000 ppm_v to 50-500 ppm_v over a year of intermittent operation (Figure 3-14). As of August 11, 1994, 7,522 kg of carbon tetrachloride have been removed from this area.

Figure 3-19. Relationship Between Applied Vacuum and Resulting Flow at the Upper Interval of Well 299-W18-252.



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 two VES systems will be used at full flow or vacuum capacity (500 ft^3/min and 1,000 ft^3/min at 140 in. H_2O) 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 ft^3/min at 140 in. H_2O 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 been performed in the 216-Z-9 wellfield since February 1994. However, characterization testing was conducted at extraction wells in spring 1993 and several times in 1994. As shown in Table 3-17, initial concentrations of carbon tetrachloride in the extracted soil vapor from wells in the 216-Z-9 wellfield initially ranged from approximately 1,000 to 28,500 ppm_v. In approximately 50 hours of

characterization testing in 1993, approximately 1,060 kg of carbon tetrachloride was removed from the subsurface in this area, an average of about 21 kg/h. Since the start of full-scale operations in February 1994, concentrations in the extracted soil gas have been reduced dramatically (Figure 3-17). As of August 11, 1994, 19,228 kg of carbon tetrachloride have been removed from this area.

3.4.3.2 Recommendations. The characterization tests at 216-Z-9 wells 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.

As expected, the high concentrations of carbon tetrachloride diminished rapidly when full-scale VES operations began. Based on 30,000 ppm$_v$ carbon tetrachloride (the approximate maximum value measured initially at this site) extracted 24 h/day at 1,500 ft^3/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 continue 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 continued. This is important because of the need to keep the high concentration contaminant plume intact for extraction.

As the high concentration contaminant plume is further 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 assumed the VES will operate at the 216-Z-9 area and will have an extraction capacity of 1,500 ft^3/min at 140 in. H_2O vacuum.

centering around the strategy used for the recommended wellfield modifications is provided in Appendix B.

Up to fifteen new dual-screened extraction wells have been identified to complete the coverage of the core of the known vapor plume. The additional coverage provided is indicated in Figures 3-10 and 3-11. The prioritized list of wells is presented in Table 3-8.

4.2.2 Passive Soil Vapor Extraction

Pending successful field testing, PSVE systems should be considered for extracting contaminated soil gas from wells that are located outside the area of influence of an active vapor extraction system and that have carbon tetrachloride concentrations of 200 ppm_v or less. A prioritized list of recommended wells from the 216-Z-1A/18 wellfield is provided in Table 3-10.

4.2.3 Expanded Soil Vapor Extraction System Capacity

The 500-ft^3/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.

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 ft^3/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.

4.2.4 Extraction Enhancement Strategies

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

4.2.5 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.O 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 x 10^9 ft^3 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 x 10^7 ft^3 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. For intermittent operations (24% operating efficiency), it will take over 10 years to reach the same carbon tetrachloride recovery levels.

If 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. However, as expected, the concentrations have decreased appreciably as operations continued 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 Wellfield Configuration

Continuous vapor extraction operations should be implemented to increase the effective area of influence of existing extraction intervals. Comparison of Figures 3-2 and 3-4 (intermittent operation) to Figures 3-3 and 3-5 (continuous operation) illustrate the increased coverage available by continuous operations.

Twenty-four existing wells in the Z-Crib Area should be modified, if feasible, and new wells added 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 resulting modified wellfield configuration is described in Tables 3-5 and 3-6 and illustrated in Figures 3-6 through 3-9. The prioritized list of wells recommended for modification is presented in Table 3-7. A discussion

4.2.6 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 2 weeks for the duration of the soil vapor extraction operations. The results of the tests should be used to identify co-contaminants and to provide insight into the changes of location and concentration of the carbon tetrachloride vapor plumes and the consequent effect on extraction strategy.

4.2.7 Tracer Gas Testing

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

4.2.8 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.

4.2.9 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.

5.0 REFERENCES

Armstrong, J. E. and E. O. Frind, 1992, "Vapor Extraction of Volatile Organic Compounds from the Aqueous and Solid Phases," abstract in *The 1992 Spring Meeting Abstract Volume*, American Geophysical Union, Washington, D.C.

DOE-RL, 1991, *Expedited Response Action Proposal for 200 West Area Carbon Tetrachloride Plume*, DOE/RL-91-32, Draft B, U.S. Department of Energy, Richland Field Office, Richland, Washington.

Driggers, S. A., 1994, *Design, Operation, and Monitoring of the Vapor Extraction System at the 216-Z-1A Tile Field*, WHC-SD-EN-TI-010, Rev. 3, Westinghouse Hanford Company, Richland, Washington.

EPA, 1991, *Guide for Conducting Treatability Studies Under CERCLA: Soil Vapor Extraction, Interim Guidance*, EPA/540/2-91/019A, U.S. Environmental Protection Agency, Risk Reduction Engineering Laboratory, Office of Research & Development, Cincinnati, Ohio and Office of Emergency & Remedial Response, Office of Solid Waste & Emergency Response, Washington, D.C.

EPA, 1993, *HyperVentilate User's Manual*, (V. 1.01 and V. 2.0), U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Washington, D.C.

Fancher, J. D., 1994, *Carbon Tetrachloride ERA Soil-Gas Baseline Monitoring*, WHC-SD-EN-TI-265, Rev. 0, Westinghouse Hanford Company, Richland, Washington.

Hasbach, A., ed., 1993, "Pneumatic Fracturing Boosts Subsurface Cleanup," *Pollution Engineering*, April 15, 1993.

Hutzler, N. J., B. E. Murphy, and J. S. Gierke, 1991, "Review of Soil Vapor Extraction System Technology," *Soil Vapor Extraction Technology*, Appendix A, Camp Dresser & McKee Inc., Cambridge, Massachusetts.

Johnson, P. C., M. W. Kemblowski, J. D. Colthart, D. L. Byers, and C. C. Stanley, 1990, "A Practical Approach to the Design, Operation, and Monitoring of In-Situ Soil Venting Systems," *Soil Vapor Extraction Technology*, Appendix E, Camp Dresser & McKee Inc., Cambridge, Massachusetts.

Joss, C. J., 1993a, "A Three-Dimensional, Multispecies Vapor Transport Model for the Design of Vapor Extraction and Bioventing Systems," in *Proceedings of the 1993 Petroleum Hydrocarbons and Organic Chemicals in Ground Water: Prevention, Detection, and Restoration*, held November 10-12, 1993 in Houston, Texas.

Joss, C. J., 1993b, "Multispecies Vapor Transport and Reactions in Porous Media Under Conditions of Induced Air Flow," Ph.D. Dissertation, Drexel University, Philadelphia, Pennsylvania, 145 pg.

Kasper, R. B., 1991, *216-Z-12 Crib Status Report*, RHO-LD-166, Rockwell Hanford Operations, Richland, Washington.

Last, G. V. and V. J. Rohay, 1993, *Refined Conceptual Model for the Volatile Organic Compounds-Arid Integrated Demonstration and 200-West Area Carbon Tetrachloride Expedited Response Action*, PNL-8597, Pacific Northwest Laboratory, Richland, Washington.

Pedersen, T. A. and J. T. Curtis, 1991, *Soil Vapor Extraction Technology*, Camp Dresser & McKee Inc., Cambridge, Massachusetts.

Piepho, M. G., A. G. Law, M. P. Connelly, and K. A. Lindsey, 1993, *Vadose Zone Modeling of Carbon Tetrachloride in 200 West Area of the Hanford Site*, WHC-SD-EN-TI-112, Rev. 0, Westinghouse Hanford Company, Richland, Washington.

Rainwater, K., B. J. Claborn, H. W. Parker, D. Wilkerson, and M. R. Zaman, 1988, "Large-Scale Laboratory Experiments for Forced Air Volatilization of Hydrocarbon Liquids in Soil," in *Proceedings of the National Water Well Association and American Petroleum Institute Conference on Petroleum Hydrocarbons and Organic Chemicals in Groundwater*, p. 501-518.

Rohay, V. J., 1994, *FY 1994 Wellfield Optimization and Site Characterization Task Plan for the Carbon Tetrachloride Expedited Response Action*, WHC-SD-EN-AP-156, Rev. 0, Westinghouse Hanford Company, Richland, Washington.

Rohay, V. J. and R. J. Cameron, 1992, *FY 93 Wellfield Enhancement Workplan*, WHC-SD-EN-AP-114, Westinghouse Hanford Company, Richland, Washington.

Rohay, V. J. and R. J. Cameron, 1994, *Wellfield Strategy and Recommendations for the 200 West Area Carbon Tetrachloride Expedited Response Action*, WHC-SD-EN-AP-159, Rev. 0, Westinghouse Hanford Company, Richland, Washington.

Rohay, V. J. and V. G. Johnson, 1991, "Site Evaluation," in *Expedited Response Action Proposal for 200 West Area Carbon Tetrachloride Plume*, DOE/RL-91-32, Draft B, U.S. Department of Energy, Richland Field Office, Richland, Washington.

Rohay, V. J., G. V. Last, V. L. King, and L. A. Doremus, 1992, *FY 92 Site Characterization Status Report and Data Package for the Carbon Tetrachloride Site*, WHC-SD-EN-TI-063, Rev. 0, Westinghouse Hanford Company, Richland, Washington.

Rohay, V. J., K. J. Swett, V. M. Johnson, G. V. Last, D. C. Lanigan, and L. A. Doremus, 1993, *FY93 Site Characterization Status Report and Data Package for the Carbon Tetrachloride Site*, WHC-SD-EN-TI-202, Rev. 0, Westinghouse Hanford Company, Richland, Washington.

Rohay, V. J., K. J. Swett, and G. V. Last, 1994, *1994 Conceptual Model of the Carbon Tetrachloride Contamination in the 200 West Area at the Hanford Site*, WHC-SD-EN-TI-248, Rev. 0, Westinghouse Hanford Company, Richland, Washington.

WHC, 1993a, *Carbon Tetrachloride Atmospheric Losses and Residual Inventory Beneath 200 West Area*, WHC-SD-EN-TI-101, Rev. 0, prepared by Ebasco Services Incorporated for Westinghouse Hanford Company, Richland, Washington.

WHC, 1993b, *Summary of Granular Activated Carbon (GAC) Canister Overheating Incident at the Carbon Tetrachloride Expedited Response Action Site*, WHC-SD-EN-TI-203, Rev. 0, prepared by Ebasco Services Incorporated for Westinghouse Hanford Company, Richland, Washington.

WHC, 1993c, *Tracer Gas Diffusion Sampling Test Plan*, WHC-SD-EN-TP-035, Rev. 0, Westinghouse Hanford Company, Richland, Washington.

WHC, 1994, *Passive Vapor Extraction Feasibility Study*, WHC-SD-EN-TI-245, Rev. 0, prepared by Enserch Environmental for Westinghouse Hanford Company, Richland, Washington.

APPENDIX A

GENERAL VAPOR EXTRACTION STRATEGIES

CONTENTS

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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. H_2O 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 new 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 ft^3/min flow at 100 in. H_2O 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 vapor extraction system (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 theses 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 ft^3/min at 137 in. H_2O 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 significant 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 vapor is in equilibrium or near equilibrium concentrations in the relatively permeable subsurface units, extraction over a wide area throughout the unsaturated zone 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, specific regions, such as low-permeability layers, within the subsurface must be addressed.

The execution of this strategy will not necessarily result in the removal of the greatest amount of carbon tetrachloride in the least amount of time. It will result in significant 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

In general, 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.

2.0 REFERENCES

DOE-RL, 1991, *Expedited Response Action Proposal for 200 West Area Carbon Tetrachloride Plume*, DOE/RL-91-32, Draft B, U.S. Department of Energy, Richland Field Office, Richland, Washington.

GAO, 1993, "Hanford's Well-Drilling Costs Can Be Reduced," *Nuclear Waste*, Government Accounting Office, Washington, D.C.

Richterich, L.R., 1993, *Fiscal Year 1993 Heavyweight Cone Penetrometer Activities at the Hanford Site*, WHC-SD-EN-TRP-006, Rev. 0, Westinghouse Hanford Company, Richland, Washington.

Rohay, V.J., J. Rossabi, B.B. Looney, R.J. Cameron, and B.B. Peters, 1993, "Well Venting and Application of Passive Soil Vapor Extraction at Hanford and Savannah River," *Proceedings of the ER '93 Conference*, U.S. Department of Energy Environmental Remediation Conference, p. 815-818.

APPENDIX B

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 volatile organic compounds (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 for 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 also considered to allow extraction from zones unattainable with existing wells, particularly those zones below the caliche layer (Figures 3-10 and 3-11).

Maximizing flow from each of the extraction wells is an important consideration for improving the effectiveness of the vapor extraction system (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 observed flow gives the measured value where available or an estimated flow based on the average of flows observed in wells in the same area.

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 B-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 cone penetrometer (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 ft^3/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 3-15, 3-16, and 3-17) 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. Three results from characterization tests illustrate this point: (1) well 229-W18-11 (open interval 180 to 211 ft below top of casing [toc]; 31-ft open interval) had a flow rate of 33 ft^3/min at 101 in. H_2O vacuum; (2) well 299-W18-10 (open interval 180 to 214 ft below toc; 34 ft long) had a flow rate of 80 ft^3/min at 100 in. H_2O vacuum; and (3) well 299-W18-97 (open interval 60 to 72 ft below toc; 12 ft long) had a flow rate of 297 ft^3/min at 102 in. H_2O vacuum.

The differences in the flow rates can primarily be assigned to differences in the permeabilities of the soils in the vicinity of the open intervals (though the actual percentage of open area resulting from casing perforation is an unknown and potentially significant factor). Tables 3-12, 3-13, and 3-14 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:

∅ = 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
toc = 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 (∅ = 8; dtb = 201; 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 flow from interval is 150 ft^3/min.
- Also to be used for extraction below the caliche. A 2-in. ∅ piezometer with packer should be used to provide access to this open interval.

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

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

Well 299-W18-9 (∅ = 6; dtb = 217; poi = 180-211)

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

Well 299-W18-10 (∅ = 6; dtb = 214; poi = 100-130 and 150-214)

- Selected to provide coverage of area not otherwise accessible.
- Re-perforate from 100 to 130 ft below toc to improve flow and future focus on caliche layer.
- Predicted flow from interval is 150 ft^3/min.

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

Well 299-W18-11 (∅ = 6; dtb = 211; poi = 100-130 and 180-211)

- Selected to provide coverage of area not otherwise accessible.
- Re-perforate from 100 to 130 ft below toc to improve flow and future focus on caliche layer.
- Predicted flow from interval is 150 ft^3/min.
- Also to be used for extraction below the caliche. A 2-in. ∅ piezometer with packer should be used to provide access at the surface for both open intervals.

Well 299-W18-12 (∅ = 6; dtb = 214; poi = 190-211)

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

Well 299-W18-76 (∅ = 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 (∅ = 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 (∅ = 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 (∅ = 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 (∅ = 6; dtb = 148; poi = none)

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

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

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

Well 299-W18-87 (∅ = 6; dtb = 148; poi = 33-38, 65-68, and 124-129)

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

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

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

Well 299-W18-89 (∅ = 6; dtb = 150; poi = 108-130)

- Perforated from 108 to 130 ft below toc in May 1994.
- Present configuration of well provides adequate extraction capabilities based on present extraction strategies.

Well 299-W18-93 (∅ = 6; dtb = 138; poi = 63-77)

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

Well 299-W18-94 (∅ = 6; dtb = 83; poi = 68-78)

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

Well 299-W18-95 (∅ = 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 (∅ = 2; dtb = 132 bgs; poi = 122-132 bgs)

- Deepened from 1972 drill depth of 83 ft and screened from 122 to 132 ft bgs in March 1993.
- Present configuration of well provides adequate extraction capabilities based on present extraction strategies.

Well 299-W18-97 (∅ = 6; dtb = 82; poi = 63-75)

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

Well 299-W18-98 (∅ = 6; dtb = 75; poi = 66-77)

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

Well 299-W18-99 (∅ = 3; dtb = 129; poi = 93-103)

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

Well 299-W18-149 (∅ = 6; dtb = 75; poi = none)

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

Well 299-W18-150 (∅ = 6; dtb = 128; poi = 65-70, 85-90, & 113-119)

- Selected to provide improved coverage of area.
- Perforate from 65 to 90 ft below toc to combine two upper 5-ft intervals into one 25-ft interval to increase flow rate.
- Predicted flow from combined upper interval is 150 ft^3/min.

Well 299-W18-158 (∅ = 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 upper 5-ft intervals into one 19-ft interval to increase flow rate.
- Predicted flow from combined upper interval is 150 ft^3/min.
- A 1.5-in. ∅ piezometer with packer should be used to provide access at the surface for both open intervals.

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

- Selected to provide improved coverage of area.
- Perforate from 90 to 120 ft below toc to lengthen present open interval from 5 to 30 ft to increase flow rate.
- Predicted flow from new interval is 150 ft^3/min.
- Only interval to be used, so extraction pipe will remain 6-in. ∅.

Well 299-W18-163 (∅ = 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 from 10 to 25 ft and combine the two lower intervals into one 27-ft interval.
- 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 flow from each interval is 150 ft^3/min.

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

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

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

- Selected to provide coverage of area not otherwise accessible.

- Perforate from 97 to 127 ft below toc to increase perforated interval from 5 to 30 ft.
- Predicted flow from interval is 150 ft^3/min.
- Only interval to be used, so extraction pipe will remain 6-in ∅.

Well 299-W18-166 (∅ = 6; dtb = 137; poi = 124-129)

- Selected to provide more complete coverage of critical area.
- Perforate from 99 to 129 ft below toc to increase perforated interval from 5 to 30 ft.
- Predicted flow from interval is 150 ft^3/min.
- Only interval to be used, so extraction pipe will remain 6-in ∅.

Well 299-W18-167 (∅ = 8; dtb = 8; poi = 89-119)

- Selected to provide coverage of area not otherwise accessible.
- Re-perforate from 89 to 119 ft below toc to improve flow.
- Predicted flow from interval is 150 ft^3/min.
- Only interval to be used, so extraction pipe will remain 8-in ∅.

Well 299-W18-168 (∅ = 8; dtb = 131; poi = 97-127)

- Selected to provide coverage of area not otherwise accessible.
- Re-perforate from 97 to 127 ft below toc to improve flow.
- Predicted flow from interval is 150 ft^3/min.
- Only interval to be used, so extraction pipe will remain 8-in ∅.

Well 299-W18-169 (∅ = 8; dtb = 132; poi = 96-126)

- Selected to provide coverage of area not otherwise accessible.
- Re-perforate from 96 to 126 ft below toc to improve flow.
- Predicted flow from interval is 150 ft^3/min.

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

Well 299-W18-170 (∅ = 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 (∅ = 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 (∅ = 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 (∅ = 4; dtb = 126 bgs; poi = 106-126 bgs)

- Deepened from 1977 drill depth of 49.5 ft and screened from 106 to 126 ft bgs in April 1993.
- Present configuration of well provides adequate extraction capabilities based on present extraction strategies.

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

- Selected to provide improved coverage of area.
- Perforate from 90 to 120 ft below toc to combine 7-ft and 5-ft intervals into one 33-ft interval to increase flow rate.
- Predicted flow from combined interval is 150 ft^3/min.

