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Rev. 3

Performance Evaluation Report for Soil Vapor Extraction Operations at the Carbon Tetrachloride Site, February 1992 – September 1998

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Prepared for the U.S. Department of Energy, Richland Operations Office
Office of Environmental Restoration

Submitted by: Bechtel Hanford, Inc.

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Performance Evaluation Report for Soil Vapor Extraction Operations at the Carbon Tetrachloride Site, February 1992 – September 1998

Author

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Date Published

June 1999

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EXECUTIVE SUMMARY

Soil vapor extraction (SVE) is being used to remove carbon tetrachloride from the vadose zone at the 200-ZP-2 Operable Unit. The purpose of this report is to evaluate both the SVE system operating data and the effectiveness of SVE in remediating the carbon tetrachloride contamination. This report has been revised to cover the operating period from February 25, 1992 through September 30, 1998. The scope of the report includes the history of SVE operations at 200-ZP-2, the efficiency of those operations over time, the volume of vapor processed per extraction system, the change in carbon tetrachloride concentrations with time, the mass of carbon tetrachloride removed per site, and recommendations for future operations and evaluations. This revision includes an update to the carbon tetrachloride conceptual model.

Carbon tetrachloride was found in the unconfined aquifer beneath the 200 West Area at the Hanford Site in the mid-1980's. Groundwater monitoring indicated that the carbon tetrachloride plume was widespread and that concentrations were increasing. The primary sources of the carbon tetrachloride contamination were three subsurface infiltration facilities (216-Z-9, 216-Z-1A, and 216-Z-18) used from 1955 through 1973 for soil column disposal of aqueous and organic liquid wastes. In response to this contamination, removal of carbon tetrachloride from the vadose zone in the 200 West Area was initiated in 1992 using SVE followed by aboveground vapor treatment on granular activated carbon. By March 1993, three SVE systems were in operation with a total capacity of 85 m^3/min.

Carbon tetrachloride concentrations in the extracted soil vapor have decreased significantly at all three sites during operation of the SVE systems. Initial carbon tetrachloride concentrations were approximately 30,000 parts per million by volume (ppmv) at the 216-Z-9 wellfield and 1,500 ppmv at the 216-Z-1A/Z-18 wellfield. Concentrations at both wellfields were approximately 23 ppmv in September 1998.

Between February 1992 and September 1998, approximately 76,000 kg of carbon tetrachloride were removed from the vadose zone using SVE. Of this total, 53,000 kg were removed from the 216-Z-9 wellfield and 23,000 kg were removed from the 216-Z-1A/Z-18 wellfield. The total

mass of carbon tetrachloride removed represents an estimated 10% of the original carbon tetrachloride inventory (approximately 750,000 kg) discharged to the soil column. Between 1955 and 1990, an estimated 21% of the original inventory was lost to the atmosphere, 2% was dissolved in groundwater, and 1% was biodegraded. The remaining 66% of the original inventory is believed to be in residual saturation and nonequilibrium sorption sites within the vadose zone and groundwater.

While all three SVE systems were shut down from November 1996 through June 1997, a study was conducted to evaluate the magnitude and rate of carbon tetrachloride concentration rebound. Soil vapor concentrations were measured in samples collected from 90 probes and wells throughout the SVE sites. The observed rebound in vapor concentrations indicates that additional carbon tetrachloride is available for removal using SVE. However, the rate of removal will be controlled by the rates of carbon tetrachloride diffusion and desorption.

The primary source of this remaining available carbon tetrachloride appears to be the relatively low-permeability zone from approximately 38 to 45 m depth. As carbon tetrachloride from this lower permeability source zone migrates into the overlying and underlying higher permeability zones, it can be removed using SVE. At many monitoring locations, including ones within the higher permeability zones, the relatively low carbon tetrachloride rebound concentrations indicate that the readily accessible mass (carbon tetrachloride already in the vapor phase or volatilizing directly from residual nonaqueous phase liquid) has been removed. At these locations, the availability of additional mass for removal using SVE is controlled by desorption and diffusion kinetics of carbon tetrachloride adsorbed within soil particle micropores and dissolved in soil moisture.

Based on the results of the fiscal year (FY) 1997 rebound study and the declining rate of carbon tetrachloride removal during continuous extraction operations, the operating strategy for FY 1998 was modified from that of FY 1997 and previous years. Rather than operating all three SVE systems continuously, only the 14.2-m^3/min system was used for carbon tetrachloride removal during FY 1998. The 14.2-m^3/min system was shut down for the winter from October 1997 through March 1998 and was operated from April 1998 through June 1998 at the

216-Z-1A/216-Z-18 wellfield and from July 1998 through September 1998 at the 216-Z-9 wellfield. The 28.3-m^3/min and 42.5-m^3/min SVE systems were maintained in standby mode during FY 1998. Carbon tetrachloride concentrations were monitored at each wellfield during each period of nonoperation.

Recommendations for future operations and data evaluation include continuing cyclic SVE operations with potential modifications to the system location and/or to the schedule to allow more efficient extraction; continuing carbon tetrachloride vapor concentration monitoring during periods of nonoperation of the SVE system but potentially discontinuing the near-surface monitoring; repeating the measurements of carbon tetrachloride rebound; and investigating the nature and magnitude of the exchange of carbon tetrachloride between the vadose zone and groundwater.

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CONTENTS

1.0 PURPOSE 1-1

2.0 BACKGROUND 2-1
2.1 CARBON TETRACHLORIDE WASTE DISPOSAL 2-1
2.2 CARBON TETRACHLORIDE WELLFIELD 2-2

3.0 SOIL VAPOR EXTRACTION SYSTEM DESIGN 3-1

4.0 HISTORY OF SOIL VAPOR EXTRACTION SYSTEM OPERATIONS 4-1

5.0 SOIL VAPOR EXTRACTION SYSTEM OPERATING DATA 5-1
5.1 SOIL VAPOR EXTRACTION SYSTEM AVAILABILITY 5-2
5.2 VOLUME OF SOIL VAPOR PROCESSED 5-3
5.3 VOLUME OF KNOCKOUT WATER DRAINED FROM SVE SYSTEMS 5-5
5.4 CHANGE IN CARBON TETRACHLORIDE CONCENTRATIONS 5-7
5.5 MASS OF CARBON TETRACHLORIDE REMOVED 5-11
5.6 IMPACT OF 200-ZP-1 PHASE III PUMP-AND-TREAT OPERATIONS 5-13

6.0 NONOPERATIONAL SOIL VAPOR MONITORING DATA 6-1
6.1 SUMMARY OF FISCAL YEAR 1997 REBOUND STUDY 6-1
6.2 FISCAL YEAR 1998 SOIL VAPOR MONITORING 6-2
6.3 COMPARISON OF SOIL VAPOR MONITORING BEFORE AND AFTER SOIL VAPOR EXTRACTION REMEDIATION 6-4

7.0 1998 CARBON TETRACHLORIDE CONCEPTUAL MODEL UPDATE 7-1
7.1 CONTAMINANT INVENTORY 7-2
7.2 ENVIRONMENTAL SETTING 7-2
7.3 CONTAMINANT DISTRIBUTION 7-2
7.3.1 Vadose Zone Concentrations 7-3
7.3.2 Groundwater Concentrations 7-3
7.4 CONTAMINANT TRANSPORT 7-4
7.4.1 Vadose Zone 7-4
7.4.2 Capillary Fringe 7-5
7.4.3 Groundwater Hydraulics 7-5
7.4.4 Groundwater 7-6
7.5 DATA GAPS 7-7

8.0 RECOMMENDATIONS 8-1
8.1 STATUS OF FY 1997 RECOMMENDATIONS 8-1
8.2 FISCAL YEAR 1998 RECOMMENDATIONS 8-2

9.0 REFERENCES 9-1

APPENDICES

A 200-ZP-2 FLOW RATE ESTIMATION METHODOLOGY ..... A-i
B CHARACTERIZATION DATA ..... B-i
C FISCAL YEAR 1998 SOIL VAPOR MONITORING DATA ..... C-i
D 1998 CARBON TETRACHLORIDE CONCEPTUAL MODEL UPDATE ..... D-i

FIGURES

2-1. Location of Extraction and Monitoring Wells at the Carbon Tetrachloride Soil Vapor Extraction Sites 2-3
2-2a. Cross Section Through the 216-Z-18/Z-12 Wellfield 2-5
2-2b. Cross Section Through the 216-Z-1A Wellfield 2-7
2-2c. Cross Section Through the 216-Z-9 Wellfield 2-9
3-1. Soil Vapor Extraction System Process Flow Diagram. 3-2
3-2. Configuration of Instrumentation Monitoring Volatile Organic Compounds at the Soil Vapor Extraction System 3-3
5-1. Combined Monthly Availability of the Three Soil Vapor Extraction Systems, November 1994 - September 1998. 5-14
5-2. Monthly Availability of the 14.2-m^3/min Soil Vapor Extraction System, January 1994 - September 1998 5-15
5-3. Monthly Availability of the 28.3-m^3/min Soil Vapor Extraction System, January 1994 - September 1998 5-16
5-4. Monthly Availability of the 42.5-m^3/min Soil Vapor Extraction System, January 1994 - September 1998 5-17
5-5. Number of Hours the Three Soil Vapor Extraction Systems Operated, February 1992 - September 1998 5-18
5-6. Daily Average Flow Rate Measured at the 14.2-m^3/min Soil Vapor Extraction System During 24-hr/day, 7-days/week Operations, August 1994 - September 1998 5-19
5-7. Daily Average Flow Rate Measured at the 28.3-m^3/min Soil Vapor Extraction System During 24-hr/day, 7-days/week Operations, July 1994 - September 1998. 5-20
5-8. Daily Average Flow Rate Measured at the 42.5-m^3/min Soil Vapor Extraction System During 24-hr/day, 7-days/week Operations, October 1994 - September 1998. 5-21
5-9. Volume of Vapor Processed by the 14.2-m^3/min Soil Vapor Extraction System, June 1994 - September 1998 5-22
5-10. Volume of Vapor Processed by the 28.3-m^3/min Soil Vapor Extraction System, February 1992 - September 1998 5-23
5-11. Volume of Vapor Processed by the 42.5-m^3/min Soil Vapor Extraction System, March 1993 - September 1998 5-24
5-12. Weekly Volume of Knockout Water Drained from Soil Vapor Extraction Systems, October 1994 - September 1997. 5-25

FIGURES (cont.)

5-13. Ratio of Cumulative Volume of Knockout Water Drained to Cumulative Volume of Vapor Extracted for Each Soil Vapor Extraction System, October 1994 - April 1995; October 1995 - June 1996; and October 1996. 5-26
5-14. Comparison of Carbon Tetrachloride Concentrations to Volume of Vapor Extracted at the 216-Z-1A/Z-18/Z-12 Wellfield, February 1992 - September 1998. 5-27
5-15. Comparison of Carbon Tetrachloride Concentrations to Volume of Vapor Extracted at the 216-Z-9 Wellfield, March 1993 - September 1998. 5-28
5-16. Carbon Tetrachloride Concentrations Measured at the 216-Z-9 Wellfield During Continuous Operations, October 1994 - September 1998. 5-29
5-17. Carbon Tetrachloride Concentrations Observed at the 14.2-m^3/min Soil Vapor Extraction System Inlet During Extraction at the 216-Z-1A/Z-18/Z-12 Wellfield, April 1998 - June 1998. 5-30
5-18. Carbon Tetrachloride Concentrations Observed at the 14.2-m^3/min Soil Vapor Extraction System Inlet During Extraction at the 216-Z-9 Wellfield, July 1998 – September 1998. 5-31
5-19. Comparison of Carbon Tetrachloride Concentrations and Mass Removal Rates Using the 14.2-m^3/min Soil Vapor Extraction System, April 1998 – September 1998. 5-32
5-20. Carbon Tetrachloride Concentrations in Vapor Extracted from the 216-Z-9 Wellfield, July 1997 - September 1997 and July 1998 – September 1998. 5-33
5-21. Carbon Tetrachloride Concentrations in Vapor Extracted from the 216-Z-1A/Z-18 Wellfield, July 1997 – September 1997 and April 1998 – June 1998. 5-34
5-22. Exponential Decay of Carbon Tetrachloride Concentrations, October 1995 Through November 1996. 5-35
5-23. Exponential Decay of Carbon Tetrachloride Concentrations, October 1995 Through September 1998. 5-36
5-24. Carbon Tetrachloride Concentrations Measured at Extraction Wells in the 216-Z-1A/Z-18 Wellfield, April 1992 - September 1998. 5-37
5-25. Carbon Tetrachloride Concentrations Measured at Extraction Wells in the 216-Z-9 Wellfield, March 1993 - September 1998. 5-38
5-26. Relationship Between Concentrations of Carbon Tetrachloride and Chloroform Measured at Extraction Wells in the 216-Z-9 Wellfield. 5-39
5-27. Relationship Between Concentrations of Carbon Tetrachloride Less Than 1,000 ppmv and Chloroform Measured at Extraction Wells in the 216-Z-9 Wellfield. 5-40
5-28. Relationship Between Concentrations of Carbon Tetrachloride and Chloroform Measured at Two 216-Z-9 Wells, W15-82 and W15-217. 5-41
5-29. Relationship Between Concentrations of Carbon Tetrachloride and Chloroform Measured at Extraction Wells in the 216-Z-1A/Z-18/Z-12 Wellfield. 5-42
5-30. Mass of Carbon Tetrachloride Removed from the 216-Z-1A/Z-18/Z-12 Wellfield, February 1992 - September 1998. 5-43
5-31. Mass of Carbon Tetrachloride Removed From the 216-Z-9 Wellfield, March 1993 - September 1998. 5-44

FIGURES (cont.)

5-32. Decline in Total Carbon Tetrachloride Mass Removal Rate Between October 1994 and September 1998. 5-45
5-33. Carbon Tetrachloride Concentrations Monitored at 216-Z-9 Wells W15-6L and W15-9L. 5-46
6-1. Vertical Profile of Maximum Carbon Tetrachloride Rebound Concentrations, November 1996 – July 1997. 6-6
6-2. Vertical Profile of Maximum Chloroform Rebound Concentrations, November 1996 – July 1997. 6-7
6-3. Relationship Between Concentrations of Carbon Tetrachloride and Chloroform Measured at Rebound Study Monitoring Locations in the 216-Z-9 Wellfield. 6-8
6-4. Relationship Between Concentrations of Carbon Tetrachloride and Chloroform Measured at Rebound Study Monitoring Locations in the 216-Z-1A/Z-18/Z-12 Wellfield. 6-9
6-5. Vertical Profile of Maximum Carbon Tetrachloride Rebound Concentrations, November 1996 – July 1997 and October 1997 – June 1998. 6-10
6-6. Vertical Profile of Maximum Carbon Tetrachloride Baseline Concentrations, December 1991 – December 1993. 6-11
6-7a. Maximum Carbon Tetrachloride Baseline Concentrations Recorded at Wells and Deep Soil Vapor Probes Open Above the Plio-Pleistocene Unit, December 1991 Through December 1993 (from Fancher 1994). 6-12
6-8a. Maximum Carbon Tetrachloride Rebound Concentrations Recorded at Wells and Deep Soil Vapor Probes Open Above the Plio-Pleistocene Unit, November 1996 Through July 1997. 6-14
7-1. Schematic Illustration of Carbon Tetrachloride and Wastewater Migration Beneath the 216-Z-9 Trench in the Higher Concentration Portion of the Plume. 7-9

TABLES

2-1. Contaminant Inventory Discharged to Carbon Tetrachloride Disposal Sites. 2-11
4-1. Mass of Carbon Tetrachloride Removed Using Soil Vapor Extraction. 4-3
5-1. Planned Operating Times for the Soil Vapor Extraction Systems. 5-47
5-2. Monthly Availability Data for the Soil Vapor Extraction Systems, January 1994 - September 1998. 5-48
5-3. Number of Hours Each Soil Vapor Extraction System Has Operated. 5-49
5-4. Volume of Vapor Processed by Soil Vapor Extraction Systems. 5-49
5-5. Volume of Vapor Extracted from Each Extraction Well Between February 1992 and September 1998. 5-50
5-6. Weekly Volume of Knockout Water Drained from Soil Vapor Extraction Systems, October 1994 - September 1998. 5-51
5-7. Analyses of 200-ZP-2 Soil Vapor Extraction Knockout Water. 5-53
5-8. Soil Vapor Extraction Well Characterization Data. 5-54
7-1. Disposition of Carbon Tetrachloride Inventory Discharged to the Soil Column. 7-10
7-2. Carbon Tetrachloride Concentrations Measured in the Vadose Zone. 7-11

ACRONYMS

B&K	Brüel & Kjaer
DBBP	dibutyl butyl phosphate
DNAPL	dense nonaqueous-phase liquid
DOE	U.S. Department of Energy
Ecology	Washington State Department of Ecology
EPA	U.S. Environmental Protection Agency
ERA	expedited response action
FY	fiscal year
GAC	granular-activated carbon
HEPA	high-efficiency particulate air
SVE	soil vapor extraction
TBP	tributyl phosphate
VOC	volatile organic compound

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1.0 PURPOSE

Soil vapor extraction (SVE) is being used to remove carbon tetrachloride from the vadose zone at the 200-ZP-2 Operable Unit. The purpose of this report is to evaluate the carbon tetrachloride SVE system operating data and to provide a summary of the effectiveness of SVE operations in addressing vadose zone contamination based on the existing remedial design. This report has been revised to cover the operating period from February 25, 1992 through September 30, 1998. The previous versions of the report covered the operating periods from February 25, 1992 through September 30, 1997 (Rev. 2); February 25, 1992 through June 30, 1996 (Rev. 1); and from February 25, 1992 through June 30, 1995 (Rev. 0). The scope of the report includes the history of SVE operations at 200-ZP-2, the efficiency of those operations over time, the volume of vapor processed per system, the change in carbon tetrachloride concentrations with time, the mass of carbon tetrachloride removed per site, and recommendations for future operations and data evaluation. This revision includes an update to the 1994 carbon tetrachloride conceptual model (Rohay et al. 1994).

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2.0 BACKGROUND

Carbon tetrachloride was found in the unconfined aquifer beneath the 200 West Area at the Hanford Site in the mid-1980's. Groundwater monitoring indicated that the carbon tetrachloride plume was widespread and that concentrations were increasing. 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, to proceed with the detailed planning, including nonintrusive field work, required to implement an Expedited Response Action (ERA) for removing carbon tetrachloride contamination from the unsaturated soils in the 200 West Area. 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 areal extent of groundwater contamination. The purpose of this ERA is to minimize carbon tetrachloride migration within the vadose zone beneath and away from the carbon tetrachloride disposal sites in the 200 West Area.

The first site evaluations were conducted from January through April 1991 to refine the preliminary conceptual model and to collect data in support of the selection and design of an initial remedial action (Hagood and Rohay 1991). These initial site evaluations included a pilot test of a SVE system. Results of the initial ERA site evaluations were summarized in September 1991 (DOE-RL 1991).

Based on the initial investigations and on the engineering evaluation and cost analysis (EE/CA), the preferred alternative for removal of the carbon tetrachloride from the vadose zone was SVE followed by aboveground vapor treatment on granular activated carbon (GAC) (DOE-RL 1991). In January 1992, the EPA and Ecology authorized the DOE to initiate SVE for cleanup of the carbon tetrachloride. The first SVE system began operating in February 1992.

2.1 CARBON TETRACHLORIDE WASTE DISPOSAL

Carbon tetrachloride, contained in aqueous and organic wastes generated during the Recuplex and Plutonium Reclamation Facility plutonium processing operations at Z Plant (currently called the Plutonium Finishing Plant), was discharged primarily to three subsurface infiltration facilities: the 216-Z-9 Trench from 1955 to 1962, the 216-Z-1A Tile Field (and the associated 216-Z-1 and 216-Z-2 Cribs) from 1964 to 1969, and the 216-Z-18 Crib from 1969 to 1973 (Figure 2-1). The Recuplex operation was discontinued after a criticality incident in April 1962, and it was replaced in May 1964 by the Plutonium Reclamation Facility; no liquid organic waste was discharged to cribs in the intervening years. No liquid organic waste was discharged to cribs after 1973. A total of 570,000 to 920,000 kg (360,000 to 580,000 L) of carbon tetrachloride is estimated to have been discharged to the soil column during this time (Table 2-1) (DOE-RL 1991).

Three other sites in the vicinity of Z Plant also received some carbon tetrachloride wastes: the 216-Z-12 Crib, the 216-Z-19 Ditch, and the 216-T-19 Crib (Figure 2-1). 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, which included carbon tetrachloride

(Kasper 1982). 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 and/or accidentally released to this ditch because heavy organic was noted in the outfall (Rohay and Johnson 1991). Between 1973 and 1976, aqueous waste saturated with carbon tetrachloride was sent to the 242-T Evaporator; during that time, the 216-T-19 Crib received approximately 1,400 kg (880 L) of carbon tetrachloride in the overhead condensate discharged from this evaporator (Rohay et al. 1993).

2.2 CARBON TETRACHLORIDE WELLFIELD

The vadose zone underlying the carbon tetrachloride area consists of approximately 66 m of relatively permeable sand and gravel interrupted by a relatively less permeable interval composed of 4 m of silt and sand and 3 m of carbonate-rich silt and sand. Because it constitutes a relatively low flow zone, this less permeable interval from approximately 38 to 45 m depth effectively divides the wellfield into two zones: an upper zone from the ground surface to the top of the less permeable layer and a lower zone from the bottom of the less permeable layer to the water table. Because of its higher concentration of calcium carbonate, the less permeable Plio-Pleistocene layer is informally referred to as the "caliche layer."

There are currently 46 drilled wells available for on-line extraction (Figure 2-1). Thirteen of these wells were drilled during 1992 and 1993 and completed as vapor extraction wells with stainless steel casing and screens; one well was drilled at a 45° incline. Existing wells, drilled between 1954 and 1978 and completed with carbon steel casing, were adapted for vapor extraction by perforating the well casing using mechanical or jet perforators. Seventeen wells have two screened or perforated open intervals isolated by downhole packers. Twenty-one well intervals are available at each of the three wellfields, 216-Z-18/Z-12, 216-Z-1A, and 216-Z-9 (Figure 2-2). Fifteen of these 63 intervals are open below the Plio-Pleistocene layer (6 at 216-Z-18/Z-12, 2 at 216-Z-1A, and 7 at 216-Z-9). Well diameters range from 6.4 to 20 cm (2.5 to 8 in.). Each SVE system extracts simultaneously from multiple wells open either above and/or below the Plio-Pleistocene layer.

Figure 2-1. Location of Extraction and Monitoring Wells at the Carbon Tetrachloride Soil Vapor Extraction Sites.

Figure 2-2a. Cross Section Through the 216-Z-18/Z-12 Wellfield.

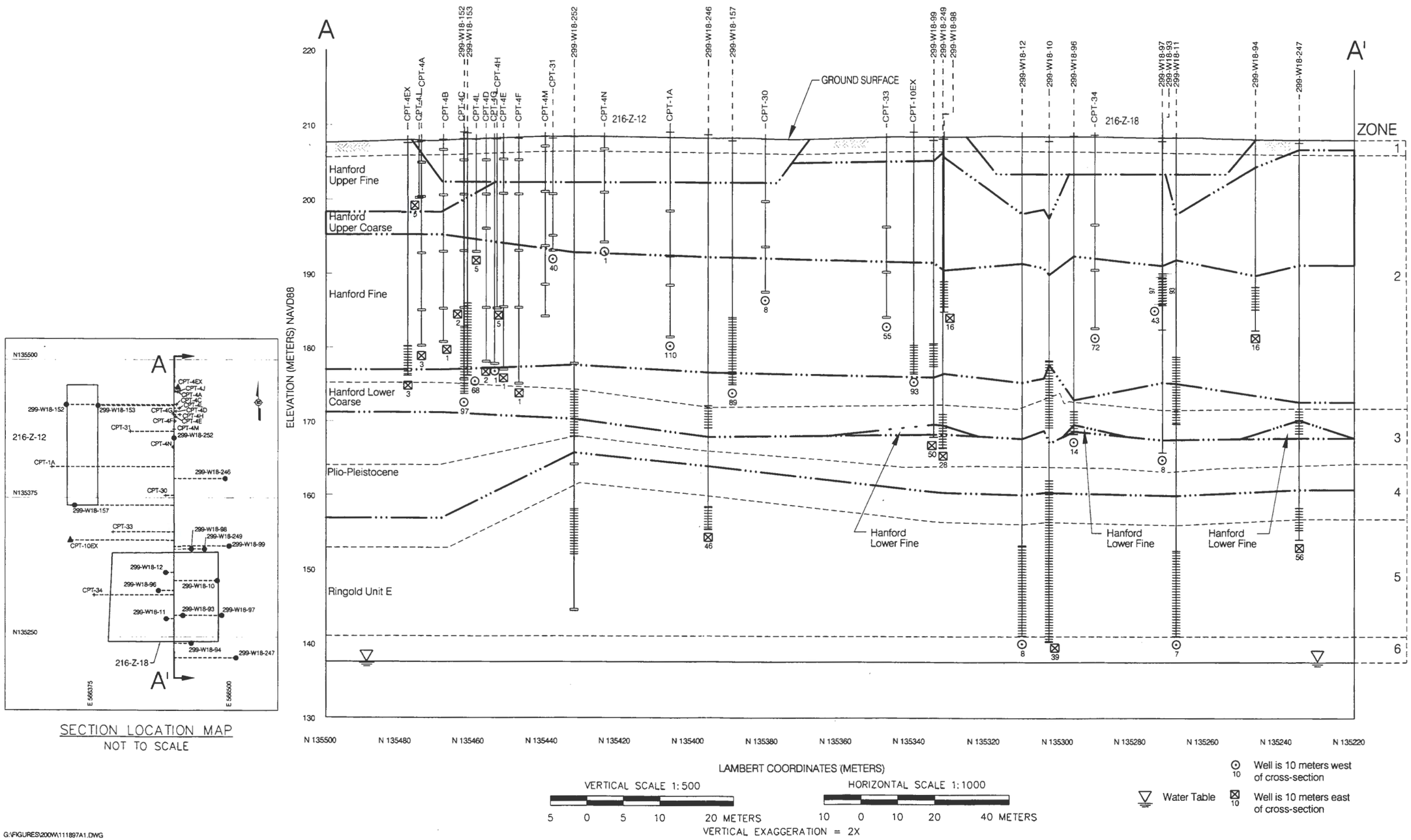

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Figure 2-2b. Cross Section Through the 216-Z-1A Wellfield.

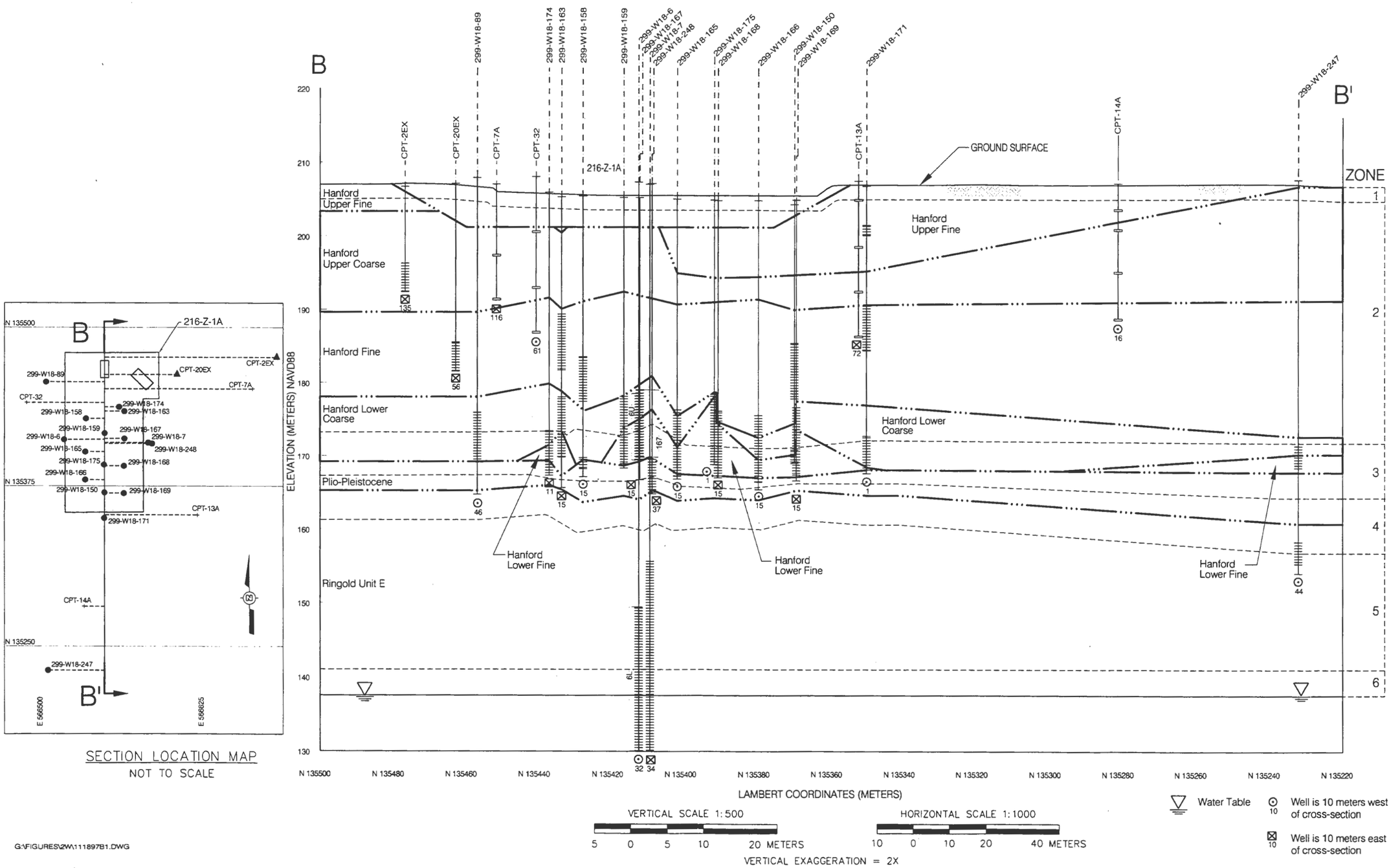

Figure 2-2c. Cross Section Through the 216-Z-9 Wellfield.

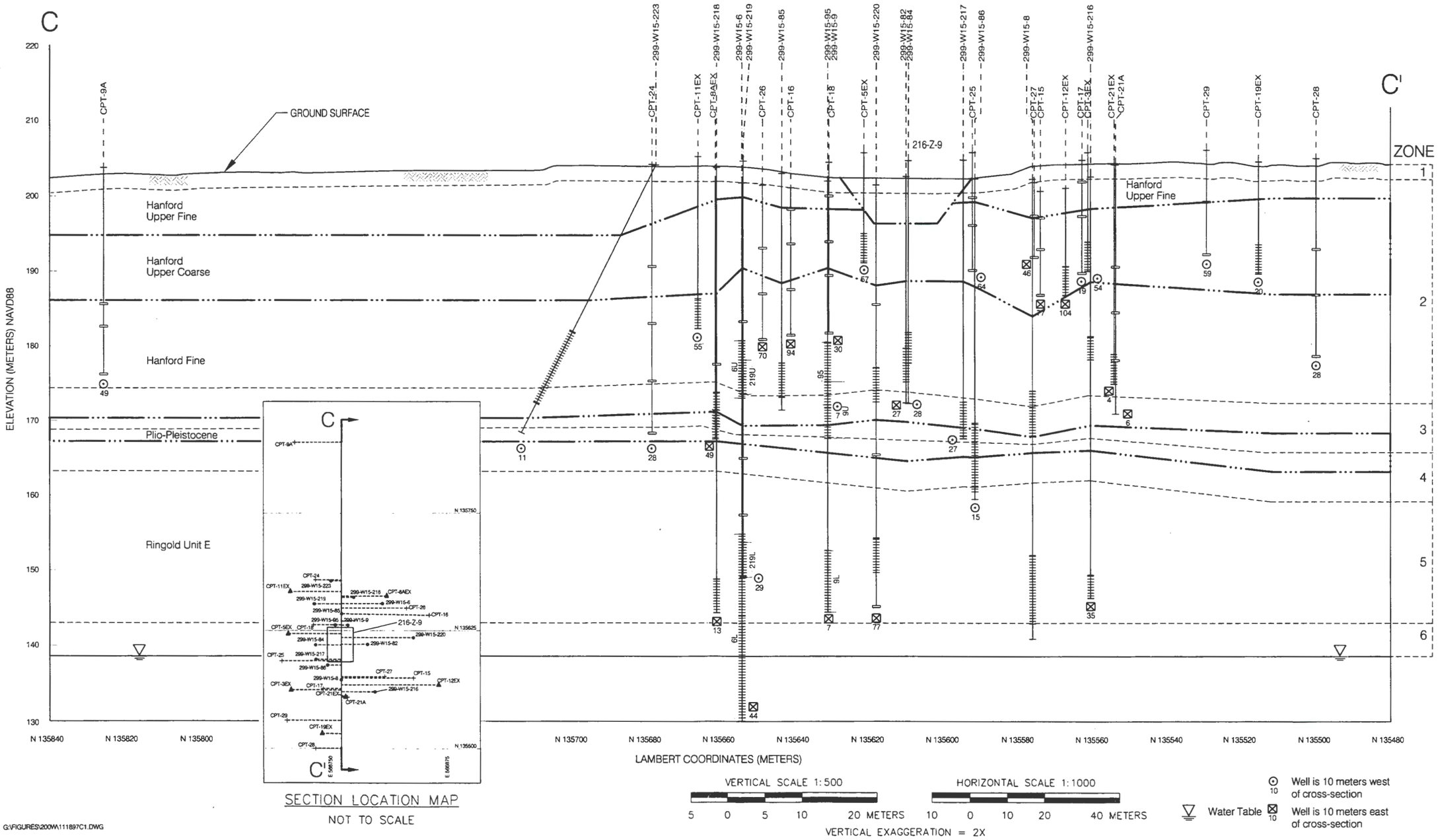

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Table 2-1. Contaminant Inventory Discharged to Carbon Tetrachloride Disposal Sites.

Site	Carbon Tetrachloride (kg)	Plutonium (kg)	Americium (kg)	Carbon Tetrachloride (L)	Total Liquid (Aqueous and Organic) (L)	Operating Dates
216-Z-9	130,000-480,000	106[a]	2.5	83,000-300,000	4.09E+06	1955-1962
216-Z-1A	270,000	57	1	170,000	5.20E+06	1964-1969
216-Z-18	170,000	23	0.4	110,000	3.86E+06	1969-1973

[a]58 kg was later removed.