Well 299-W18-246 (∅ = 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 (∅ = 4; dtb = 172 bgs; poi = 119-129 & 162-172 bgs)

- Predicted flow from upper interval is 150 ft^3/min.

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

Well 299-W18-248 (∅ = 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 (∅ = 4; dtb = 137 bgs; poi = 122-137 bgs)

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

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

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

CPT-2 (∅ = 1; dtb = 37 bgs; poi = 34-37 bgs)

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

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

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

CPT-20 (∅ = 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 (∅ = 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 flow from interval is 150 ft^3/min.

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

Well 299-W18-2 (∅ = 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 flow from interval is 150 ft^3/min.
- Also to be used for extraction below the caliche. A 2-in. ∅ piezometer with packer should be used to provide access at the surface for both open intervals.

Well 299-W18-4 (∅ = 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 flow from interval is 150 ft^3/min.
- Also to be used for extraction below the caliche. A 2-in. ∅ piezometer with packer should be used to provide access at the surface for both open intervals.

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

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

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

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

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

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

Well 299-W18-71 (∅ = 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 (∅ = 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 (∅ = 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 (∅ = 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 (∅ = 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 (∅ = 8; dtb = 118; poi = 88-118)

- Perforated from 88 to 118 ft below toc in May 1994.
- Predicted flow from interval is 150 ft^3/min.

Well 299-W18-153 (∅ = 8; dtb = 110; poi = 80-110)

- Perforated from 80 to 110 ft below toc in May 1994.
- Predicted flow from interval is 150 ft^3/min.

Well 299-W18-154 (∅ = 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 (∅ = 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 (∅ = 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 (∅ = 8; dtb = 110; poi = 80-110)

- Perforated from 80 to 110 ft below toc in May 1994.
- Predicted flow from interval is 150 ft^3/min.

CPT-10 (∅ = 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 (∅ = 8; dtb = 599; poi = 173-217)

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

Well 299-W15-6 (∅ = 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 flow from interval is 200 ft^3/min.
- Also to be used for extraction below the caliche. A 2-in. ∅ piezometer with packer should be used to provide access at the surface for both open intervals.

Well 299-W15-8 (∅ = 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 flow from interval is 200 ft^3/min.
- Also to be used for extraction below the caliche. A 2-in. ∅ piezometer with packer should be used to provide access at the surface for both open intervals.

Well 299-W15-9 (∅ = 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 flow from interval is 200 ft^3/min.
- Also to be used for extraction below the caliche. A 2-in. ∅ piezometer with packer should be used to provide access at the surface for both open intervals.

Well 299-W15-82 (∅ = 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 (∅ = 8; dtb = 106 bgs; poi = 75-90 bgs)

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

Well 299-W15-85 (∅ = 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 (∅ = 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 flow from interval is 200 ft^3/min.
- Only interval to be used, so extraction pipe will remain 8-in ∅.

Well 299-W15-95 (∅ = 8; dtb = 100 bgs; poi = 73-98 bgs)

- Selected to provide coverage of area not otherwise accessible.
- Re-perforate from 73 to 98 ft below toc to improve extraction capabilities.
- Predicted flow from interval is 200 ft^3/min.
- Only interval to be used, so extraction pipe will remain 8-in ∅.

Well 299-W15-216 (∅ = 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 (∅ = 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 (∅ = 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 (∅ = 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 (∅ = 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; ∅ = 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 (∅ = 1; dtb = 52 bgs; poi = 39-52 bgs)

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

CPT-5 (∅ = 1; dtb = 48 bgs; poi = 35-48 bgs)

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

CPT-8A (∅ = 1; dtb = 113 bgs; poi = 100-113 bgs)

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

CPT-11 (∅ = 1; dtb = 77 bgs; poi = 64-77 bgs)

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

CPT-12 (∅ = 1; dtb = 49 bgs; poi = 36-49 bgs)

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

CPT-19 (∅ = 1; dtb = 49 bgs; poi = 36-49 bgs)

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

CPT-21 (∅ = 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 (∅ = 8; dtb = 201; poi = 190-201)

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

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

- Selected to provide coverage of area not otherwise accessible.
- Perforate from 175 to 190 ft below toc to increase open interval from 13 to 28 ft.

- Predicted flow from interval is 300 ft^3/min.
- Only interval to be used, so extraction pipe will remain 8-in ∅.

Well 299-W18-9 (∅ = 6; dtb = 217; poi = 180-211)

- Predicted flow from interval is 145 ft^3/min.
- Present configuration of well provides adequate extraction capabilities based on present extraction strategies.

Well 299-W18-10 (∅ = 6; dtb = 214; poi = 150-214)

- Perforated from 150 to 180 ft below toc in May 1994.
- Present configuration of well provides adequate extraction capabilities based on present extraction strategies.
- Also to be used for extraction above the caliche. A 2-in. ∅ piezometer with packer should be used to provide access at the surface for both open intervals.

Well 299-W18-11 (∅ = 6; dtb = 211; poi = 180-211)

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

Well 299-W18-12 (∅ = 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 flow from interval is 145 ft^3/min.
- Only interval to be used, so extraction pipe will remain 6-in ∅.

Well 299-W18-76 (∅ = 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 (∅ = 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 (∅ = 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 (∅ = 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 (∅ = 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 (∅ = 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 (∅ = 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 (∅ = 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 (∅ = 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 (∅ = 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 (∅ = 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 (∅ = 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 (∅ = 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 (∅ = 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 (∅ = 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 (∅ = 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 (∅ = 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 (∅ = 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 (∅ = 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 (∅ = 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 (∅ = 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 (∅ = 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 (∅ = 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 (∅ = 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 (∅ = 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 (∅ = 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 (∅ = 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 (∅ = 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 (∅ = 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 (∅ = 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 (∅ = 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 (∅ = 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 (∅ = 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 (∅ = 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 (∅ = 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 (∅ = 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.

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

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

CPT-2 (∅ = 1; dtb ≐ 37 bgs; poi = 34-37 bgs)

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

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

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

CPT-20 (∅ = 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 (∅ = 8; dtb = 381; poi = 195-200)

- Selected to provide coverage of area not otherwise accessible.
- Perforate from 175 to 195 ft below toc to increase open interval from 5 to 25 ft.
- Predicted flow from interval is 145 ft^3/min.

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

Well 299-W18-2 (∅ = 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 flow from interval is 145 ft^3/min.
- Also to be used for extraction above the caliche. A 2-in. ∅ piezometer with packer should be used to provide access at the surface for both open intervals.

Well 299-W18-4 (∅ = 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 140 ft^3/min.
- Also to be used for extraction above the caliche. A 2-in. ∅ piezometer with packer should be used to provide access at the surface for both open intervals.

Well 299-W18-5 (∅ = 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 flow from interval is 145 ft^3/min.
- Only interval to be used, so extraction pipe will remain 8-in ∅.

Well 299-W18-8 (∅ = 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 (∅ = 4; dtb = 235; poi = 205-213)

- Selected for use "as is." Well 299-W18-24 is a *Resource Conservation and Recovery Act* (RCRA) well 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, so coordination must occur between its uses for soil vapor extraction and groundwater monitoring.

- Predicted flow from interval is 145 ft^3/min.

Well 299-W18-71 (∅ = 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 (∅ = 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 (∅ = 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 (∅ = 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 (∅ = 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 (∅ = 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 (∅ = 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 (∅ = 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 (∅ = 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 (∅ = 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 (∅ = 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.

CPT-10 (∅ = 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 (∅ = 8; dtb = 599; poi = 173-217)

- Selected for use "as is" due to other uses of well, regulatory limitations, or physical restrictions.
- Predicted flow from interval is 115 ft^3/min.

Well 299-W15-6 (∅ = 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 flow from interval is 115 ft^3/min.

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

Well 299-W15-8 (∅ = 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 flow from interval is 115 ft^3/min.
- Also to be used for extraction above the caliche. A 2-in. ∅ piezometer with packer should be used to provide access at the surface for both open intervals.

Well 299-W15-9 (∅ = 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 flow from interval is 115 ft^3/min.
- Also to be used for extraction above the caliche. A 2-in. ∅ piezometer with packer should be used to provide access at the surface for both open intervals.

Well 299-W15-82 (∅ = 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 (∅ = 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 (∅ = 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 (∅ = 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 (∅ = 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 (∅ = 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 (∅ = 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 (∅ = 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 (∅ = 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 (∅ = 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; ∅ = 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 (∅ = 1; dtb = 52 bgs; poi = 39-52 bgs)

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

CPT-5 (∅ = 1; dtb = 48 bgs; poi = 35-48 bgs)

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

CPT-8A (∅ = 1; dtb = 113 bgs; poi = 100-113 bgs)

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

CPT-11 (∅ = 1; dtb = 77 bgs; poi = 64-77 bgs)

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

CPT-12 (∅ = 1; dtb = 49 bgs; poi = 36-49 bgs)

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

CPT-19 (∅ = 1; dtb = 49 bgs; poi = 36-49 bgs)

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

CPT-21 (∅ = 1; dtb = 97 bgs; poi = 84-97 bgs)

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

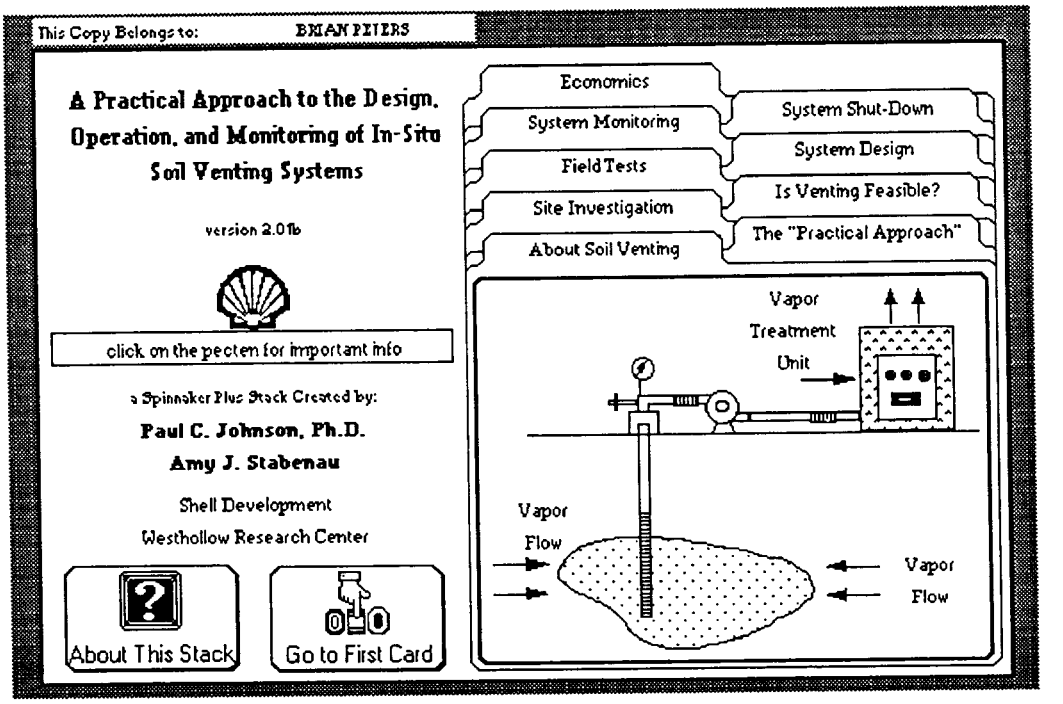
Table B-1. Maximum Flow at 10 in. Hg Column Pressure Drop.

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

APPENDIX C

VAPOR EXTRACTION NUMERICAL MODELING

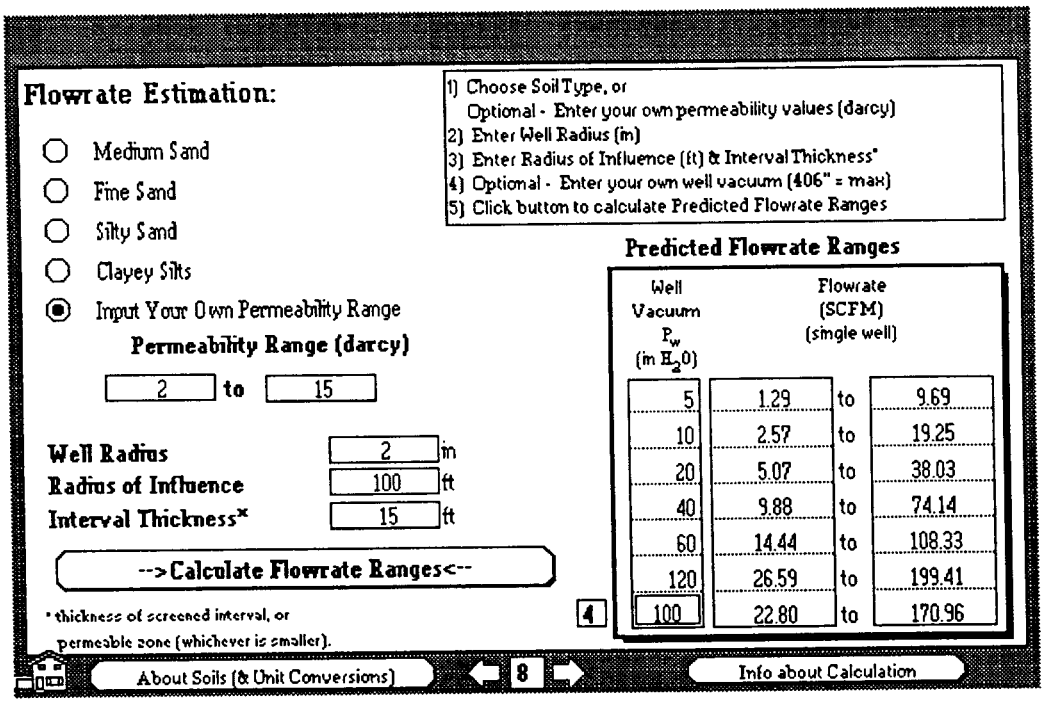
APPENDIX C
VAPOR EXTRACTION NUMERICAL MODELING



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.



PERMEABILITY RANGE

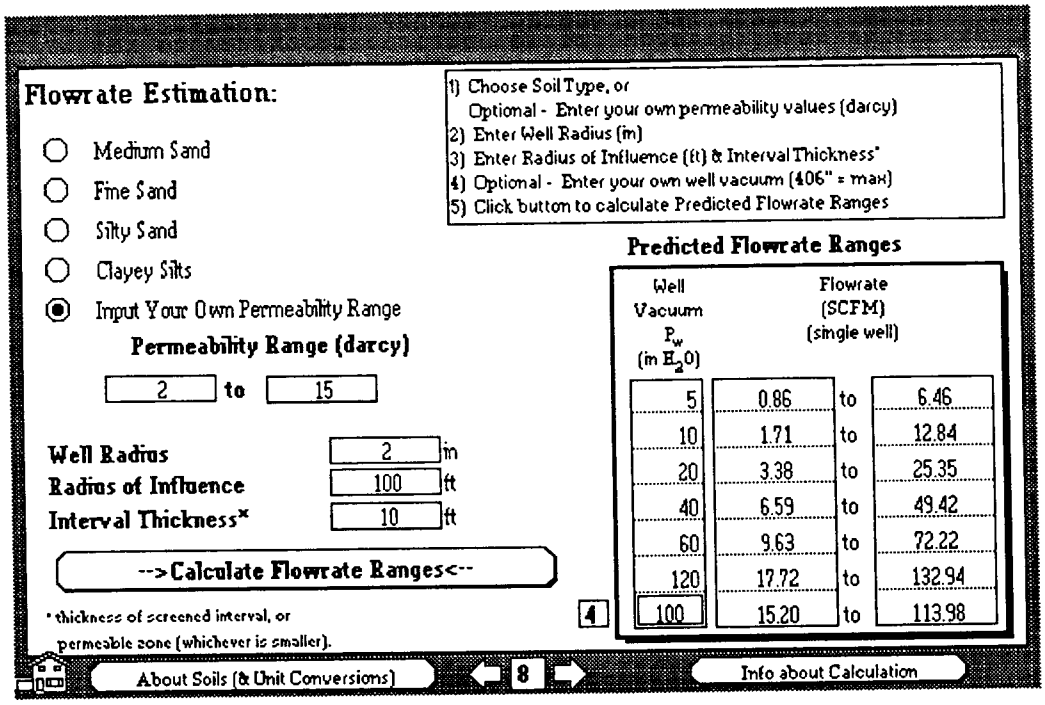
DOE-RL (1991), Appendix F, gave permeabilities for well 299-W18-171 (216-Z-1A) ranging from 2 to 15 darcy for the three screened intervals of this well. These same values were used for modeling.

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.

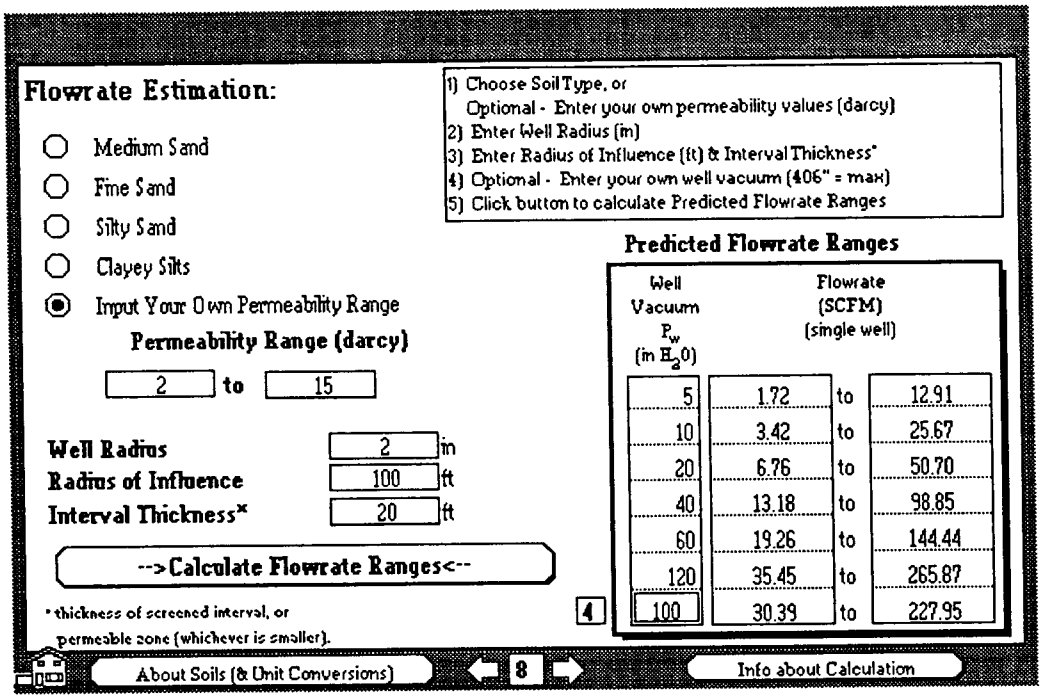
RADIUS OF INFLUENCE

DOE-RL (1991), Appendix F, estimated a radius of influence for 299-W18-171 of 70 to 220 ft at 300 to 320 stdft^3/min flow. A conservative 100 ft was used for modeling.



INTERVAL THICKNESS

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



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	napthalene	0.00	128.2	0.00014
61	n-hexylbenzene	0.00	162.3	0.0001
62	methylnapthalene	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

1.00000 = Sum of Mass Fractions

Sum

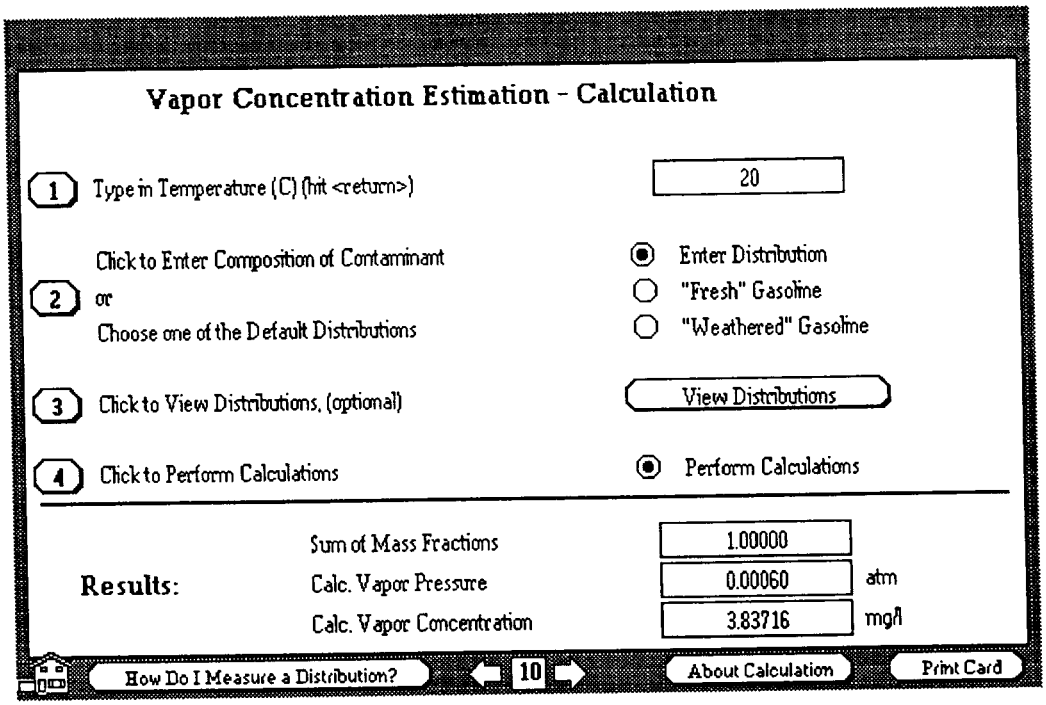
How Do I Measure a Distribution? | Return to Vapor Conc. Estimation Card | Print Lists

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.



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

CCl_4, 0.5% of saturation.

Vapor Concentration

3.84 mg/L ≈ 600 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)	20
Soil Type	User Defined
Soil Permeability Range (darcy)	2 to 15
Well Radius (m)	2
Radius of Influence (ft)	100
Contaminant Type	User Defined
Permeable Zone Thickness (ft)	15

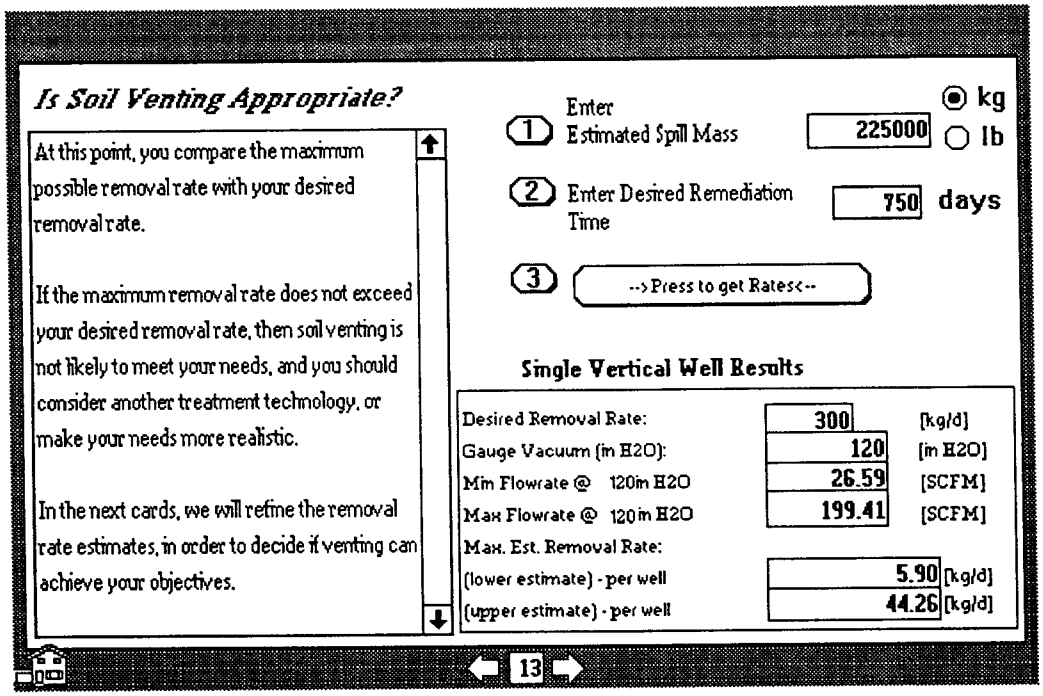
P_w - Well Vacuum (in H_2O)	Flowrate Estimates [SCFM] (single well)			Max. Removal Rate Estimates [kg/d] (single well)		
5	1.29	to	9.69	0.20	to	1.54
10	2.57	to	19.25	0.41	to	3.09
20	5.07	to	38.03	0.83	to	6.26
40	9.88	to	74.14	1.71	to	12.87
60	14.44	to	108.33	2.65	to	19.88
120	26.59	to	199.41	5.90	to	44.26
100	22.80	to	170.96	4.73	to	35.47

12 Print Card

16-Z-1A MODEL

Maximum Removal Rate

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



216-Z-1A MODEL

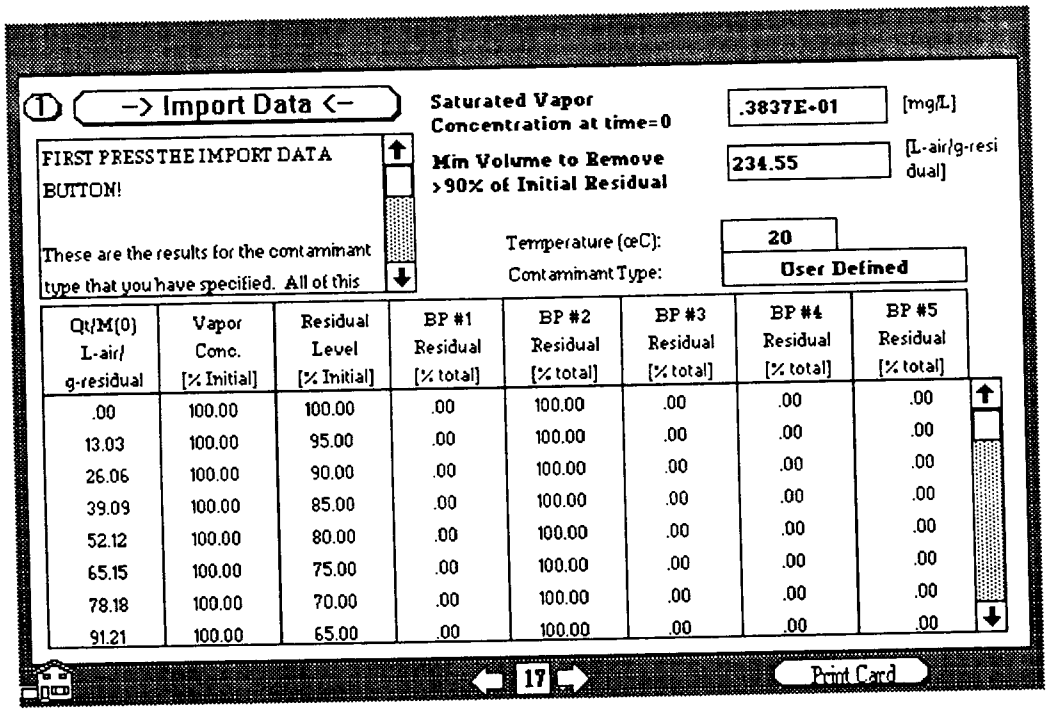
Spill Mass

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 <-

FIRST PRESS THE IMPORT DATA BUTTON!

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

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

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

Temperature (oC): 20

Contaminant Type: User Defined

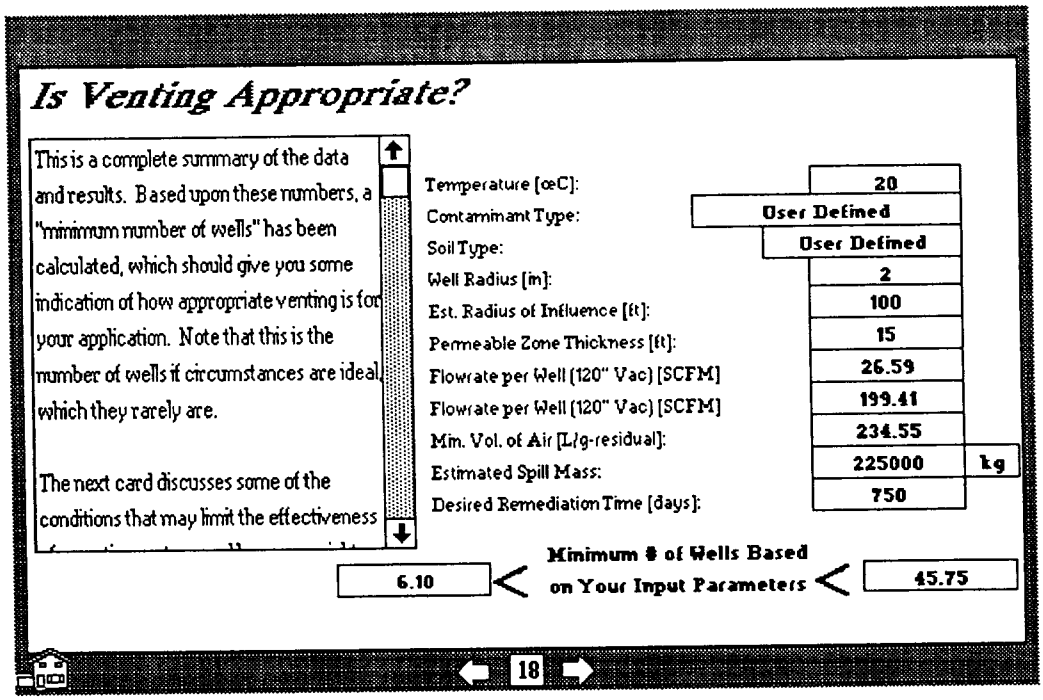
Qt/M(0) L-air/ g-residual	Vapor Conc. [% Initial]	Residual Level [% Initial]	BP #1 Residual [% total]	BP #2 Residual [% total]	BP #3 Residual [% total]	BP #4 Residual [% total]	BP #5 Residual [% total]
.00	100.00	100.00	.00	100.00	.00	.00	.00
13.03	100.00	95.00	.00	100.00	.00	.00	.00
26.06	100.00	90.00	.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

216-Z-1A MODEL

Air/Residual Ratio

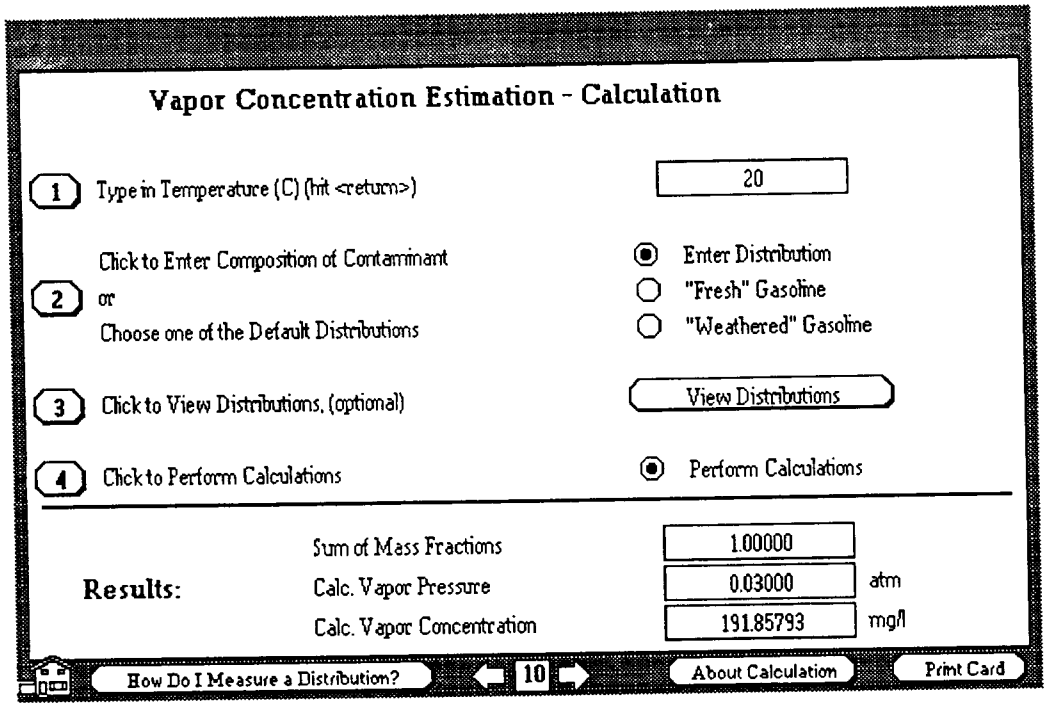
The calculated minimum volume of air to remove >90% of the initial residual contamination is 234.55 L-air/g-residual.

Therefore an inventory of 225,000 kg would require the extraction of 5.3 x 10^{10} L (1.9 x 10^{9} ft^3) of soil gas at 600 ppm, to remediate. This is equivalent to operating a 1,500 $stdft^3$/min soil vapor extraction system continuously for 3.5 years assuming a 68% TOE.



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.



216-Z-9 MODEL

Temperature

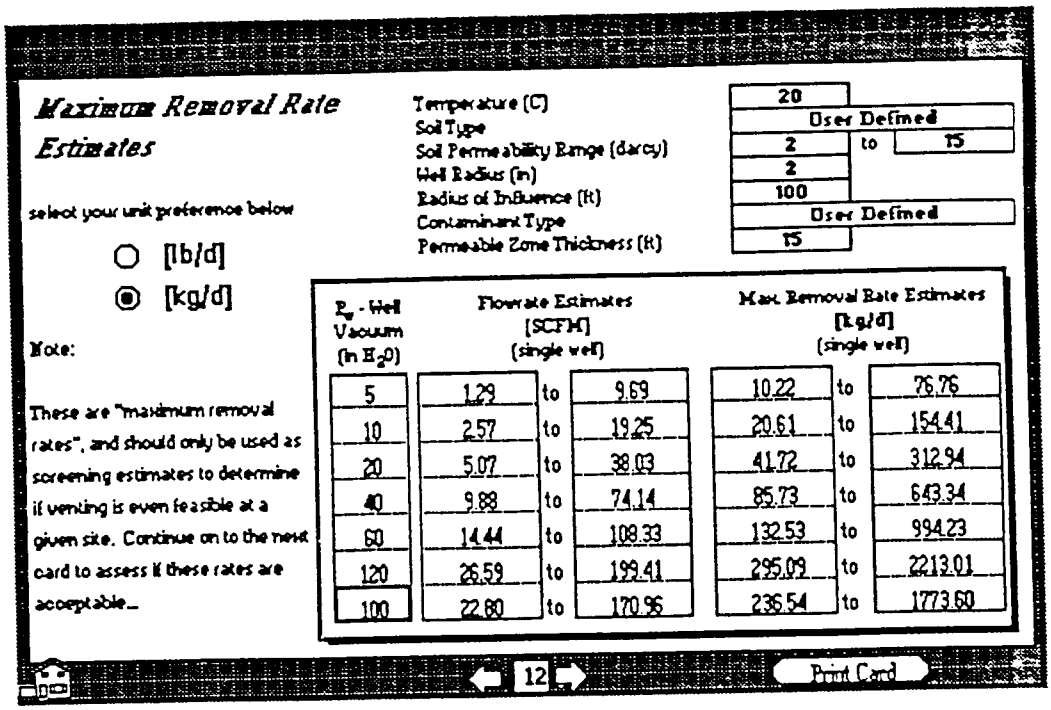
DOE-RL (1991) lists the soil temperature at 15 to 22 °C. An average temperature of 20 °C was assumed.

Composition

CCl_4, 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)	20
Soil Type	User Defined
Soil Permeability Range (darcy)	2 to 15
Well Radius (in)	2
Radius of Influence (ft)	100
Contaminant Type	User Defined
Permeable Zone Thickness (ft)	15

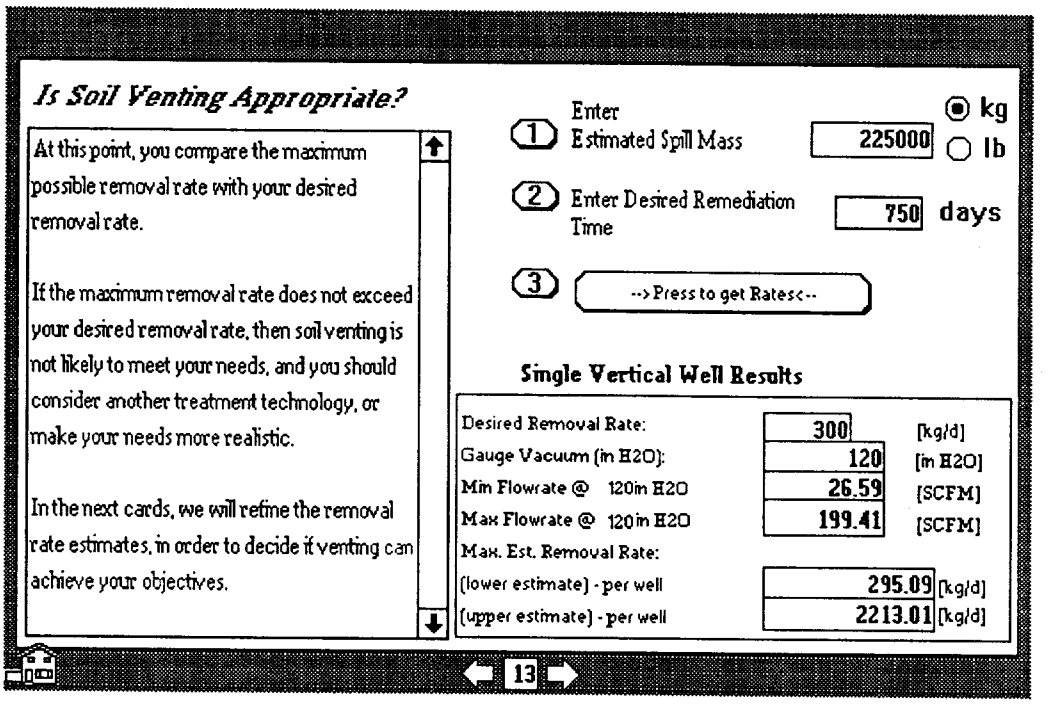
P_w - Well Vacuum (in H_2O)	Flowrate Estimates [SCFM] (single well)			Max. Removal Rate Estimates [kg/d] (single well)		
5	1.29	to	9.69	10.22	to	76.76
10	2.57	to	19.25	20.61	to	154.41
20	5.07	to	38.03	41.72	to	312.94
40	9.88	to	74.14	85.73	to	643.34
60	14.44	to	108.33	132.53	to	994.23
120	26.59	to	199.41	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.