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3.0 SOIL VAPOR EXTRACTION SYSTEM DESIGN

To meet the accelerated ERA startup schedule, constrain costs, and fulfill the requirements for working in a radiologically controlled area, the initial approach to the ERA maximized the use of field screening-level data, existing boreholes, and off-the-shelf technology. During subsequent phases, additional characterization data collected during SVE system operations were used to upgrade the remediation design and performance objectives.

The initial SVE system, purchased for the pilot test, was upgraded to expedite initiation of extraction operations. It consisted of a water knockout tank to remove entrained water droplets that would otherwise damage downstream equipment; a high-efficiency particulate air (HEPA) filter to remove entrained particulate matter, including radionuclides; a blower to extract the soil vapor; GAC-filled canisters in series for adsorbing carbon tetrachloride; and a stack for venting the treated vapor to the atmosphere (Figure 3-1). A chiller to cool the vapor was added later between the blower and the GAC-filled canisters. Two other SVE system units purchased later had a similar design.

The SVE systems were designed for completely automated operations monitoring, requiring only routine checks to ensure that the systems were functioning properly. The pilot-scale SVE test unit was designed with continuous air monitoring instruments for detection of volatile organic compounds (VOCs) and alpha and beta radiation. The output from these instruments, along with other system parameters such as vapor flow rate and system vacuum, were connected to a personal computer (PC)-based data logging system. During the test period, however, it was discovered that the instrumentation required almost constant operator attention to maintain extraction operations. VOC sampling was performed using an on-line flame ionization detector that proved unable to specifically target detection of carbon tetrachloride and required frequent calibration and maintenance. Instruments for monitoring alpha and beta radiation and radon gas (added in 1992) were removed in 1994 once baseline operating data were accumulated.

To support an improved design for the first production-mode SVE system, an alternative VOC monitoring instrument was investigated. A new technology was pursued that used a solid-state VOC sensing device. Testing indicated that the instrument produced both accurate and repeatable measurements of carbon tetrachloride concentrations. During the first year of operations, however, it was discovered that carbon tetrachloride degraded the solid-state sensor, causing unpredictable instrument failures. Following the overheating of a GAC canister in June 1993, revised operating procedures required that concentrations of other, more readily reactive VOCs, such as methyl ethyl ketone, be routinely measured during operations. For these reasons, another VOC monitoring technology using a photoacoustic infrared detector, the Brüel & Kjaer Type 1302 gas monitor (B&K, a trademark of Brüel & Kjaer, DK-2850), was purchased. During its initial use, manual sampling every 2 hours was performed during 8-hr/day operating periods to test the performance of the instrument. The B&K instrument proved to be accurate and reliable, and had the added feature of being able to measure several other targeted VOCs, in addition to being readily adaptable to automated operation. The B&K instrument is currently being used to support 24-hr/day SVE system operations providing automated sampling and analysis at the SVE system inlet, between GAC canisters, and at the vent stack (Figure 3-2).

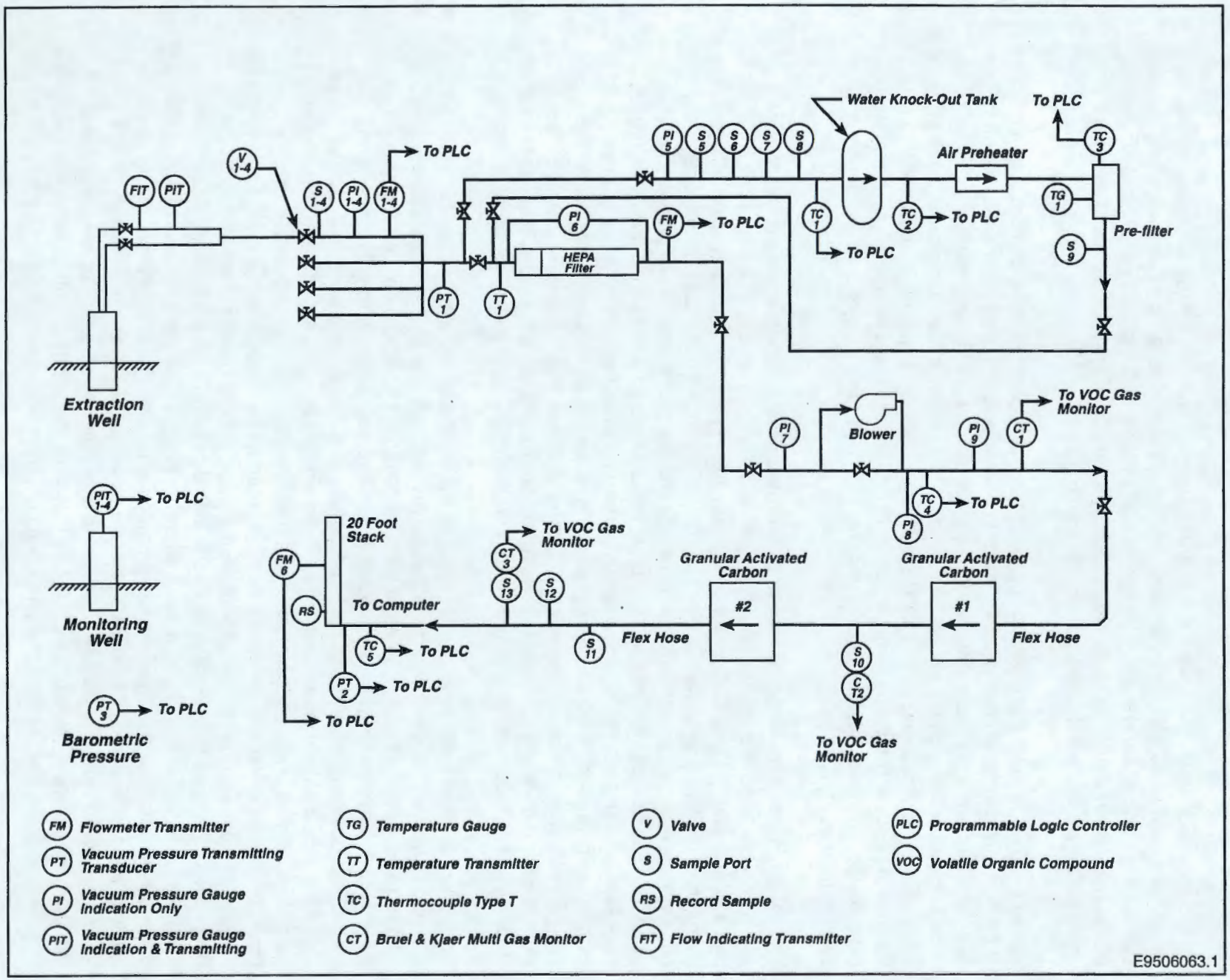
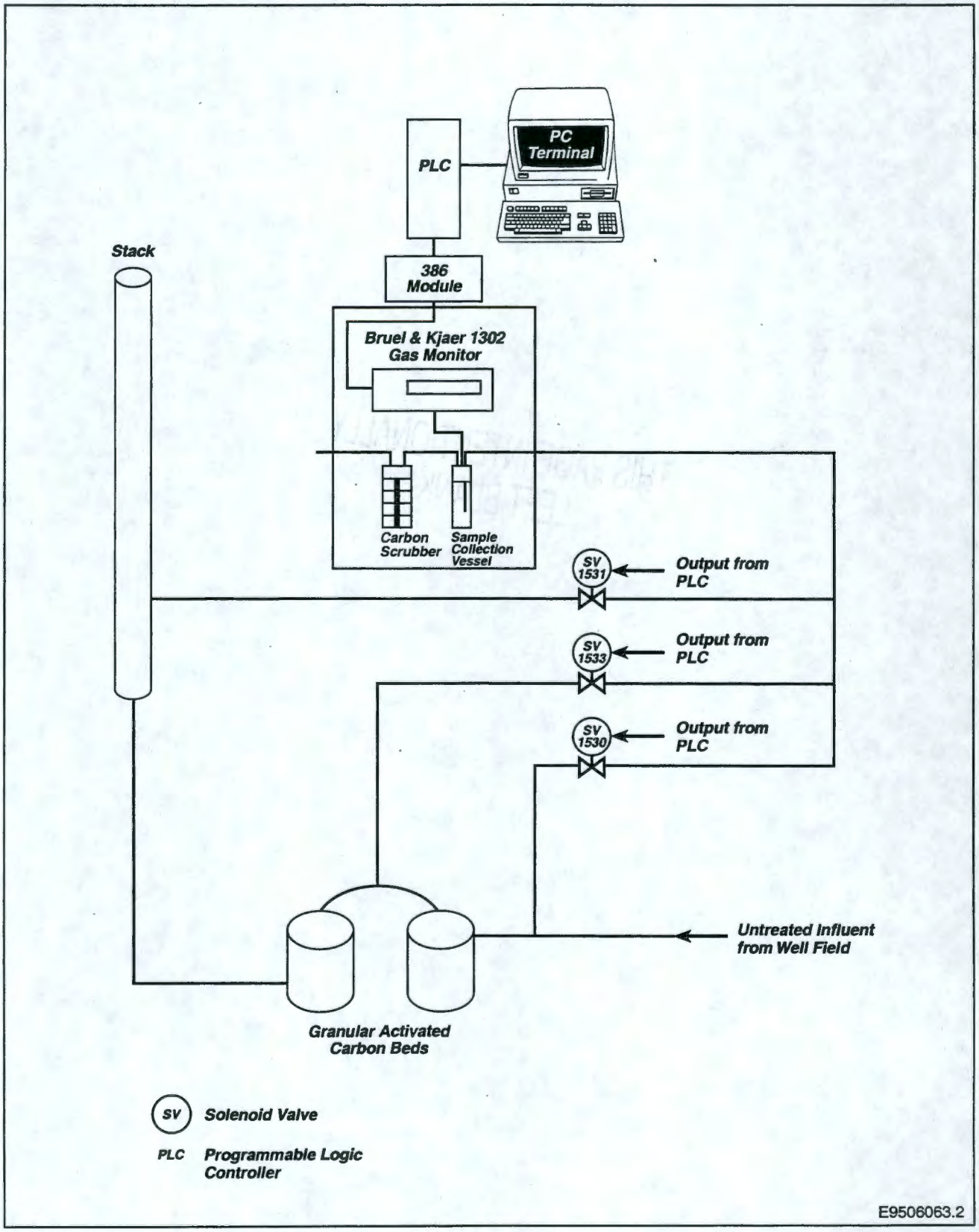


Figure 3-1. Soil Vapor Extraction System Process Flow Diagram.

Figure 3-2. Configuration of Instrumentation Monitoring Volatile Organic Compounds at the Soil Vapor Extraction System.



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4.0 HISTORY OF SOIL VAPOR EXTRACTION SYSTEM OPERATIONS

A pilot SVE system was tested at the 216-Z-1A Tile Field in April 1991 (DOE-RL 1991). Based on the results of this testing and as part of the ERA, a full-scale SVE system was installed and began extracting from wells at the tile field in February 1992. Two of the 216-Z-18 Crib wells were added to the same system in May 1992. This system originally had a design capacity of 14.2 m^3/min (500 ft^3/min), but was upgraded to 28.3 m^3/min (1,000 ft^3/min) in March 1993. Two additional SVE systems, one with 42.5-m^3/min (1,500-ft^3/min) capacity and the other with 14.2-m^3/min (500-ft^3/min) capacity, began operating in March 1993 at the 216-Z-9 Trench. These three areas, the 216-Z-1A Tile Field, 216-Z-9 Trench, and 216-Z-18 Crib, were selected for initial SVE operations because they were the primary known disposal sites for carbon tetrachloride.

Extracted carbon tetrachloride is collected on GAC contained in 2.4-m- (8-ft) tall, 1.2-m- (4-ft) diameter carbon steel canisters. All three systems were shut down on June 3, 1993, because of a GAC canister overheating incident at 216-Z-9 (Driggers 1994). The 28.3-m^3/min system resumed operation at the 216-Z-1A/18 wellfield on November 12, 1993; the 42.5-m^3/min system resumed operation at the 216-Z-9 wellfield on February 23, 1994; and the 14.2-m^3/min system, which was moved to the 216-Z-18 wellfield, resumed operation on June 30, 1994.

Upon initial startup and restart following the overheating incident, each system was operated during the regular workshift only, Monday through Friday. This schedule was necessary to allow manual sampling of the VOC sensors to ensure compliance with operating limits. With the incorporation of a reliable, automated VOC sensor (the B&K instrument), the SVE systems began continuous operations. The 28.3-m^3/min SVE system began operating 24 hr/day, 7 days/week on July 11, 1994; the 14.2-m^3/min SVE system began on August 3, 1994; and the 42.5-m^3/min SVE system began on October 19, 1994.

On August 15, 1995, SVE operations using the 14.2-m^3/min SVE system were expanded to include the 216-Z-12 site. This disposal site was known to have received some carbon tetrachloride, and ERA characterization activities indicated significant concentrations of carbon tetrachloride in the subsurface soil vapor.

A rebound study was conducted throughout the carbon tetrachloride SVE sites from November 1996 through July 1997 (Rohay 1997). The purpose of the study was to determine the increase in carbon tetrachloride vapor concentrations following shutdown of the extraction systems. All three SVE systems were shut down on November 4, 1996 and restarted on July 18, 1997. The results of the 1997 study are summarized in Section 6.1 of this report. All three SVE systems continued to operate until September 30, 1997.

Based on the results of the fiscal year (FY) 1997 rebound study and the declining rate of carbon tetrachloride removal during continuous extraction operations (Rohay 1997), the operating strategy for FY 1998 was modified. Rather than operating all three SVE systems continuously, only the 14.2-m^3/min system was used for carbon tetrachloride removal during FY 1998. The 14.2-m^3/min system was modified so that it could be moved between the 216-Z-1A/Z-18/Z-12

and 216-Z-9 wellfields. The 28.3- and 42.5-m^3/min SVE systems were maintained in standby mode during FY 1998.

The 14.2-m^3/min SVE system was operated from March 30 through June 30, 1998 at the combined 216-Z-1A/Z-18/Z-12 wellfield and from July 7 through September 30, 1998 at the 216-Z-9 wellfield. The system was shut down for the winter from October 1, 1997 through March 29, 1998.

For the 6 months that the system was shut down, the rebound in carbon tetrachloride concentrations was monitored at nonoperational wells and probes covering both wellfields. For the 3 months that the system was operated at 216-Z-1A/Z-18/Z-12, carbon tetrachloride concentrations were monitored at nonoperational wells and probes primarily at the 216-Z-9 wellfield; and for the 3 months that the system was operated at the 216-Z-9 wellfield, carbon tetrachloride concentrations were monitored at nonoperational wells and probes primarily at the 216-Z-1A/Z-18/Z-12 wellfield. Results of 1998 the rebound measurements are summarized in Section 6.2 of this report.

As of September 30, 1998, 75,630 kg of carbon tetrachloride had been removed from the subsurface using SVE (Table 4-1). The mass of carbon tetrachloride removed from the 216-Z-1A, 216-Z-18, and 216-Z-12 sites is reported as a combined value because wells from the 216-Z-1A and 216-Z-18 sites were undergoing extraction simultaneously using the 28.3-m^3/min SVE system in 1992 and 1993, and wells from the 216-Z-18 and Z-12 site have been undergoing extraction simultaneously using the 14.2-m^3/min SVE system since 1995. The wellfields at these sites overlap.

Table 4-1. Mass of Carbon Tetrachloride Removed Using Soil Vapor Extraction.

Site	Carbon Tetrachloride Removed Each Calendar Year (kg)								
	1991	1992	1993	1994	1995	1996	1997	1998	Total
216-Z-18/ Z-12									
216-Z-1A	140	959	2,541	8,757	7,307	2,581	583	254	23,123
216-Z-9	--	--	1,065	35,029	11,500	3,150	1,239	523	52,507
Total	140	959	3,606	43,786	18,807	5,731	1,822	777	75,630

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5.0 SOIL VAPOR EXTRACTION SYSTEM OPERATING DATA

Soil vapor extraction system operating data that are routinely recorded include carbon tetrachloride concentrations, applied vacuums, system flow rates, and hours of operation. All instruments (e.g., flowmeters, vacuum gauges, and volatile organic analyzers) are calibrated. All calibration data on each instrument are retained and available for review. The VOC monitoring instruments are checked frequently and periodically challenged with calibrated gas standards. The detection limit for carbon tetrachloride is 1 part per million by volume (ppmv).

As part of operations, the SVE system technicians complete daily, weekly, and monthly surveillance checklists on which they verify system startup, shutdown, and compliance monitoring. These records are stored by Document and Information Services and are available for review.

When operations began in 1992, the system data were automatically recorded, first on a datalogger and then using the Strawberry Tree software program (a trademark of Strawberry Tree Incorporated, Computer Instrumentation and Controls, Sunnyvale, California), in binary format. These recording systems sampled the SVE system parameters every 15 minutes without distinguishing between ongoing operations, calibration checks, etc. As a result, these data are essentially raw instrument data and require careful evaluation for validity prior to use for determining SVE system performance. These data were not used in this report.

Field activities, including operation of the SVE systems, are recorded daily by the SVE system technicians in field logbooks. The technicians carefully reviewed the logbooks to reconstruct the operating history for each SVE system, including flow rate, vacuum, carbon tetrachloride concentration, and operating hours. These data were used in preparation of this report, particularly for the 1992-1993 operating period.

As an upgrade to the Strawberry Tree software, a programmable logic controller (PLC) was installed to control the SVE process. The Interact (a registered trademark of Computer Technology Corporation, Milford, Ohio) software was implemented as an operator interface to the PLC. A PLC was incorporated into the 28.3-m^3/min SVE system in March 1993 and into the 14.2-m^3/min system upon restart in 1994. The 42.5-m^3/min system was equipped with an Allen-Bradley (Milwaukee, Wisconsin) PLC and operator interface software when it was purchased. Each PLC records flow and vacuum data every 15 minutes and concentration data every 2 hours; the SVE system technicians use these data to establish daily records of representative system variables. For example, at the 14.2-m^3/min system, five data points (midnight, 6:00 a.m., noon, 6:00 p.m., and midnight) are averaged to establish the loading data for a given day.

Following the GAC overheating incident in 1993, revised operating procedures required a more structured format for recording representative system data. Therefore, beginning in 1994, the representative daily data were recorded on spreadsheets created by the technicians. That same year, a more reliable automated VOC monitor (the B&K instrument) was used at all three SVE systems to collect concentration data. Data for the 14.2- and 28.3-m^3/min SVE systems were entered onto spreadsheets manually until December 1995 when the system was automated; data for the 42.5-m^3/min system were always recorded automatically. These spreadsheets were the

source of the 1994-1997 data used in this report. Representative daily data provided weekly by the SVE technician were the source of the 1998 data used in this report.

5.1 SOIL VAPOR EXTRACTION SYSTEM AVAILABILITY

The availability of each SVE system is evaluated by comparing the amount of time it was operating to the amount of time it was planned to be operating. This comparison is summarized as "percent availability." Availability data are provided for 1994, 1995, 1996, 1997, and 1998.

The amount of time each SVE system was planned to be operating changed as operations became more routine (Table 5-1). In addition, for 16 days during November and December 1994 and 14 days during November and December 1995, the systems were not expected to be operational. Using only the planned operating time to define the maximum possible system availability directly reflects the impacts that GAC changeouts, system malfunctions, and scheduled maintenance have on system operations.

The operating efficiency of all three systems since November 1994, the first full month of 24-hr/day, 7-days/week operations, is illustrated in Figure 5-1. Between November 1994 and September 1998, the monthly availability for all three systems averaged 92%.

With the following exceptions, each system was operated at greater than 65% availability, selected as a minimum reference value, during 1994, 1995, 1996, 1997, and 1998 (Table 5-2). The 14.2-m^3/min SVE system operated at less than 65% availability during July 1994, its initial startup month, and January and February 1995 (Figure 5-2). For 5 weeks during January and February 1995, extraction operations at the 14.2-m^3/min SVE system were limited to 9 hr/day, 5 days/week because malfunction of the automated sampling system necessitated manual sampling of VOC concentrations. The 28.3-m^3/min SVE system, which was restarted in November 1993, dropped to 65% availability in November 1994, when extraction operations were limited to 9 hr/day, 5 days/week for 1 week because of malfunction of the automated VOC sampling system (Figure 5-3). The 42.5-m^3/min SVE system operated at less than 65% availability only during March and April 1994, its initial restart months (Figure 5-4).

In general, operation of the systems is most difficult to maintain during the winter months, as illustrated by comparing the combined monthly availability of the three systems from November 1994 through June 1996 (Figure 5-1). This reflects in part the time needed for draining water from the extraction hoses and water knockout tanks during cold weather. The increased volume of water in the hoses and knockout tanks during the winter months results from condensation of moisture in the extracted soil vapor when it encounters colder temperatures. In addition, when the water in the hoses freezes before it can be drained, operation of the extraction system is limited or impossible, which also contributes to lower availability. These cold weather operational difficulties were the basis of the decision to shutdown the SVE systems during the winter rather than the summer months in 1998.

Significant changes in the rate at which each SVE system was operated are reflected in the changes in slope of the cumulative hours plotted with time (Figure 5-5). For example, the loss of operating time during January and February 1995 at the 14.2-m^3/min system is reflected by the

decrease in slope; the change from 7-hr/day operations to 24-hr/day operations in October 1994 at the 42.5-m^3/min system is reflected by the increase in slope. As of September 1998, the three SVE systems together have operated 64,000 hours: the 14.2-m^3/min system has operated a total of 22,517 hours; the 28.3-m^3/min system has operated a total of 23,464 hours; and the 42.5-m^3/min system has operated a total of 18,103 hours (Table 5-3).

5.2 VOLUME OF SOIL VAPOR PROCESSED

For each SVE system, the volume of soil vapor processed was calculated using the hours the system operated and the measured flow rate of soil vapor exiting the system (FM6, Figure 3-1). The average daily flow rates measured at each system since 24-hr/day operations began are shown in Figures 5-6 through 5-8.

The flow rate measured at the SVE system represents the combined flow from all the on-line wells and may change as the selection of on-line wells changes. For a given applied vacuum, the flow produced from each well is a function of the air permeability of the soil, the open area of the screened or perforated interval, the well diameter, and the radius of influence of the well.

The flow rate at each SVE system may also be adjusted by the SVE system technicians to meet varying conditions and requirements. For example, during the winter months, flow rates were reduced by the technicians to minimize the volume of knockout water generated. Ice blockages within the vapor extraction hoses occasionally also limited the flow to the extraction system. During the warmer months, flow rates are generally established at approximately 90% to 95% of blower capacity (e.g., 14.2 m^3/min) to avoid exceeding the operating limits. A well with an open interval in a lower permeability soil layer that produces vapor at a lower flow rate may be placed on line because it has higher contaminant concentrations; typically, the flow rate will increase as extraction continues and airflow pathways are established.

With the exception of the winter months, the flow rate at the 14.2-m^3/min SVE system was generally maintained between 11 and 14.2 m^3/min between July 1994 and August 1996 (Figure 5-6). The flows were reduced for two separate weeks in April and May 1995 during testing at a single extraction well. Between September 1996 and September 1998, the flow rate was often between 14 and 16 m^3/min (Figure 5-6). The flows were lower in August 1997 during testing associated with the rebound study. The initial extraction wells selected for SVE restart operations at 216-Z-9 in July 1998 produced flows that were lower than 14.2 m^3/min.

From July 1994 through mid-April 1995, the flow rate at the 28.3-m^3/min SVE system varied between 14.2 and 22.7 m^3/min (Figure 5-7). In March and April 1995, flow rates were significantly improved by jet perforating 10 of these extraction wells, which previously had been mechanically perforated. Since then, flow rates at the 28.3-m^3/min SVE system generally have varied from 22.7 to 28.3 m^3/min. The improved flow rates allow the 28.3-m^3/min SVE system to operate at lower vacuums, which reduces the heat generated at the blower motor. Prior to jet perforating, the system vacuum had to be reduced during hot weather to avoid overheating the blower motor, which resulted in lower flow rates. The flows were reduced for a week in August 1997 for a low-flow test to estimate the impact of low SVE flow on carbon tetrachloride removal rates.

From mid-February through June 1995, the flow rate at the 42.5-m^3/min SVE system tended to be either 36.8 to 39.6 m^3/min or 28.3 to 33.9 m^3/min (Figure 5-8). During this time, an off-gas treatment system was being tested that frequently shut down operations. Between July 1995 and January 1996, the flow rate using all three blowers varied from 34 to 42.5 m^3/min. From February through August 1996, the system operated on only two blowers at flow rates ranging between 28.3 and 34 m^3/min.

Between February 1992 and September 1998, 82 million m^3 of soil vapor was extracted and processed using the three SVE systems (Table 5-4). Of this volume, 37 million m^3 was extracted from the 216-Z-9 wellfield and 45 million m^3 was extracted from the 216-Z-1A/18/12 wellfield. The volume of vapor extracted daily by each system is shown in Figures 5-9 through 5-11.

The flow rates at individual extraction wells were estimated by apportioning the flow rates measured at the SVE systems among the on-line wells (Appendix A). For each well, the system flow rate was multiplied by the ratio of that well's open area to the sum of the open areas for all the wells in operation on that system on that particular day. These daily flow rates and the number of operating hours were then used to estimate the cumulative flow from each extraction well. At the 216-Z-9 wellfield, an estimated 26 million m^3 of soil vapor was extracted from wells open above the Plio-Pleistocene layer, and 12 million m^3 was extracted from wells open below the Plio-Pleistocene layer (Table 5-5). For the 216-Z-1A/18/12 wellfield, an estimated 26 million m^3 of soil vapor was extracted from wells open above the Plio-Pleistocene layer, and 18 million m^3 was extracted from wells open below the Plio-Pleistocene layer.

Based on an average areal zone of influence of 55,000 m^2 above the Plio-Pleistocene layer in the 216-Z-9 area, an average Hanford formation thickness of 38 m, an average porosity of 20%, and assuming a uniform distribution of flow, 62 pore volumes of soil vapor have been extracted by the 42.5-m^3/min and 14.2-m^3/min SVE systems above the Plio-Pleistocene layer. Similarly, for the 216-Z-1A/ Z-18/Z-12 area, based on an average areal zone of influence of 155,000 m^2, 22 pore volumes of soil vapor have been extracted by the 28.3- and 14.2-m^3/min SVE systems above the Plio-Pleistocene layer.

Based on an average areal zone of influence of 40,000 m^2 below the Plio-Pleistocene layer in the 216-Z-9 area, an average Ringold Unit E thickness of 21 m in the unsaturated zone, an average porosity of 20%, and assuming a uniform distribution of flow, 71 pore volumes of soil vapor have been extracted by the 42.5-m^3/min and 14.2-m^3/min SVE systems below the Plio-Pleistocene layer. Similarly, for the 216-Z-1A/Z-18/Z-12 area, based on an average areal zone of influence of 100,000 m^2, 43 pore volumes of soil vapor have been extracted by the 28.3- and 14.2-m^3/min SVE systems below the Plio-Pleistocene layer.

The areal zones of influence at the 216-Z-9 and 216-Z-1A/Z-18/Z-12 wellfields were estimated using numerical airflow modeling (Rohay and McMahon 1996). Two sets of wellfield flow and monitoring data were used to calibrate the model; each set produced a different estimate of the zones of influence above and below the Plio-Pleistocene layer. In this report, the results were averaged to estimate the pore volumes of soil vapor that have been extracted since 1992.

Approximately 1,051,000 kg of water was removed from the subsurface in the 82,440,000 m^3 of soil vapor extracted between February 1992 and September 1998. An equal volume of ambient air drawn into the subsurface added 496,000 kg of water over the same time period. These estimates were made by updating the calculations provided by Cameron (1997) for the period February 1992 through June 1996. The calculations are based on an average temperature of 15 °C and a relative humidity of 100% for the extracted soil vapor and an average temperature of 12 °C and a relative humidity of 59% for the ambient air. When the additional water added to the subsurface through natural recharge is factored into the water balance, the impact of SVE on soil moisture content in the vadose zone becomes negligible (Cameron 1997). However, as Cameron (1997) points out, some subsurface zones of higher air conductivity have been exposed to greater rates of vapor flow and may have been more dried out than the average subsurface volume; when the soil moisture content approaches zero, the rate of partitioning of volatile contaminants from the soil particle to the vapor phase is substantially reduced, apparently because sorption of the contarninant to the soil particle is generally stronger (Pankow and Cherry 1996).

5.3 VOLUME OF KNOCKOUT WATER DRAINED FROM SVE SYSTEMS

Water condensate was first noticed in the water knockout tank on the 28.3-m^3/min SVE system on October 20, 1992. Between October 20, 1992 and February 9, 1994, approximately 1,022 L of knockout water was collected from the 28.3-m^3/min SVE system from operations at the 216-Z-1A and 216-Z-18 sites. This water was sent to the purgewater storage facility using purgewater trucks. After February 9, 1994 (approximately March 1), the carbon tetrachloride was designated as a listed waste, and shipments of the condensate as purgewater ceased.

Since February 9, 1994, SVE knockout water has been transferred to the 200-ZP-1 pump-and-treat operation for treatment. The first transfer, in January 1995, consisted of 92 drums of condensate water stored in 208-L (55-gal) drums with 90-mil liners. The SVE technicians recall that these drums were nearly full. Assuming that each drum held 170 L (45 gal) of water, this transfer represents an additional 15,700 L of knockout water. Approximately 3,500 L of this water is assumed to have been collected during the 1993-1994 winter after February 9, 1994 (15,700 L minus the October-December 1994 volumes listed in Table 5-6).

Between October 1994 and April 1995, 27,290 L of water was drained from the SVE systems (Table 5-6). Significant amounts of water did not accumulate after April 1995 during the 1994-1995 winter season (Figure 5-12). Between October 1995 and June 1996, 66,741 L of water was drained from the SVE systems. Although most of the water had accumulated by the end of April 1996, additional water was drained as late as June (Figure 5-12). During October 1996, 5,564 L of water was drained from the SVE systems. The systems were shut down for the rest of the 1996-1997 winter on November 4, 1996; the rebound study was conducted during this planned shutdown. In April 1998, approximately 189 L of water was drained from the SVE hoses when SVE operations resumed after the 1997–1998 winter.

More than twice as much water was drained from the SVE systems during the 1995-1996 winter season as during the 1994-1995 winter season. This increase is partly a result of the increased volume of vapor extracted during 1995-1996. During the 6 months of the 1994-1995 winter

(October 20, 1994-April 19, 1995), 10 million m^3 of vapor was extracted, producing 26,000 L of water. During the same 6 months of the 1995-1996 winter (October 19, 1995-April 17, 1996), 15 million m^3 of vapor was extracted, producing 62,000 L of water.

The cumulative liters of water drained per million m^3 of vapor extracted are compared for the three SVE systems during the 1994-1995, 1995-1996, and 1996-1997 seasons in Figure 5-13. During 1994-1995, the 28.3-m^3/min SVE system produced a significantly higher volume of water per million cubic meters of vapor extracted than either the 14.2- or 42.5-m^3/min systems (Figure 5-13). Between October 20, 1994 and April 26, 1995, the 28.3-m^3/min SVE system produced an average of 3,600 L of water per million cubic meters of vapor extracted. During this same period, the 14.2-m^3/min SVE system produced an average of 2,300 L of water per million cubic meters of vapor, and the 42.5-m^3/min SVE system produced an average of 2,200 L of water per million cubic meters of vapor. The maximum water production rate was also higher for the 28.3-m^3/min SVE system (5,400 L of water per million cubic meters of vapor) than for the 14.2- and 42.5-m^3/min systems (2,800 and 3,300 L of water per million cubic meters of vapor, respectively). Unlike the water knockout tanks on the 14.2- and 42.5-m^3/min systems, one of the two water knockout tanks on the 28.3-m^3/min system was not insulated during this time. The cooler temperature of the knockout tank on the 28.3-m^3/min SVE system is the most likely explanation for its higher water accumulation rate.

During 1995-1996, however, the 14.2-m^3/min SVE system produced a slightly higher volume of water per million cubic meters of vapor extracted than the other two SVE systems. Between October 19, 1995 and April 17, 1996, the 14.2-m^3/min SVE system produced an average of 5,100 L of water per million cubic meters of vapor extracted. During this same period, the 28.3-m^3/min SVE system produced an average of 4,500 L of water per million cubic meters of vapor, and the 42.5-m^3/min SVE system produced an average of 3,500 L of water per million cubic meters of vapor. The maximum water production rate was also higher for the 14.2-m^3/min system (6,200 L of water per million cubic meters vapor) than for the 28.3- and 42.5-m^3/min systems (4,700 and 4,100 L of water per million cubic meters of vapor, respectively). Use of the 14.2-m^3/min SVE system to extract from the 216-Z-12 Crib beginning in August 1995 added a long hose run to the system, which may be responsible for the increased water production from September 1995 through January 1996 by allowing more cooling to take place. Decreased flow rates at the 14.2-m^3/min SVE system during the 1995-1996 winter (Figure 5-6) also lengthened the travel time through the extraction hoses, potentially increasing the volume of water generated for a given volume of vapor extracted. The second water knockout tank on the 28.3-m^3/min SVE system was insulated in October 1995.

Other factors that may have caused increased water production in 1995-1996 include differences in the mix of on-line wells and the depths of their open intervals, differences in the daily temperature fluctuations, and/or changes in the method of measuring the volumes.

The water production rates for the three SVE systems appear to be similar during October 1996. However, the data are insufficient to allow detailed evaluation.

Eight composite samples from the 60 drums of knockout water present in November 1994 were analyzed for radionuclide activity prior to being released for processing in the 200-ZP-1 treatment system. The samples were below minimum detectable activity for both alpha and beta-

gamma contamination. These data, plus analyses of a sample collected June 30, 1994 and a sample collected February 22, 1993, indicate that there is no activity above natural background in the SVE condensate water.

Three samples of SVE knockout water have been analyzed for VOCs. On June 30, 1994, a composite condensate water sample was collected and analyzed by an offsite laboratory; the volatile organic analyses followed the EPA protocol except that the sample was not preserved. A sample collected on January 26, 1995 was analyzed the following day onsite. The sample was not preserved, did not maintain zero headspace, and was not stored on ice.

Two samples were analyzed December 12, 1995 using the 200-ZP-1 pump-and-treat process equipment. Analytical results for carbon tetrachloride, chloroform, tetrachloroethylene, and trichloroethylene are summarized in Table 5-7.

The mass of carbon tetrachloride removed in the SVE knockout water is estimated as 1 to 40 g, based on the total volume of water, 104,299 L (Table 5-6), and the range of carbon tetrachloride concentrations, 10 μg/L to 380 μg/L (Table 5-7).