216-Z-9 MODEL

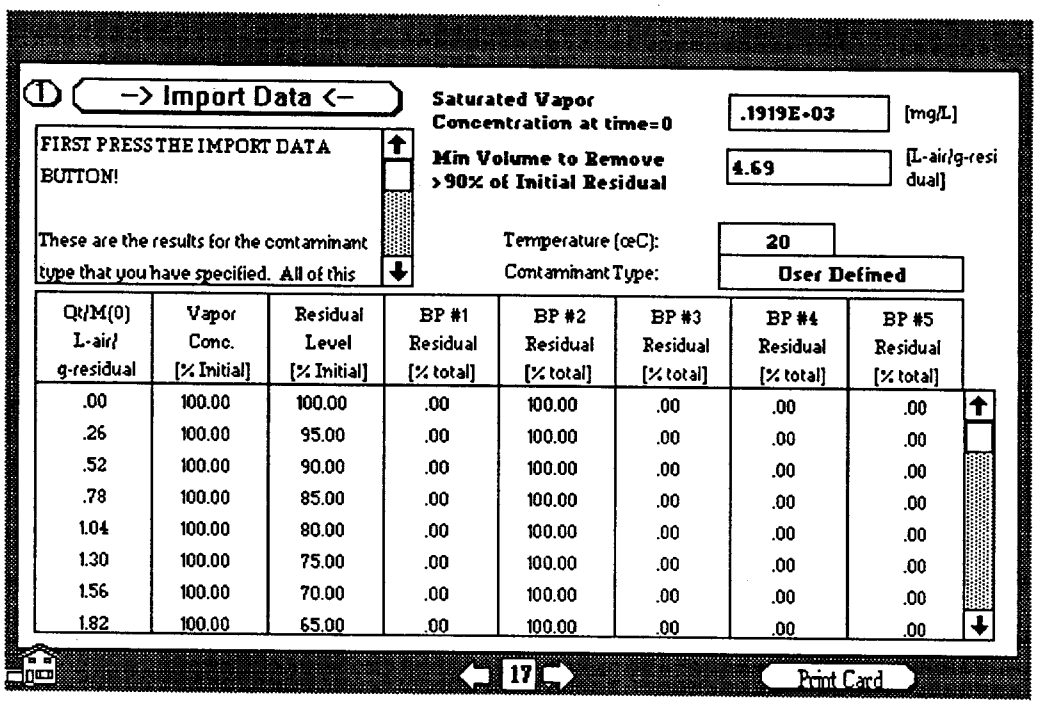
Spill Mass

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 PRESS THE 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-residual]

Temperature (oC): 20

Contaminant Type: User Defined

Qt/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

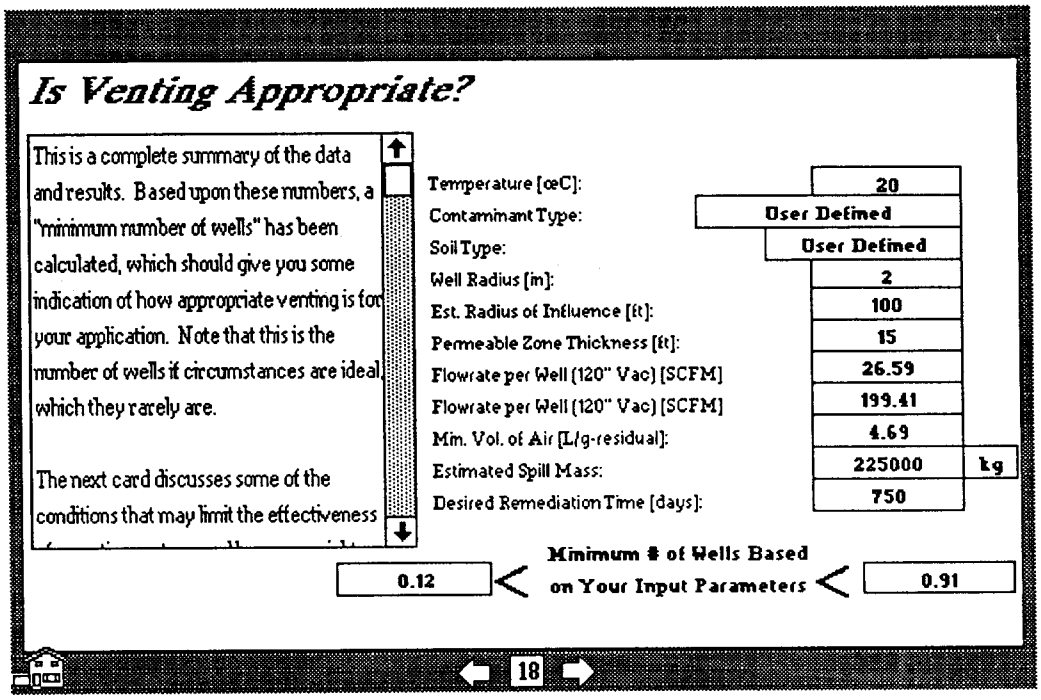
17 Print Card

216-Z-9 MODEL

Air/Residual Ratio

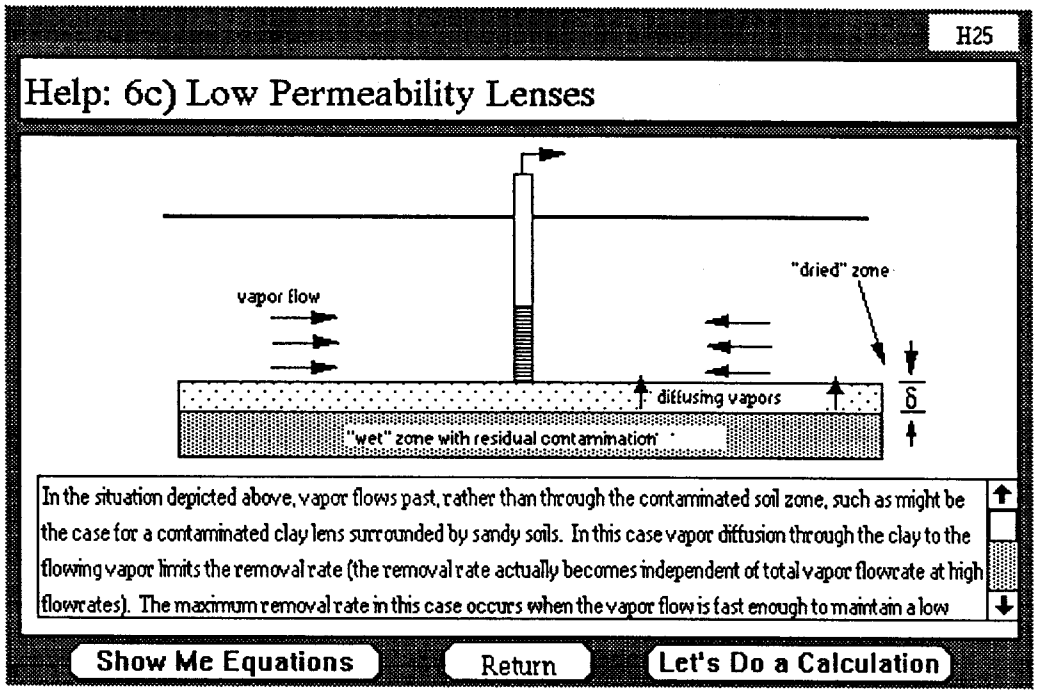
The calculated minimum volume of air to remove >90% of the initial residual contamination is 4.69 L-air/g-residual.

Therefore, an inventory of 225,000 kg would require the extraction of 1.1 x 10^9 L (3.7 x 10^7 ft^3) of soil gas at 30,000 ppm_v to remediate. This is equivalent to operating a 1,500 $stdft^3$/min soil vapor extraction system continuously for 1 month assuming a 68% TOE.



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 3 years.



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

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

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

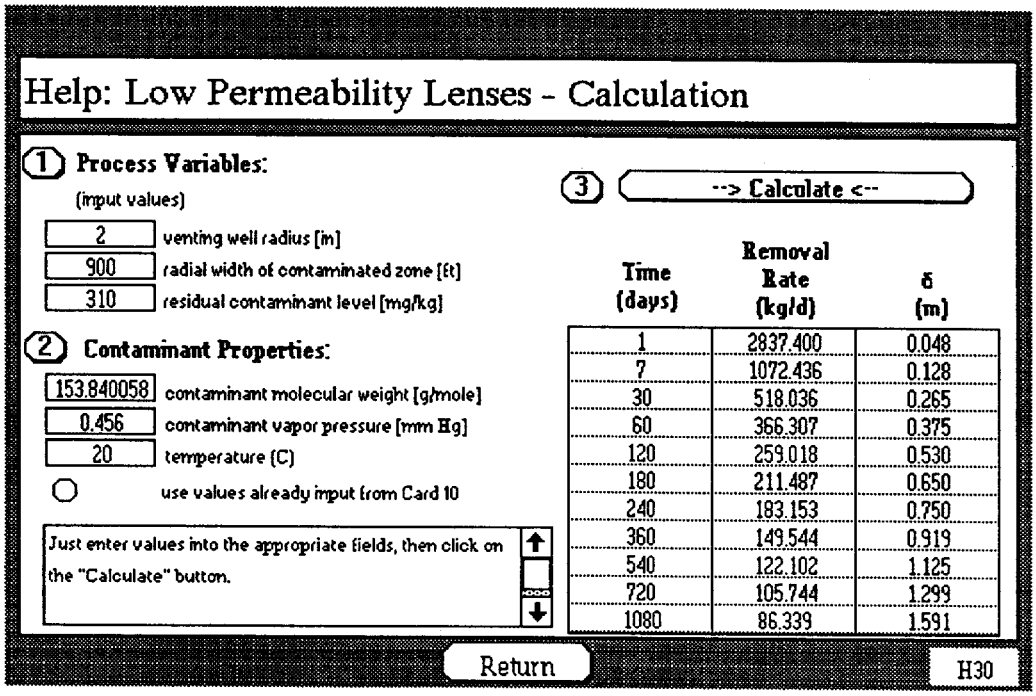
where:

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



VENTING WELL RADIUS

Radius of the well is 2 in.

RADIAL WIDTH OF CONTAMINATED ZONE

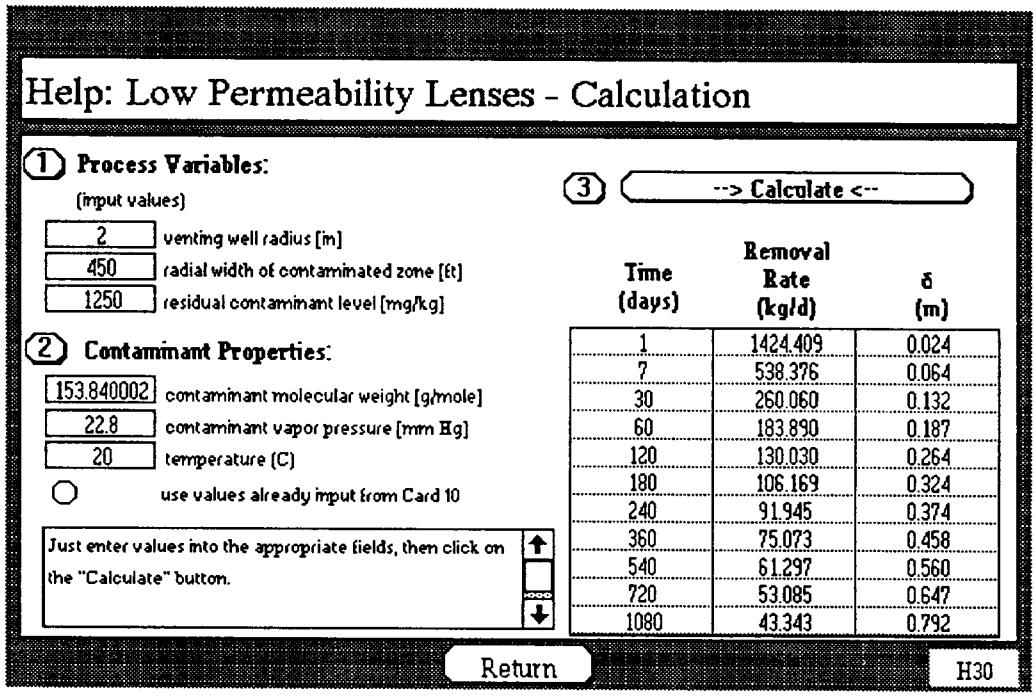
The radius of a circle with an area enclosing the soil vapor plume around 216-Z-1A Tile Field, 216-Z-18 Crib, and 216-Z-12 Crib (Figure 2-2) is 900 ft.

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 kg 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.



VENTING WELL RADIUS

Radius of the well is 2 in.

RADIAL WIDTH OF CONTAMINATED ZONE

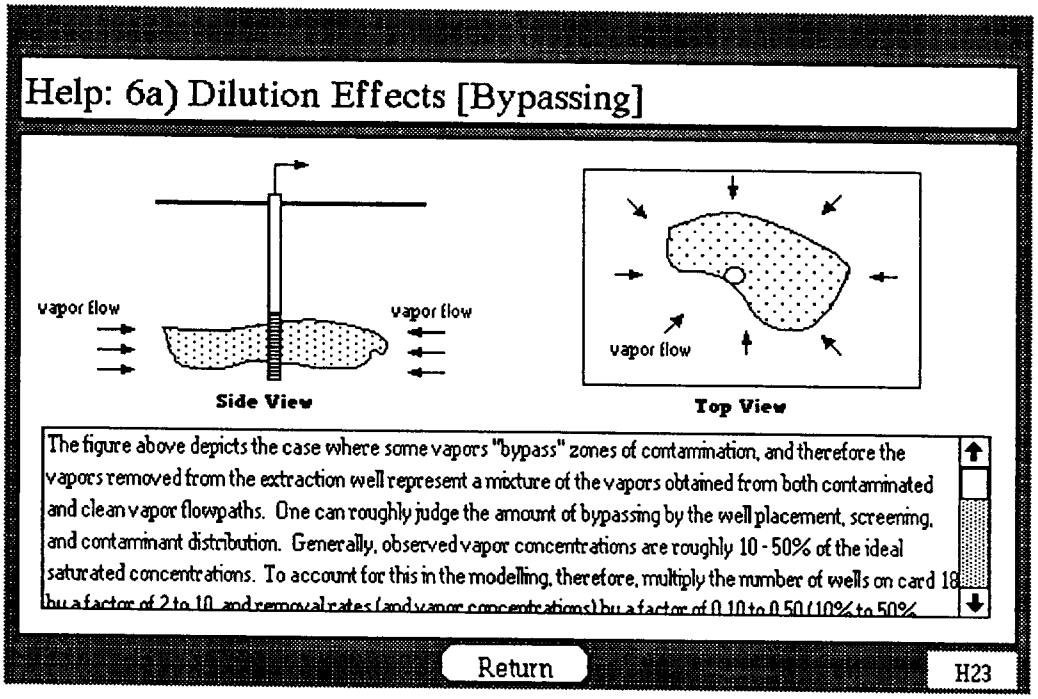
The radius of a circle with an area enclosing the soil vapor plume around 216-Z-9 Crib (Figure 2-2) is 450 ft.

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 kg tetrachloromethane in the area of 216-Z-9 Crib.

CONTAMINANT VAPOR PRESSURE

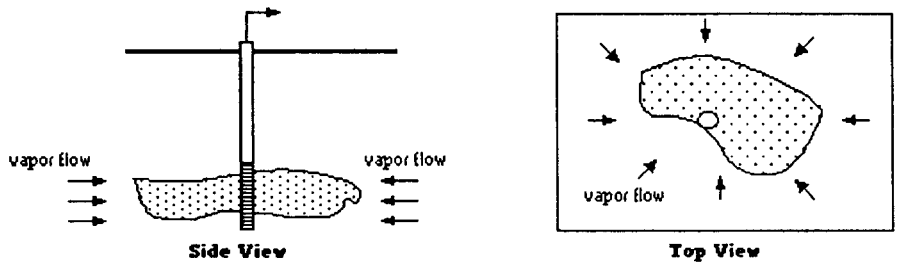
The vapor pressure equivalent to 0.5% tetrachloromethane is 22.8 mm Hg.



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 be obtained during an air permeability test, when soil gas concentrations at vadose monitoring installations, and extraction well concentrations are compared

Return

H23

REFERENCES

DOE-RL, 1991, *Expedited Response Action Proposal for 200 West Area Carbon Tetrachloride Plume*, DOE/RL-91-32, Draft B, U.S. Department of Energy, Richland Field Office, Richland, Washington.

Johnson, P.C., 1990, "A Practical Approach to the Design, Operation, and Monitoring of In-Situ Soil Venting Systems", *Soil Vapor Extraction Technology*, Appendix E, Camp Dresser & McKee Inc., Cambridge, Massachusetts.

APPENDIX D

CARBON TETRACHLORIDE CHEMICAL CHARACTERISTICS

APPENDIX D
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:

$$P = (X)(P^o) \tag{1}$$

where:

P = vapor pressure of the component over the solution
X = mole fraction of the component in the solution
P^o = 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:

$$P = (X)(H_c) \tag{2}$$

where:

H_c = Henry's Constant, unitless (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):

$$\log H_c = 5.853 - 1718/T[K] \tag{4}$$

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 D-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 E

VAPOR PHASE PARTITIONING COEFFICIENT DETERMINATION

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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.

$$q_e = K_v C_e \tag{1}$$

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, 3 (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 °C for 3 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 °C for 2 hours and quantifying the carbon tetrachloride vapor phase concentration (Voice 1993). The concentration measured at 96 °C was corrected for the loss of carbon tetrachloride that resulted from the analysis at 18 °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.

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

where:

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

Equation (3):

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

where:

q_e	= Solid phase concentration (μg/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 E-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 E-1 and E-2 indicate a maximum solid phase carbon tetrachloride concentration of approximately 3,500 μg/g at a vapor phase equilibrium concentration of ~16,000 μg/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 E-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 E-1 and E-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 E-1 and are plotted in Figure E-4 along with the WSU laboratory data from Table E-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:

$$Q_e(\mu g/kg) = 0.73 C_e(ppm_v) \; . \tag{4}$$

Table E-1. Well Sample Carbon Tetrachloride Data.

Well #	Depth (ft)	CCl_4 Concentration in soil gas (ppm_v)[a]	CCl_4 Concentration in soil (ppb)[b]
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

[a]Field gas sample, analyzed by GC/ECD.
[b]Soil sample preserved in methanol, analyzed by GC.