5.4 CHANGE IN CARBON TETRACHLORIDE CONCENTRATIONS

Carbon tetrachloride concentrations in the extracted soil vapor have decreased significantly at both the 216-Z-1A/Z-18/Z-12 and 216-Z-9 wellfields during operation of the SVE systems. This is typical of SVE operations and represents removal of the volatile contaminant readily available in the pore spaces swept out by extracted vapor. Extracted contaminant concentrations approach an asymptotic level as the supply of volatile contaminant to the high-flow zone becomes limited by desorption and diffusion of the contaminant from the sediment particles and soil moisture. Diffusion also controls contaminant migration from the pore spaces between sediment particles in the lower permeability, lower flow zones to pore spaces in the higher permeability, higher flow zones.

Measurements made at the inlet to the extraction system represent the combined soil vapor concentrations from all on-line wells connected to the system.

Carbon tetrachloride concentrations in soil vapor extracted from the 216-Z-1A/Z-18/Z-12 wellfield using the 28.3- and 14.2-m^3/min SVE systems have declined from approximately 1,500 ppmv in 1992 to 23 ppmv in September 1998 (Figure 5-14). The increase in August 1995 was caused by addition of an extraction well in the 216-Z-12 wellfield.

The most dramatic decline in carbon tetrachloride concentrations has been at the 216-Z-9 wellfield using the 42.5- and 14.2-m^3/min SVE systems. Carbon tetrachloride concentrations in extracted soil vapor have declined from approximately 30,000 ppmv at startup to 24 ppmv in September 1998 (Figures 5-15 and 5-16).

In FY 1997, all three SVE systems were shut down from November 1996 through July 1997 for the rebound study. All three systems were operated from July 1997 through September 1997.

In FY 1998, SVE resumed March 30, 1998 at the 216-Z-1A/Z-18/Z-12 wellfield using the 14.2-m^3/min SVE system, which was on the northern side of the 216-Z-18 Crib (Figure 5-17). Fifteen extraction wells distributed throughout the wellfield were selected to optimize both protection of groundwater and mass removal of contaminant. Initial characterization of the 15 on-line wells indicated that the system was extracting soil vapor effectively from only the closest wells and that the applied vacuum at the distant wells was insufficient to produce flow. Tests showed that the SVE system could, however, extract soil vapor effectively from isolated, distant wells. Therefore, the mix of on-line extraction wells was periodically switched among one set of seven relatively nearby wells and various sets of four relatively distant wells. Each set included wells open near the groundwater and wells open near the lower permeability Plio-Pleistocene unit. As a result, the SVE system was extracting from wells primarily associated with the 216-Z-18 site for the first 7 weeks (March 30 through May 17) and from wells primarily associated with the 216-Z-1A site for the following 6 weeks (May 18 through June 30). Comparison of the changes in inlet concentrations to the changes in the sets of on-line wells indicated that the higher concentrations observed from May 18 through June 30 tended to be associated with the 216-Z-1A wells (Figure 5-17).

Soil vapor extraction resumed July 7, 1998 at the 216-Z-9 wellfield using the 14.2-m^3/min SVE system. Initial on-line wells were selected close to the 216-Z-9 Trench (Figure 5-18). As extraction continued, wells farther away from the crib were brought on line. Each selection of on-line wells included wells open near the groundwater and wells open near the lower permeability Plio-Pleistocene unit. The daily mass removal rate increased significantly twice during the 3 months of extraction as a result of changes in extraction wells (Figure 5-19):

- Two additional wells were brought on line on July 29, 1998. (A third additional well added on July 29 was removed on July 31.) The mass removal rate increased, despite a continued decline in concentrations, because the flow rate increased (flow rate is shown in Figure 5-6).

- The mix of on-line wells was changed again on September 1, 1998. The mass removal rate increased, despite a constant flow rate, because the inlet concentrations increased.

The trend of the 1992-1998 concentration data is compared to the volume of soil vapor extracted in Figures 5-14 and 5-15. As expected, concentrations decrease with increasing volume of soil vapor extracted. The data also indicate that concentrations rebound during periods of nonoperation as a result of carbon tetrachloride accumulating in the pore spaces after apparently diffusing from sediment micropores, soil moisture, and low-permeability zones. When SVE operations resume, the initial extracted contaminant concentrations are higher. This concentration rebound can be seen at both wellfields in July 1997 following the 8-month shutdown for the rebound study and in 1998 following the winter shutdown (Figures 5-14 and 5-15). The increase in concentrations can also be detected for shorter duration shutdowns. For example, during 12 days in December 1994 and 10 days in December 1995, the systems did not operate, and when operations resumed the following January, concentrations were slightly higher (e.g., Figure 5-15). This shorter duration rebound phenomenon is more apparent in Figure 5-16, which shows the carbon tetrachloride concentration data for the 216-Z-9 site since 24-hr/day operations began in October 1994. The rebound was apparently faster and of greater magnitude

in January 1995 when concentrations were still relatively high, indicating a more accessible and extensive contaminant source.

Carbon tetrachloride rebound concentrations measured in extracted soil vapor at the 216-Z-9 site following the 8-month shutdown in 1997 are lower than concentrations measured following the 12-month shutdown in 1998 (Figure 5-20). The longer time for rebound in 1998 would typically produce higher concentrations. However, in 1997 all wells were placed on line as part of the rebound test, whereas in 1998 the higher concentration wells were selected to optimize mass removal. In addition, the lower flow 14.2-m^3/min SVE system used in 1998 might have resulted in less dilution of the soil vapor.

Carbon tetrachloride rebound concentrations measured in extracted soil vapor at the 216-Z-1A and 216-Z-18 sites following the 8-month shutdown in 1997 are higher than concentrations measured following the 6-month shutdown in 1998 (Figure 5-21). However, the initial 1998 on-line wells were primarily from the 216-Z-18 site, and within a week the concentrations were equal to the 1997 concentrations measured from 216-Z-18 wells. (After approximately 25 days of operations in 1997, selected 216-Z-18 wells were taken off line to support rebound testing, and the concentrations decreased significantly.) Concentrations observed at the 216-Z-1A wells during 1998 (during the last 6 weeks of operations) are lower than the initial 1997 concentrations from 216-Z-1A wells. This may reflect the longer time available for rebound in 1997 and/or the increased capacity of the 28.3-m^3/min SVE system used in 1997 to extract from more wells simultaneously.

As an initial approach to estimating the future decline in carbon tetrachloride inlet concentrations, exponential curves were used to model the carbon tetrachloride concentration data measured at each SVE system from October 1995 through November 1996 (Figure 5-22). October 1995 was selected as the beginning of the interval because it occurs after the decline of the last major increase in inlet concentrations (the August 1995 concentration spike at the 14.2-m^3/min SVE system caused by addition of the 216-Z-12 wellfield, Figure 5-14). The interval of October 1995 through November 1996 thus represents the last continuous operating run that illustrates the decline in SVE inlet concentrations simultaneously at all three systems. In addition, for the purpose of predicting future concentrations, the emphasis was placed on the concentration data more representative of the later, tailing phase of operations rather than of the initial, rapid removal phase. Two or more different equations may be needed to describe the entire curve of concentration decline if two or more different carbon tetrachloride removal mechanisms were operating over the life of the SVE remediation.

The exponential decay curves, fitted to the data through November 1996, were projected to March 1999 in order to evaluate their relationship to the concentration data following the 1997 rebound study and the 1998 winter shutdown (Figure 5-23). The equation values as of November 4, 1996 were held constant until July 18, 1997 and then allowed to resume the exponential decline until September 30, 1997. The equation values as of September 30, 1997 were held constant until March 30, 1998 for the 216-Z-1A and Z-18 wellfields and until July 7, 1998 for the 216-Z-9 wellfield and then allowed to resume the exponential decline. Relative to the exponential decay curves, both sets of rebound data are initially elevated, as expected. The carbon tetrachloride concentrations decline to concentrations that approach the exponential decay curves in September 1997 but do not appear to approach the exponential decay curves in 1998.

In 1997, all the available wells were on line continuously; in 1998, the mix of on-line wells was periodically changed to optimize mass removal.

This preliminary evaluation suggests that these decay curves can be used to provide a reasonable estimate of future concentration decline only under similar operating conditions and similar carbon tetrachloride removal mechanisms. For example, the physical and chemical processes that control carbon tetrachloride removal in the near term may be different than those that determine the removal rate in the long term.

The characterization data routinely measured for individual extraction wells include vacuum, flow, and carbon tetrachloride concentration (Tables B-1 through B-3, Appendix B). To monitor concentrations at individual extraction wells, a sampling apparatus is placed in line at the wellhead to collect a soil-gas sample in a Tedlar™ (E. I. du Pont de Nemours & Company, Wilmington, Delaware) bag. Concentrations are typically monitored monthly at individual on-line extraction wells and quarterly at individual off-line monitoring wells. One "snap-shot" sample is collected at each on-line extraction well. Three samples are collected during an hour of continuous extraction at wells that have been off-line during the month in which quarterly sampling is conducted; only the last of the three samples is included in Tables B-1 through B-3.

Carbon tetrachloride concentrations measured at individual extraction wells have also been decreasing with continued vapor extraction operations. At the 216-Z-1A/Z-18 wellfield, concentrations measured in wells with perforated or screened intervals open above the Plio-Pleistocene layer have been the same order of magnitude as those measured in wells open below the Plio-Pleistocene layer throughout extraction operations (Figure 5-24). At the 216-Z-9 wellfield, concentrations measured above the Plio-Pleistocene layer before April 1994 were generally an order of magnitude higher than those measured below; after approximately 6 months, concentrations measured above and below the Plio-Pleistocene layer had reached comparable levels (Figure 5-25).

In general, carbon tetrachloride concentrations at individual extraction wells measured when SVE operations resumed in 1997 after the rebound study are slightly higher than concentrations measured at the same wells when operations resumed in 1998 after the winter shutdown (Table 5-8). At the 216-Z-1A wellfield, the time available for rebound was slightly less in 1998 (6 months) than in 1997 (8 months). However, at the 216-Z-9 wellfield, the time available for rebound was similar in 1998 (9 months) and 1997 (8 months). Longer time available for rebound would typically favor higher concentrations.

The concentrations of chloroform measured at individual extraction wells have been proportional to the concentrations of carbon tetrachloride measured at individual extraction wells. The chloroform is assumed to have been produced primarily through biodegradation of carbon tetrachloride during the early phases of soil column disposal and migration. The linear relationship suggests that the fate and transport of the chloroform has been similar to that of the carbon tetrachloride. For concentrations measured at 216-Z-9 wells, the ratio between carbon tetrachloride and chloroform is relatively constant for carbon tetrachloride concentrations between 25,000 and 1,000 ppmv (Figure 5-26). At carbon tetrachloride concentrations less than 1,000 ppmv, two different linear trends between carbon tetrachloride and chloroform are apparent (Figure 5-26). These two linear trends are still apparent when the same data are plotted

at a finer scale (Figure 5-27). (The data shown in Figure 5-27 are the same as those shown in Figure 5-26 for carbon tetrachloride concentrations less than 1,000 ppmv.) Each trend includes data from above and below the Plio-Pleistocene layer. The reason for the two trends is unknown. Data from two individual wells suggest that the contaminant ratios may decrease more rapidly at relatively low carbon tetrachloride concentrations (Figure 5-28).

The concentration data measured at 216-Z-1A/Z-18/Z-12 wells also suggest two different chloroform-to-carbon tetrachloride trends for carbon tetrachloride concentrations less than 1,000 ppmv, although the trends are not as well-defined as at 216-Z-9 (Figure 5-29). Based on the apparent trends, the chloroform-to-carbon tetrachloride ratios at 216-Z-9 wells appear to be higher than at 216-Z-1A/Z-18/Z-12 wells. If the chloroform is a degradation product of the carbon tetrachloride under anaerobic conditions, higher ratios would be expected at 216-Z-9, where aqueous soil column disposal might have been sufficient to create saturated conditions under the disposal site and induce anaerobic conditions.

All of the data used to construct Figures 5-24 through 5-29 were measured using the B&K instrument. Because the minimum detection limit for carbon tetrachloride on the B&K instrument is 1 ppmv, only carbon tetrachloride and chloroform data recorded as greater than 1 ppmv were used in this evaluation.

5.5 MASS OF CARBON TETRACHLORIDE REMOVED

The mass of carbon tetrachloride removed from each wellfield was calculated using the measured flow, concentration, and hours of operation data. Between February 1992 and September 1998, approximately 23,100 kg of carbon tetrachloride was removed from the 216-Z-1A and 216-Z-18/Z-12 wellfields (Table 4-1). Between March 1993 and September 1998, approximately 52,500 kg of carbon tetrachloride was removed from the 216-Z-9 wellfield (Table 4-1). The total mass of carbon tetrachloride removed represents an estimated 10% of the original carbon tetrachloride inventory (approximately 750,000 kg) discharged to the soil column (Table 2-1).

Based on the following assumptions, the total mass of carbon tetrachloride removed represents an average of 13% of the residual mass potentially available in the vadose zone. An estimated 440,000 kg of carbon tetrachloride was initially discharged to the 216-Z-1A and 216-Z-18 Cribs, and 310,000 kg was initially discharged to the 216-Z-9 Crib (Table 2-1). (The mass of carbon tetrachloride discharged to the 216-Z-12 Crib is unknown and therefore not included in this calculation.) Of this original inventory, an estimated 21% had been lost to the atmosphere by 1990, 1% to 2% had been dissolved in the upper 10 m of the unconfined aquifer, and 1% had biodegraded (WHC 1993, Rohay and Johnson 1991, Hooker et al. 1996). (These calculations and the 1990 inventory estimates both use the average of the estimated range of carbon tetrachloride discharged to 216-Z-9, Table 2-1.) For the purpose of these calculations, all of the mass that has not been lost to atmosphere, dissolved in groundwater, or biodegraded is assumed to remain as residual mass in the vadose zone. Assuming that 330,000 kg of carbon tetrachloride remained as residual mass in the vadose zone beneath the 216-Z-1A and 216-Z-18 sites, 7% (23,000 kg ÷ 330,000 kg) of the residual mass potentially available at 216-Z-1A and 216-Z-18 has been removed using SVE. Similarly, assuming that 240,000 kg remained as residual mass in

the vadose zone beneath the 216-Z-9 site, 22% (53,000 kg ÷ 240,000 kg) of the available mass potentially available at 216-Z-9 has been removed using SVE.

These estimates of the percent of residual mass removed at each site cannot be correlated to the estimate made by Yonge et al. (1996) that SVE can remove only 10% to 15% of the initial mass in contaminated zones through which flow is passing directly. Yonge et al. established known initial conditions for their laboratory experiments in order to compare the amount they removed to the amount they loaded into the soil. At the carbon tetrachloride site, the corresponding initial conditions are unknown, and the data are not available to determine what percent of the "initial" mass has been removed by SVE. In addition, no dense nonaqueous phase liquid (DNAPL) carbon tetrachloride was included in this particular experiment by Yonge et al., but concentrations observed at the 216-Z-9 site in 1993 and 1994 suggest that some carbon tetrachloride was present in the vadose zone as a DNAPL at that time (Rohay et al. 1994).

One indication that DNAPL was present in the vadose zone beneath 216-Z-9 is based on the inlet SVE concentrations. If a major fraction of the carbon tetrachloride originally discharged to the 216-Z-9 site were still present in the soil column as a nonaqueous phase liquid, a relatively high soil vapor concentration would be expected. For example, a pure, nonaqueous carbon tetrachloride liquid phase in the soil pore space should result in a maximum soil vapor concentration of 120,000 ppmv at 20 °C (DOE-RL 1991). As a rule-of-thumb, for soils saturated with an organic contaminant, standard SVE will produce a vapor stream containing one-tenth to one-half the expected concentration (EPA 1993). Therefore, vapor extraction concentrations greater than 12,000 ppmv of carbon tetrachloride may indicate that the soil near the extraction well is saturated with a nonaqueous-phase liquid. During initial SVE operations at the 216-Z-9 site, soil vapor concentrations extracted from wells open above the Plio-Pleistocene layer were in excess of 12,000 ppmv, suggesting the presence of a nonaqueous carbon tetrachloride phase (Figure 5-15). In situ soil vapor samples collected during drilling prior to initiation of SVE remediation also exceeded 12,000 ppmv in one well above the Plio-Pleistocene layer at the 216-Z-9 site (Rohay 1997).

Another indication that DNAPL might have been present in the vadose zone beneath 216-Z-9 prior to SVE remediation is based on comparison of the mass removed to the predicted mass present. Approximately 17% (53,000 kg ÷ 310,000 kg) of the original inventory at the 216-Z-9 site has been removed since 1993. Using available carbon tetrachloride soil vapor concentrations (primarily baseline monitoring of naturally venting boreholes) and equilibrium partitioning relationships, it was estimated that in 1990 12% of the original carbon tetrachloride inventory was present in the vadose zone as vapor, dissolved in soil moisture, or adsorbed to soil particles (WHC 1993). It was not possible to calculate a mass of DNAPL carbon tetrachloride using the equilibrium partitioning relationships, and thus a large fraction (65%) of the inventory was termed "unaccounted." The removal of more than 12% of the original inventory from this site suggests that additional mass was present in the vadose zone as residual liquid saturation and/or in nonequilibrium sorption sites.

The mass of carbon tetrachloride removed daily is compared to the cumulative total for each wellfield in Figures 5-30 and 5-31. The rate of mass removal has decreased with decreasing carbon tetrachloride concentrations. The decline in the total mass removal rate from both wellfields since 24-hr/day, 7-days/week operation began is shown in Figure 5-32. Despite this

decline, in September 1997 the three SVE systems were still removing an average of approximately 100 kg of carbon tetrachloride every week (38 kg from the 216-Z-1A/18 wellfield and 64 kg from the 216-Z-9 wellfield). In October 1996, prior to the rebound study, the three SVE systems were removing an average of 100 kg of carbon tetrachloride every week. At the close of operations at the 216-Z-1A wellfield in 1998, the 14.2-m^3/min SVE system was removing an average of 20 kg of carbon tetrachloride every week; at the close of operations at the 216-Z-9 wellfield in 1998, the system was removing an average of 23 kg of carbon tetrachloride every week.

5.6 IMPACT OF 200-ZP-1 PHASE III PUMP-AND-TREAT OPERATIONS

The 200-ZP-1 groundwater pump-and-treat system has been in operation since August 1994 (DOE-RL 1999). Phase III of the remediation operations was initiated in August 1997 to include extraction wells in the vicinity of the 216-Z-9 wellfield. In particular, Phase III groundwater extraction well 299-W15-32 is 11 m northeast of SVE well 299-W15-9 and 34 m southwest of SVE well 299-W15-6. Full-scale groundwater extraction from well 299-W15-32 began on August 27, 1997. Drawdown of the water table at this well was only 1.5 m below pre-operational levels. Lowering of the water table in the vicinity of this well has the potential to volatilize additional carbon tetrachloride, either from the introduction of soil vapor in previously saturated pores and/or from the additional agitation of the groundwater. However, the carbon tetrachloride concentration in vapor samples collected from nearby wells 299-W15-9L and 299-W15-6L has not measurably increased (Figure 5-33). As of September 30, 1998, groundwater extraction operations have had no detectable impact on carbon tetrachloride concentrations in vapor extracted from multiple wells and measured at the inlet to either the 42.5- or 14.2-m^3/min SVE system (Figure 5-20).

Measurement of groundwater extraction effects may be hampered because of differences in the completion/configuration of the groundwater and vapor extraction wells. The screened interval in well 299-W15-32 is 59 to 72 m below ground surface. The SVE interval in well 299-W15-6L extends from 47 m below ground surface to the current water table at 64 m below ground surface (the well is perforated to 109 m below ground surface), and the SVE interval in well 299-W15-9L is 49 to 58 m below ground surface.

Figure 5-1. Combined Monthly Availability of the Three Soil Vapor Extraction Systems, November 1994 - September 1998.

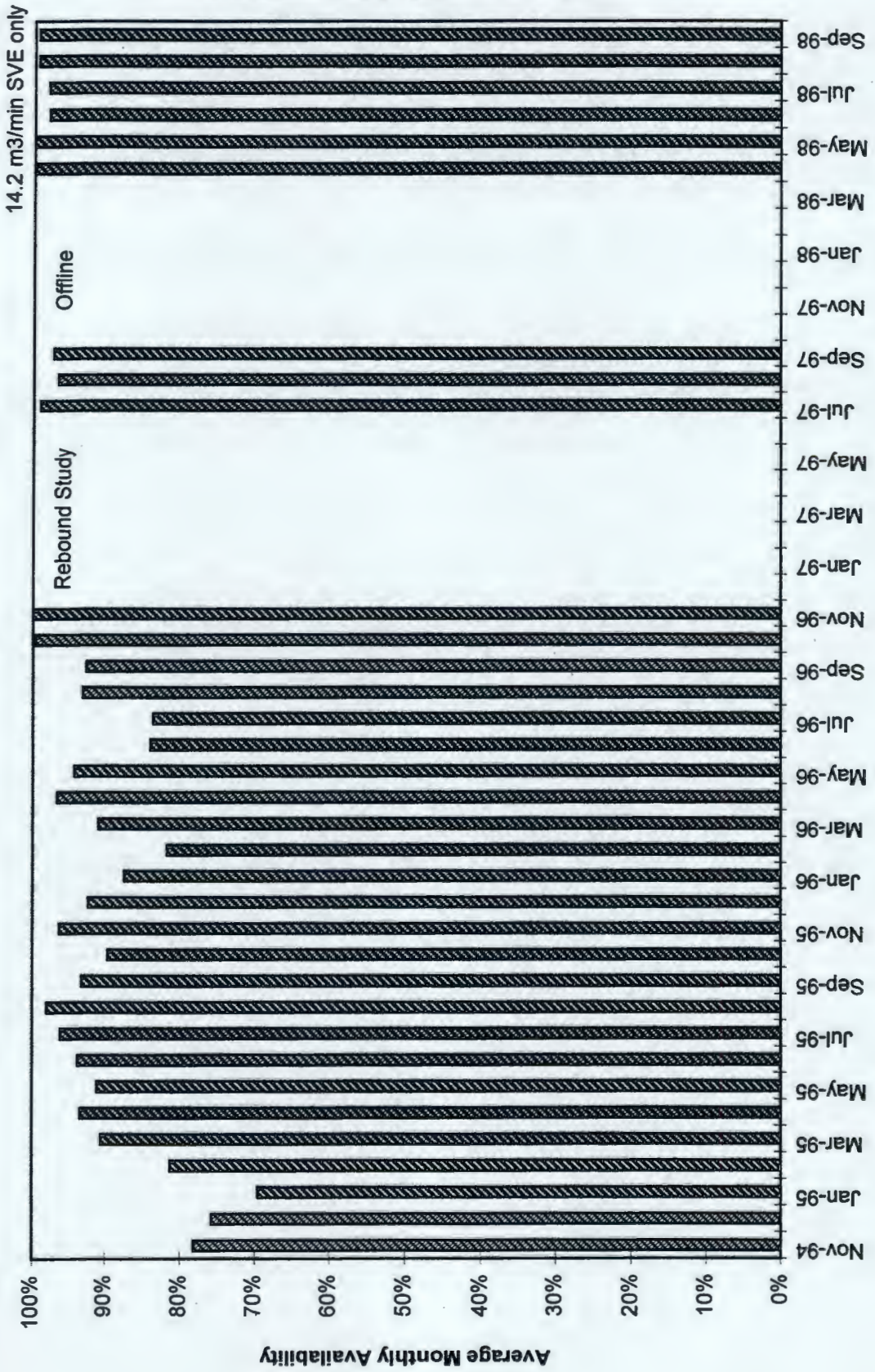


Figure 5-2. Monthly Availability of the 14.2-m^3/min Soil Vapor Extraction System, January 1994 - September 1998.

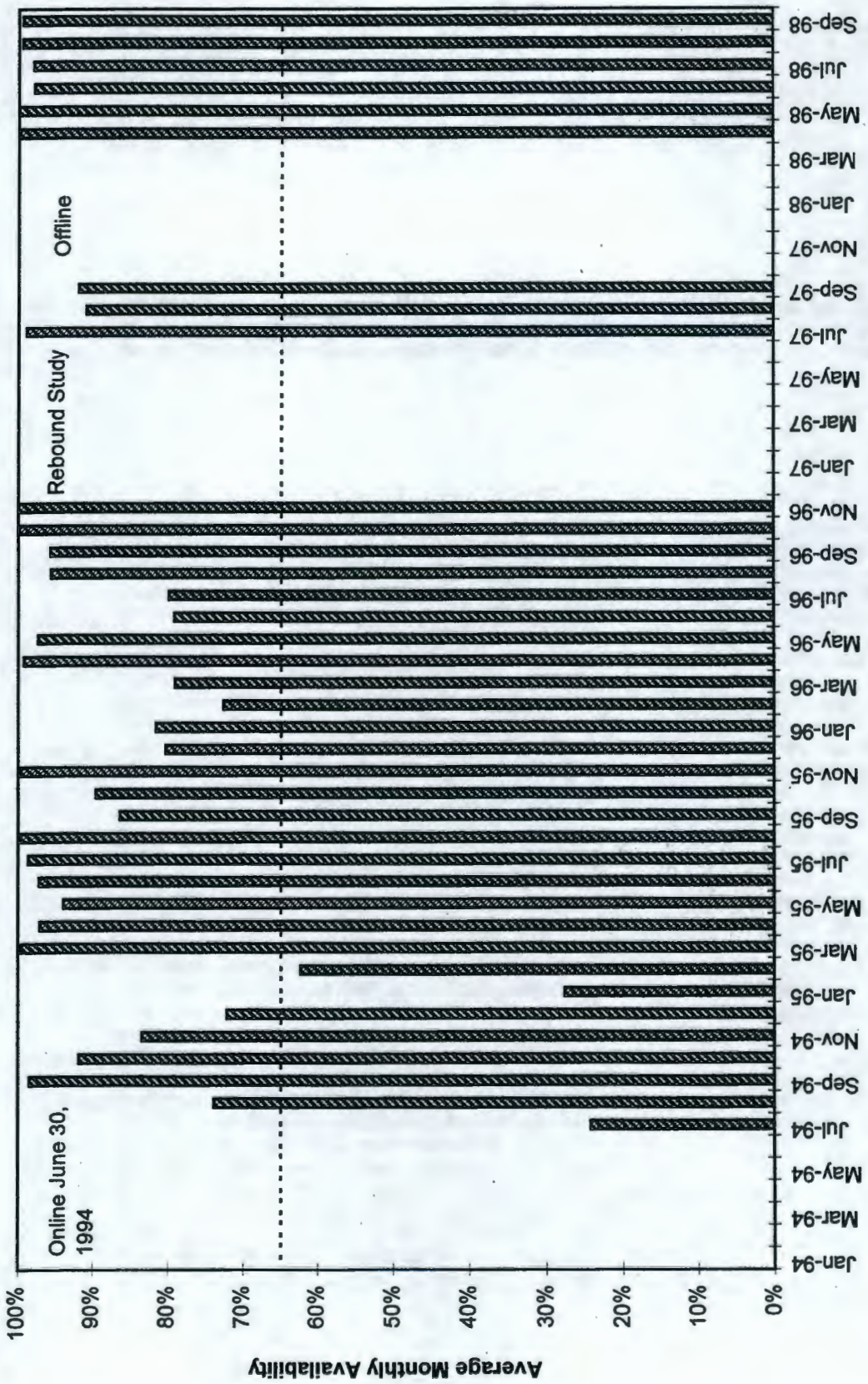


Figure 5-3. Monthly Availability of the 28.3-m^3/min Soil Vapor Extraction System, January 1994 - September 1998.

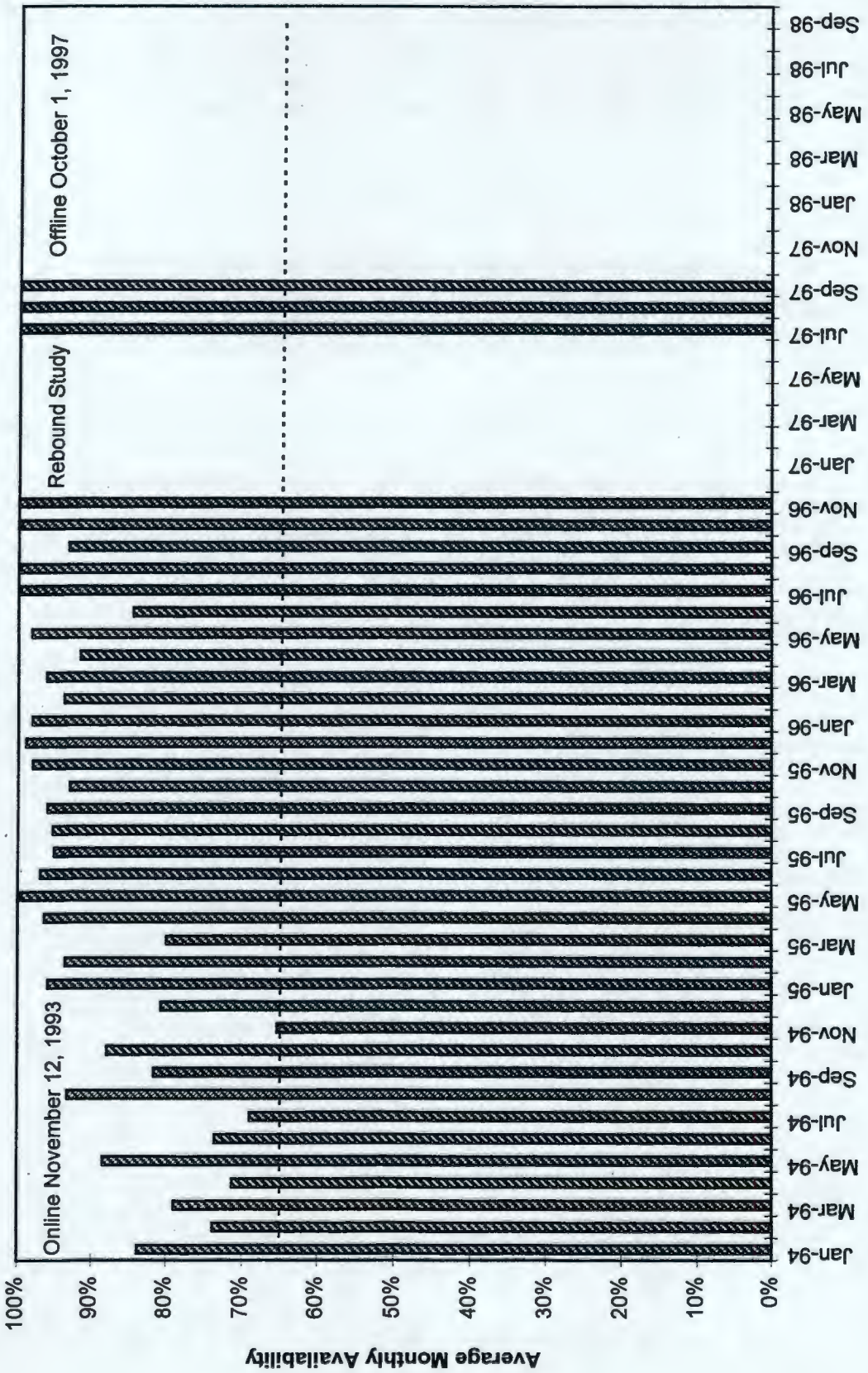
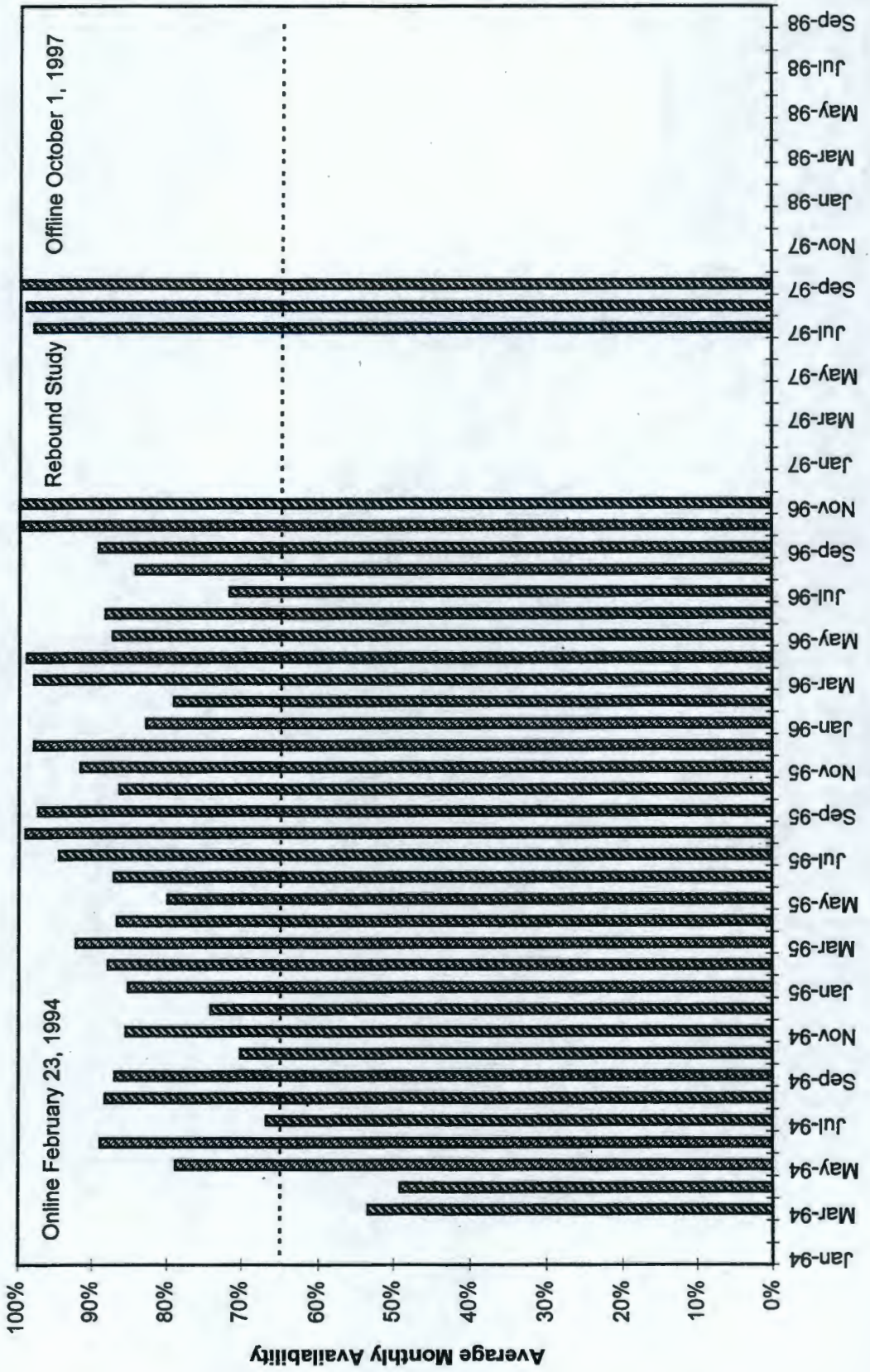


Figure 5-4. Monthly Availability of the 42.5-m^3/min Soil Vapor Extraction System, January 1994 - September 1998.