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

Bottle No.	gas vol (mL)	soil mass (g)	C_e 18° (ppm)	C 96° (ppm)	adj C 96° (ppm)[4]	adj C 96° (μg/L)	C_e 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 E-1. Equilibrium Carbon Tetrachloride Sorption Isotherm for Sandy Silt Soil.

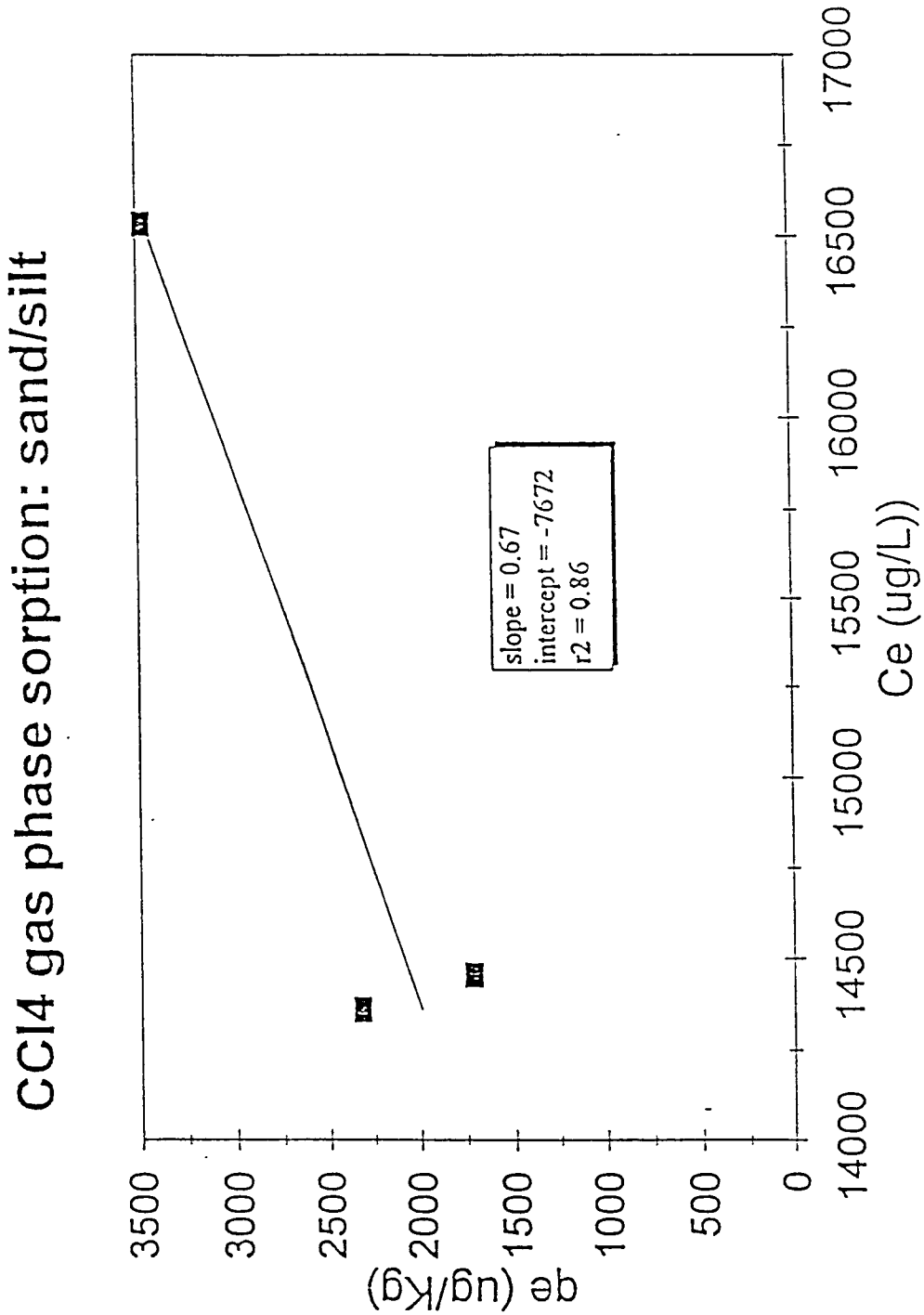


Figure E-2. Equilibrium Sorption Isotherm for Sandy Gravel Soil.

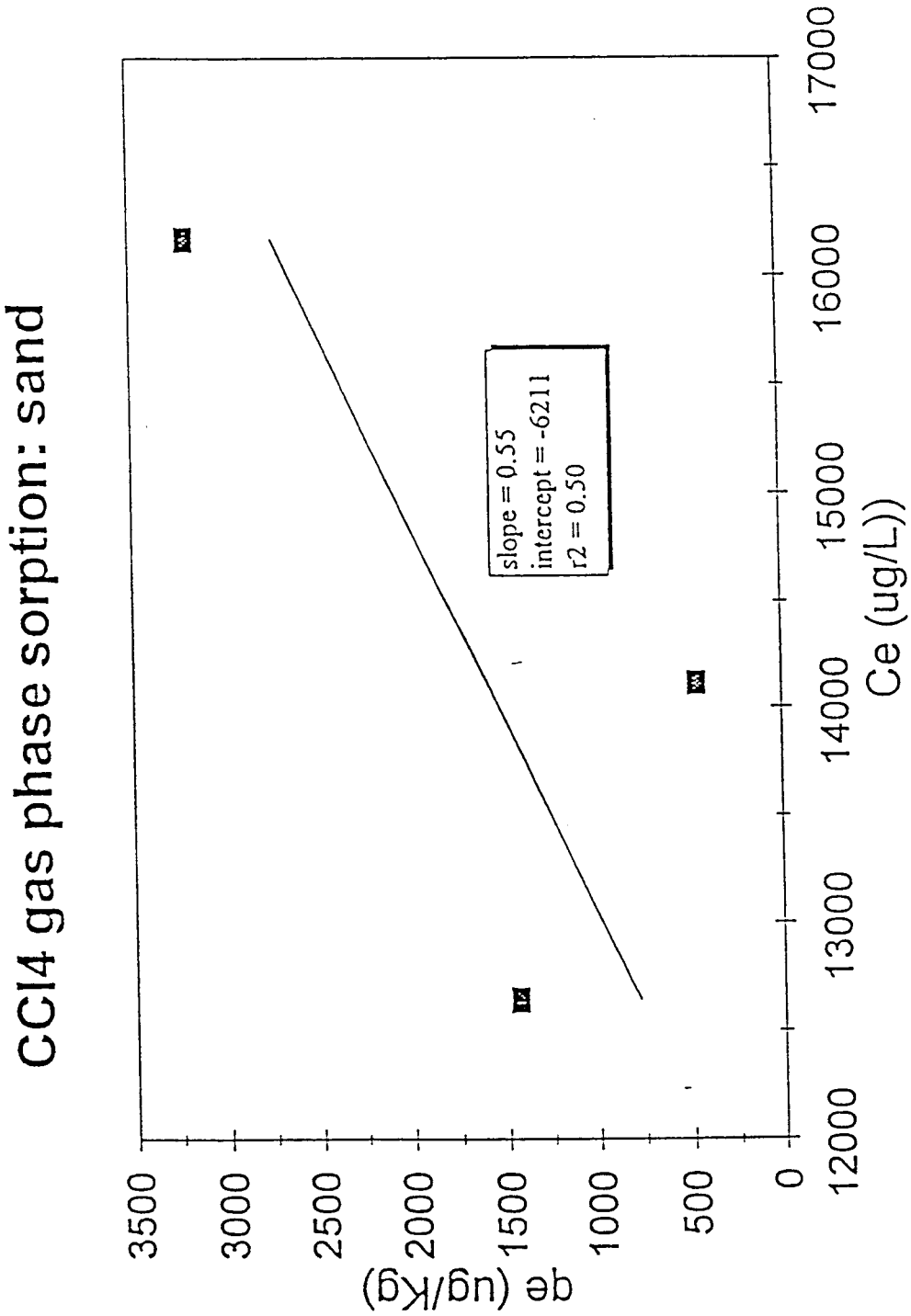


Figure E-3. Equilibrium Sorption Isotherm for Data From Both Sandy Silt and Sandy Gravel Soil Samples.

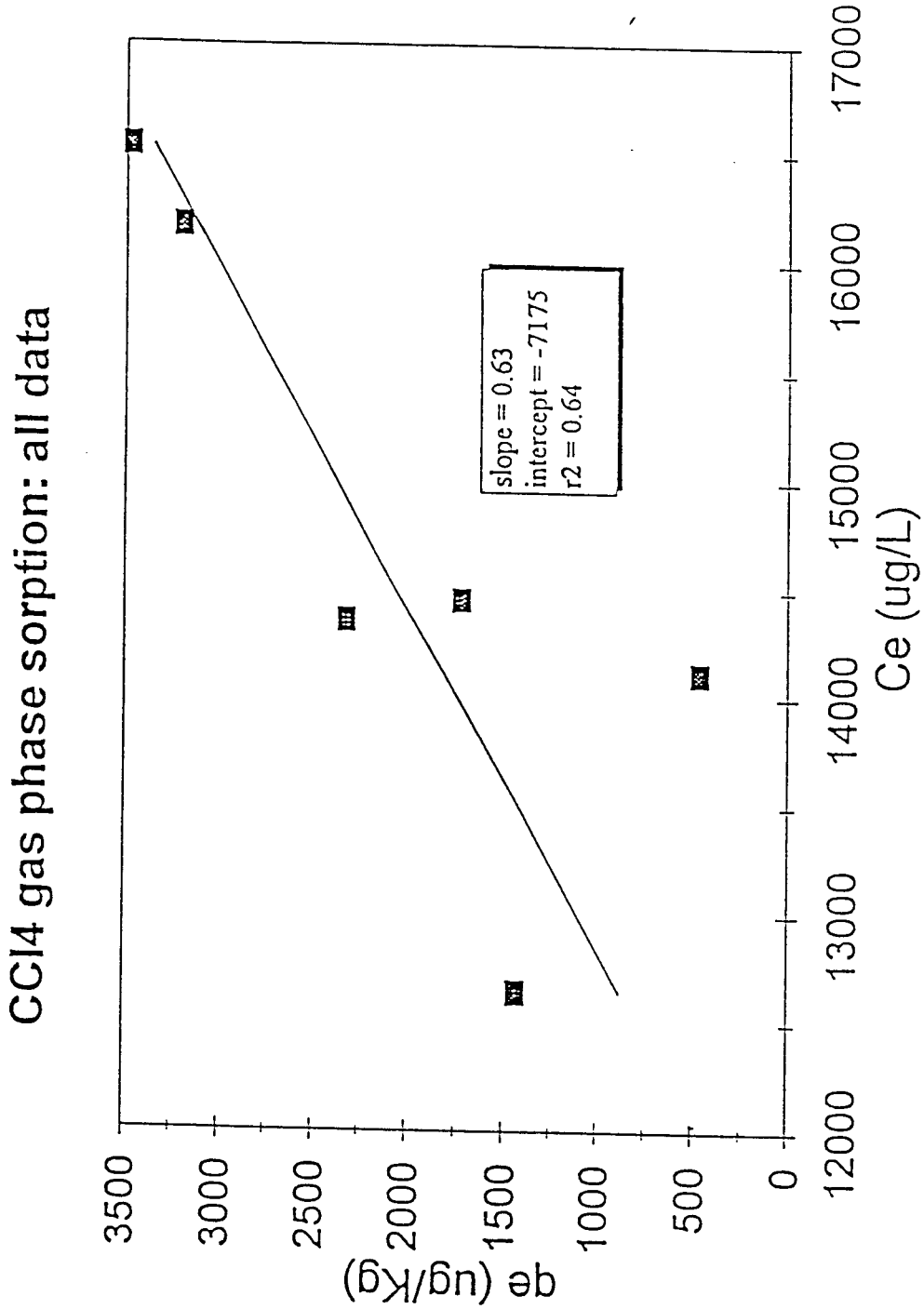
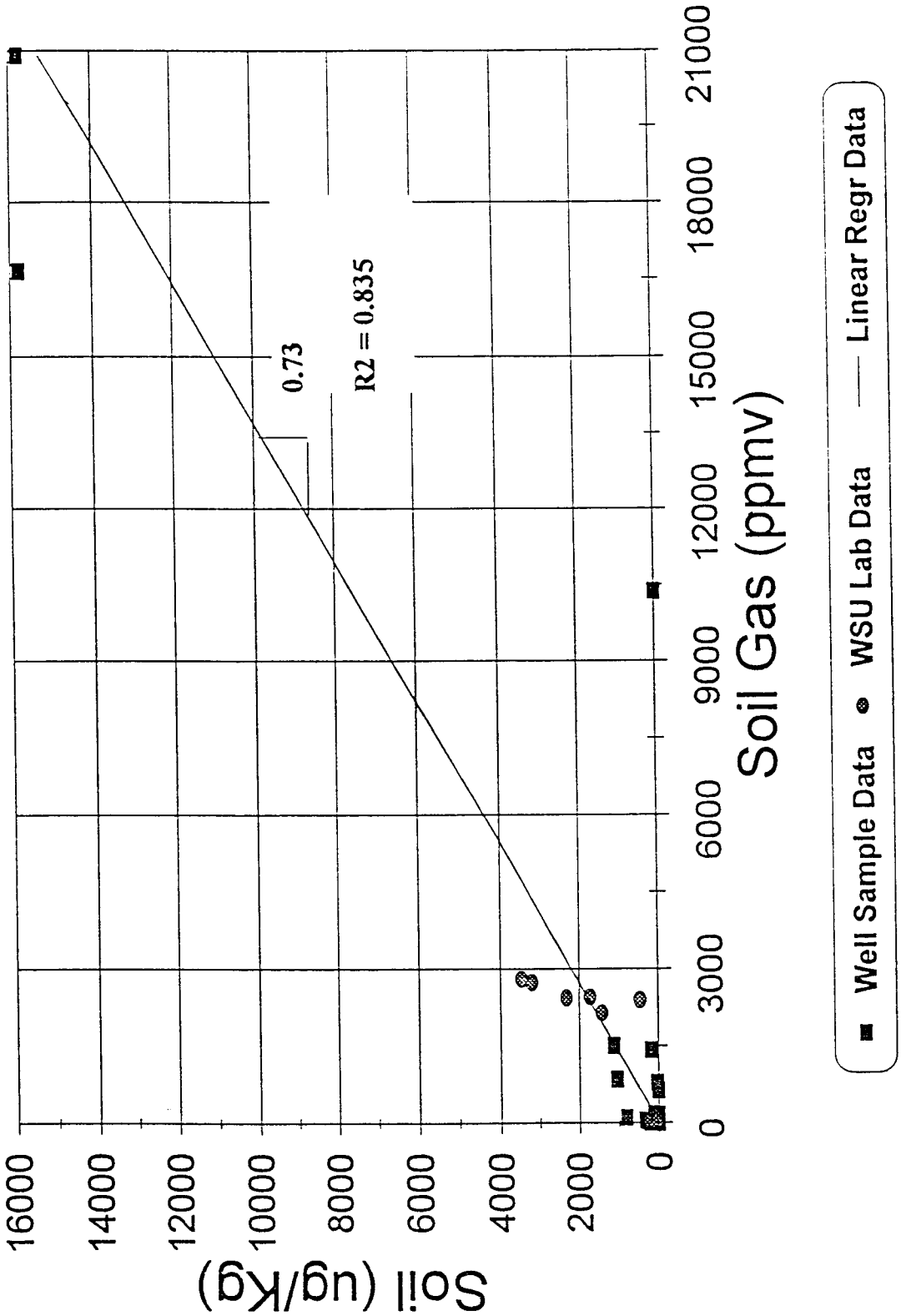


Figure E-4. Soil Gas Isotherm.



4.0 REFERENCES

Voice, T.C., 1993, "Static and Dynamic Headspace Analysis of VOCs in Soils," *Environmental Science Technology*, 1993, vol. 27, pp. 709-13.

WHC, 1993, *Carbon Tetrachloride Atmospheric Losses and Residual Inventory Beneath the 200 West Area*, WHC-SD-EN-TI-101, Rev. 0, Westinghouse Hanford Company, Richland, Washington.

Rohay, V.J., K.J. Swett, V.M. Johnson, G.V. Last, D.C. Lanigan, and L.A. Doremus, 1993, *FY 1993 Site Characterization Status Report and Data Package for the Carbon Tetrachloride Site*, WHC-SD-EN-TI-202, Rev. 0, Westinghouse Hanford Company, Richland, Washington.

APPENDIX F

VAPOR EXTRACTION CHARACTERIZATION TESTS
WELL 299-W18-252U

APPENDIX F
VAPOR EXTRACTION CHARACTERIZATION TESTS
WELL 299-W18-252U

Four vapor extraction characterization tests have been performed on the upper interval of well 299-W18-252, located west of the 216-Z-1A Tile Field. The tests were completed on January 5, 6, and 20, and March 10, 1994. The first two tests were routine characterization tests in which a vacuum is applied to a single open interval and the resulting flow and concentration are measured. The third test was used to determine the radius of influence of well 299-W18-252U. The fourth test was conducted to determine the relationship between applied vacuum and flow at this interval.

On January 5, a vacuum of 33 in. H_2O was applied at the wellhead, resulting in a flow of 150 ft^3/min containing 80 ppm_v of carbon tetrachloride. The vacuum at the vapor extraction system was 92 in. H_2O. On January 6, a vacuum of 70 in. H_2O was applied at the wellhead, resulting in a flow of 230 ft^3/min containing 518 ppm_v of carbon tetrachloride. The vacuum at the vapor extraction system was 127 in. H_2O. On January 20, the vapor extraction system vacuum was 127 in. H_2O, which again produced a wellhead vacuum of 70 in. H_2O and a flow of 230 to 240 ft^3/min containing 500 ppm_v of carbon tetrachloride. On March 10, the vacuum at the wellhead was varied from 14 to 70 in. H_20, resulting in flows ranging from 118 to 269 ft^3/min.

The vapor extraction system, which includes a 500-ft^3/min blower, was connected to well 299-W18-252U through a 4-in.-diameter, 5-ft-long manifold positioned near the well. Approximately 500 ft of 4-in.-diameter flex hose runs from the extraction system to the manifold, which is connected to the wellhead with approximately 15 ft of 2-in.-diameter flex hose (Figure F-1).

Well 299-W18-252 is completed with 4-in.-diameter schedule 5 stainless steel casing extending 210.3 ft below ground surface (bgs) with two louvered, 0.020-slot screened intervals from 113.24 to 133.21 ft bgs and from 165.13 to 185.09 ft bgs (Figure F-2). Filter packs were installed from 111.0 to 134.7 ft and from 163.0 to 187.2 ft bgs (Rohay et al. 1993). A 2-in.-outer diameter pipe is located in the center of the casing and extends to approximately 135 ft bgs. An air bladder packer is placed between the inner pipe and the casing to isolate the upper and lower screened intervals. Thus the soil gas extracted from the upper interval flows through a 4-in. by 2-in. annulus. Because this well was installed in 1993, it is assumed that the steel surfaces are smooth and clean.

Three pressure transducer vent lines, consisting of 1/8-in.-diameter stainless steel tubing, were strapped to the exterior of the permanent well casing during completion. These were open ended, terminating at 100.0, 145.2, and 210.0 ft. Each open tube end was filter packed with approximately 3 to 4 ft of filter pack to provide continuity with the formation. The transducer tube and screen filter packs were isolated from each other by installing portland cement grout annular seals and bentonite annular seals between the filter packs. A portland cement grout annular seal was also installed across the Plio-Pleistocene unit to prevent contaminant transport across the confining unit. A bentonite annular seal was installed from 9.0 ft to the top of the upper transducer cement grout seal at 90.2 ft, and a cement grout seal was installed from the ground surface to 9.0 ft bgs (Rohay et al. 1993).

An array of subsurface monitoring ports was installed north of well 299-W18-252 using a cone penetrometer in 1993 (Figure F-3). The north end of the array is anchored by extraction well CPT-4. Ten monitoring locations, each consisting of one to five subsurface ports, were installed between 299-W18-252 and CPT-4. The monitoring ports range in depth from 10 to 109 ft bgs (Figure F-4).

During the January 20 radius-of-influence test, a vacuum was applied to well 299-W18-252U for approximately 6.5 hours, and subsurface differential pressures were monitored every 15 minutes at the 299-W18-252 lower screened interval (299-W18-252L); at the three stainless steel transducer tubes at 299-W18-252 [252/1 (100 ft), 252/2 (145 ft), 252/3 (210 ft)]; and at eight subsurface monitoring ports [CPT-4F (75 ft and 109 ft), CPT-4E (75 ft and 103 ft), CPT-4D (75 and 99 ft), CPT-4C (107 ft), and CPT-4B (90 ft)]. Spots check of the pressure were also made at the other CPT-4 monitoring ports.

Extraction was initiated at approximately 8:45 a.m. on January 20, 1994 and continued until approximately 3:15 p.m. Differential pressures were monitored from 3:15 p.m. on January 19 through 1:15 p.m. on January 21. Barometric pressure was also recorded.

Vacuums measured during the test are shown on a cross section of well 299-W18-252 and the CPT-4 monitoring array (Figure F-5). These vacuums have been corrected for the effects of barometric pressure. Based on the corrected January 20 subsurface vacuum readings, the radius of influence is estimated to be 125 ft (Figure F-6).

The data recorded during the January 20 test are illustrated in Figures F-7 through F-12. These graphs show the absolute pressure in in. H_2O for the barometric and subsurface monitoring points. The sample points which were affected by vapor extraction are shown with areas of hatch marks. The upper curve of the hatched areas represents an approximation of the subsurface pressure in the absence of the applied extraction vacuum. The lower portion of the hatched areas are the measured subsurface pressures. The height of the hatched areas represents the vacuum that was induced by the vapor extraction system. The times that the test started and stopped are indicated in the figures as vertical bars.

Monitoring at 299-W18-252L and 252/3, which are the lower screened interval and lowest stainless steel transducer tube, respectively, at well 299-W18-252, shows no response to the vacuum applied at the upper screened interval (Figure F-7). This indicates that the Plio-Pleistocene caliche layer is effective as a barrier to vertical air flow in this area.

Results of the March 10 flow step test are shown in Figure F-13. As the vacuum is increased, the resulting flow increases but appears to reach a maximum of approximately 250 to 300 ft^3/min. This suggests that increasing the wellhead vacuum above approximately 70 in. H_2O will not significantly increase the resulting air flow.

REFERENCE

Rohay, V.J., Swett, K.J., Johnson, V.M., Last, G.V., Lanigan, D.C., and Doremus, L.A., 1993, *FY93 Site Characterization Status Report and Data Package for the Carbon Tetrachloride Site*, WHC-SD-EN-TI-202, Rev. 0, prepared by V.J. Rohay, K.J. Swett, and V.M. Johnson, Westinghouse Hanford Company, and G.V. Last, D.C. Lanigan, and L.A. Doremus, Pacific Northwest Laboratory, for Westinghouse Hanford Company, Richland, Washington.

Figure F-1. Flow Diagram for Extraction at Well 299-W18-252 Upper Interval.

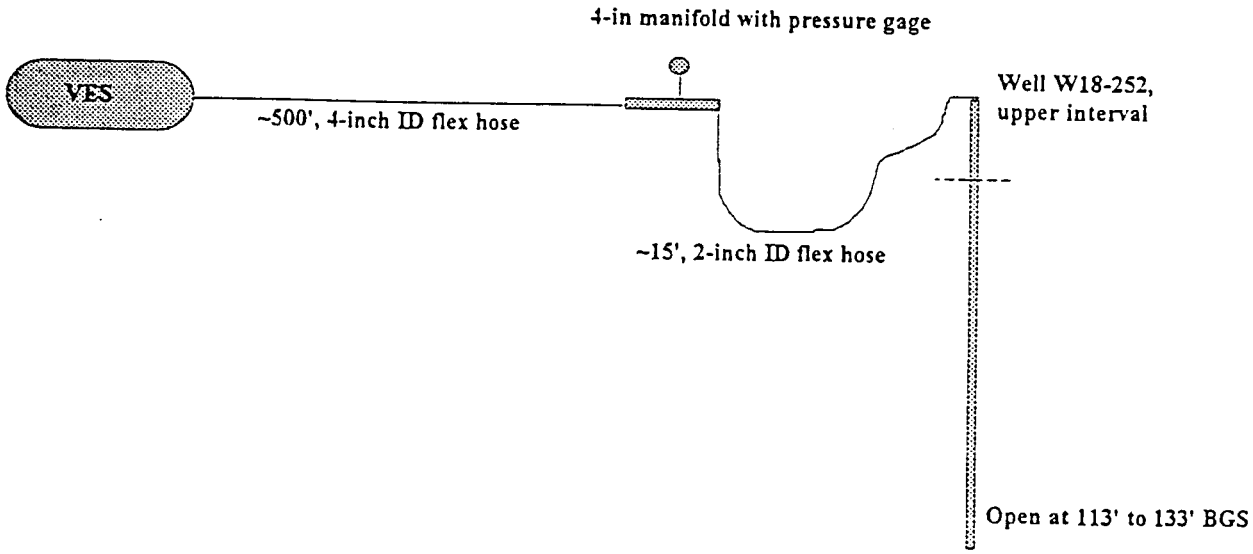


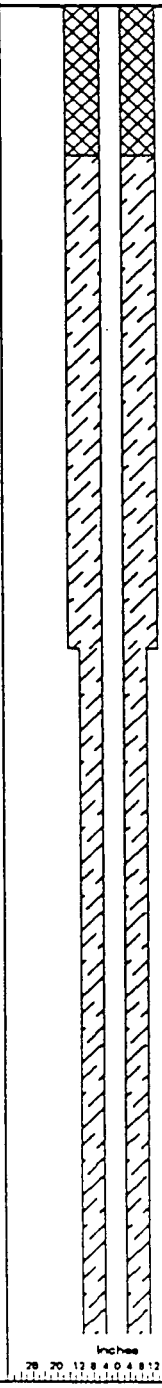
Figure F-2. Well Summary Sheet for Well 299-W18-252 (from Rohay et al. 1993). (sheet 1 of 3)

WELL SUMMARY SHEET

Boring or Well No. 299-W18-252
Northing 135429.48 Easting 566447.02
Sheet 1 of 3

Location 200 West
Project VOC/Arid ID
Elevation 680.59
Drilling Contractor Kaiser Engineers Hanford
Driller G. Howell
Drilling Method and Equipment Cable Tool Walker Neer WS-31
Prepared by J. Flinn (Sign/Print Name)

CONSTRUCTION DATA		Depth in Feet	GEOLOGIC/HYDROLOGIC DATA	
Description	Well Construction		Graphic Log	Lithologic Description
CEMENT (0.0' to 9.0')				0'-1' Stabilization (Fill) 1.0'-7.0' SAND
				7.0'-11.5' Gravelly SAND
		10		11.5'-16.5' Sandy GRAVEL
16" TEMPORARY CARBON STEEL CASING SET AT 38.71'				16.5'-22.0' SAND
		20		22.0'-33.5' Gravelly SAND
		30		
				33.5'-37.0' SAND
				37.0'-38.0' GRAVEL
		40		38.0'-42.5' SAND
				42.5'-51.0' Sandy GRAVEL
		50		51.0'-101.0' SAND 51.0'-52.5' Stratified medium sand, coarse sand, and fine gravel.
4" DIAM T-304 SCH 5 STAINLESS STEEL CASING W/ CENTRALIZERS TO 113.2'		60		
8-20 MESH BENTONITE CRUMBLES (9.0'-90.2')		70		
		80		



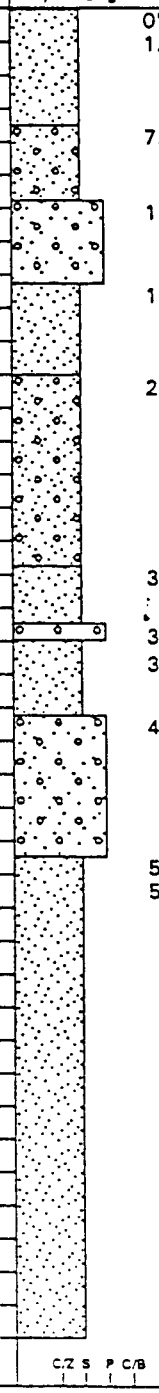


Figure F-2. Well Summary Sheet for Well 299-W18-252 (from Rohay et al. 1993). (sheet 2 of 3)

WELL SUMMARY SHEET

Boring or Well No. 299-W18-252
Northing 135429.48 Easting 566447.02
Sheet 2 of 3

Location 200 West
Elevation 680.59
Driller G. Howell
Prepared by J. Flinn (Sign/Print Name)

Project VOC/Arid ID
Drilling Contractor Kaiser Engineers Hanford
Drilling Method and Equipment Cable Tool Walker Neer WS-31

CONSTRUCTION DATA		Depth in Feet	GEOLOGIC/HYDROLOGIC DATA	
Description	Well Construction		Graphic Log	Lithologic Description
12" TEMPORARY CARBON STEEL CASING SET AT 138.28'				
CEMENT (90.2'-95.6')		90		
8-20 MESH BETONITE CRUMBLES (95.6'-97.9')				
10-20 MESH SILICA SAND (97.9'-101.9')		100		
TRANDUCER SET @ 100.0'				101.0'-109.0' Sandy GRAVEL
8-20 MESH BENTONITE CRUMBLES (101.9'-102.5')				
CEMENT (102.5'-109.2')				
8-20 MESH BENTONITE CRUMBLES (109.2'-110.0')		110		109.0'-120.0' GRAVEL
10-20 MESH SILICA SAND (111.0'-134.7')				
4" DIAM 20.0'.020-SLOT LOUVERED SS SCREEN (113.2'-133.2')				
		120		118.5' Trace of CALICHE in cuttings. 120.0'-125.0' Sandy GRAVEL
				125.0'-137.5' Silty SAND Sharp Contact @ 125.0'.
		130		130.0' Sandy SILT (80% SILT 20% SAND)
8-20 MESH BENTONITE CRUMBLES (134.7'-135.7')				
CEMENT (135.7'-141.0')				137.0' Slightly Silty SAND (80% SAND 20% SILT)
		140		137.5'-139.5' CALICHE-Sandy GRAVEL 137.5' Irregular, sharp contact w/ CALICHE.
8-20 MESH BETONITE CRUMBLES (141.0'-142.9')				
10-20 MESH SILICA SAND (142.9'-146.9')				139.5'-149.0' Sandy GRAVEL
TRANDUCER SET @ 145.2'				
8-20 MESH BENTONITE CRUMBLES (146.9'-157.2')		150		149.0'-159.0' SAND
4" DIAM T-304 SCH 5 STAINLESS STEEL CASING W/ CENTRALIZERS (133.2'-165.1')				
CEMENT (157.2'-161.2')				
		160		

Inches 28 20 12 8 4 0 4 8 12 20 28

C/Z S P C/B

Figure F-2. Well Summary Sheet for Well 299-W18-252 (from Rohay et al. 1993). (sheet 3 of 3)

WELL SUMMARY SHEET

Boring or Well No. 299-W18-252
Northing 135429.48 Easting 566447.02
Sheet 3 of 3

Location 200 West
Elevation 680.59
Driller G. Howell
Prepared by J. Flinn (Sign/Print Name)

Project VOC/Arid ID
Drilling Contractor Kaiser Engineers Hanford
Drilling Method and Equipment Cable Tool Walker Neer WS-31

CONSTRUCTION DATA

Description

8-20 MESH BENTONITE CRUMBLES (161.2'-163.0')
10-20 MESH SILICA SAND (163.0'-187.2')
4" DIAM 20.0' .020-SLOT SS LOUVERED SCREEN (165.1'-185.1')

10" DIAM TEMPORARY CARBON STEEL CASING SET AT 227.38'
8-20 MESH BENTONITE CRUMBLES (187.2'-194.1')

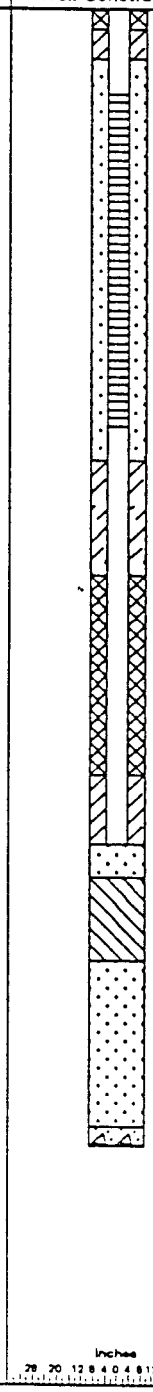
CEMENT (194.1'-206.1')
4" DIAM T-304 SCH 5 STAINLESS STEEL CASING W/ CENTRALIZERS (185.1'-210.3')

8-20 MESH BENTONITE CRUMBLES (206.1'-208.1')
10-20 MESH SILICA SAND (208.1'-212.3')
TRANDUCER SET @ 210.0'
BENTONITE HOLEPLUG (212.3'-217.3')

10-20 MESH SILICA SAND (217.3'-227.3')

SLOUGH (227.3'-228.5')
BOTTOM OF BOREHOLE 228.5'

Well Construction

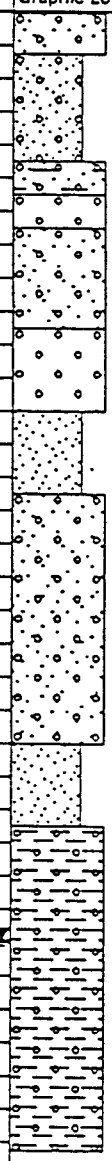


Depth in Feet

170
180
190
200
210
220
230
240

GEOLOGIC/HYDROLOGIC DATA

Graphic Log



Lithologic Description

159.0'-162.5' Sandy GRAVEL
162.5'-169.0' Gravelly SAND
169.0'-171.0' Silty Sandy GRAVEL
171.0'-173.0' GRAVEL
173.0'-179.0' Sandy GRAVEL
179.0'-184.0' GRAVEL
184.0'-189.0' SAND
189.0'-204.0' Sandy GRAVEL
204.0'-209.0' SAND
209.0'-228.5' Silty GRAVEL
213' Heavily oxidized
Static Water Level @ 217.3' BGS (7/20/93)

Figure F-3. Location of Well 299-W18-252 and CPT-4 Array.

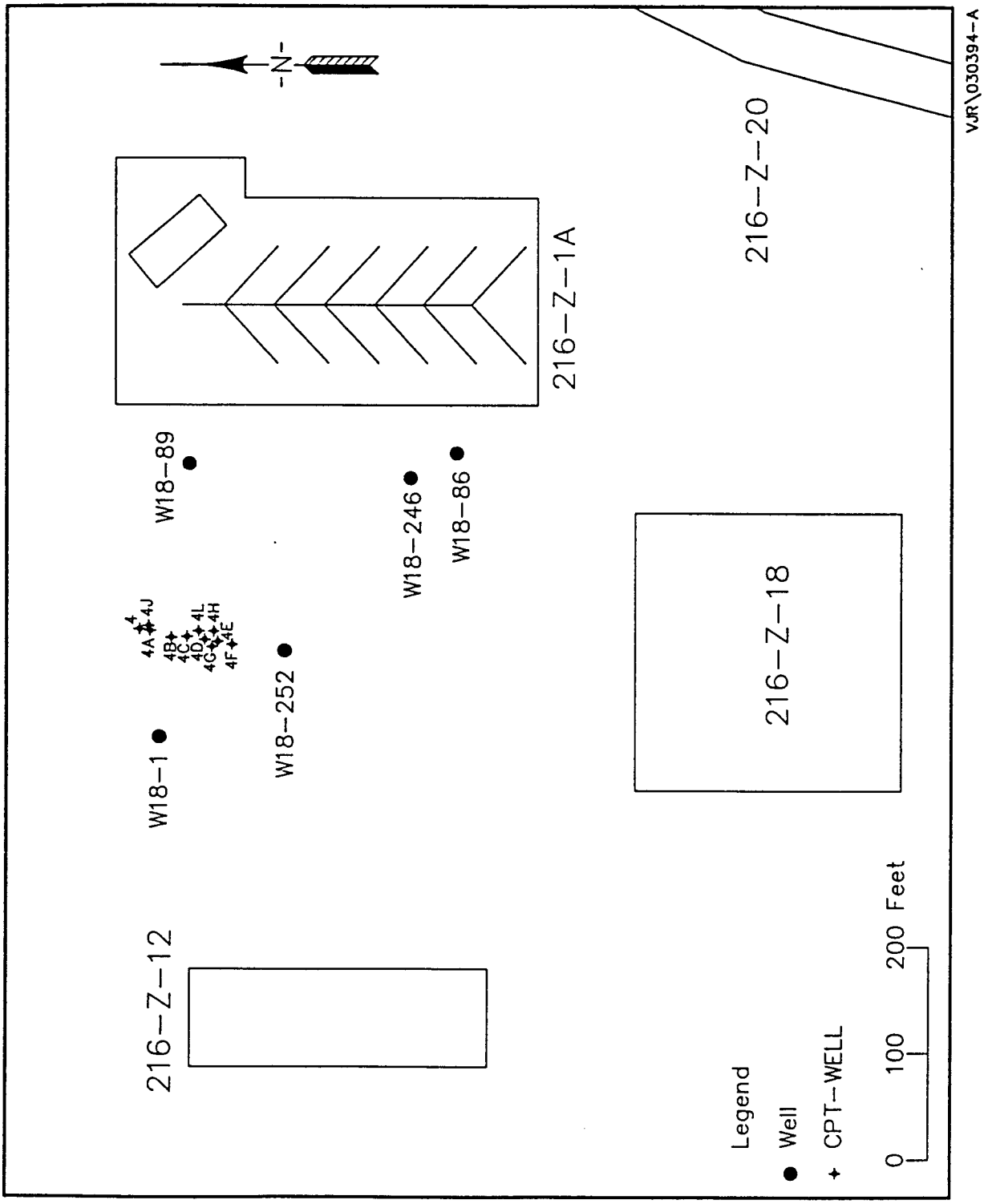


Figure F-4. Location and Depths of Subsurface Monitoring Ports in CPT-4 Array.