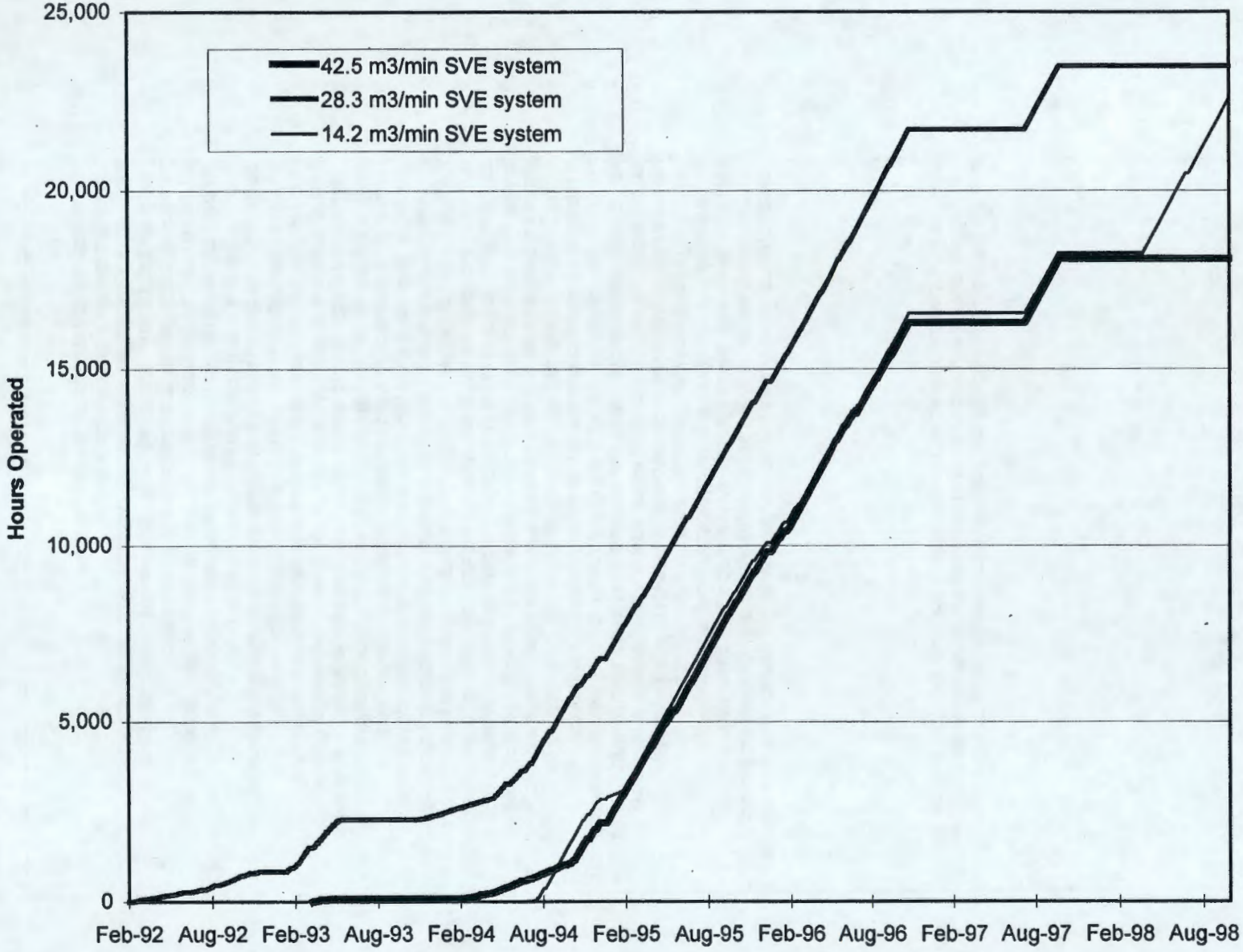


Figure 5-5. Number of Hours the Three Soil Vapor Extraction Systems Operated, February 1992 - September 1998.

Figure 5-6. Daily Average Flow Rate Measured at the 14.2-m^3/min Soil Vapor Extraction System During 24-hr/day, 7-days/week Operations, August 1994 - September 1998.

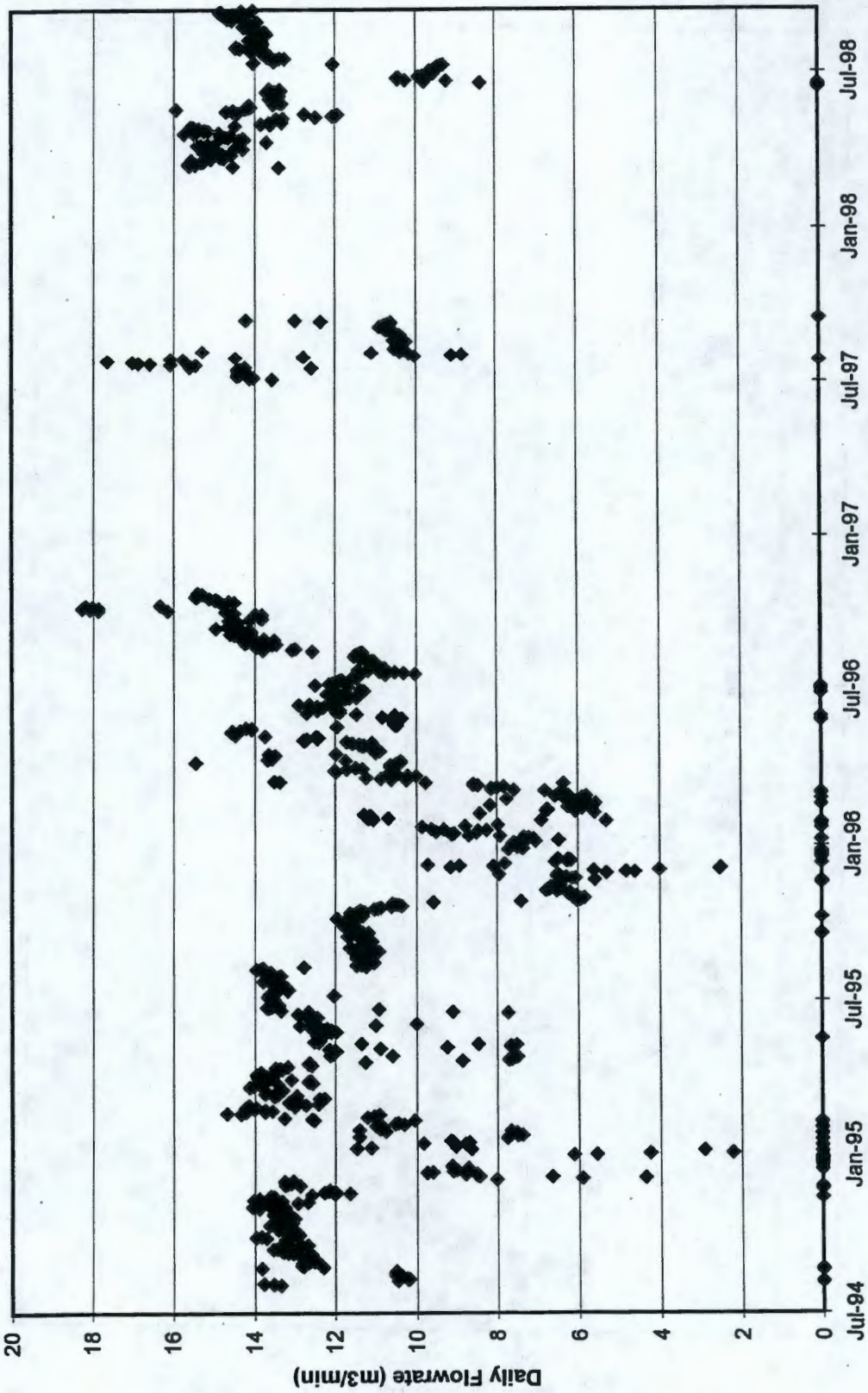


Figure 5-7. Daily Average Flow Rate Measured at the 28.3-m^3/min Soil Vapor Extraction System During 24-hr/day, 7-days/week Operations, July 1994 - September 1998.

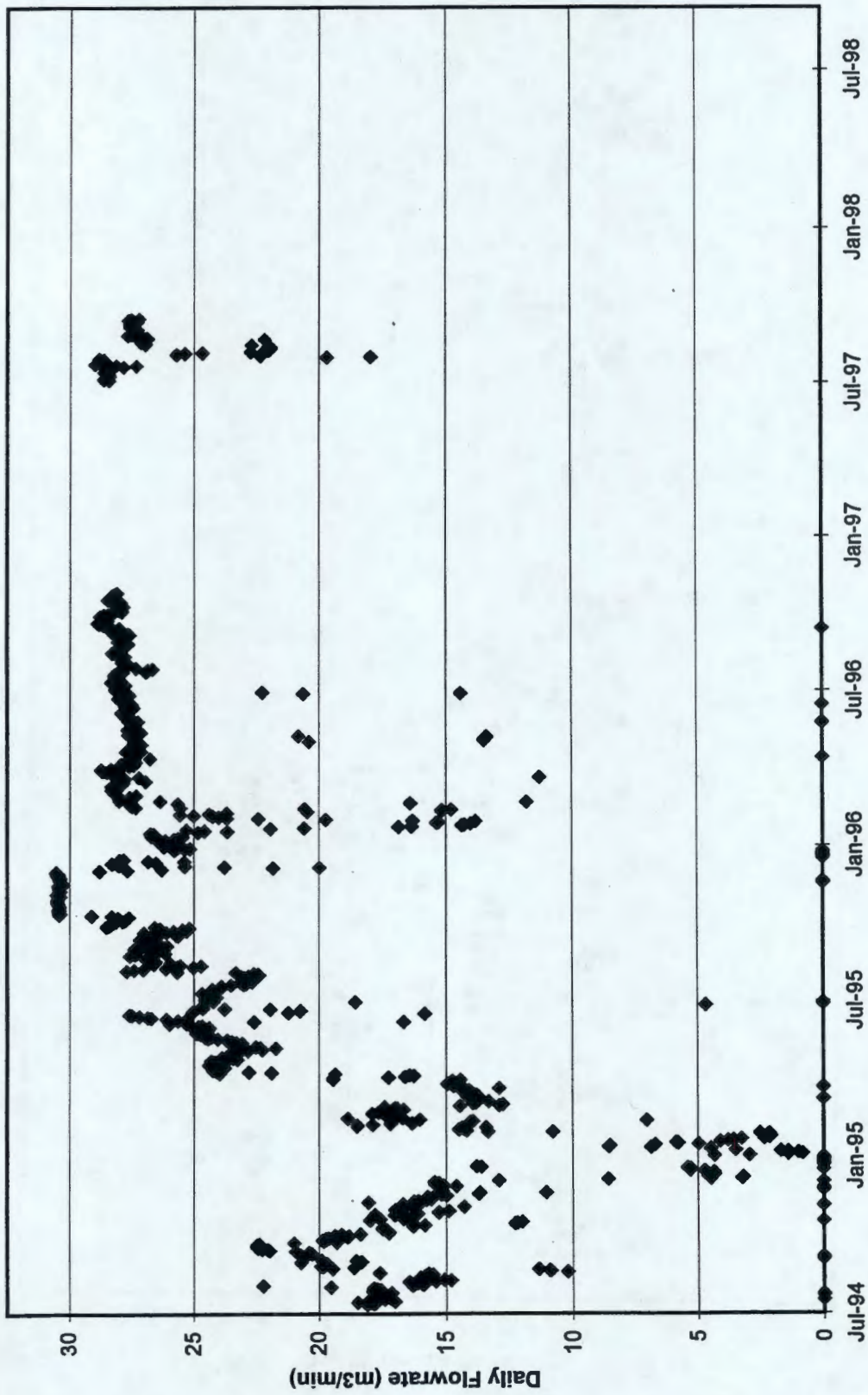


Figure 5-8. Daily Average Flow Rate Measured at the 42.5-m^3/min Soil Vapor Extraction System During 24-hr/day, 7-days/week Operations, October 1994 - September 1998.

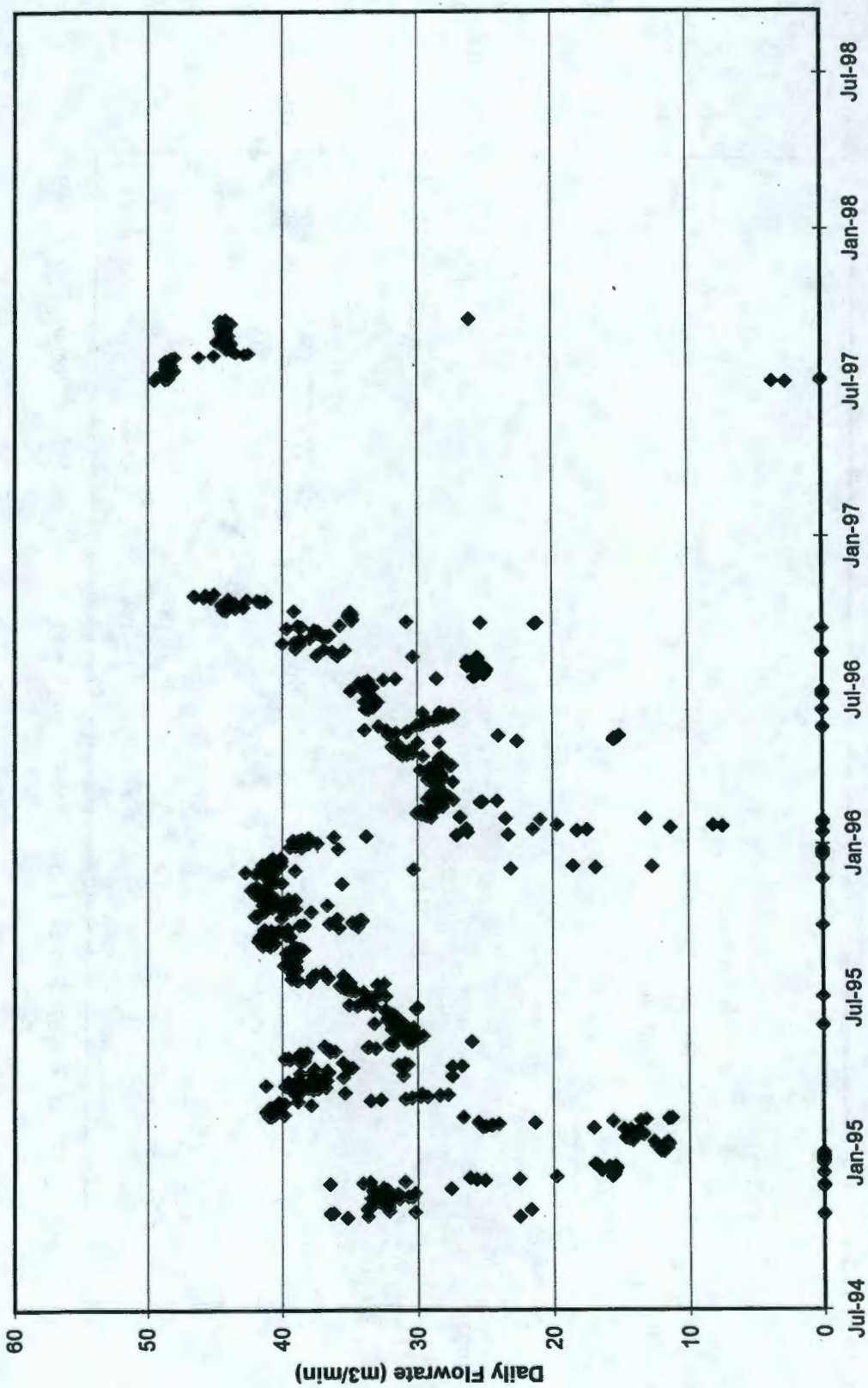


Figure 5-9. Volume of Vapor Processed by the 14.2-m^3/min Soil Vapor Extraction System, June 1994 - September 1998.

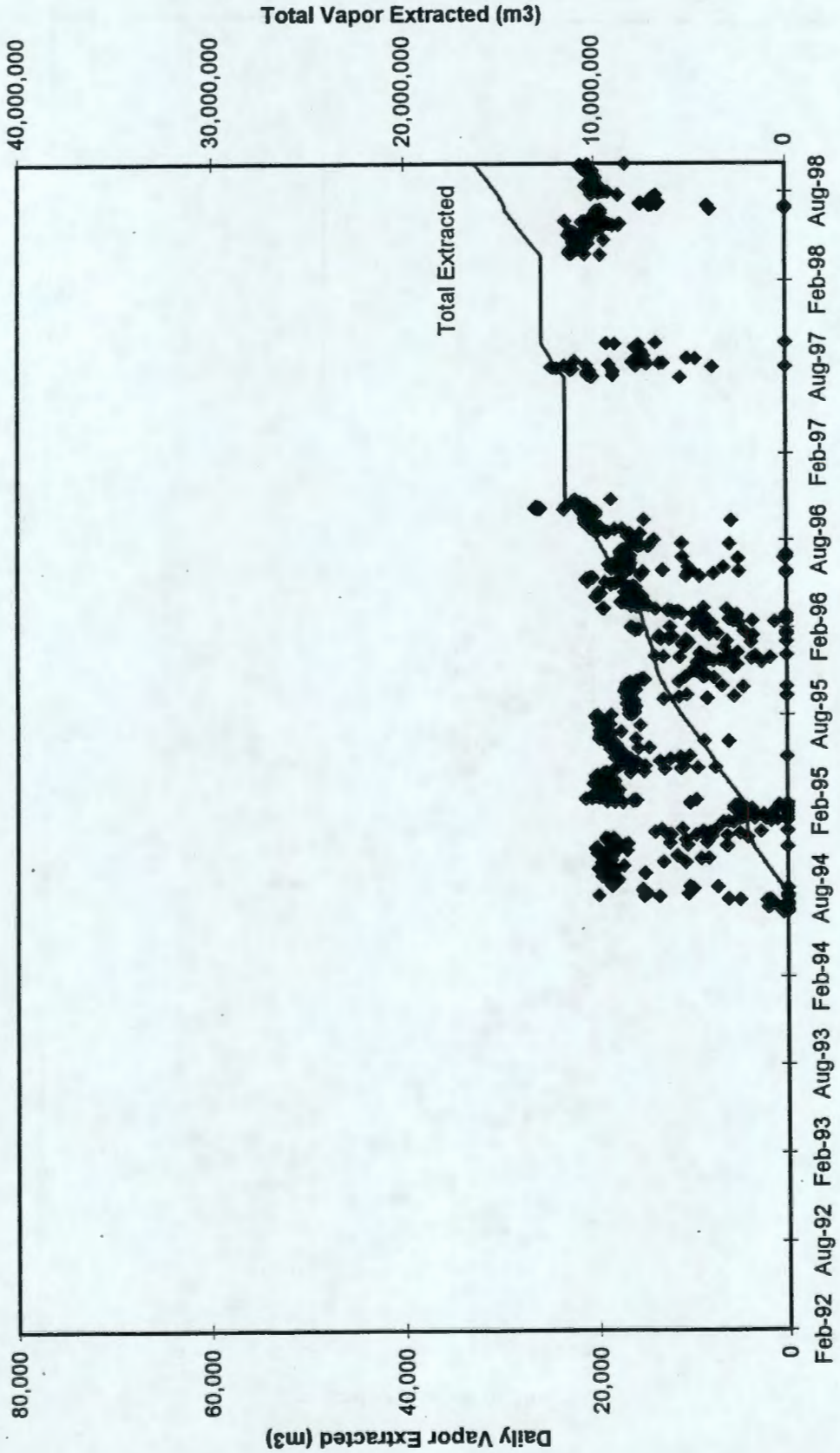


Figure 5-10. Volume of Vapor Processed by the 28.3-m^3/min Soil Vapor Extraction System, February 1992 - September 1998.

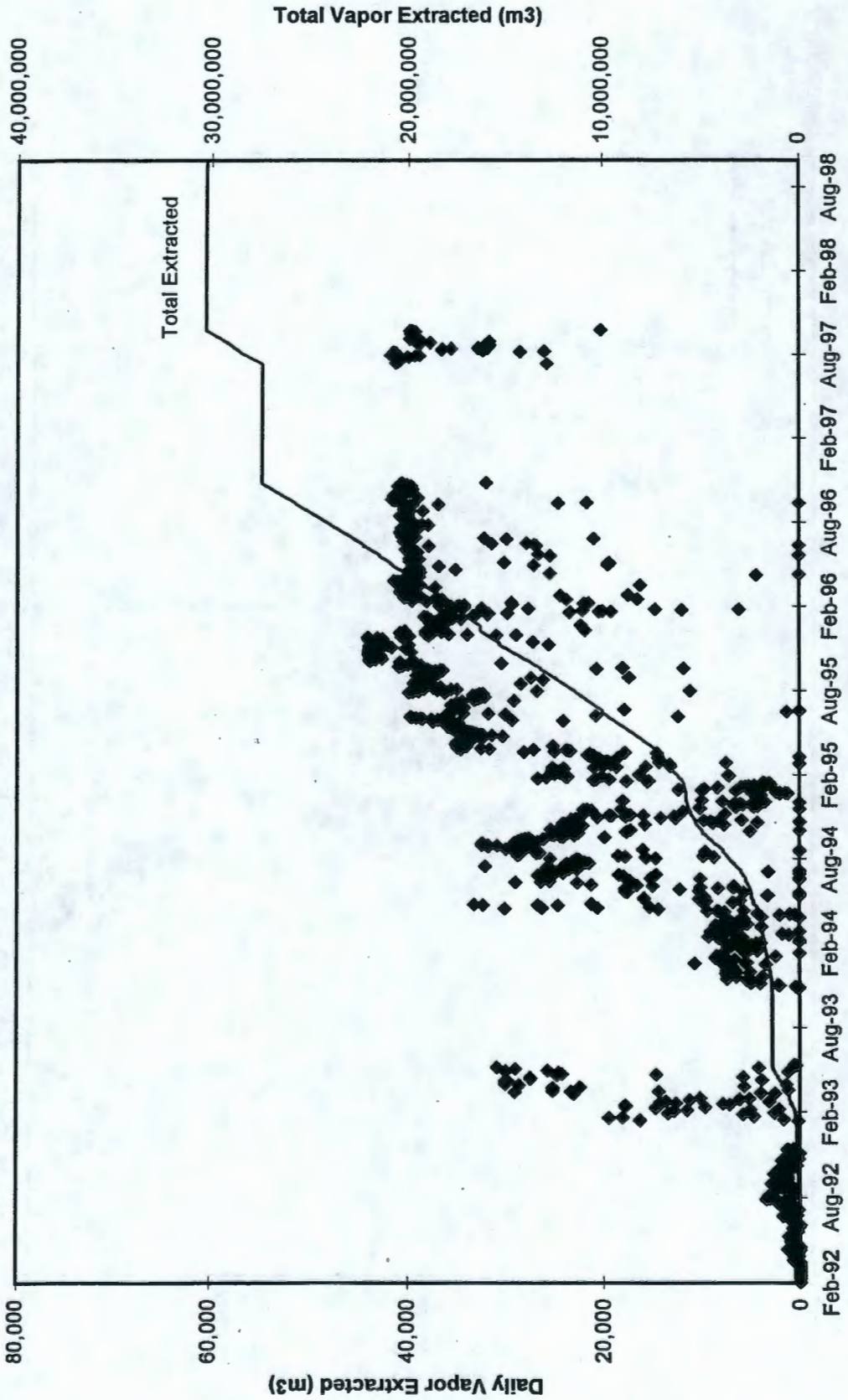


Figure 5-11. Volume of Vapor Processed by the 42.5-m^3/min Soil Vapor Extraction System, March 1993 - September 1998.

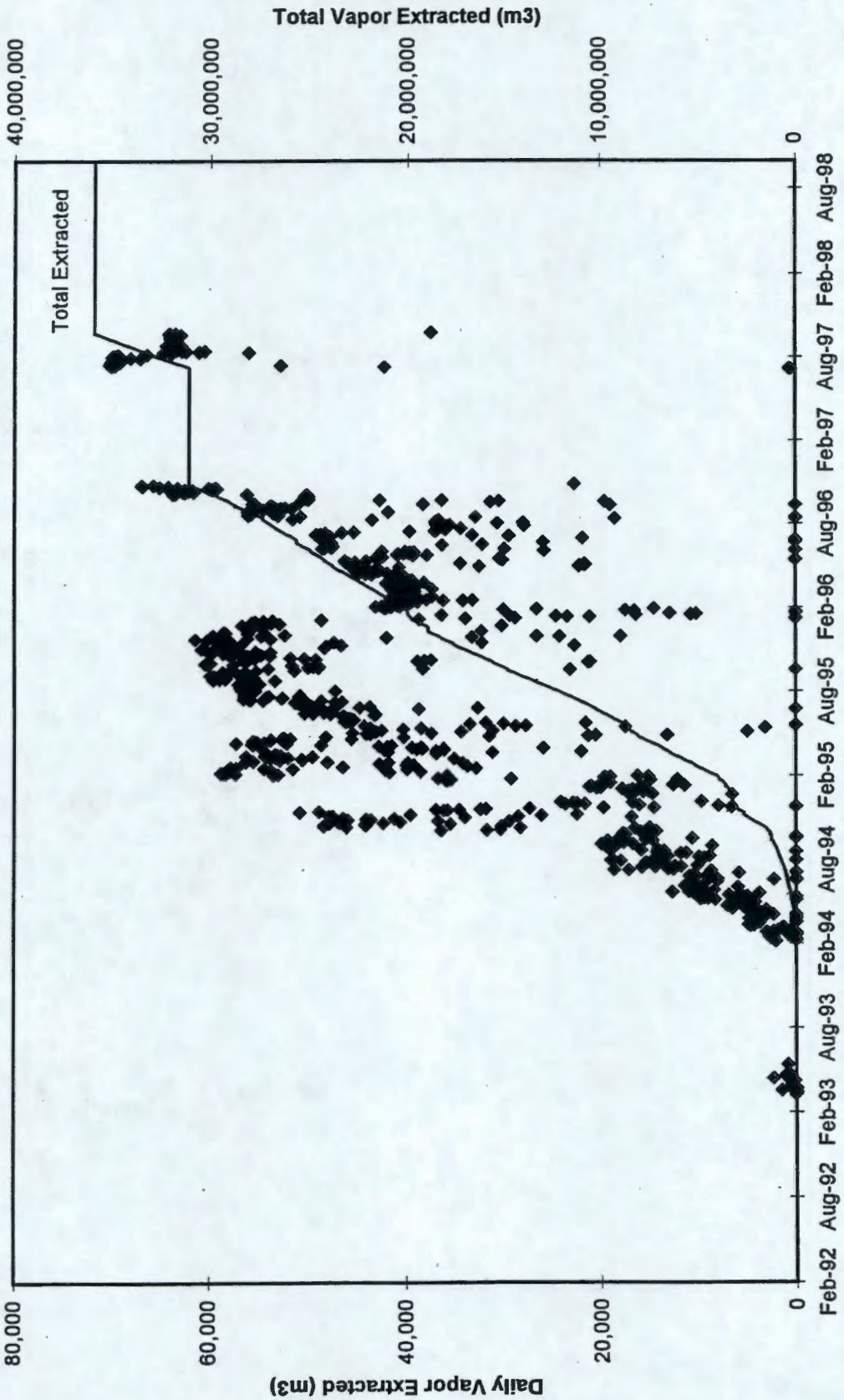


Figure 5-12. Weekly Volume of Knockout Water Drained from Soil Vapor Extraction Systems, October 1994 - September 1997.

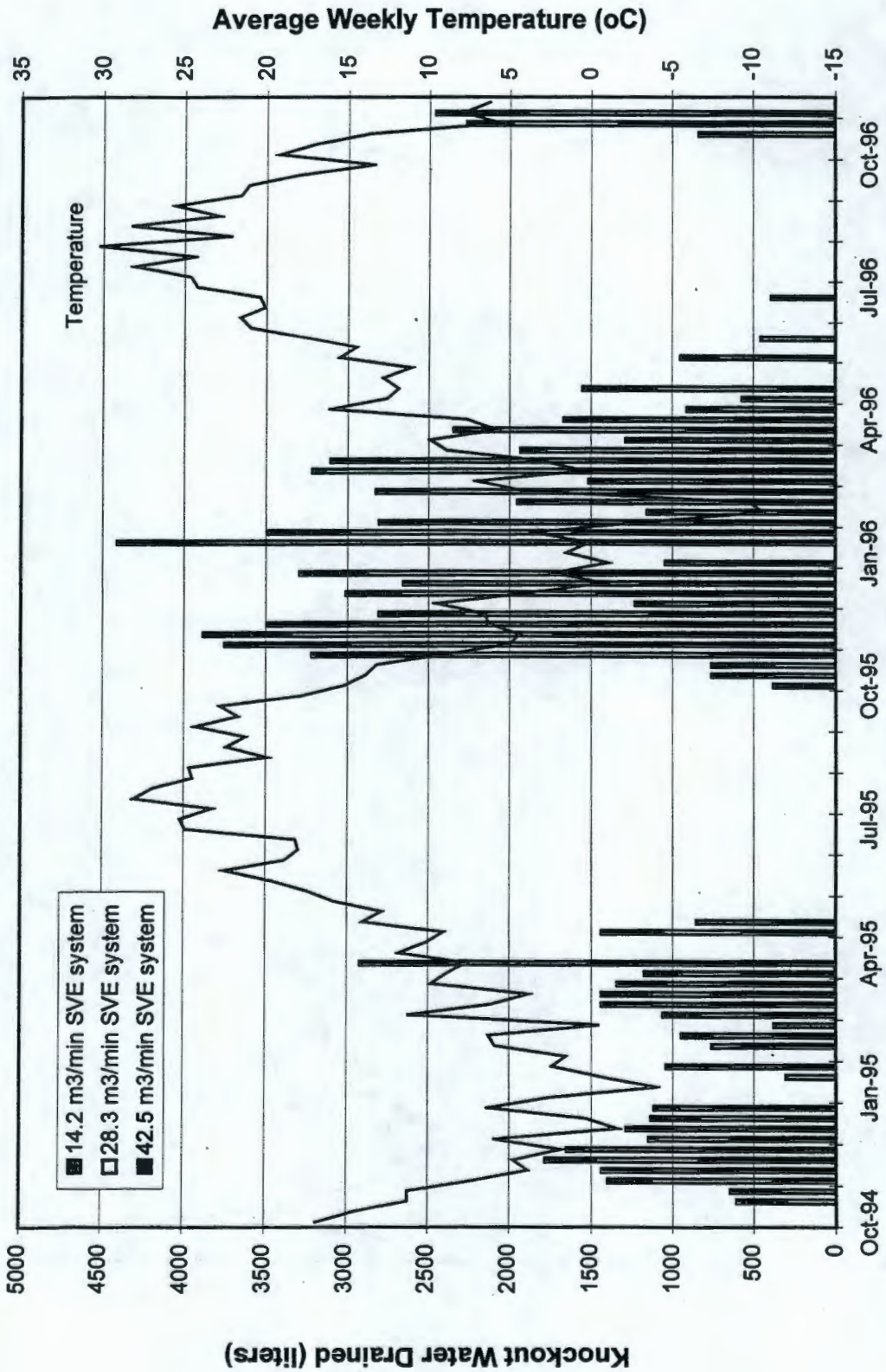


Figure 5-13. Ratio of Cumulative Volume of Knockout Water Drained to Cumulative Volume of Vapor Extracted for Each Soil Vapor Extraction System, October 1994 - April 1995; October 1995 - June 1996; and October 1996.

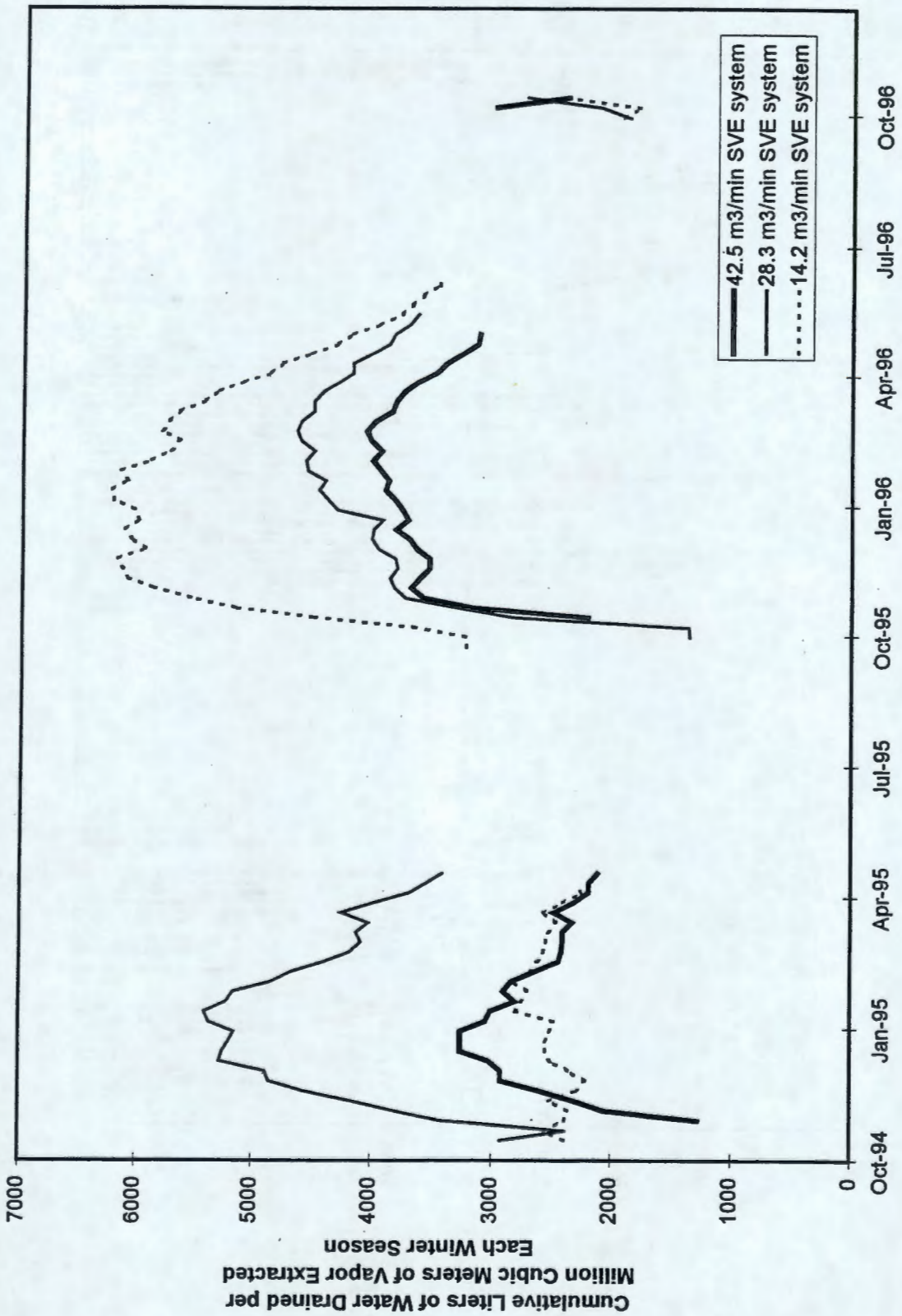


Figure 5-14. Comparison of Carbon Tetrachloride Concentrations to Volume of Vapor Extracted at the 216-Z-1A/Z-18/Z-12 Wellfield, February 1992 - September 1998.