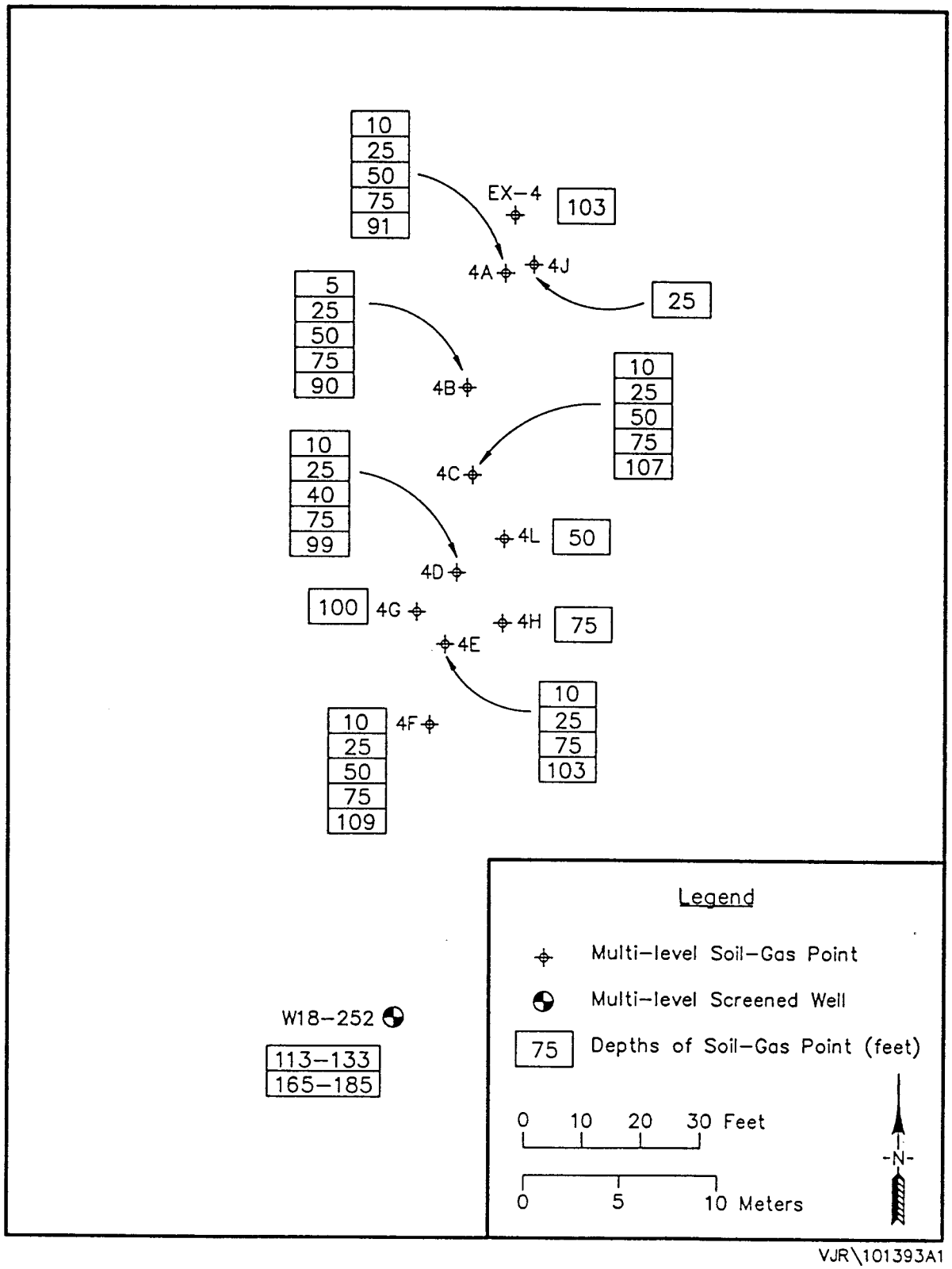


Figure F-5. Subsurface Vacuums During January 20, 1994 299-W18-252 Extraction Test.

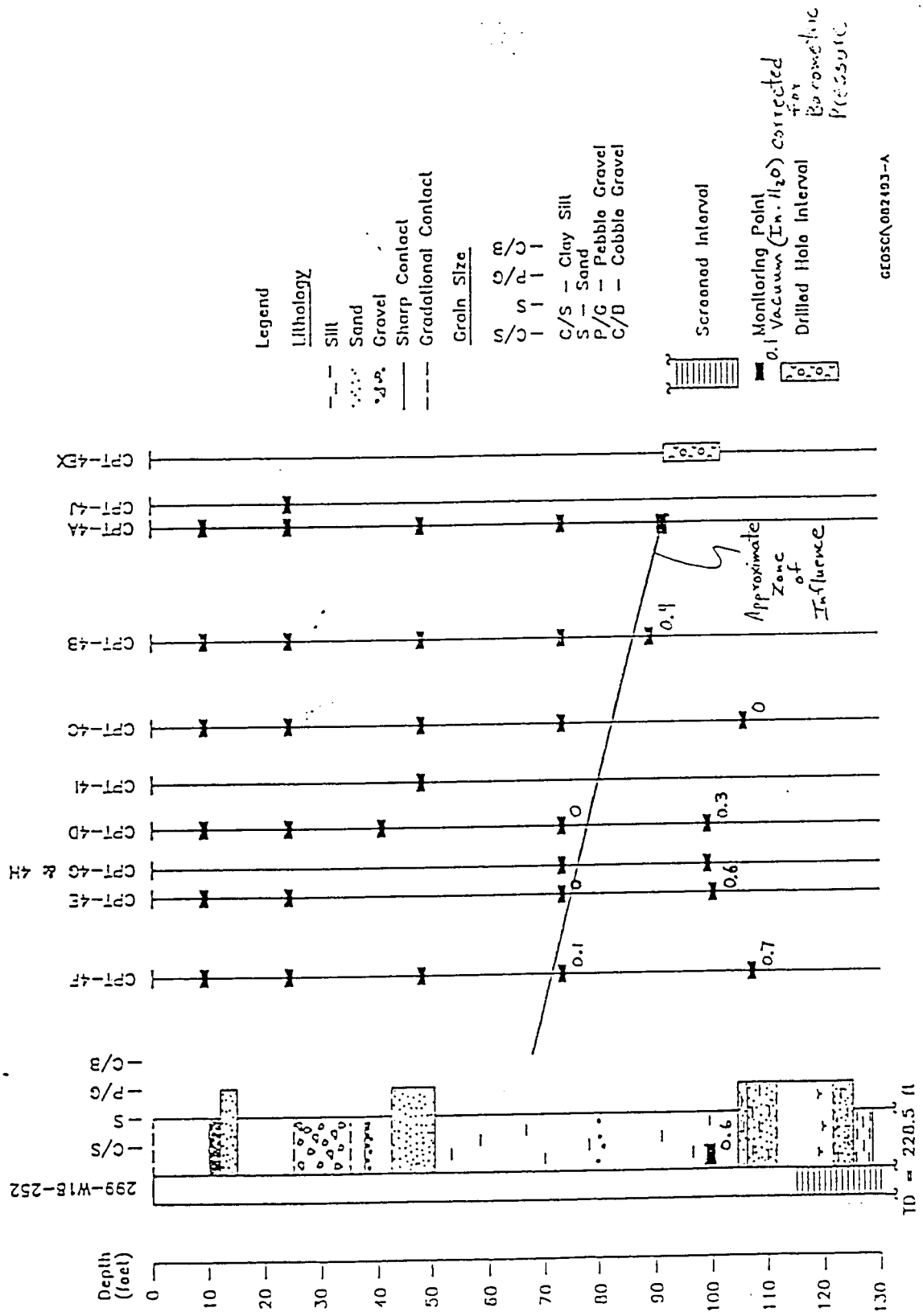


Figure F-6. Radius of Influence During January 20, 1994 299-W18-252 Extraction Test.

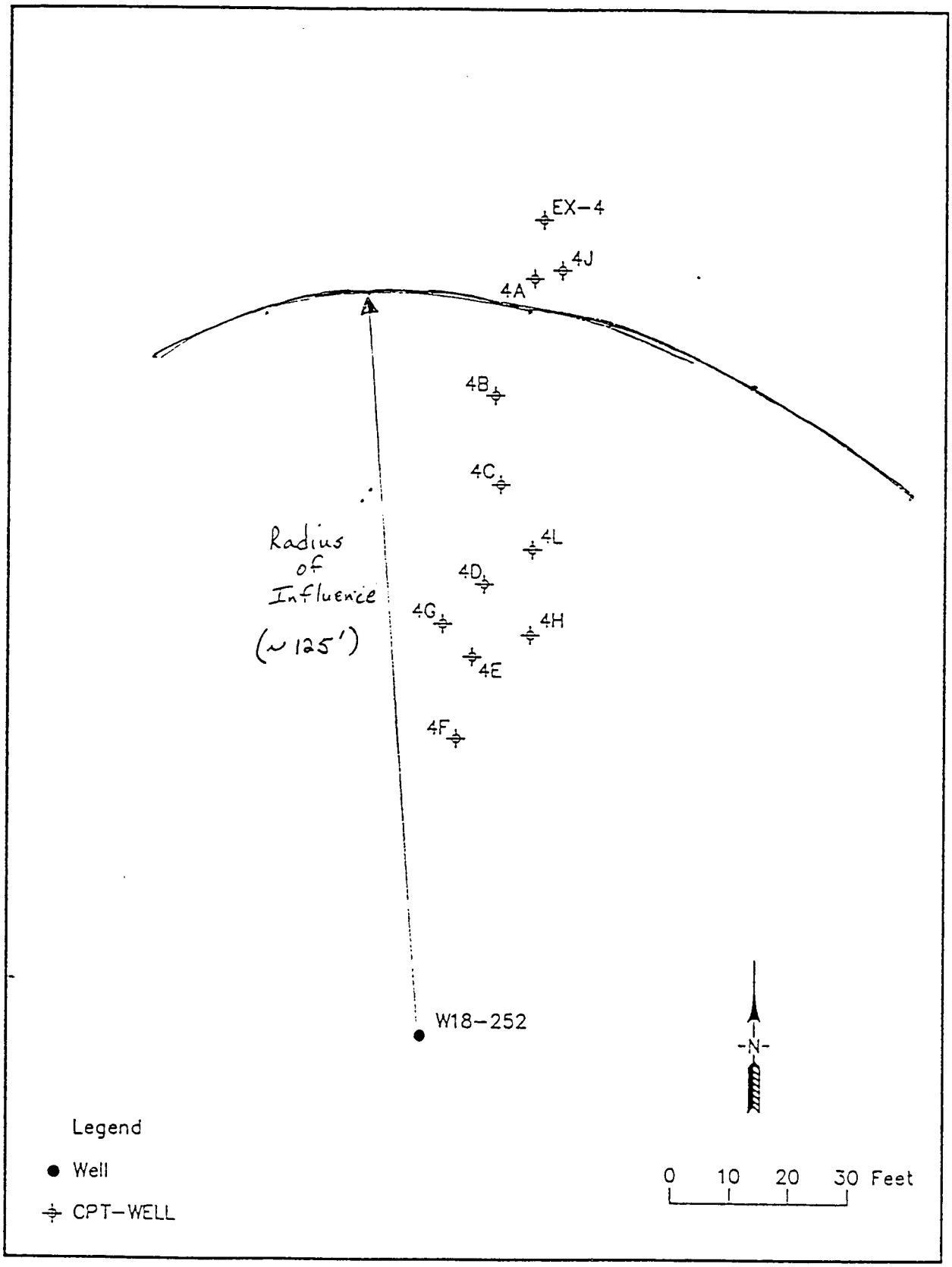


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Figure F-7. Pressures Measured at 299-W18-252 Monitoring Points.

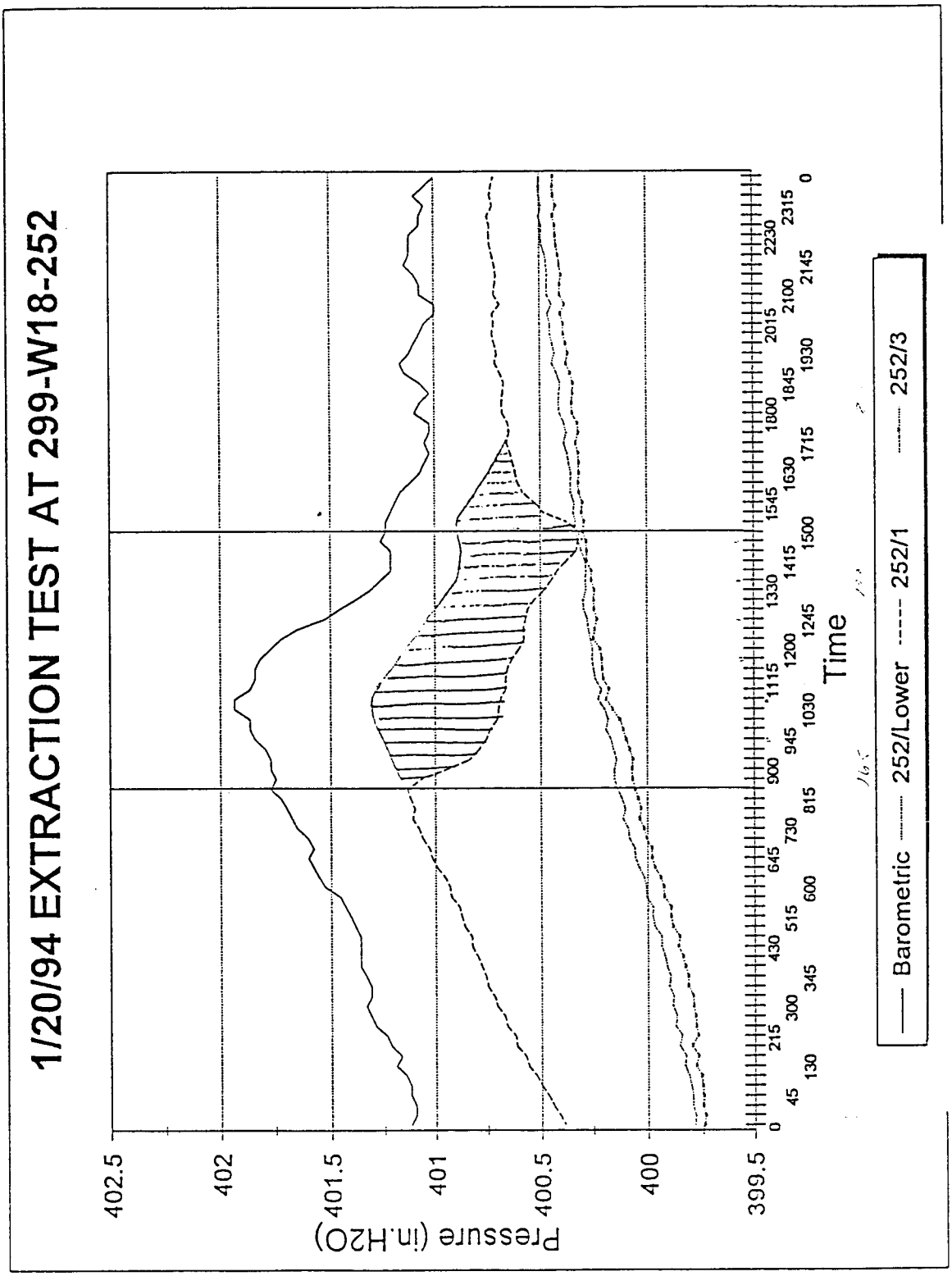


Figure F-8. Pressures Measured at CPT4-F Monitoring Points.

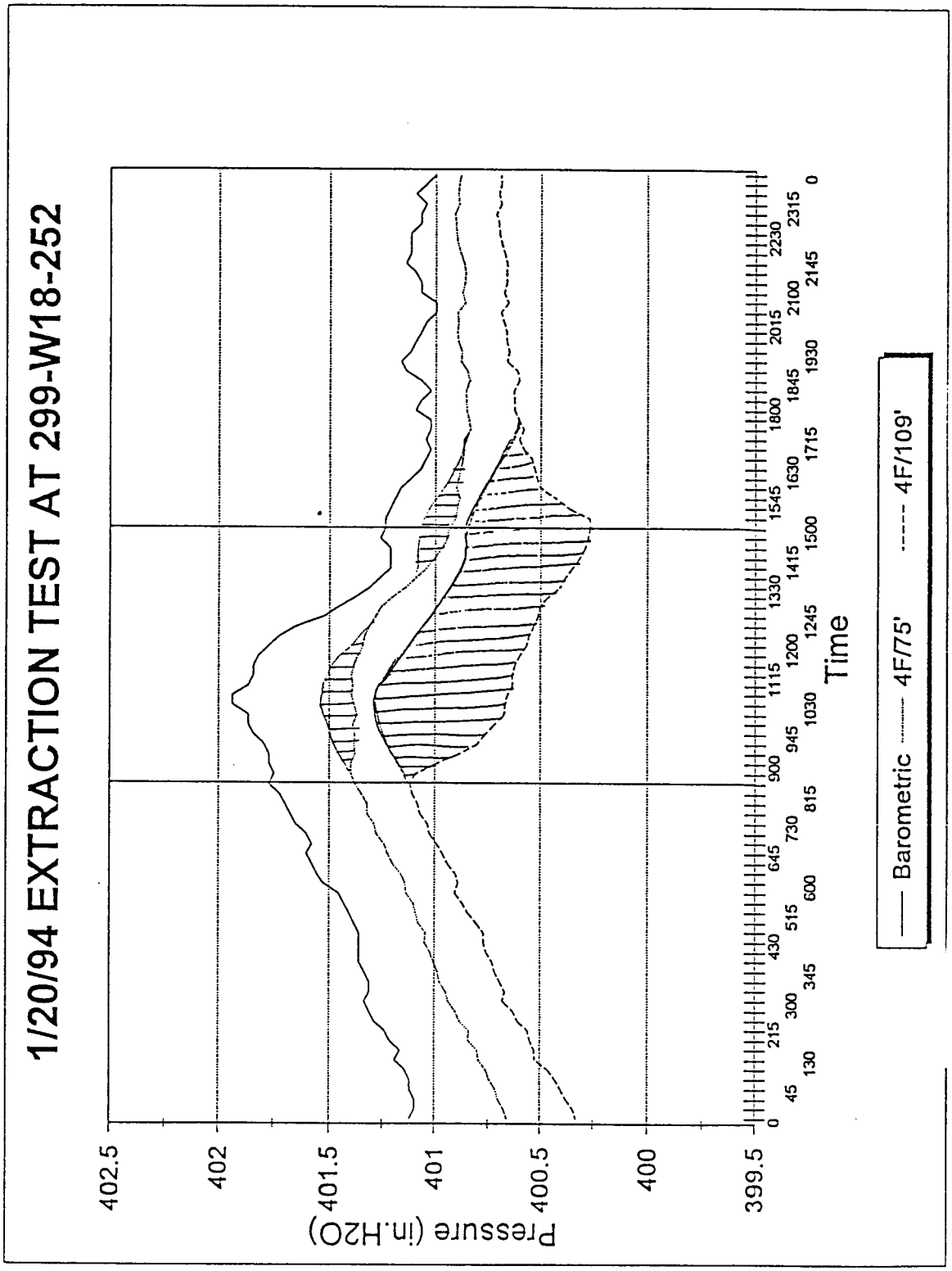


Figure F-9. Pressures Measured at CPT4-E Monitoring Points.