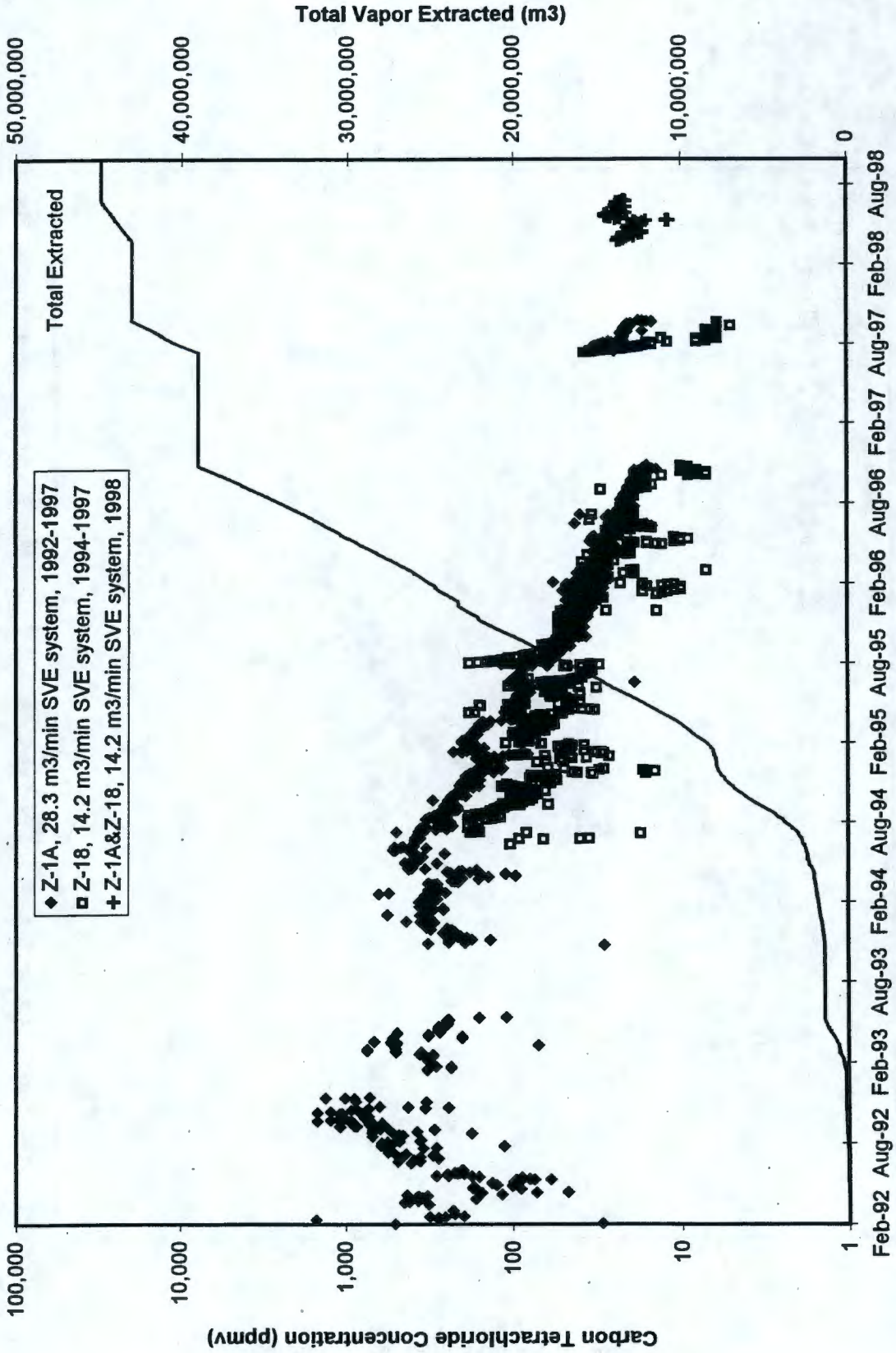


Figure 5-15. Comparison of Carbon Tetrachloride Concentrations to Volume of Vapor Extracted at the 216-Z-9 Wellfield, March 1993 - September 1998.

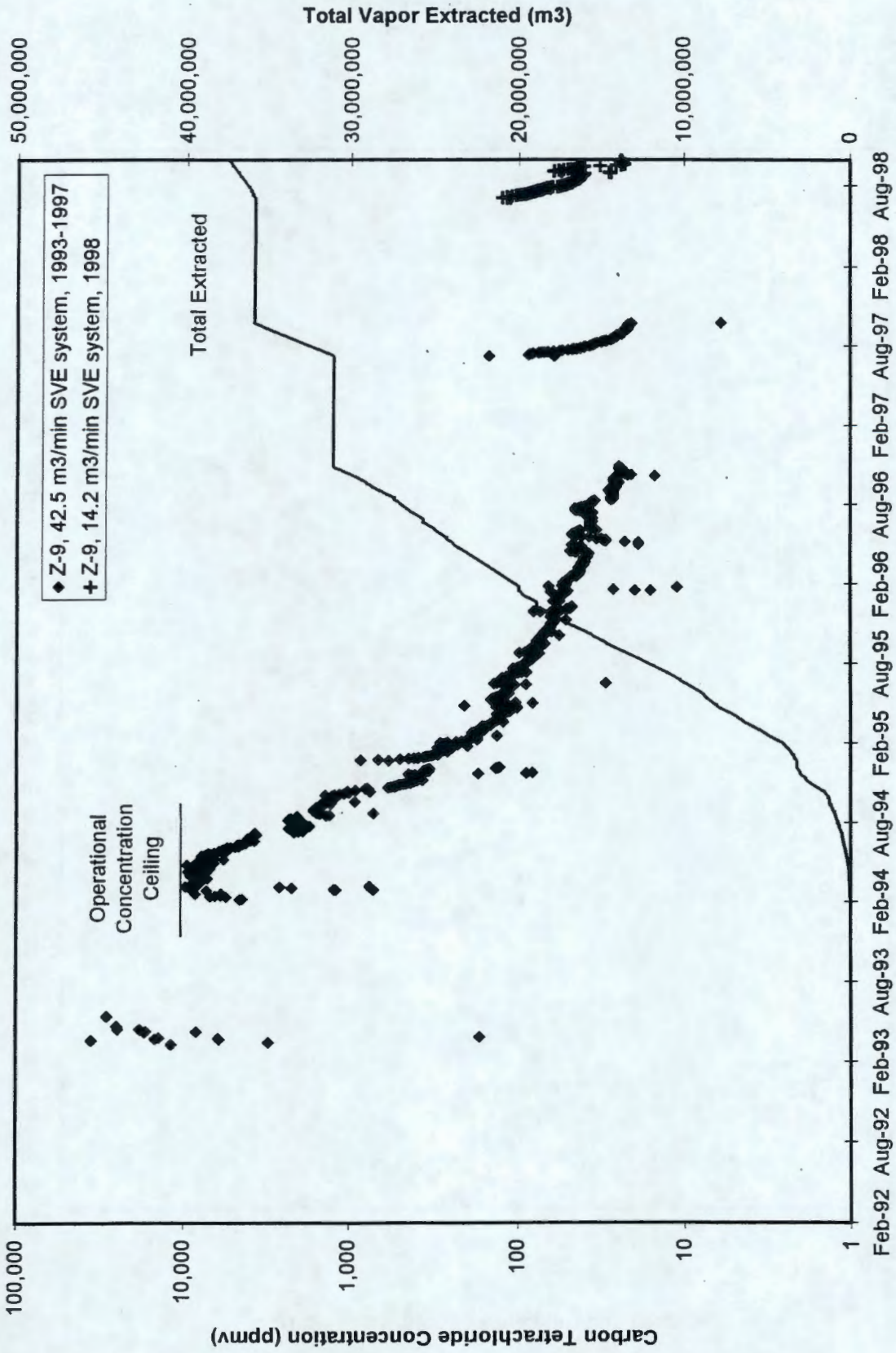


Figure 5-16. Carbon Tetrachloride Concentrations Measured at the 216-Z-9 Wellfield During Continuous Operations, October 1994 - September 1998.

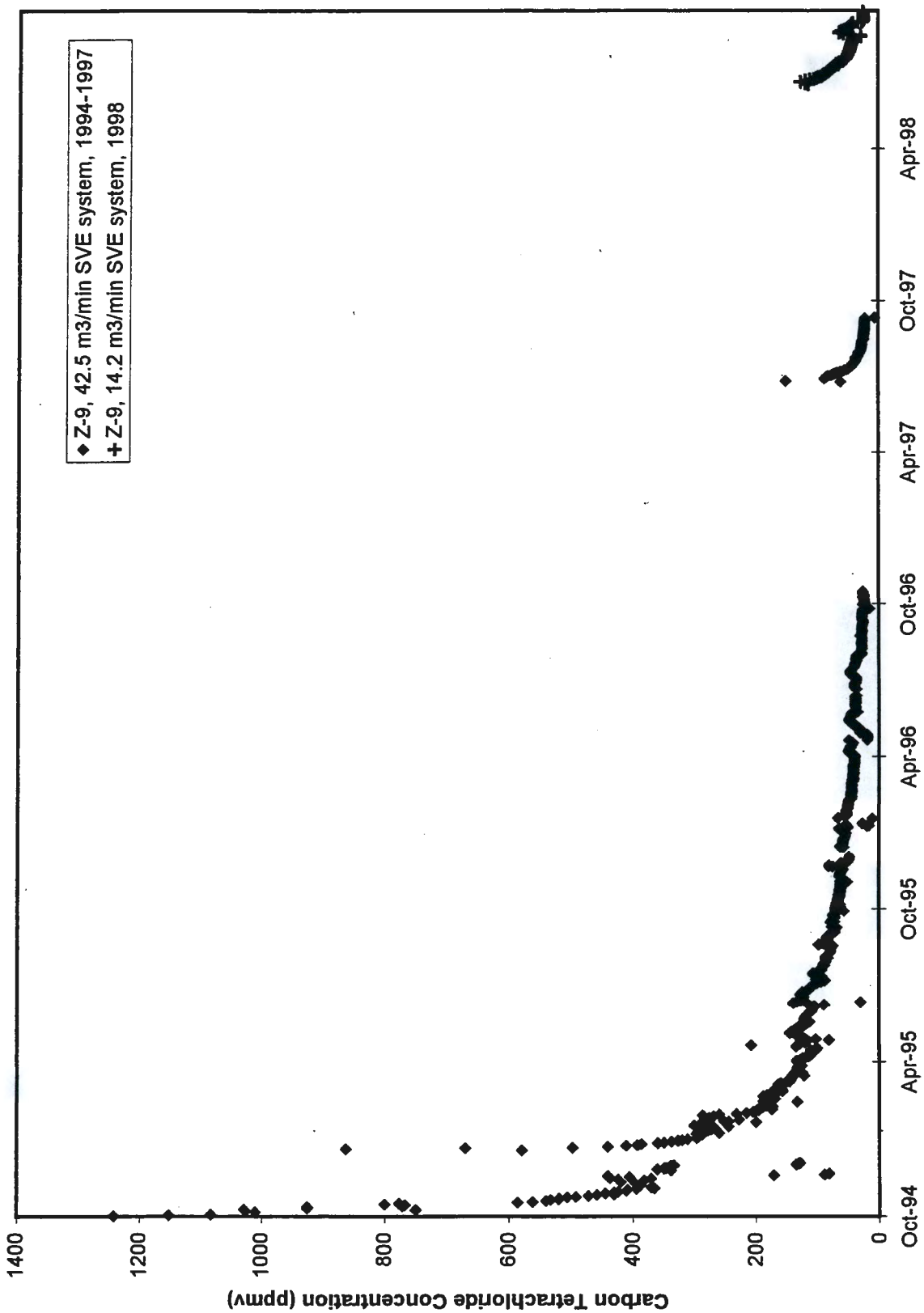


Figure 5-17. Carbon Tetrachloride Concentrations Observed at the 14.2-m^3/min Soil Vapor Extraction System Inlet During Extraction at the 216-Z-1A/Z-18/Z-12 Wellfield, April 1998 - June 1998.

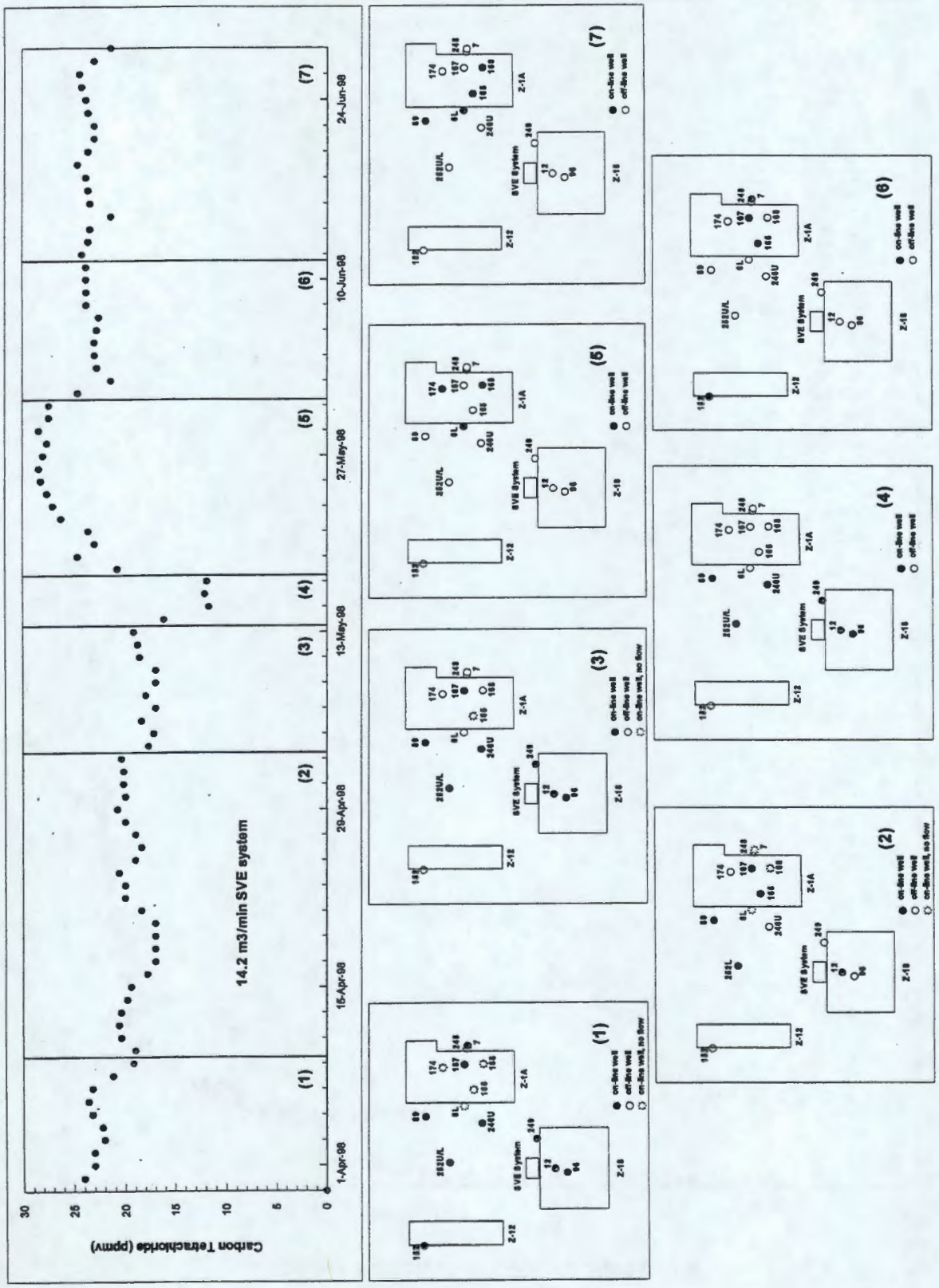


Figure 5-18. Carbon Tetrachloride Concentrations Observed at the 14.2-m^3/min Soil Vapor Extraction System Inlet During Extraction at the 216-Z-9 Wellfield, July 1998 – September 1998.

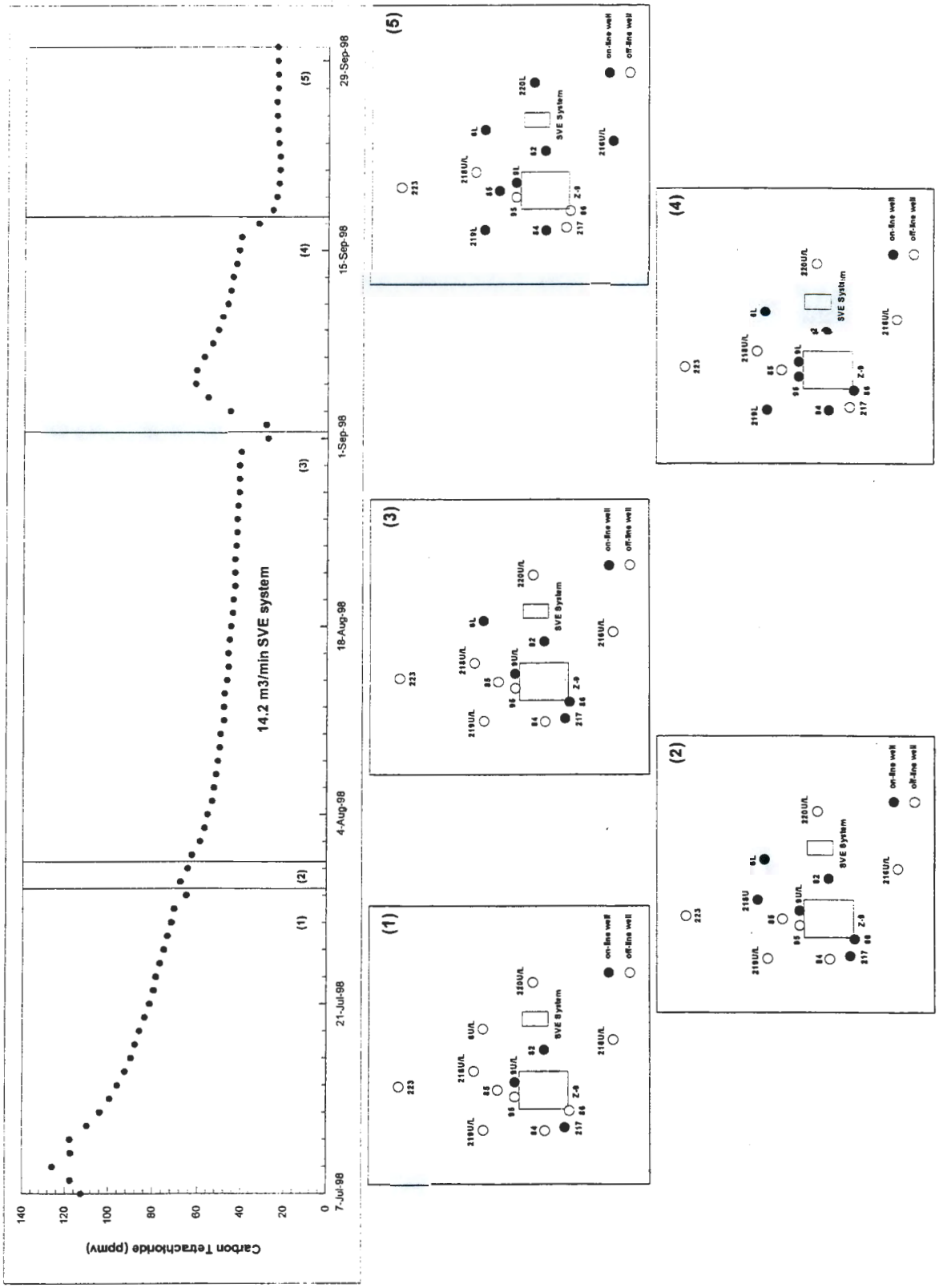


Figure 5-19. Comparison of Carbon Tetrachloride Concentrations and Mass Removal Rates Using the 14.2-m^3/min Soil Vapor Extraction System, April 1998 – September 1998.

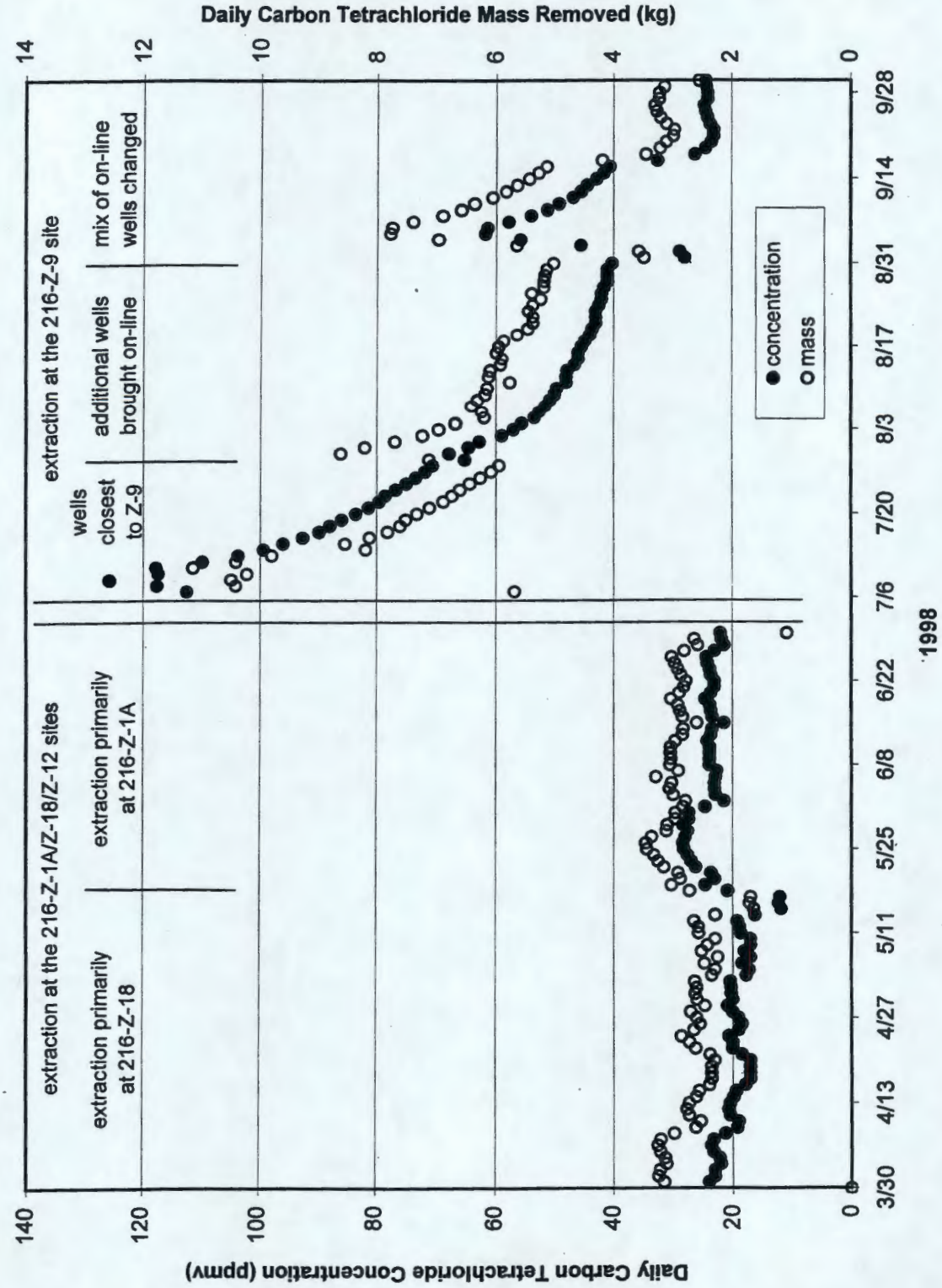


Figure 5-20. Carbon Tetrachloride Concentrations in Vapor Extracted from the 216-Z-9 Wellfield, July 1997 - September 1997 and July 1998 – September 1998.

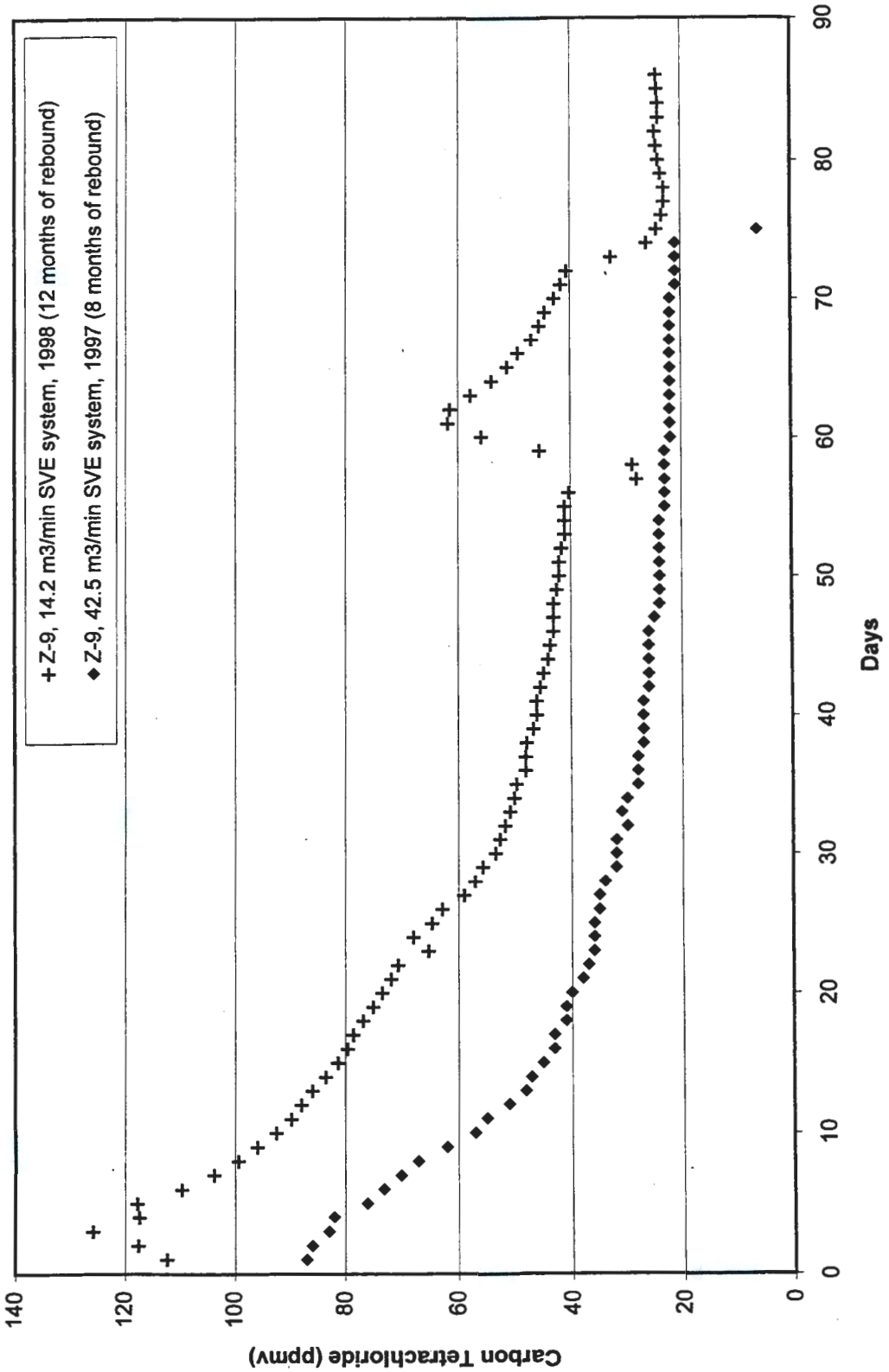


Figure 5-21. Carbon Tetrachloride Concentrations in Vapor Extracted from the 216-Z-1A/Z-18 Wellfield, July 1997 – September 1997 and April 1998 – June 1998.

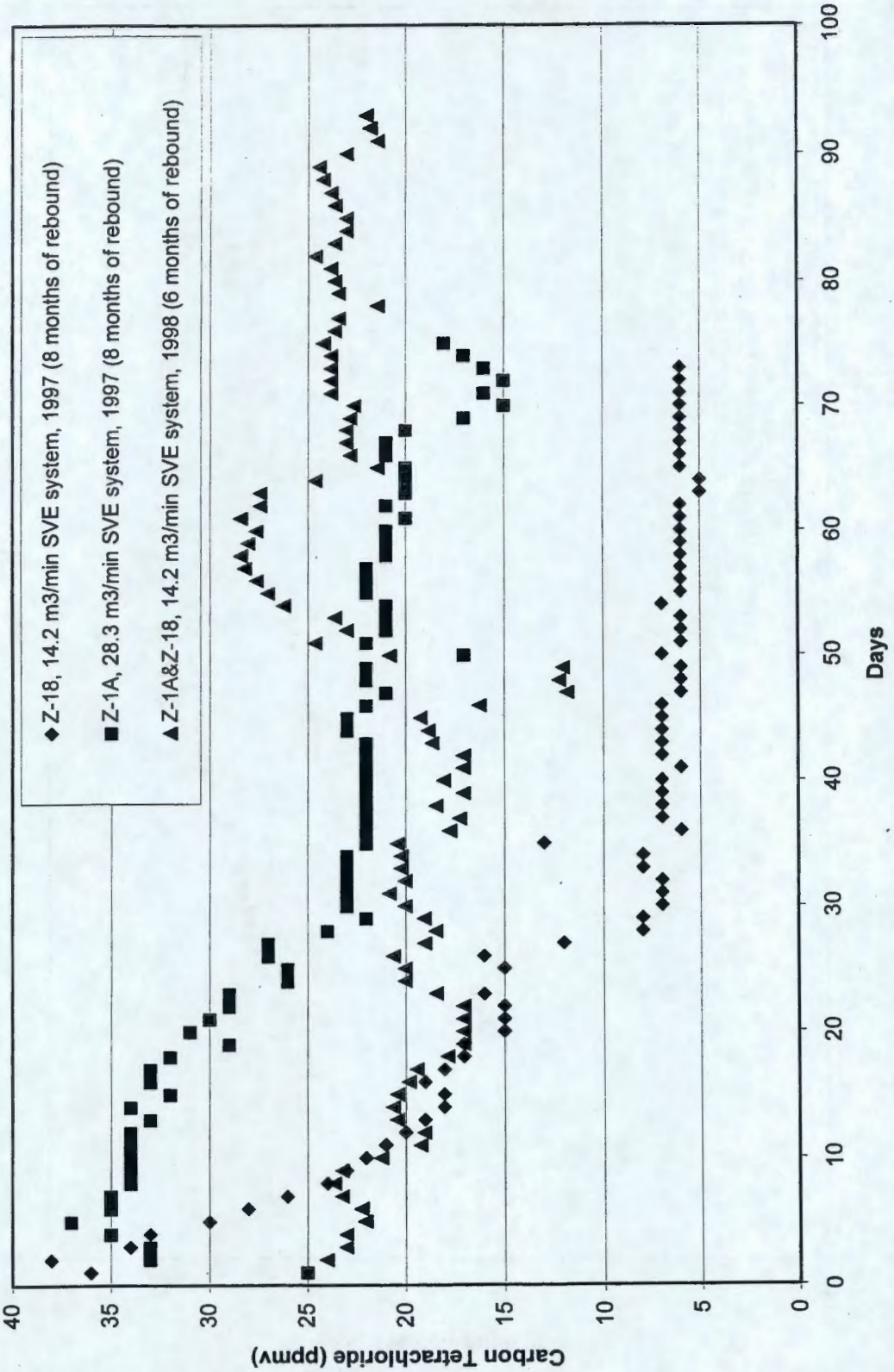


Figure 5-22. Exponential Decay of Carbon Tetrachloride Concentrations, October 1995 Through November 1996.