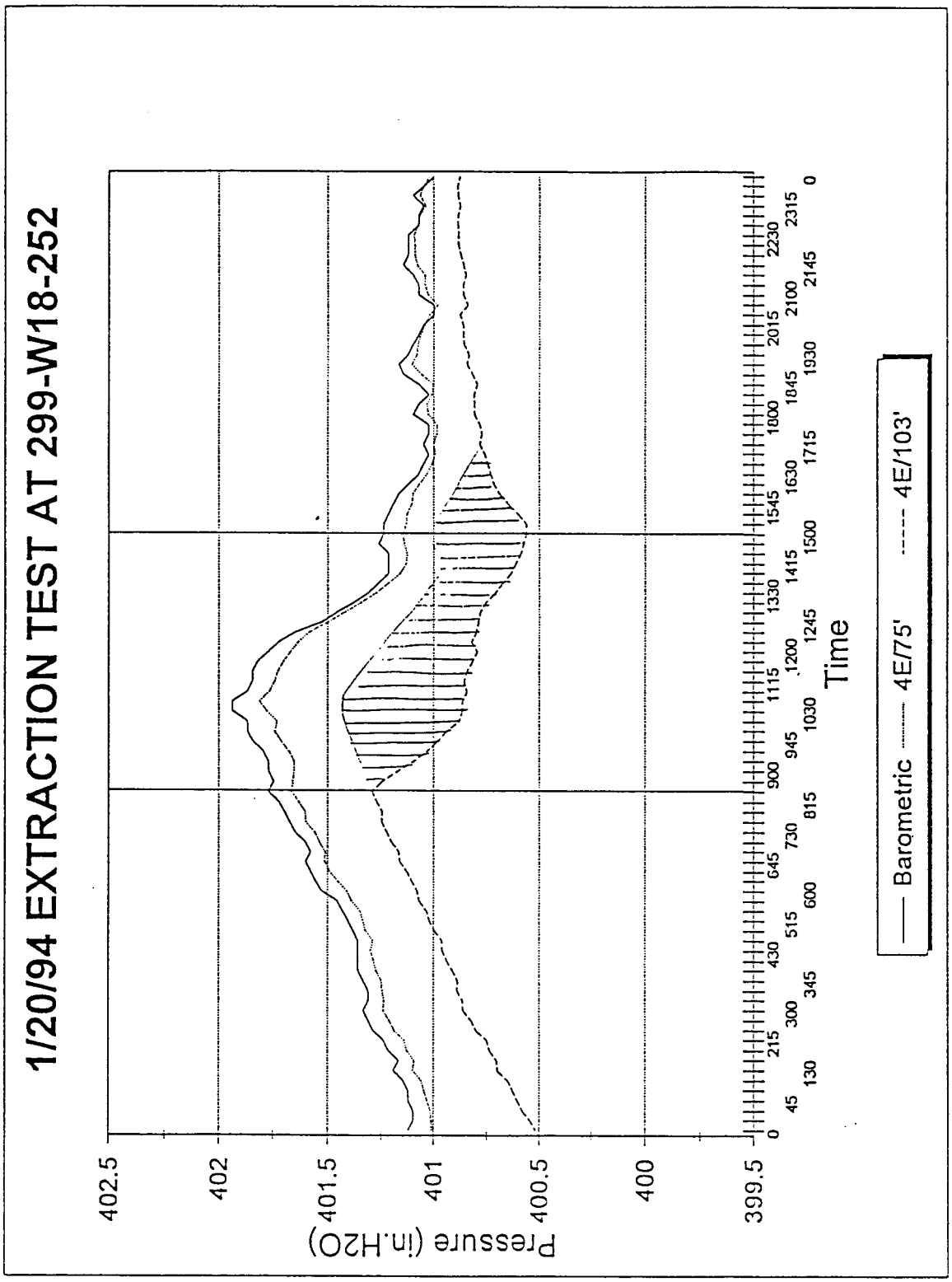


Figure F-10. Pressures Measured at CPT4-D Monitoring Points.

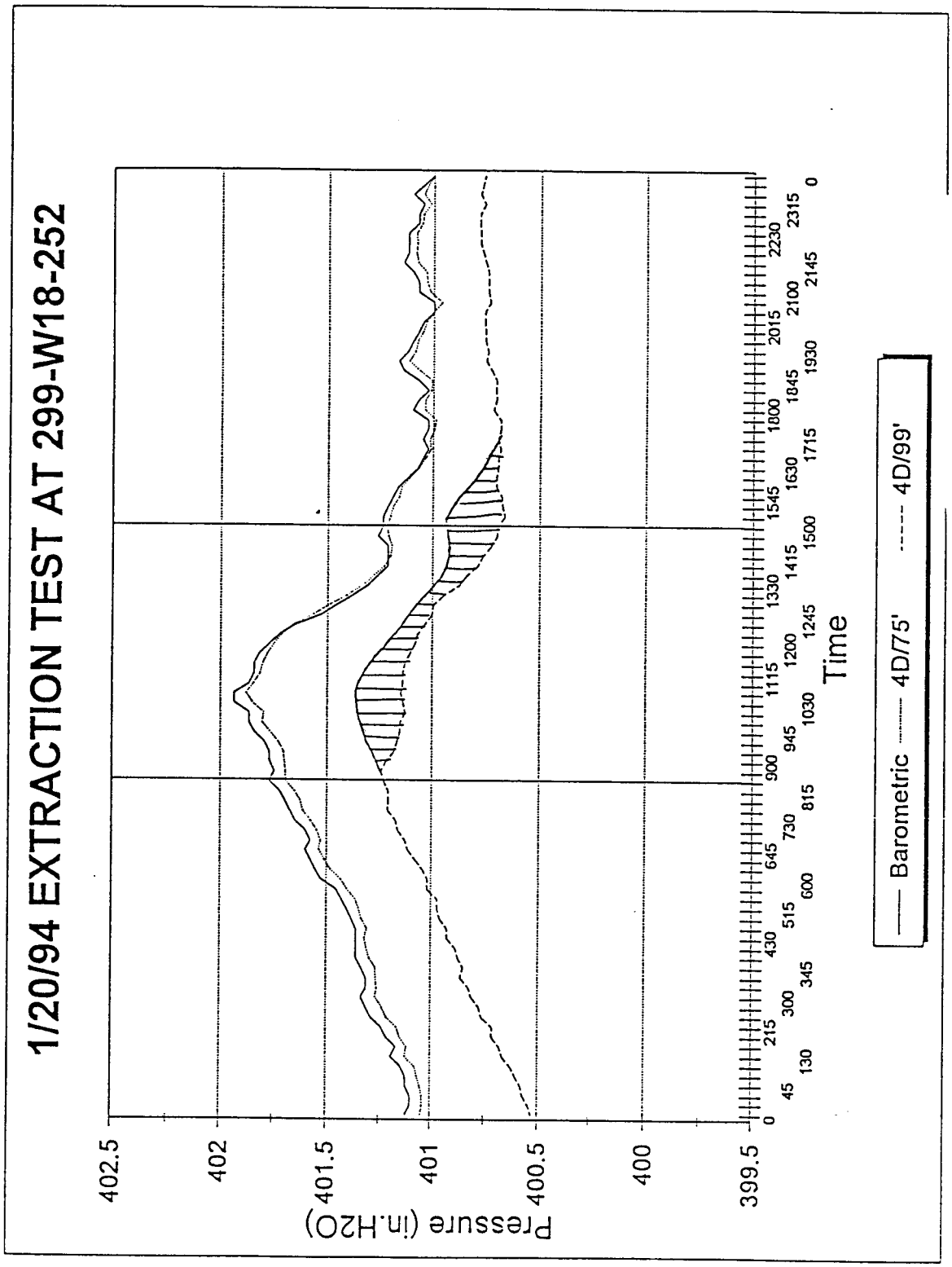


Figure F-11. Pressures Measured at CPT4-C Monitoring Points.

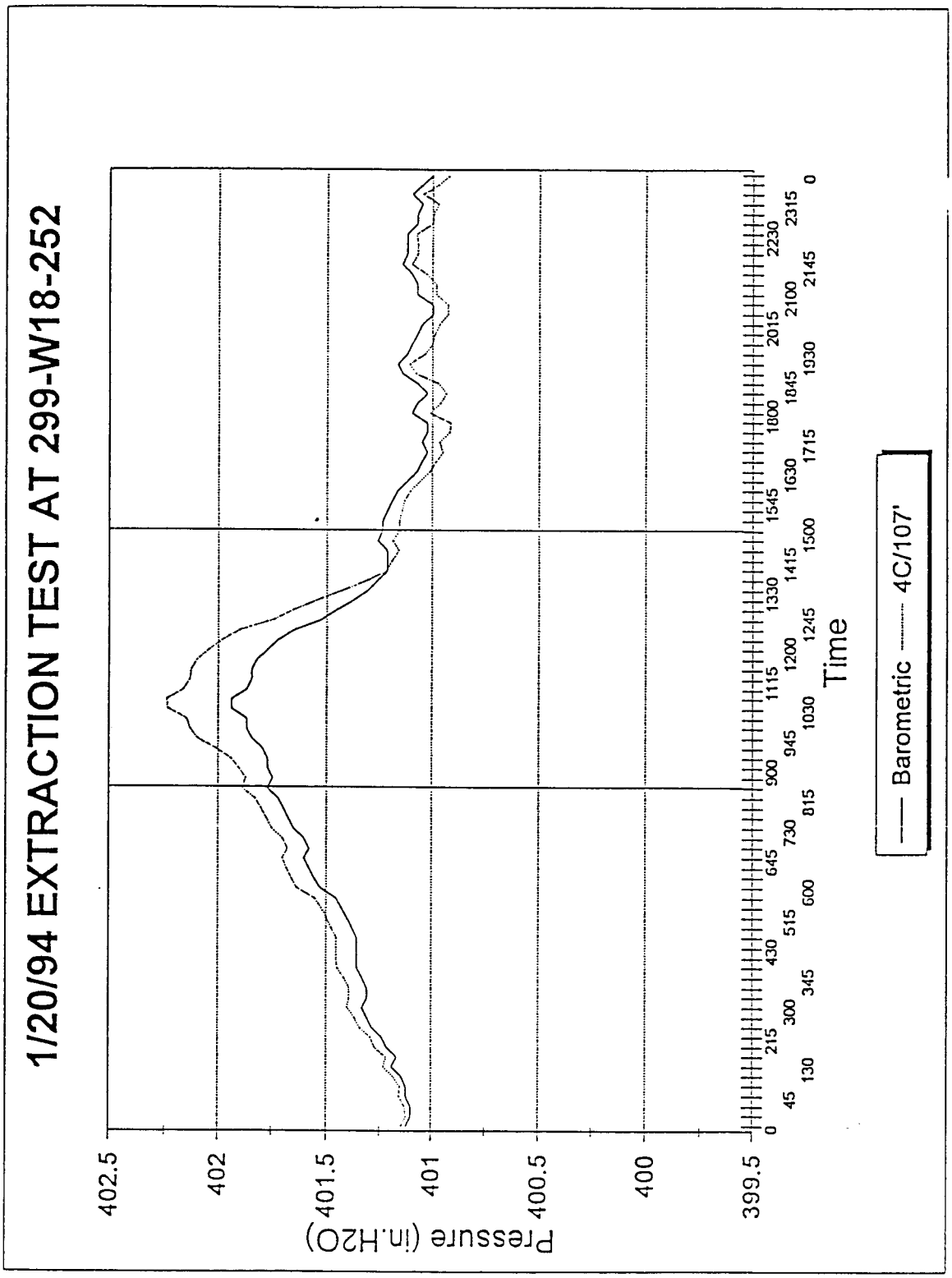


Figure F-12. Pressures Measured at CPT4-B Monitoring Points.

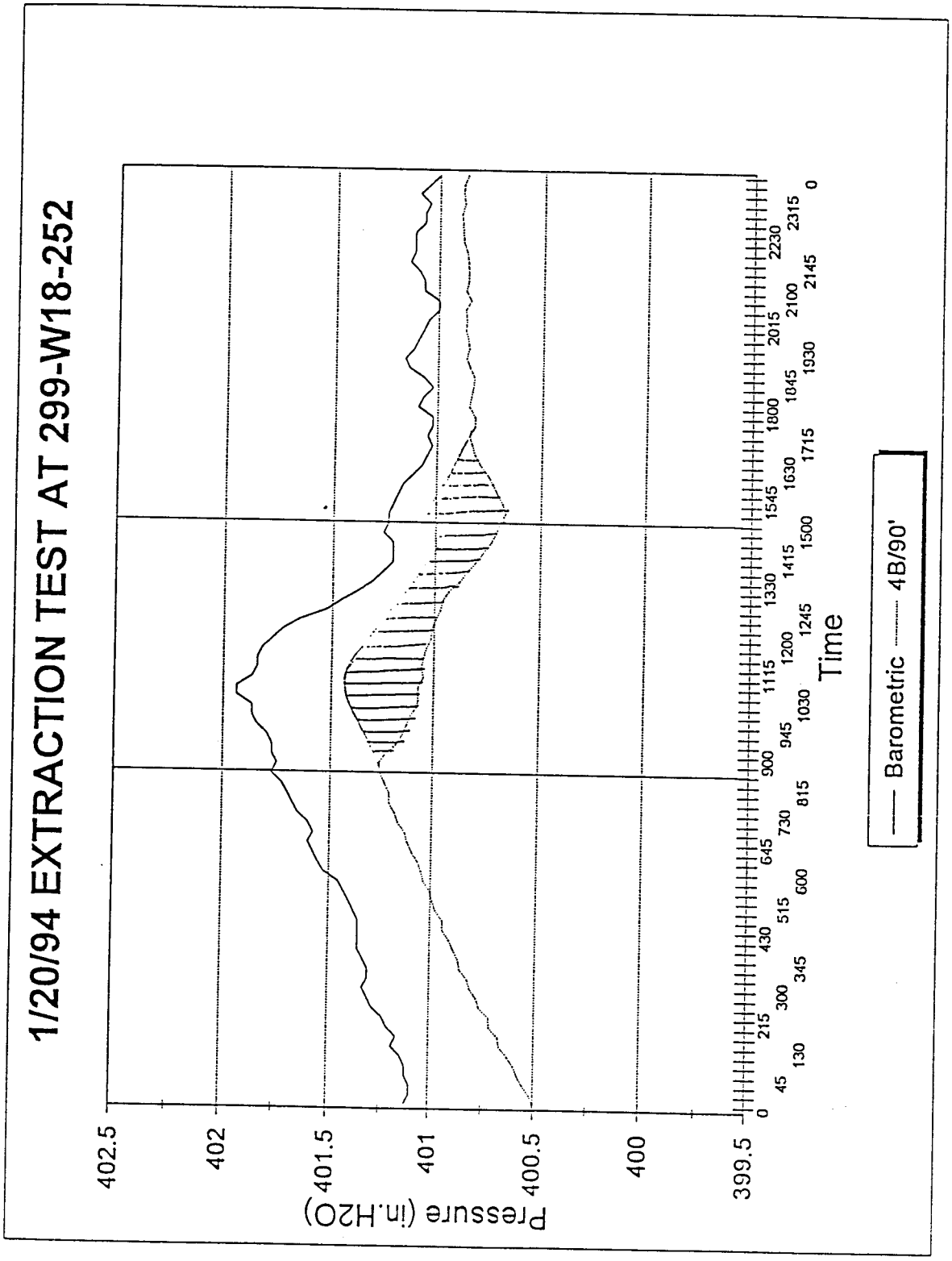
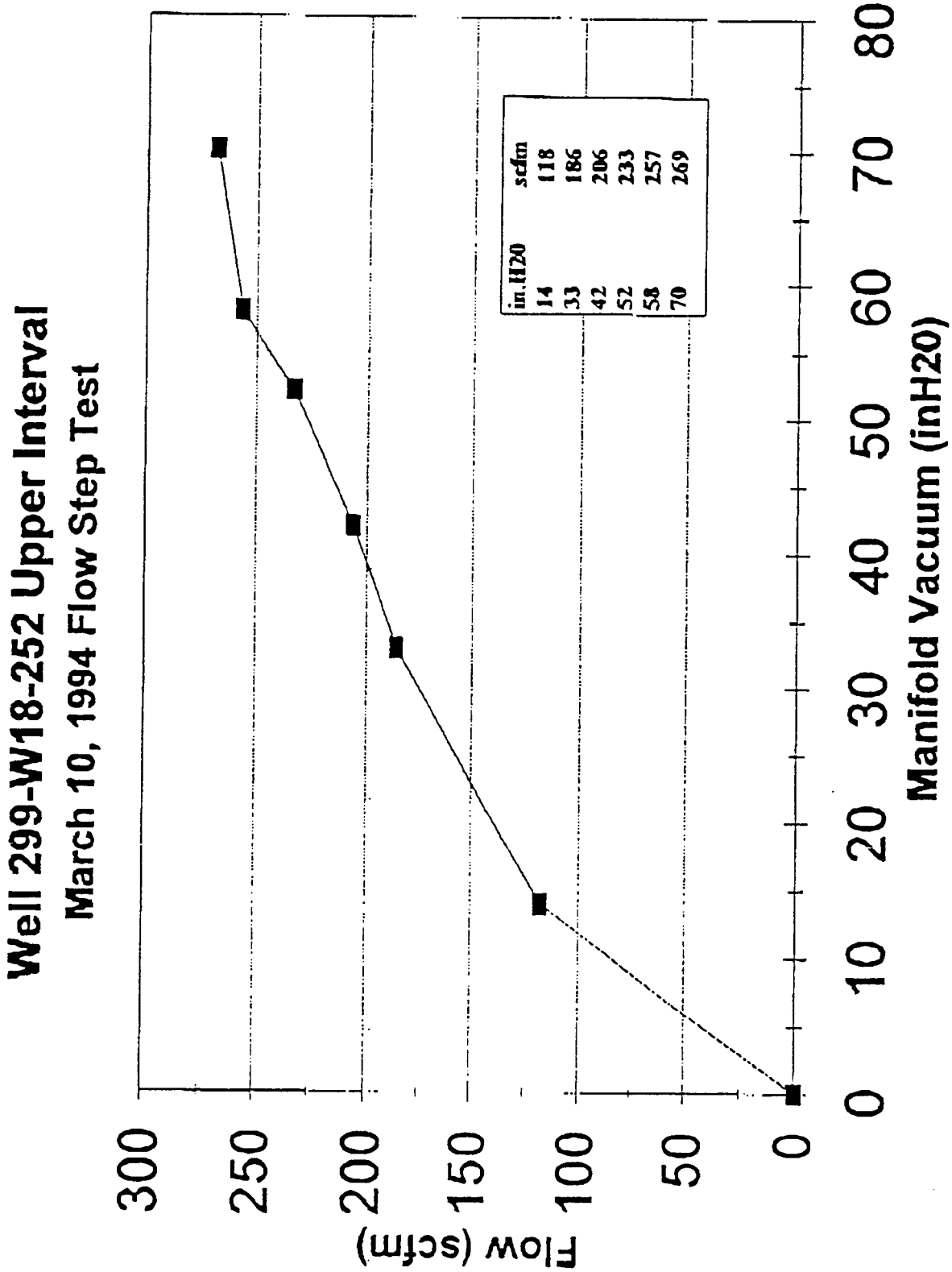


Figure F-13. Flow Step Test at Well 299-W18-252U.



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