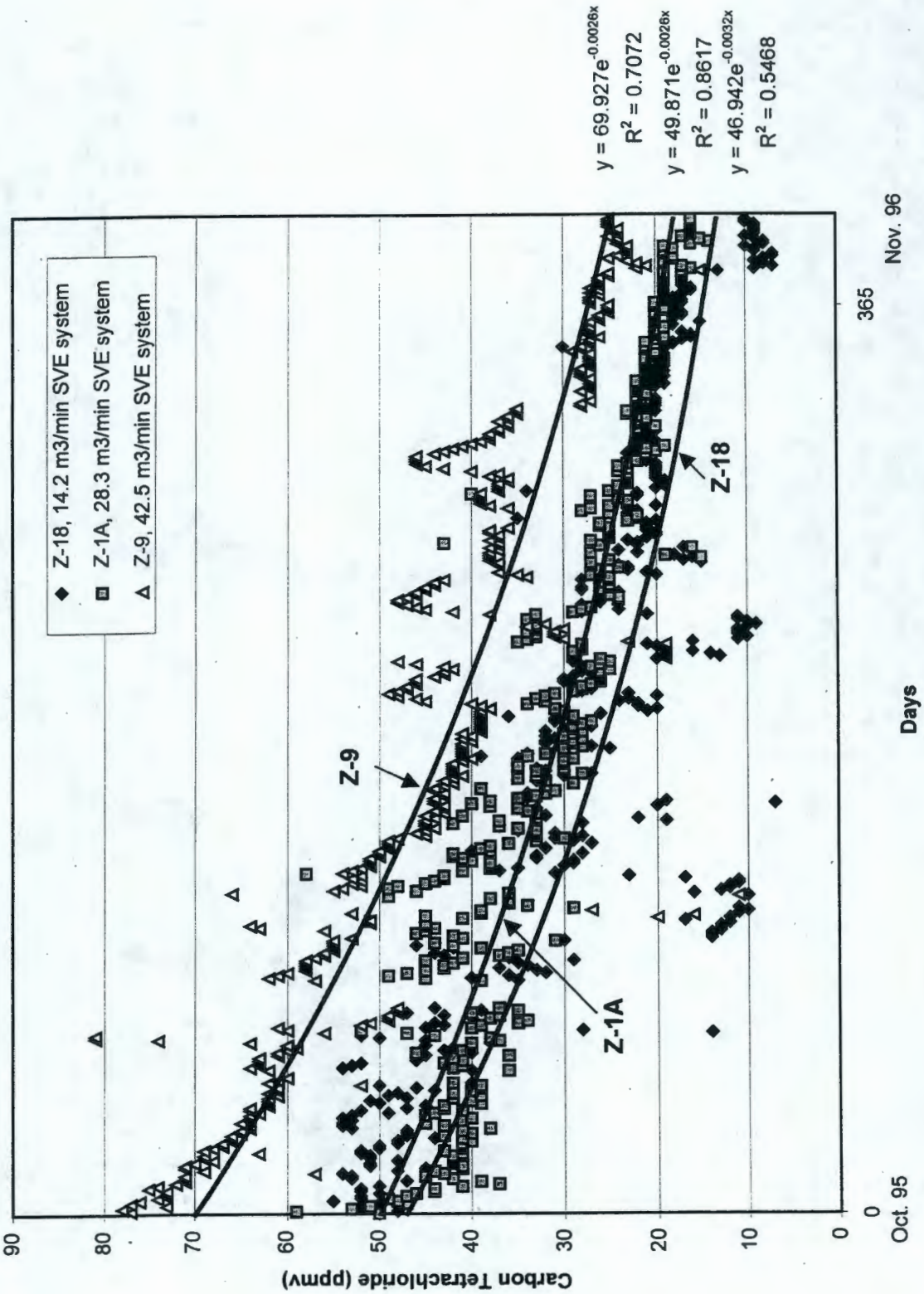


Figure 5-23. Exponential Decay of Carbon Tetrachloride Concentrations, October 1995 Through September 1998.

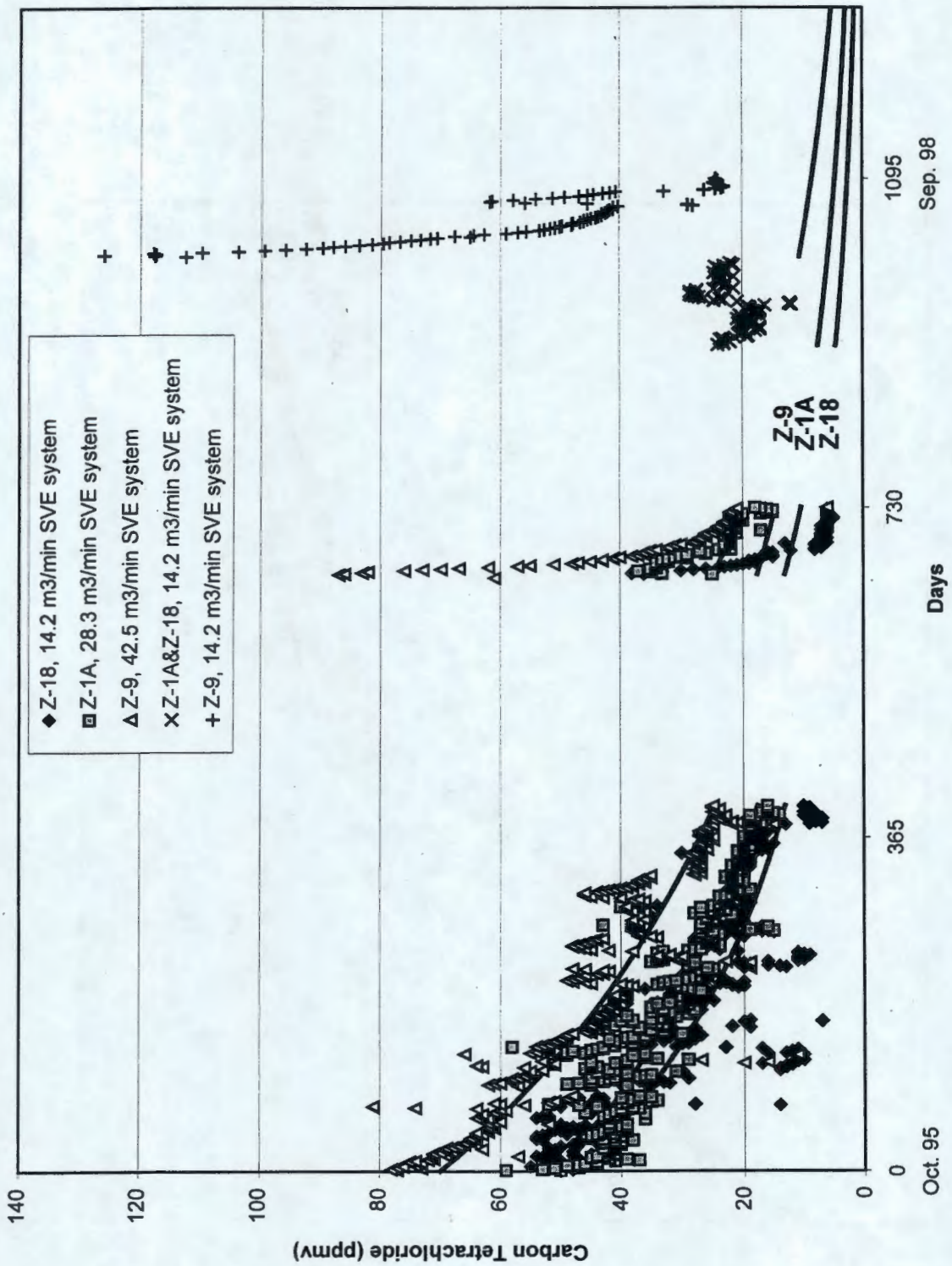


Figure 5-24. Carbon Tetrachloride Concentrations Measured at Extraction Wells in the 216-Z-1A/Z-18 Wellfield, April 1992 - September 1998.

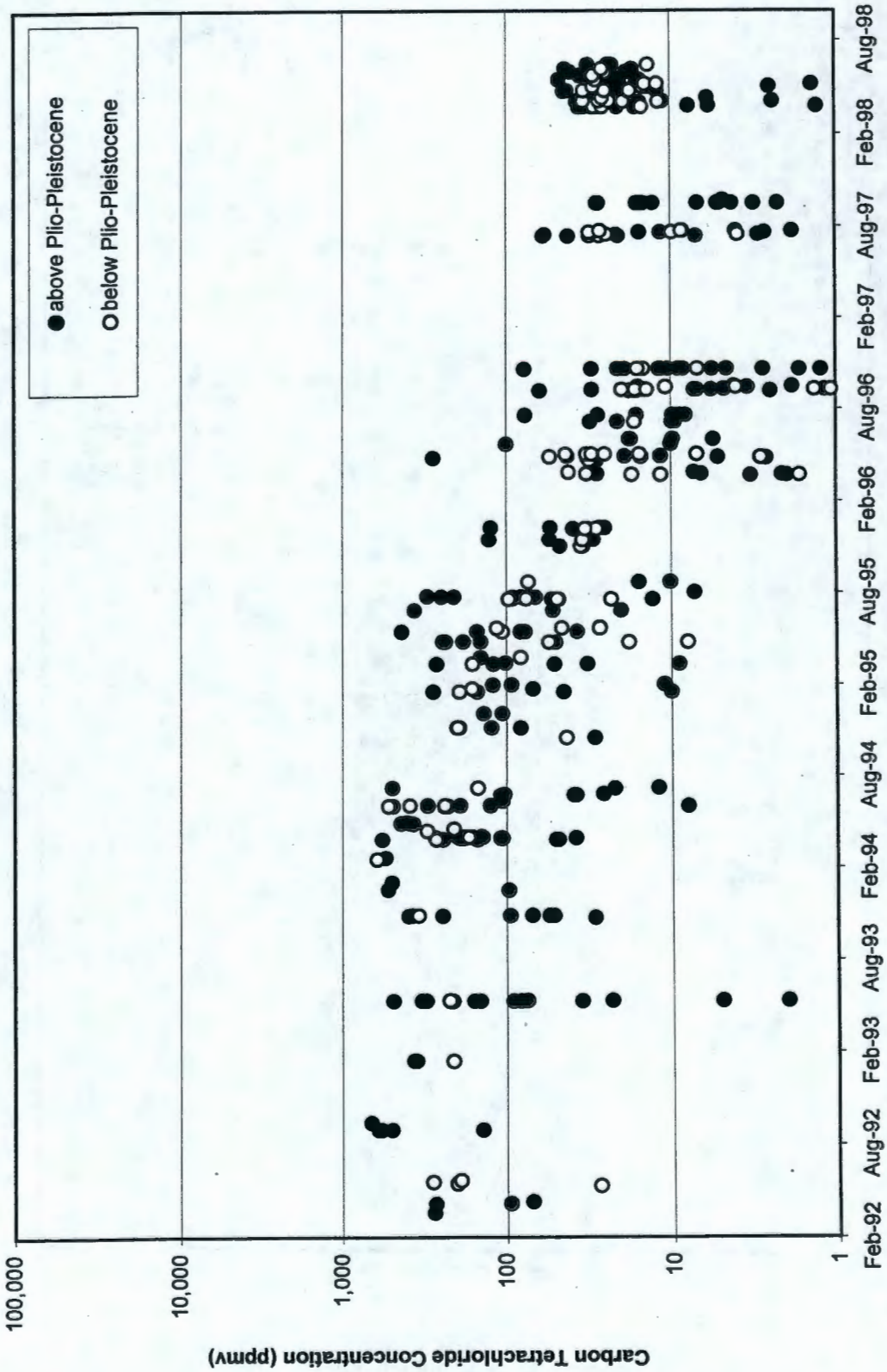


Figure 5-25. Carbon Tetrachloride Concentrations Measured at Extraction Wells in the 216-Z-9 Wellfield, March 1993 - September 1998.

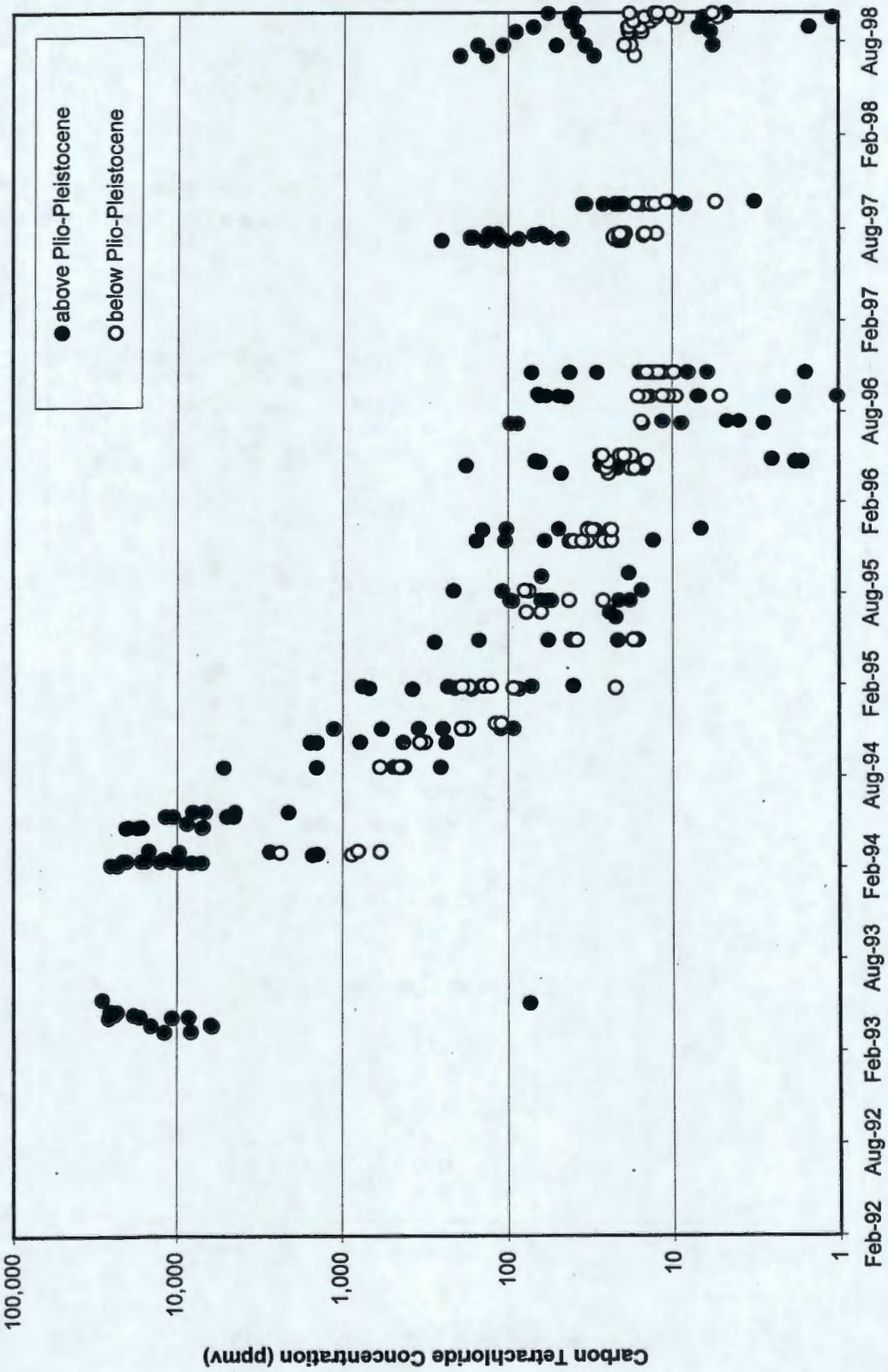


Figure 5-26. Relationship Between Concentrations of Carbon Tetrachloride and Chloroform Measured at Extraction Wells in the 216-Z-9 Wellfield.

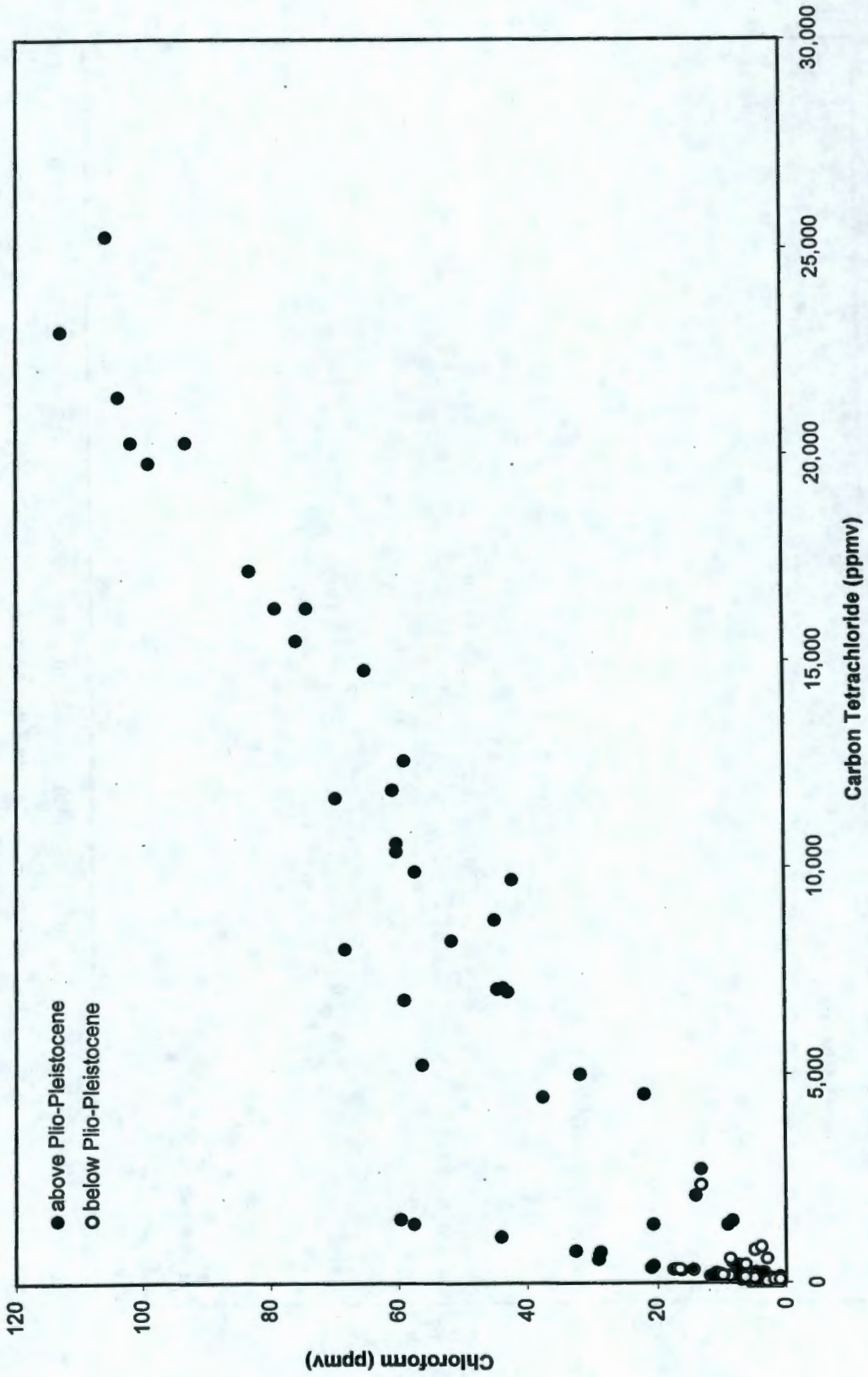


Figure 5-27. Relationship Between Concentrations of Carbon Tetrachloride Less Than 1,000 ppmv and Chloroform Measured at Extraction Wells in the 216-Z-9 Wellfield.

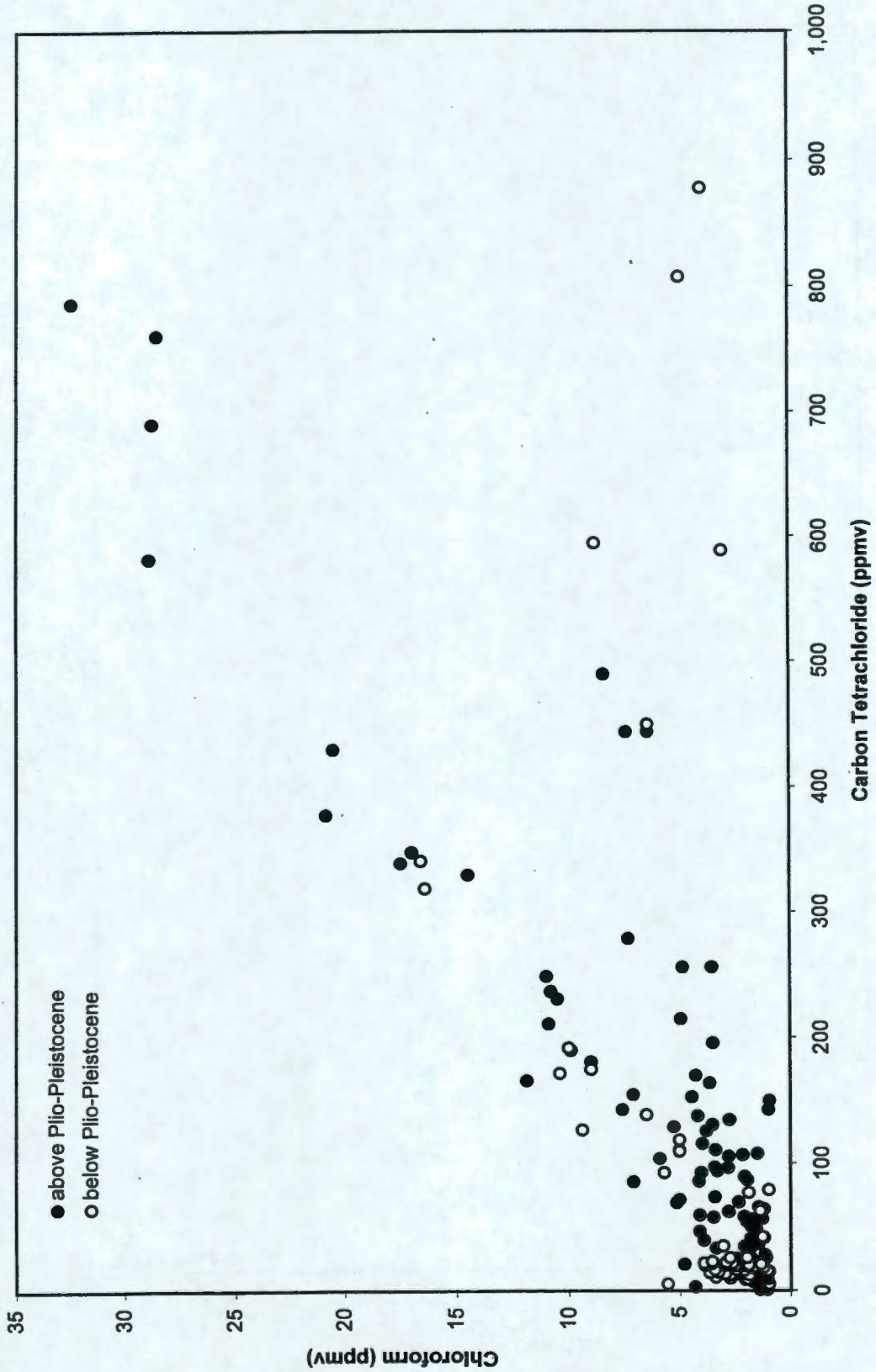


Figure 5-28. Relationship Between Concentrations of Carbon Tetrachloride and Chloroform Measured at Two 216-Z-9 Wells, W15-82 and W15-217.

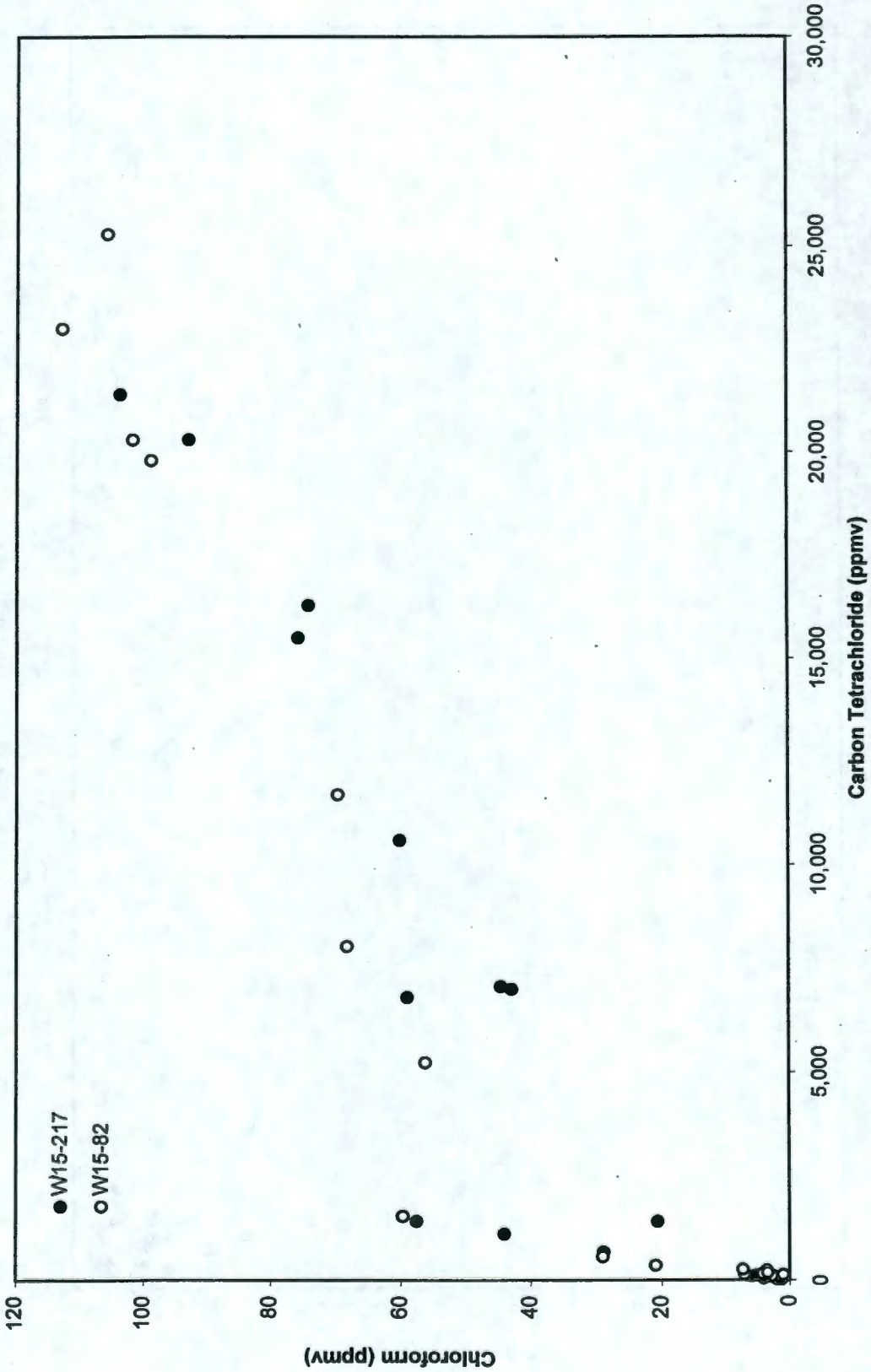


Figure 5-29. Relationship Between Concentrations of Carbon Tetrachloride and Chloroform Measured at Extraction Wells in the 216-Z-1A/Z-18/Z-12 Wellfield.

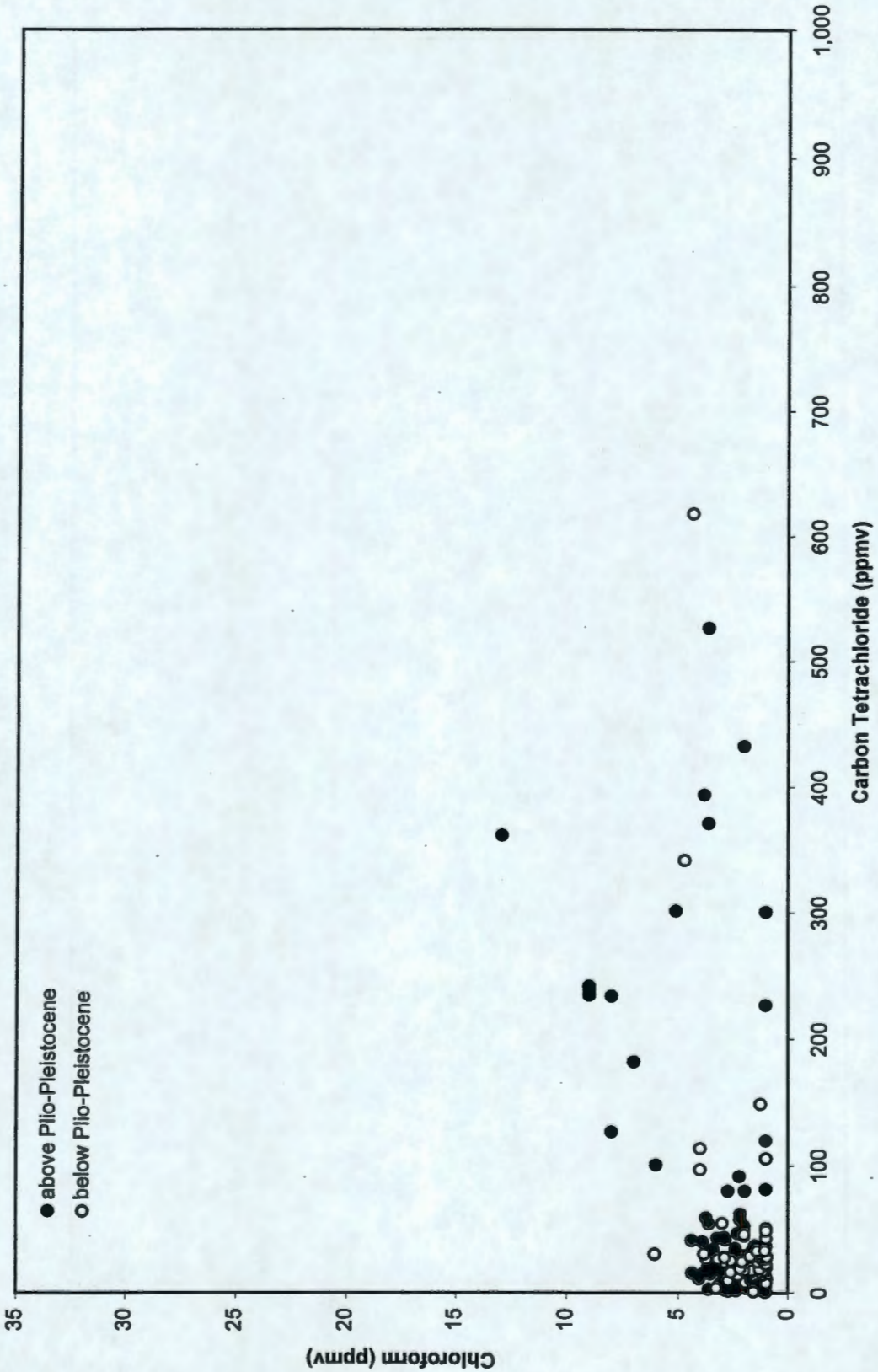


Figure 5-30. Mass of Carbon Tetrachloride Removed from the 216-Z-1A/Z-18/Z-12 Wellfield, February 1992 - September 1998.

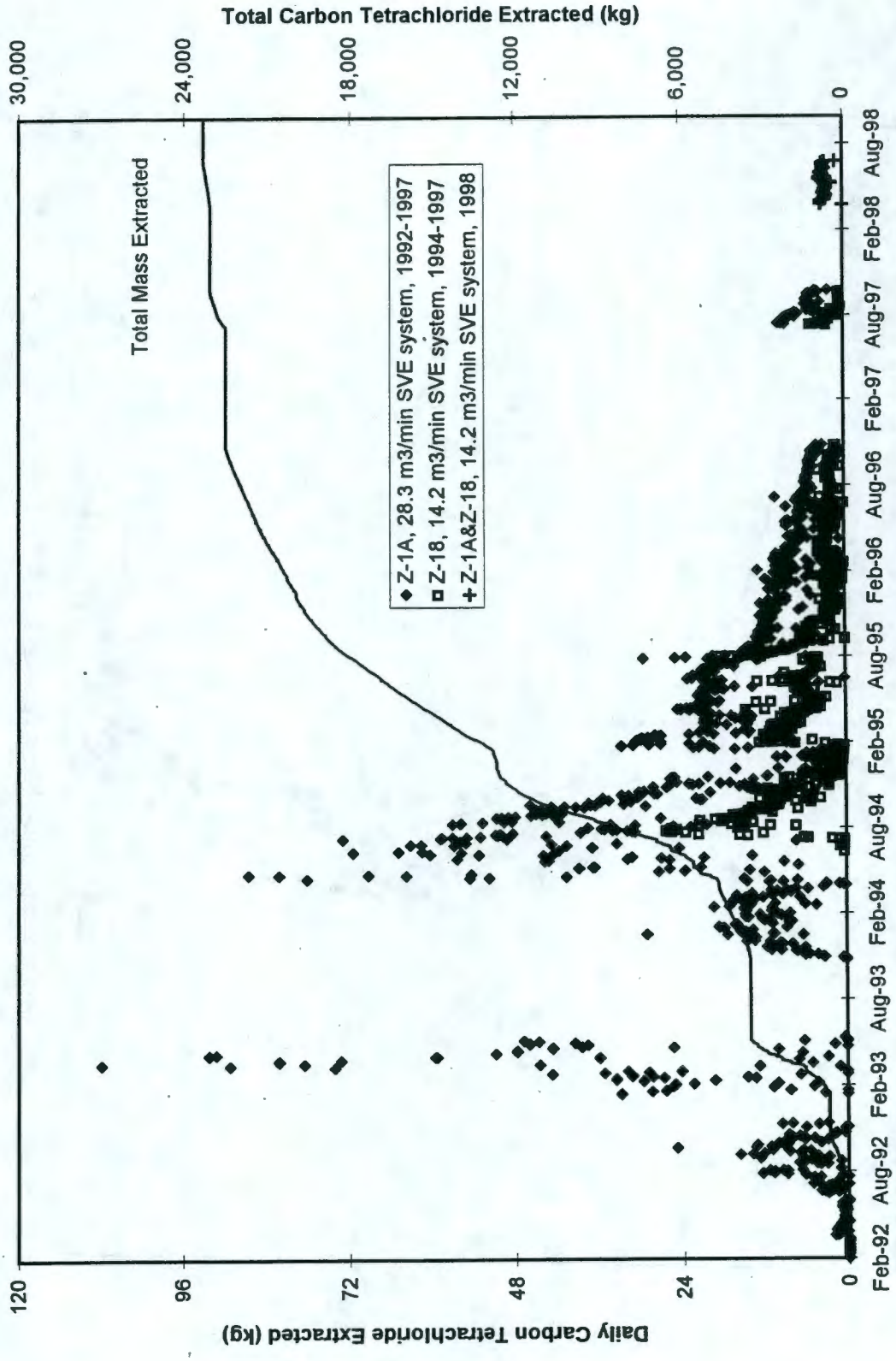


Figure 5-31. Mass of Carbon Tetrachloride Removed From the 216-Z-9 Wellfield, March 1993 - September 1998.

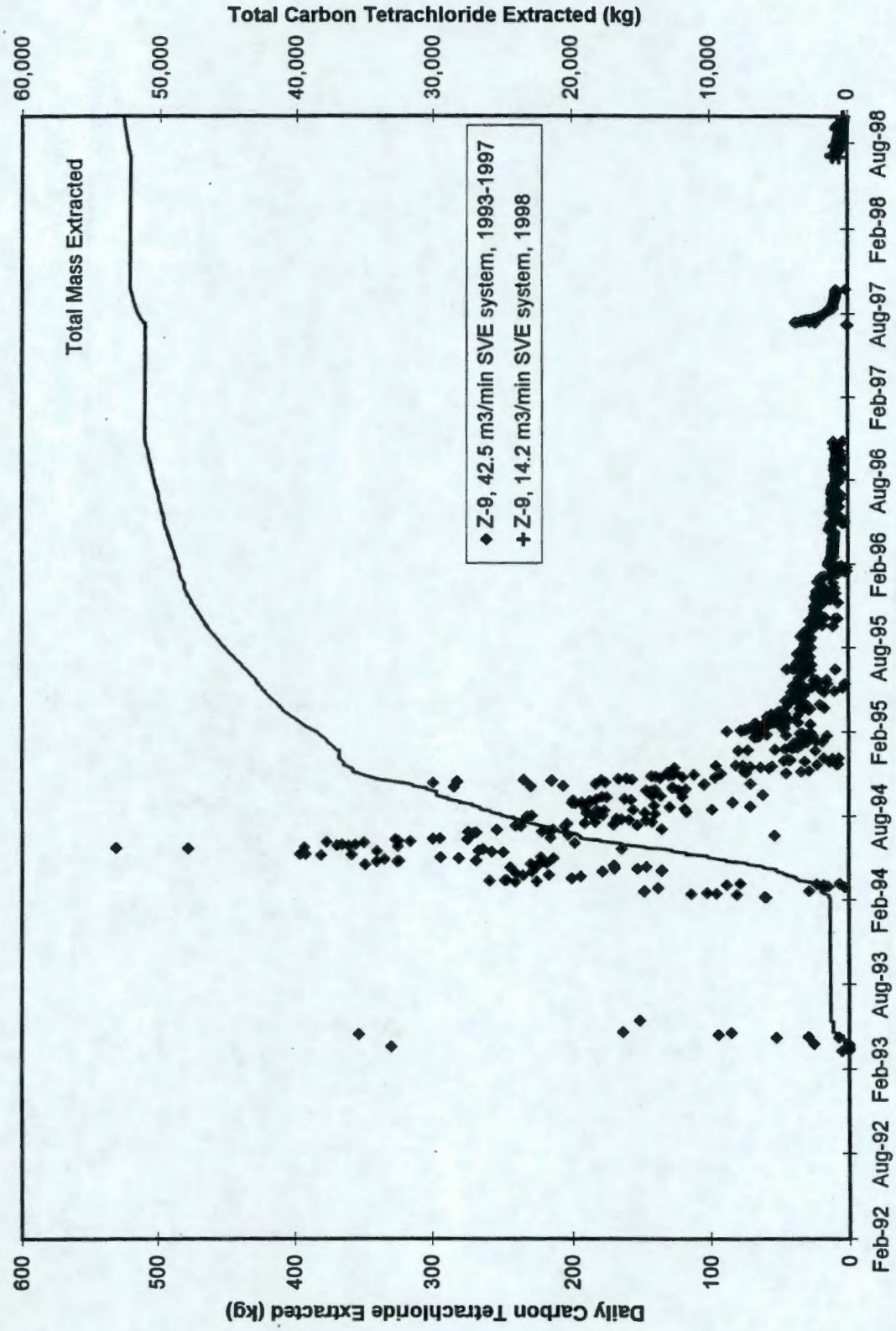
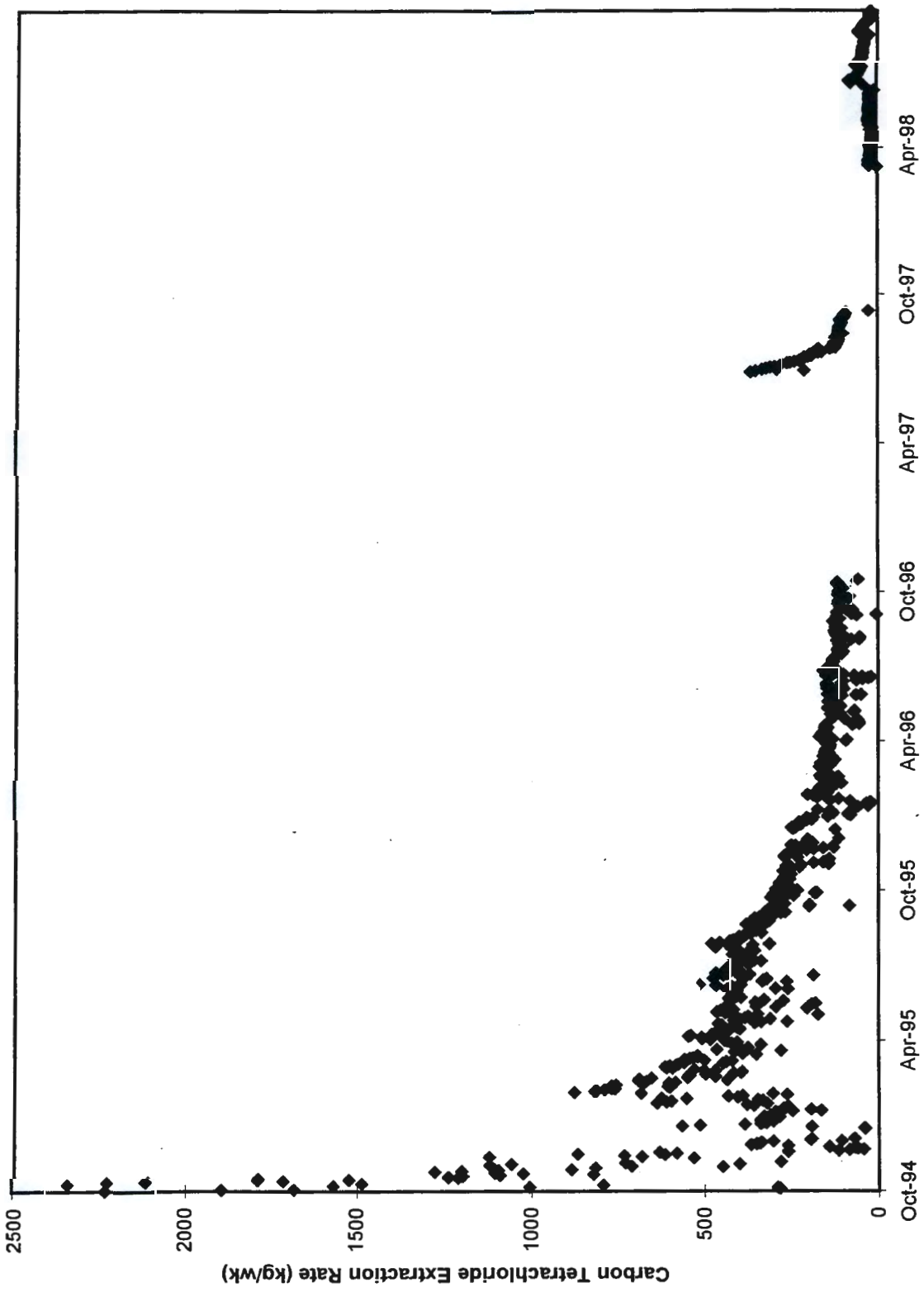


Figure 5-32. Decline in Total Carbon Tetrachloride Mass Removal Rate Between October 1994 and September 1998.



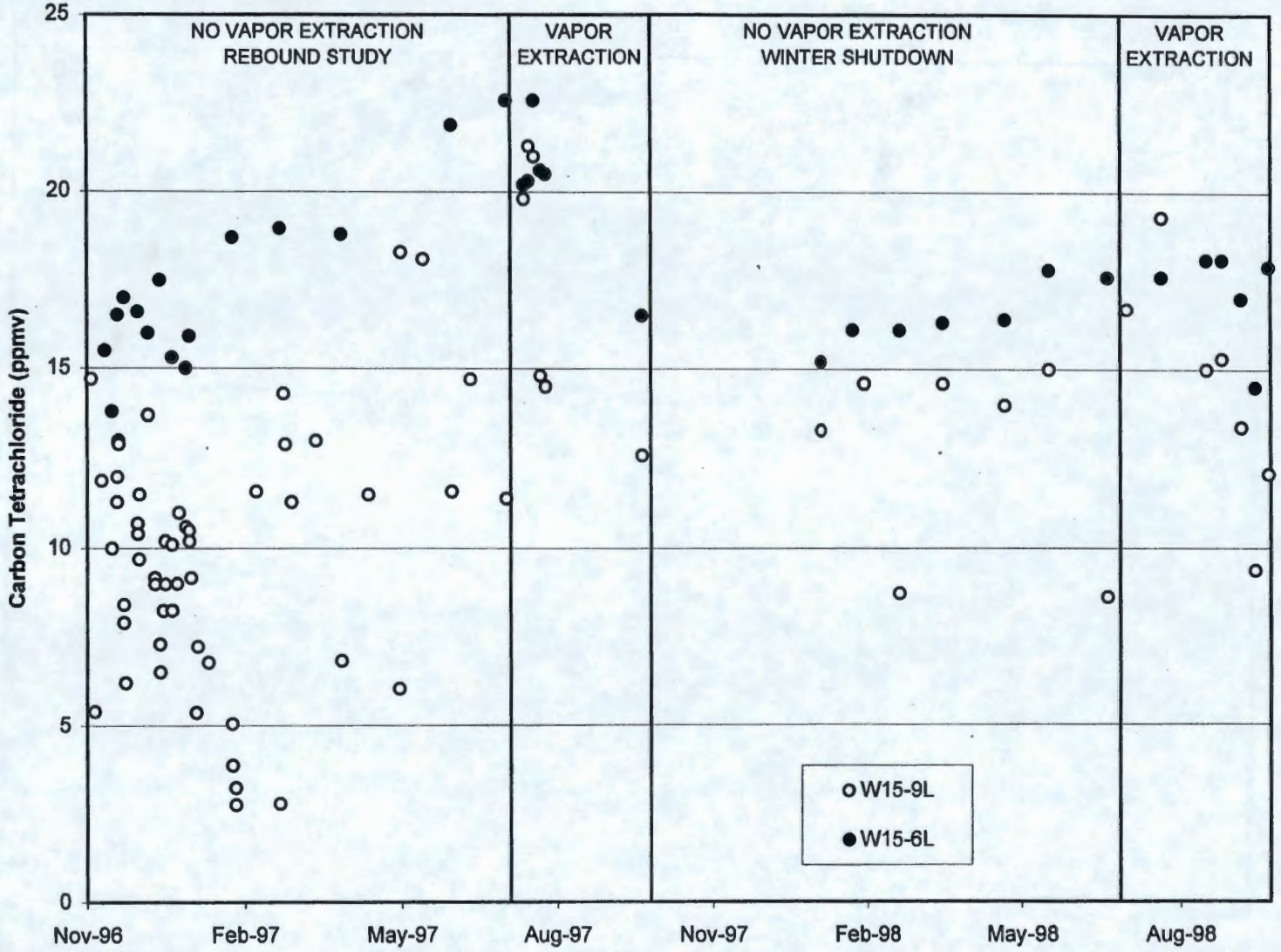


Figure 5-33. Carbon Tetrachloride Concentrations Monitored at 216-Z-9 Wells W15-6L and W15-9L.

Table 5-1. Planned Operating Times for the Soil Vapor Extraction Systems.

Soil Vapor Extraction System (m^3/min)	Time Period	Operating Hours/Day	Operating Days/Week
42.5	2/23/94 – 5/9/94	7	5
	5/10/94 – 10/18/94	9	5
	10/19/94 – 11/3/96	24	7
	11/4/96 – 7/17/97	0	0
	7/18/97 – 9/30/97	24	7
28.3	1/3/94 - 4/29/94	7	5
	5/2/94 - 7/10/94	24	5
	7/11/94 – 11/3/96	24	7
	11/4/96 – 7/17/97	0	0
	7/18/97 – 9/30/97	24	7
14.2	6/30/94 - 8/2/94	9	5
	8/3/94 – 11/3/96	24	7
	11/4/96 – 7/17/97	0	0
	7/18/97 – 9/30/97	24	7
	3/30/98 – 9/30/98	24	7

Table 5-2. Monthly Availability Data for the Soil Vapor Extraction Systems, January 1994 - September 1998.

Monthly Availability (= monthly operating hours/monthly available operating hours)												
Month	42.5 m3/min			28.3 m3/min			14.2 m3/min			Total		
	Op. Hrs	Avail. Hrs	Availability	Op. Hrs	Avail. Hrs	Availability	Op. Hrs	Avail. Hrs	Availability	Op. Hrs	Avail. Hrs	Availability
Jan-94				123	147	84%				123	147	84%
Feb-94				103	140	74%				103	140	74%
Mar-94	101	189	53%	127	161	79%				228	350	65%
Apr-94	72	147	49%	105	147	71%				177	294	60%
May-94	144	183	79%	400	452	88%				544	635	86%
Jun-94	175	197	89%	339	460	74%				514	657	78%
Jul-94	111	166	67%	397	575	69%	44	180	24%	551	921	60%
Aug-94	179	203	88%	694	744	93%	522	707	74%	1395	1654	84%
Sep-94	168	193	87%	589	720	82%	709	720	98%	1466	1633	90%
Oct-94	261	372	70%	655	744	88%	684	744	92%	1600	1860	86%
Nov-94	534	624	86%	408	624	65%	521	624	83%	1463	1872	78%
Dec-94	374	504	74%	417	516	81%	364	504	72%	1154	1524	76%
Jan-95	593	696	85%	668	696	96%	192	696	28%	1453	2088	70%
Feb-95	591	672	88%	629	672	94%	419	672	62%	1639	2016	81%
Mar-95	687	744	92%	596	744	80%	741	744	100%	2023	2232	91%
Apr-95	625	720	87%	694	720	96%	699	720	97%	2018	2160	93%
May-95	595	744	80%	741	744	100%	700	744	94%	2035	2232	91%
Jun-95	628	720	87%	698	720	97%	700	720	97%	2026	2160	94%
Jul-95	704	744	95%	639	672	95%	734	744	99%	2077	2160	96%
Aug-95	737	744	99%	709	744	95%	741	744	100%	2188	2232	98%
Sep-95	701	720	97%	691	720	96%	623	720	86%	2015	2160	93%
Oct-95	643	744	86%	692	744	93%	667	744	90%	1994	2208	90%
Nov-95	617	672	92%	593	606	98%	603	605	100%	1813	1883	96%
Dec-95	507	518	98%	512	517	99%	416	517	80%	1434	1552	92%
Jan-96	590	711	83%	697	710	98%	580	710	82%	1866	2131	88%
Feb-96	552	696	79%	653	696	94%	506	696	73%	1710	2088	82%
Mar-96	729	744	98%	715	744	96%	589	744	79%	2034	2232	91%
Apr-96	713	720	99%	661	720	92%	715	720	99%	2088	2160	97%
May-96	651	744	87%	731	744	98%	725	744	97%	2106	2232	94%
Jun-96	637	720	88%	610	720	85%	570	720	79%	1817	2160	84%
Jul-96	533	744	72%	742	744	100%	595	744	80%	1871	2232	84%
Aug-96	628	744	84%	742	744	100%	712	744	96%	2082	2232	93%
Sep-96	644	720	89%	671	720	93%	690	720	96%	2005	2160	93%
Oct-96	741	744	100%	741	744	100%	743	744	100%	2225	2232	100%
Nov-96	80	80	100%	91	91	100%	92	92	100%	263	263	100%
Jul-97	320	326	98%	327	327	100%	322	326	99%	969	979	99%
Aug-97	738	744	99%	741	744	100%	678	744	91%	2157	2232	97%
Sep-97	720	720	100%	707	708	100%	663	720	92%	2090	2148	97%
Apr-98							767	768	100%	767	768	100%
May-98							744	744	100%	744	744	100%
Jun-98							706	720	98%	706	720	98%
Jul-98							589	600	98%	589	600	98%
Aug-98							740	744	99%	740	744	99%
Sep-98							716	720	99%	716	720	99%

Table 5-3. Number of Hours Each Soil Vapor Extraction System Has Operated.

Soil Vapor Extraction System (m^3/min)	Number of Hours Operated Each Calendar Year							
	1992	1993	1994	1995	1996	1997	1998	Total
14.2	--	--	2,843	7,235	6,516	1,663	4,261	22,517
28.3	852	1,565	4,357	7,862	7,054	1,775	0	23,464
42.5	--	76	2,119	7,628	6,496	1,784	0	18,103
Total	852	1,641	9,319	22,725	20,066	5,222	4,261	64,084

Table 5-4. Volume of Vapor Processed by Soil Vapor Extraction Systems.

Soil Vapor Extraction System (m^3/min)	Volume of Vapor Processed Each Calendar Year							
	1992 (m^3)	1993 (m^3)	1994 (m^3)	1995 (m^3)	1996 (m^3)	1997 (m^3)	1998 (m^3)	Total (m^3)
14.2	--	--	2,100E+03	4,900E+03	4,550E+03	1,220E+03	3,490E+03	16,250E+03
28.3	150E+03	1,420E+03	4,190E+03	10,470E+03	11,190E+03	2,830E+03	--	30,260E+03
42.5	--	10E+03	3,190E+03	15,690E+03	12,180E+03	4,860E+03	--	35,930E+03
Total	150E+03	1,430E+03	9,480E+03	31,060E+03	27,920E+03	8,910E+03	3,490E+03	82,440E+03

Table 5-5. Volume of Vapor Extracted from Each Extraction Well Between February 1992 and September 1998.

216-Z-9 Wells	Vapor Extracted (m^3)	216-Z-18/12 Wells	Vapor Extracted (m^3)	216-Z-1A Wells	Vapor Extracted (m^3)
W15-6L	1,880E+03	W18-10L	2,440E+03	W18-6L	1,730E+03
W15-6U	150E+03	W18-10U	660E+03	W18-6U	140E+03
W15-8	0E+03	W18-11L	240E+03	W18-7	8,040E+03
W15-9L	480E+03	W18-12	710E+03	W18-87L	40E+03
W15-9U	580E+03	W18-93	10E+03	W18-87M	20E+03
W15-82	4,090E+03	W18-94	0E+03	W18-87U	40E+03
W15-84	2,400E+03	W18-96	410E+03	W18-89	6,030E+03
W15-85	2,610E+03	W18-97	230E+03	W18-150L	240E+03
W15-86	450E+03	W18-98	0E+03	W18-150M	40E+03
W15-95	760E+03	W18-99	160E+03	W18-150U	40E+03
W15-216L	1,140E+03	W18-152	1,720E+03	W18-158L	210E+03
W15-216U	530E+03	W18-153	480E+03	W18-158M	0E+03
W15-217	3,760E+03	W18-246L	1,450E+03	W18-158U	820E+03
W15-218L	3,500E+03	W18-246U	610E+03	W18-159	870E+03
W15-218U	3,370E+03	W18-249	530E+03	W18-163L	150E+03
W15-219L	2,660E+03	W18-252L	3,160E+03	W18-163M	10E+03
W15-219U	2,770E+03	W18-252U	1,020E+03	W18-163U	360E+03
W15-220L	1,400E+03			W18-165	1,430E+03
W15-220U	2,000E+03			W18-166	670E+03
W15-223	1,370E+03			W18-167	1,130E+03
				W18-168	1,210E+03
				W18-169	130E+03
				W18-171L	440E+03
				W18-171M	390E+03
				W18-171U	460E+03
				W18-174	2,240E+03
				W18-175	350E+03
				W18-248	1,950E+03
Above Plio-Pleistocene	24,830E+03		5,840E+03		19,410E+03
Below Plio-Pleistocene	11,070E+03		8,000E+03		9,770E+03
Total	35,900E+03		13,840E+03		29,180E+03

Table 5-6. Weekly Volume of Knockout Water Drained from Soil Vapor Extraction Systems, October 1994 - September 1998. (2 Pages)

		Knock-out Water Drained (liters)			
		SVE System			Total
Week Start	Week End	42.5 m3/min	28.3 m3/min	14.2 m3/min	
10/20/92	2/9/94	0	1,022	0	1,022
2/10/94	6/30/94	1747	1747	0	3,493
1992-1994 Total*		1747	2769	0	4,515
10/13/94	10/19/94	0	303	303	606
10/20/94	10/26/94	0	341	303	643
10/27/94	11/2/94	379	757	265	1,400
11/3/94	11/9/94	833	303	303	1,438
11/10/94	11/16/94	833	643	303	1,779
11/17/94	11/23/94	795	757	98	1,650
11/24/94	11/30/94	643	454	53	1,151
12/1/94	12/7/94	530	454	303	1,287
12/8/94	12/14/94	303	530	303	1,136
12/15/94	12/21/94	738	227	151	1,117
12/22/94	12/28/94	0	0	0	0
12/29/94	1/4/95	0	0	0	0
1/5/95	1/11/95	0	303	0	303
1/12/95	1/18/95	284	379	379	1,041
1/19/95	1/25/95	0	0	0	0
1/26/95	2/1/95	568	189	0	757
2/2/95	2/8/95	379	379	189	946
2/9/95	2/15/95	0	379	0	379
2/16/95	2/22/95	454	379	227	1,060
2/23/95	3/1/95	757	379	303	1,438
3/2/95	3/8/95	757	379	303	1,438
3/9/95	3/15/95	662	379	303	1,344
3/16/95	3/22/95	568	379	227	1,173
3/23/95	3/29/95	1,514	871	530	2,914
3/30/95	4/5/95	0	0	0	0
4/6/95	4/12/95	0	0	0	0
4/13/95	4/19/95	568	492	379	1,438
4/20/95	4/26/95	379	473	0	852
1994-1995 Total		11,942	10,125	5,223	27,290
9/28/95	10/4/95	0	0	379	379
10/5/95	10/11/95	0	379	379	757
10/12/95	10/18/95	0	379	379	757
10/19/95	10/25/95	757	1,703	757	3,217
10/26/95	11/1/95	1,571	1,419	757	3,747
11/2/95	11/8/95	1,722	1,628	530	3,880
11/9/95	11/15/95	1,628	1,287	568	3,482
11/16/95	11/22/95	1,136	1,154	511	2,801
11/23/95	11/29/95	757	303	170	1,230
11/30/95	12/6/95	1,457	1,211	341	3,009
12/7/95	12/13/95	1,192	1,363	95	2,650
12/14/95	12/20/95	1,646	1,230	416	3,293
12/21/95	12/27/95	700	208	132	1,041
12/28/95	1/3/96	0	0	0	0
1/4/96	1/10/96	1,609	2,309	492	4,410
1/11/96	1/17/96	1,609	1,382	492	3,482

Table 5-6. Weekly Volume of Knockout Water Drained from Soil Vapor Extraction Systems, October 1994 - September 1998. (2 Pages)

		Knock-out Water Drained (liters)			
		SVE System			Total
Week Start	Week End	42.5 m3/min	28.3 m3/min	14.2 m3/min	
1/18/96	1/24/96	852	1,400	549	2,801
1/25/96	1/31/96	341	662	151	1,154
2/1/96	2/7/96	530	1,173	246	1,949
2/8/96	2/14/96	1,325	1,173	322	2,820
2/15/96	2/21/96	795	568	151	1,514
2/22/96	2/28/96	1,514	1,628	76	3,217
2/29/96	3/6/96	1,325	1,363	416	3,104
3/7/96	3/13/96	757	1,022	151	1,930
3/14/96	3/20/96	246	700	341	1,287
3/21/96	3/27/96	908	1,249	189	2,347
3/28/96	4/3/96	606	681	379	1,665
4/4/96	4/10/96	303	397	208	908
4/11/96	4/17/96	0	454	114	568
4/18/96	4/24/96	341	757	454	1,552
4/25/96	5/1/96	0	0	0	0
5/2/96	5/8/96	0	0	0	0
5/9/96	5/15/96	454	265	227	946
5/16/96	5/22/96	0	0	0	0
5/23/96	5/29/96	0	454	0	454
5/30/96	6/5/96	0	0	0	0
6/6/96	6/12/96	0	0	0	0
6/13/96	6/19/96	0	0	0	0
6/20/96	6/26/96	0	0	390	390
1995-1996 Total		26,079	29,902	10,761	66,741
10/10/96	10/16/96	0	530	303	833
10/17/96	10/23/96	1,325	662	284	2,271
10/24/96	10/30/96	757	1,136	568	2,460
1996-1997 Total **		2,082	2,328	1,154	5,564
1997-1998 Total ***		0	0	189	189
1992-1998 Total		41,849	45,123	17,328	104,299

* No soil vapor extraction 6/4/93 through 11/11/93 following GAC overheating incident on 6/3/93; volume 2/10/94 through 6/30/94 divided equally between 28.3 and 42.5 m3/min SVE systems

** No soil vapor extraction 11/4/96 through 7/17/97 during rebound study

*** No soil vapor extraction 10/1/97 through 3/29/98 during planned winter shutdown. 14.2 m3/min SVE system operated 3/30/98 through 9/30/98.

Table 5-7. Analyses of 200-ZP-2 Soil Vapor Extraction Knockout Water.

Volatile Organic Compound	6/30/94		1/26/95		12/12/95	
	Result (µg/L)	Detection Limit (µg/L)	Result (µg/L)	Detection Limit (µg/L)	Result (µg/L)	Detection Limit (µg/L)
Carbon tetrachloride	10 J	10	380	N/A	130-140	N/A
Chloroform	130	10	19	N/A	<10	N/A
Tetrachloroethylene	10 U	10	0.7 J	2.0	<5	N/A
Trichloroethylene	10 U	10	<1	N/A	<5	N/A

J = Estimated value
N/A = Not Available
U = Analyzed for but not detected

Table 5-8. Soil Vapor Extraction Well Characterization Data.

216-Z-1A	Restart 7/18/97								Restart 3/30/98			
Well/ Interval	Date	Well Vacuum (kPa)	Flow (m^3/min)	CCl_4 (ppmv)					Date	Well Vacuum (kPa)	Flow (m^3/min)	CCl_4 (ppmv)
W18-6L	7/21/97	1.5	0.5	27					3/30/98	6.0	0	26
W18-7	7/21/97	2.5	2.8	31					3/30/98	1.2	0.7	15
W18-167	7/21/97	1.7	4.8	21					4/1/98	0.3	1.0	27
W18-174	7/21/97	2.5	0.4	7					4/1/98	0.4	0	8
W18-248	7/21/97	3.2	0.1	59					3/30/98	2.5	0	1
W18-252U	7/21/97	3.7	4.2	42					3/30/98	9.0	1.7	36
W18-152									3/30/98	6.5	0.4	21
W18-96									3/30/98	9.2	1.6	16
W18-12									3/30/98	8.7	0.4	29
W18-89									3/30/98	1.2	0.4	28
W18-246U									3/30/98	8.7	1.2	30
W18-252L									3/30/98	12.0	0.5	29
W18-249									3/30/98	7.0	2.7	33
W18-168									4/1/98	0.4	0	1
W18-165									4/1/98	0.3	0	6
216-Z-9	Restart 7/18/97								Restart 7/7/98			
Well/ Interval	Date	Well Vacuum (kPa)	Flow (m^3/min)	CCl_4 (ppmv)	Date	Well Vacuum (kPa)	Flow (m^3/min)	CCl_4 (ppmv)	Date	Well Vacuum (kPa)	Flow (m^3/min)	CCl_4 (ppmv)
W15-9L	7/18/97	16.2	1.7	20	7/21/97	19.4	1.8	21	7/10/98	19.4	2.3	17
W15-82	7/18/97	15.9	1.6	106	7/21/97	13.7	2.1	47	7/10/98	17.4	2.1	196
W15-217	7/18/97	15.7	4.7	256	7/21/97	12.5	5.8	86	7/10/98	14.9	4.4	135
W15-6L	7/18/97	10.0	2.7	20	7/21/97	8.0	2.4	20	7/30/98	9.5	2.1	18
W15-86	7/18/97	15.2	4.8	138	7/21/97	12.5	5.1	111	7/30/98	13.0	4.1	107
W15-218L	7/18/97	19.9	3.0	20	7/21/97	12.7	2.4	22				
W15-218U	7/18/97	17.4	6.0	21	7/21/97	11.5	4.6	22	7/30/98	12.0	2.4	6
W15-9U									7/10/98	19.9	2.0	30

CCl_4 = carbon tetrachloride

6.0 NONOPERATIONAL SOIL VAPOR MONITORING DATA

6.1 SUMMARY OF FISCAL YEAR 1997 REBOUND STUDY

A rebound study was conducted at the carbon tetrachloride SVE sites from November 1996 through July 1997 (Rohay 1997). The purpose of the study was to determine the increase in carbon tetrachloride vapor concentrations following shutdown of the extraction systems. During the time when the systems were off line, carbon tetrachloride concentrations were monitored at 90 subsurface monitoring locations, ranging in depth from 1.5 to 64 m.

The magnitude and rate of rebound can be used to indicate the distribution of remaining carbon tetrachloride sources and the transfer of additional carbon tetrachloride to the vapor phase that can be remediated using SVE. However, based on the results of a bench-scale experimental study conducted by Yonge et al. (1996), the mass of carbon tetrachloride remaining in the soil at the vapor extraction sites cannot be reliably determined using the rebound study vapor-phase data. Yonge et al. conducted experiments using pure carbon tetrachloride and clean site-specific soils and concluded that calculation of carbon tetrachloride soil concentrations using measured vapor-phase concentrations and either empirical relationships or adsorption isotherms to estimate the soil-partitioning coefficient can lead to significant error (Yonge et al. 1996). This conclusion was based on comparison of calculated and measured soil concentrations using data generated during the experiments. The predictive equations generally assume equilibrium partitioning between phases. However, these relationships do not account for the nonequilibrium partitioning of carbon tetrachloride within the soil particles (the apparent "irreversible" adsorption).

The maximum carbon tetrachloride concentration measured at each individual sampling location is plotted with depth in Figure 6-1. This vertical profile indicates that the remaining carbon tetrachloride available for removal using SVE is primarily associated with the silt and underlying Plio-Pleistocene caliche layers (zones 3 and 4, Figure 2-2). Remaining carbon tetrachloride sources are located in these layers as a result of (1) the initial accumulation of carbon tetrachloride in these finer grained, lower permeability layers, observed during characterization in 1991-1993 (Rohay et al. 1994); and (2) the relative inability of the extraction systems to induce airflow through this lower permeability zone to effectively remove the carbon tetrachloride.

The maximum chloroform concentration measured at each sampling location is plotted with depth in Figure 6-2. The results are similar to those of carbon tetrachloride with two exceptions: maximum chloroform concentrations tend to be relatively high near the ground surface (zone 1, Figure 2-2) and also near the water table (zone 6, Figure 2-2). Two shallow soil vapor probes, one approximately 30 m west of 216-Z-12 and one approximately 270 m northeast of 216-Z-9, had relatively high maximum chloroform concentrations (20 to 30 ppmv), represented by one data point at 1.5 m depth in Figure 6-2. The maximum chloroform concentration at the other shallow probes in the 216-Z-1A/Z-18/Z-12 area was 4.3 ppmv and in the 216-Z-9 area was 8.7 ppmv, represented by the other data point at 1.5 m depth in Figure 6-2. At the monitoring locations near the groundwater (zone 6), the maximum chloroform concentration in the 216-Z-1A area was 8.1 ppmv and in the 216-Z-9 area was 7.5 ppmv. The cause of the apparently elevated chloroform is undetermined.

The concentrations of carbon tetrachloride and chloroform are compared for the 216-Z-9 site in Figure 6-3 and for the 216-Z-1A/Z-18/Z-12 site in Figure 6-4. These data are plotted at the same scales as in Figures 5-25 and 5-27 for ease of comparison. The chloroform to carbon tetrachloride trends for the rebound data at the 216-Z-9 and 216-Z-1A/Z-18/Z-12 monitoring locations appear to be similar. For carbon tetrachloride rebound concentrations greater than approximately 100 ppmv, the trends of the chloroform to carbon tetrachloride ratios follow the shallower of the two trends identified in the extracted soil vapor (Figures 5-25 and 5-27). The data in Figures 6-3 and 6-4 include all the rebound data for zones 2 through 6 (not just the maximum values).

Carbon tetrachloride concentrations rebounded significantly (i.e., by an order of magnitude) at only five locations monitored during the study, indicating that in many areas the readily accessible mass has been removed. The continuing rebound at many locations indicates that the supply of additional carbon tetrachloride to the high flow zone pore spaces affected by SVE is limited by diffusion of the contaminant from soil moisture and micropores and/or from the lower permeability zones. These data also indicate that the distribution of carbon tetrachloride sources is not uniform. During the first 3 weeks of SVE operations in July 1997 following rebound, the three SVE systems combined were extracting an average of 178 kg/week, compared to 102 kg/week in November 1996 and in September 1997. These comparisons indicate that carbon tetrachloride is still available for extraction using SVE.

Carbon tetrachloride concentrations rebounded most rapidly in the 8 to 16 weeks following SVE shutdown but continued rebounding (at the same rate or more slowly) for 8 months and presumably would continue for years. Carbon tetrachloride concentrations decreased most rapidly in the first 4 to 8 weeks following SVE restart, after which they continued decreasing more slowly with continued SVE operations. Therefore, to optimize the carbon tetrachloride mass removal efficiency (in terms of mass of carbon tetrachloride removed per volume of soil vapor extracted), the minimum operating cycle should be 4 to 8 weeks of SVE operation followed by 8 to 16 weeks of rebound.

Carbon tetrachloride concentrations near the water table remained relatively constant or increased slowly, suggesting that volatilization of carbon tetrachloride from the dissolved source in the groundwater into the unsaturated zone is occurring slowly relative to the 8-month-long rebound study period. Based on comparison of measured vapor concentrations to theoretical vapor concentrations that would be in equilibrium with measured groundwater concentrations, the groundwater and vapor do not appear to be in equilibrium. The expected direction of carbon tetrachloride migration is from the groundwater to the vadose zone, based on the comparison of measured to theoretical vapor concentrations.

6.2 FISCAL YEAR 1998 SOIL VAPOR MONITORING

Soil vapor monitoring at off-line wells and probes was conducted in FY 1998 using the sampling methods developed for the rebound study conducted in FY 1997 (Rohay 1997). A low-flow (0.8 L/min) sampling pump was used to draw soil vapor samples from wells and probes into a 1-L Tedlar bag for analysis using the field B&K sensor. Two purge volumes were drawn before the sample was collected. For most of the wells in which the sampling pump was used, a tube

was lowered to the target depth where the casing is perforated (i.e., open to the sediment and its pores) to minimize the volume of air to be purged. A metal filter attached to the end of the tube also served as a weight. Each sampling tube remained in the well for the duration of the monitoring period. Each well equipped with a sampling tube remained sealed at the surface throughout the monitoring period. As a test, at a limited number of wells the sampling pump was used to collect a sample at the wellhead without use of a sampling tube extended to the perforated interval. These wells were purged for either 3 minutes or 10 minutes using the sampling pump. The wells remained sealed, and the sample pump was used to collect samples in 1-L Tedlar bags for analysis using the B&K.

Soil vapor samples were collected from approximately 25 off-line wells and probes once per month. All of the FY 1998 soil vapor monitoring data are included in Appendix C.

Soil vapor samples were analyzed primarily to monitor for carbon tetrachloride. However, the samples collected from off-line wells and probes were also analyzed for chloroform, methylene chloride, methyl ethyl ketone, and water vapor because the B&K sensors had been configured to analyze for all four contaminants plus water vapor to support routine monitoring during extraction operations.

During October 1997 through March 1998, soil vapor concentrations were monitored near the groundwater and near the ground surface to assess whether nonoperation of the SVE system was allowing carbon tetrachloride to migrate out of the vadose zone to the atmosphere and/or to the groundwater. The maximum concentration detected between depths of 1.5 and 4.5 m below ground surface was 1 ppmv; the maximum concentration detected between depths of 7.6 and 18.3 m was 43 ppmv (Figure 6-5). Near the groundwater, at depths ranging from 56.0 to 63.4 m below ground surface, maximum concentrations ranged from 14.6 to 31.3 ppmv. These results, after 6 months of rebound, are similar to those obtained during the 8-month rebound study conducted in FY 1997 (Rohay 1997).

During April through June 1998, soil vapor monitoring was continued at the shallow and deep locations at the 216-Z-9 site. Monitoring locations were added near the lower permeability Plio-Pleistocene unit at the 216-Z-9 site to provide an indication of concentrations that could be expected during restart of SVE in July 1998. Concentrations detected in the near-surface and near-groundwater zones during these three additional months of rebound were similar to those observed during the previous 6 months. Nearer the Plio-Pleistocene layer, at depths ranging from 18.3 and 36.0 m below ground surface, maximum concentrations ranged from 0 to 630 ppmv (Figure 6-5). The highest concentration was detected at well 299-W15-217 (35.1 m deep), the well at which the highest concentration was detected during the FY 1997 rebound study. These results were obtained after 9 months of rebound and are similar to those obtained during the 8-month rebound study conducted in FY 1997 (Rohay 1997).

During July through September 1998, soil vapor monitoring was resumed at the 216-Z-1A and 216-Z-18 sites. Monitoring was conducted in the near-surface, near-Plio-Pleistocene, and near-groundwater zones. The maximum concentration detected was 143 ppmv at well 299-W18-158L (37.5 m deep) in the 216-Z-1A Tile Field. These results were obtained after only 3 months of rebound.

Samples were collected initially from well 299-W15-217 at the wellhead before the downhole sampling tube was installed to evaluate the effect of the sampling tube. In March and April 1998, these wellhead samples contained 65 and 25 ppmv of carbon tetrachloride, respectively. Samples collected in May and June 1998 using the downhole sampling tube contained 630 and 504 ppmv of carbon tetrachloride, respectively. Other wells sampled without the sampling tube had anomalously low to nondetectable carbon tetrachloride concentrations. Based on these results, samples collected at the wellhead when the wells are not venting are not representative of in situ concentrations. These results were not used in evaluation of the monitoring data.

Because carbon tetrachloride concentrations did not increase significantly at the shallow probes monitored in FY 1998, temporarily suspending operation of the SVE system for 6 to 9 months appears to have caused minimal detectable vertical transport of carbon tetrachloride through the soil surface to the atmosphere. Because carbon tetrachloride concentrations did not increase significantly near the water table during this time, temporarily suspending operation of the SVE systems appears to have had no negative impact on groundwater quality.

6.3 COMPARISON OF SOIL VAPOR MONITORING BEFORE AND AFTER SOIL VAPOR EXTRACTION REMEDIATION

Baseline monitoring was conducted to estimate the magnitude of carbon tetrachloride subsurface vapor concentrations prior to initiation of SVE operations to remove carbon tetrachloride from the vadose zone. The baseline monitoring program for the vapor extraction system consisted of 116 selected wells and deep soil vapor probes that were monitored twice per week from December 1991 through December 1993 (Fancher 1994).

The wells and deep soil vapor probes were monitored using a total organic vapor monitor (a photo-ionization detector (PID) equipped with an 11.8-eV lamp). The range for the instrument was 0.1 to 2,000 ppmv. The total VOC measurement was assumed to consist solely of carbon tetrachloride, based on confirmation at selected sample stations using carbon tetrachloride-specific colorimetric tubes and the predominance of carbon tetrachloride in other samples analyzed using gas chromatography (Fancher 1994, Rohay et al. 1994).

The wells were sampled at the wellhead by inserting the PID probe a few centimeters into the well and allowing air to be drawn through the instrument for at least 10 seconds before a reading was taken. At soil vapor probes, the PID was directly coupled to the sample tube leading from the subsurface probe to the surface. At least two purge volumes were extracted from the tube before the vapor was monitored. At both wells and probes, the vapor was monitored while readings increased; once the readings peaked, the maximum value was recorded (Fancher 1994).

Observed carbon tetrachloride concentrations (measured as total organic vapor) ranged from 0 to over 2,000 ppmv; in this report, readings above 2,000 ppmv (observed at five locations in the 216-Z-9 wellfield) were set equal to 2,000 ppmv (the maximum calibration value). Because the contaminant concentrations fluctuate in response to barometric pressure, the maximum baseline monitoring value for each well or probe was judged to have the greatest likelihood of representing equilibrium conditions.

Although the highest concentrations for the baseline monitoring network measured between December 1991 and December 1993 appear to be associated with the lower permeability Plio-Pleistocene layer, relatively high concentrations are observed throughout the vadose zone (Figure 6-6). (Although SVE was initiated at the 216-Z-1A and Z-18 sites in 1992, operations were limited to 7 hours/day, 5 days/week using up to 11 wells.. The baseline monitoring data set presented here is considered generally representative of pre-remediation conditions.) Vertical profiles for carbon tetrachloride concentrations monitored at wells and deep soil vapor probes after remediation in 1997 and 1998 (Figure 6-5) suggest that SVE has been relatively successful in remediating the higher permeability, higher flow zones in the sands and gravels above and below the Plio-Pleistocene unit.

The maximum values measured between December 1991 and December 1993 at wells and deep soil vapor probes with open areas above the Plio-Pleistocene unit are shown in Figure 6-7a; the maximum values for wells with open areas below the Plio-Pleistocene unit are shown in Figure 6-7b. In constructing these figures, it was assumed that the results collected at various monitoring points are comparable to each other despite the differing ages, locations, depths, and completions of individual wells and probes. Open intervals in the boreholes range from approximately 23 to 48 m below ground surface. The deep soil vapor probes range in depth from 3 to 33 m. In addition, the distributions of vapor shown in Figure 6-7 are limited by the extent of the monitoring network. Laterally, the highest concentrations were observed at the 216-Z-9 wellfield. Concentrations observed at the 216-Z-12 Crib wells were comparable in magnitude to those observed at the 216-Z-1A Tile Field.

The maximum values observed during the 1997 rebound monitoring are shown in Figure 6-8.

Figure 6-1. Vertical Profile of Maximum Carbon Tetrachloride Rebound Concentrations, November 1996 – July 1997.

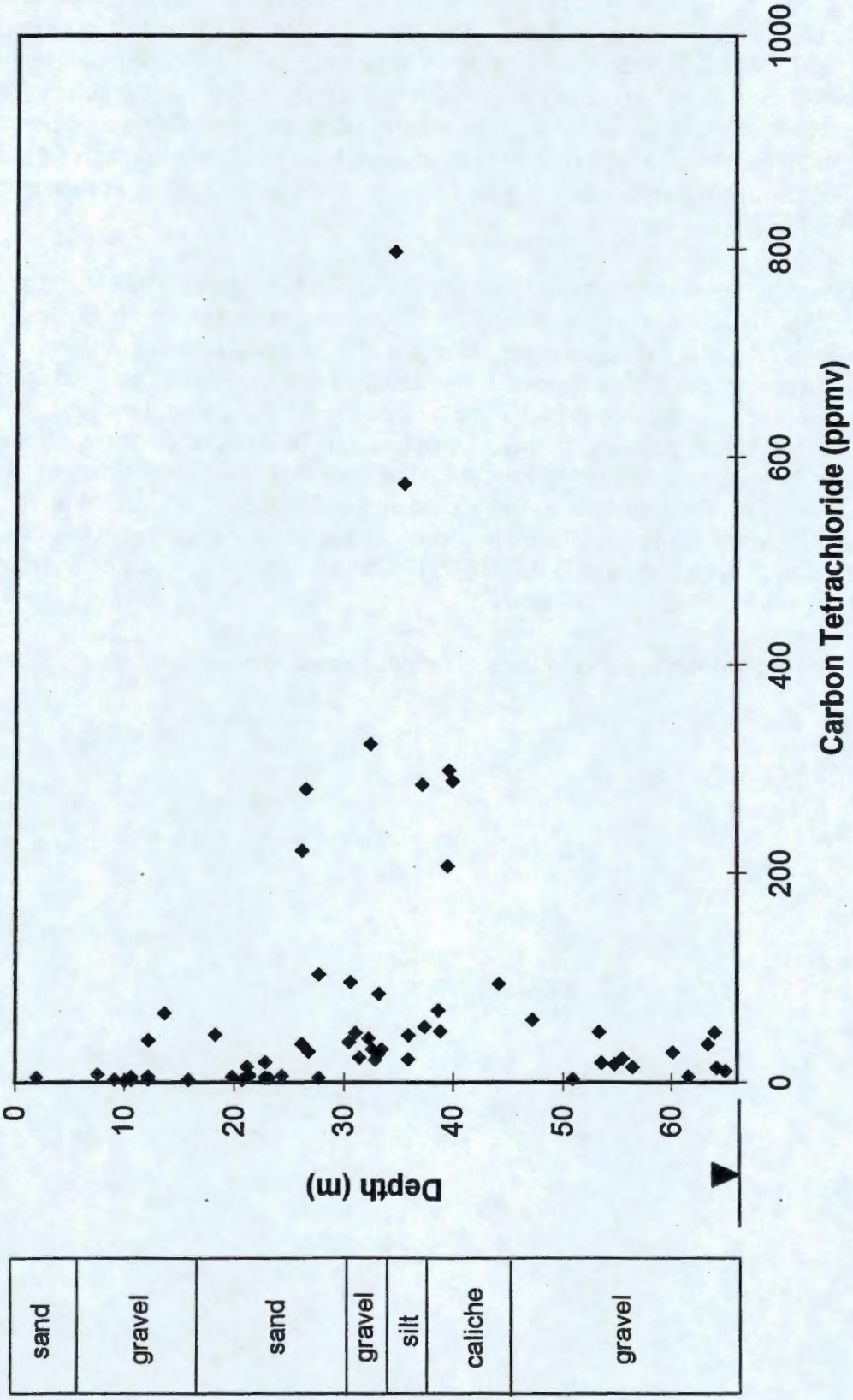


Figure 6-2. Vertical Profile of Maximum Chloroform Rebound Concentrations, November 1996 – July 1997.

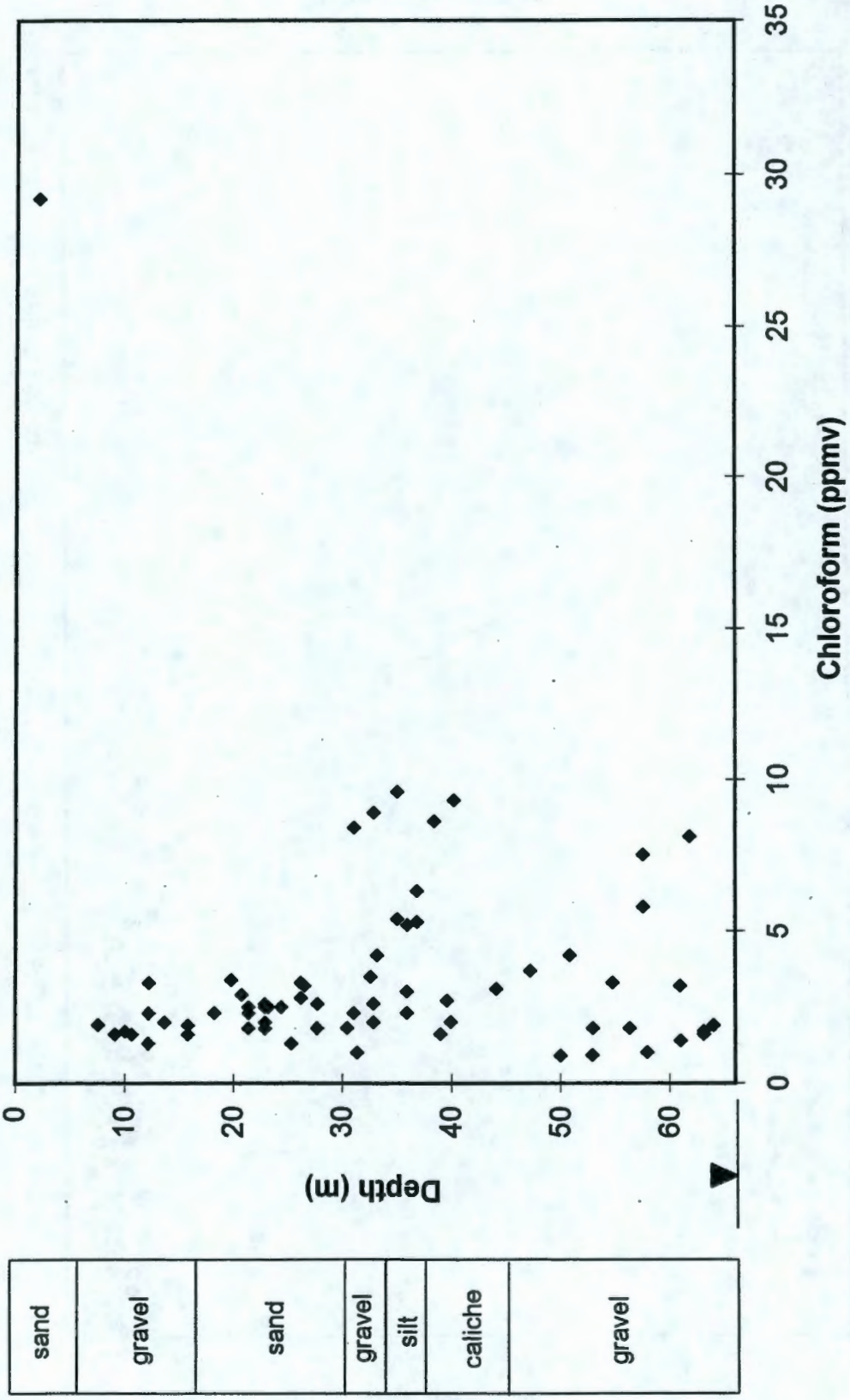


Figure 6-3. Relationship Between Concentrations of Carbon Tetrachloride and Chloroform Measured at Rebound Study Monitoring Locations in the 216-Z-9 Wellfield.

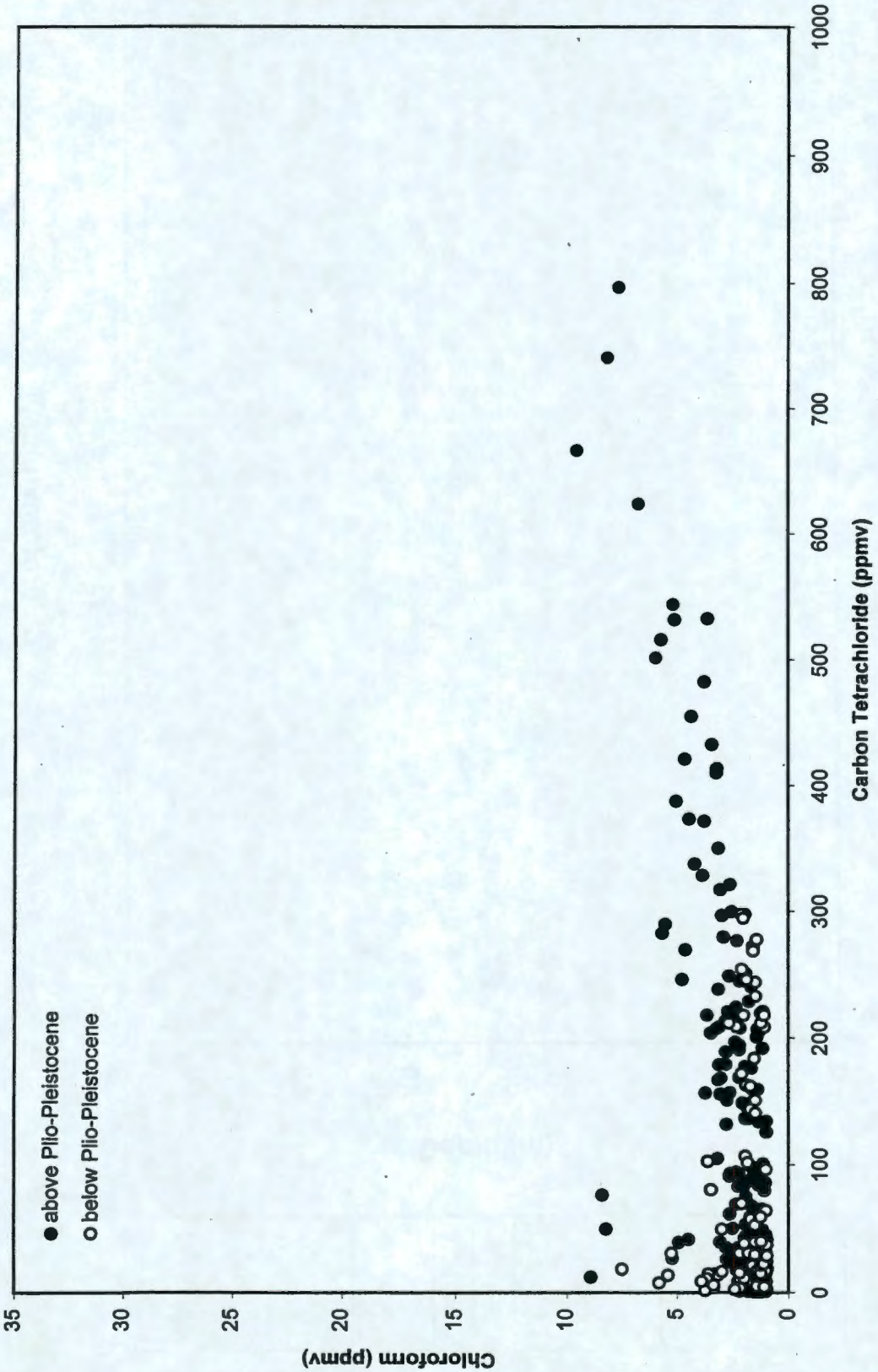


Figure 6-4. Relationship Between Concentrations of Carbon Tetrachloride and Chloroform Measured at Rebound Study Monitoring Locations in the 216-Z-1A/Z-18/Z-12 Wellfield.

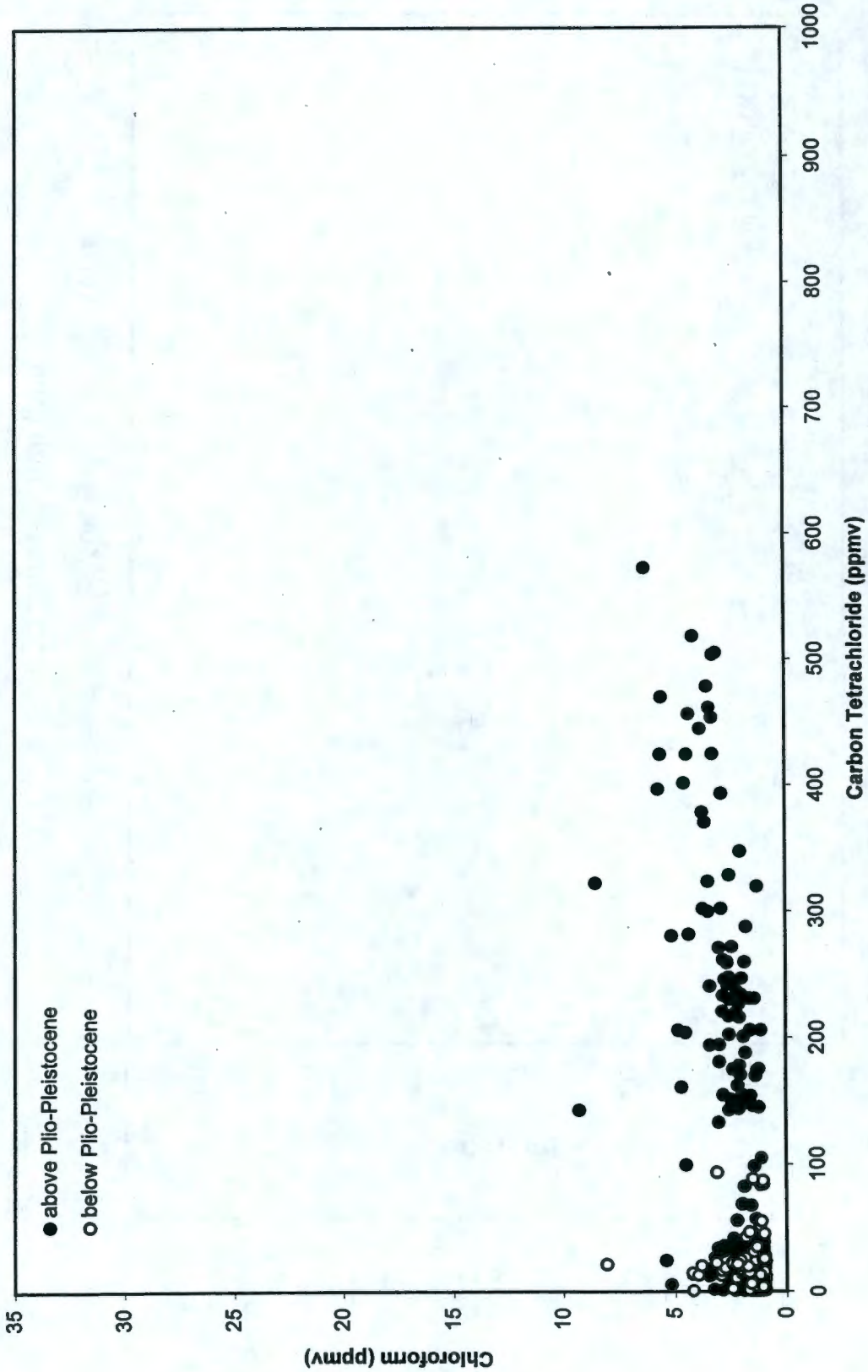


Figure 6-5. Vertical Profile of Maximum Carbon Tetrachloride Rebound Concentrations, November 1996 – July 1997 and October 1997 – June 1998.

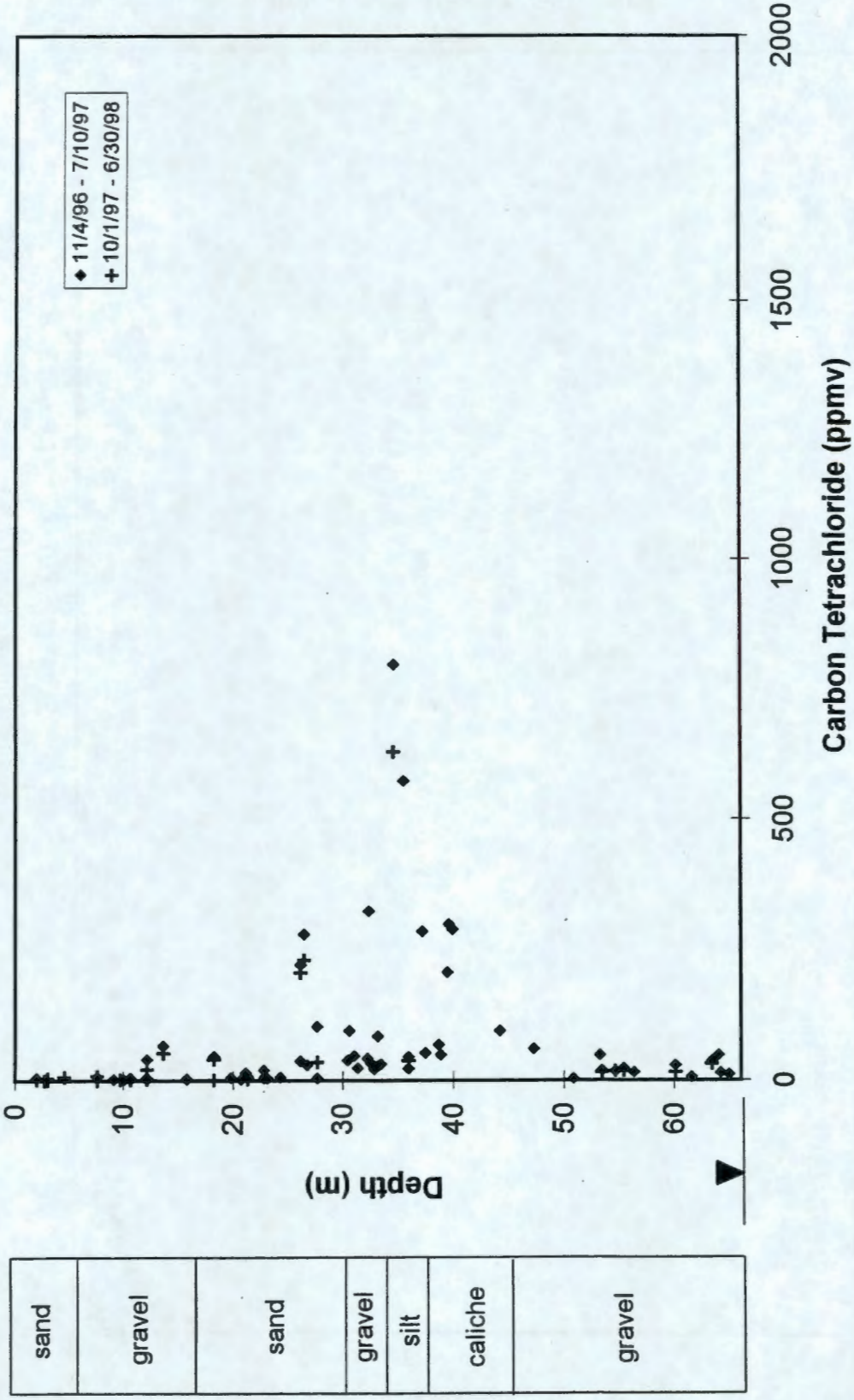


Figure 6-6. Vertical Profile of Maximum Carbon Tetrachloride Baseline Concentrations, December 1991 – December 1993.

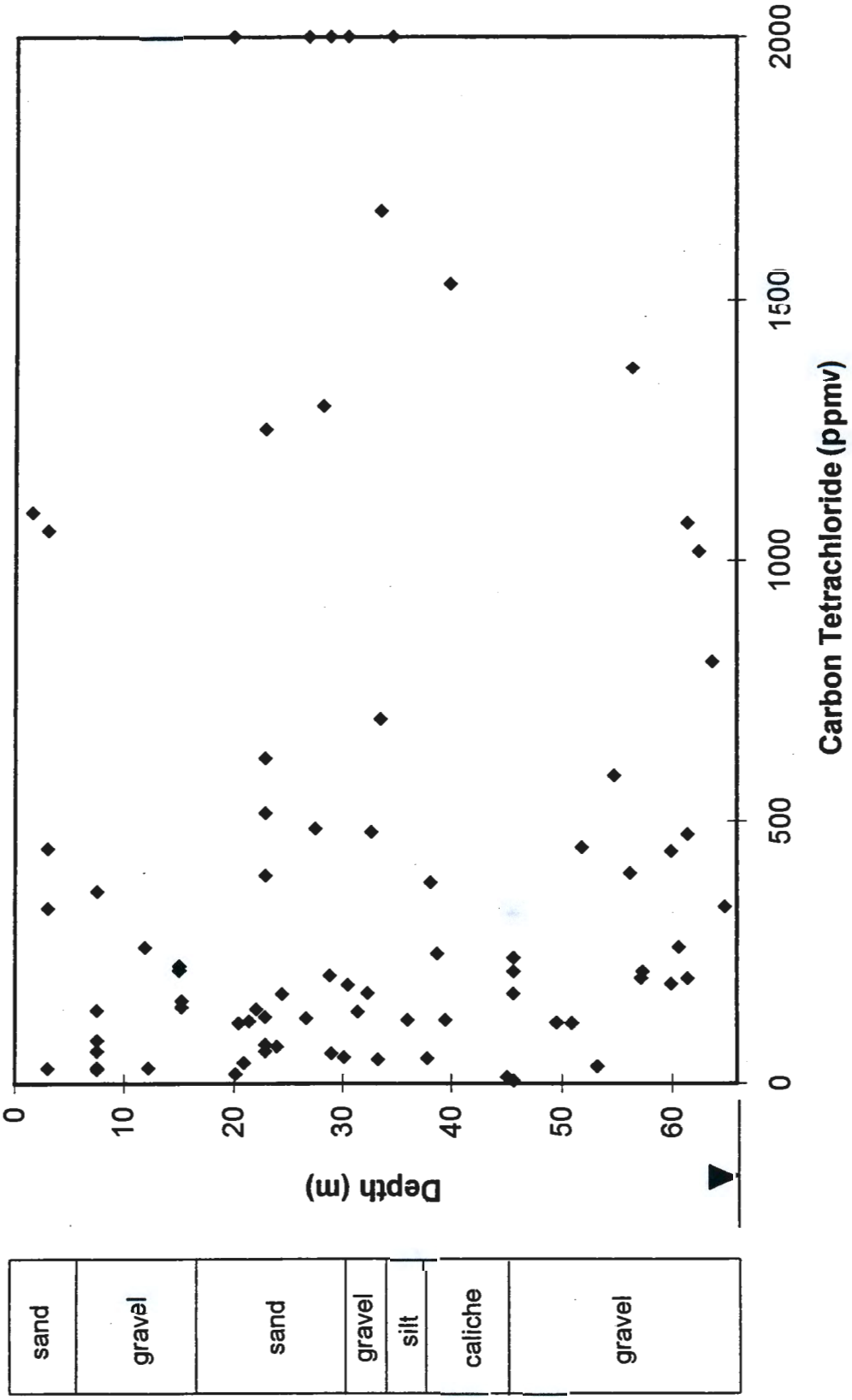


Figure 6-7a. Maximum Carbon Tetrachloride Baseline Concentrations Recorded at Wells and Deep Soil Vapor Probes Open Above the Plio-Pleistocene Unit, December 1991 Through December 1993 (from Fancher 1994).

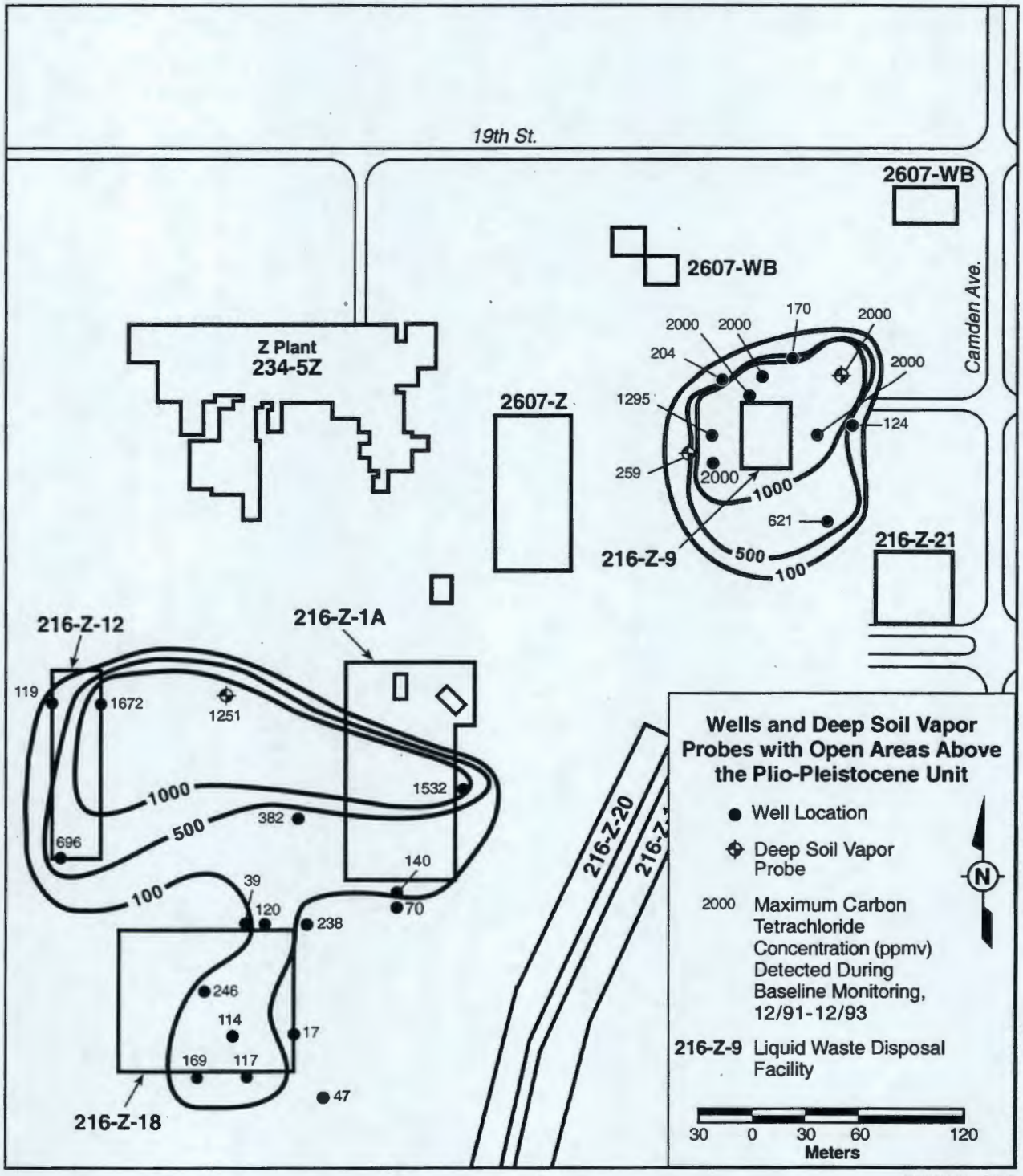


Figure 6-7b. Maximum Carbon Tetrachloride Baseline Concentrations Recorded at Wells Open Below the Plio-Pleistocene Unit, December 1991 Through December 1993 (from Fancher 1994).

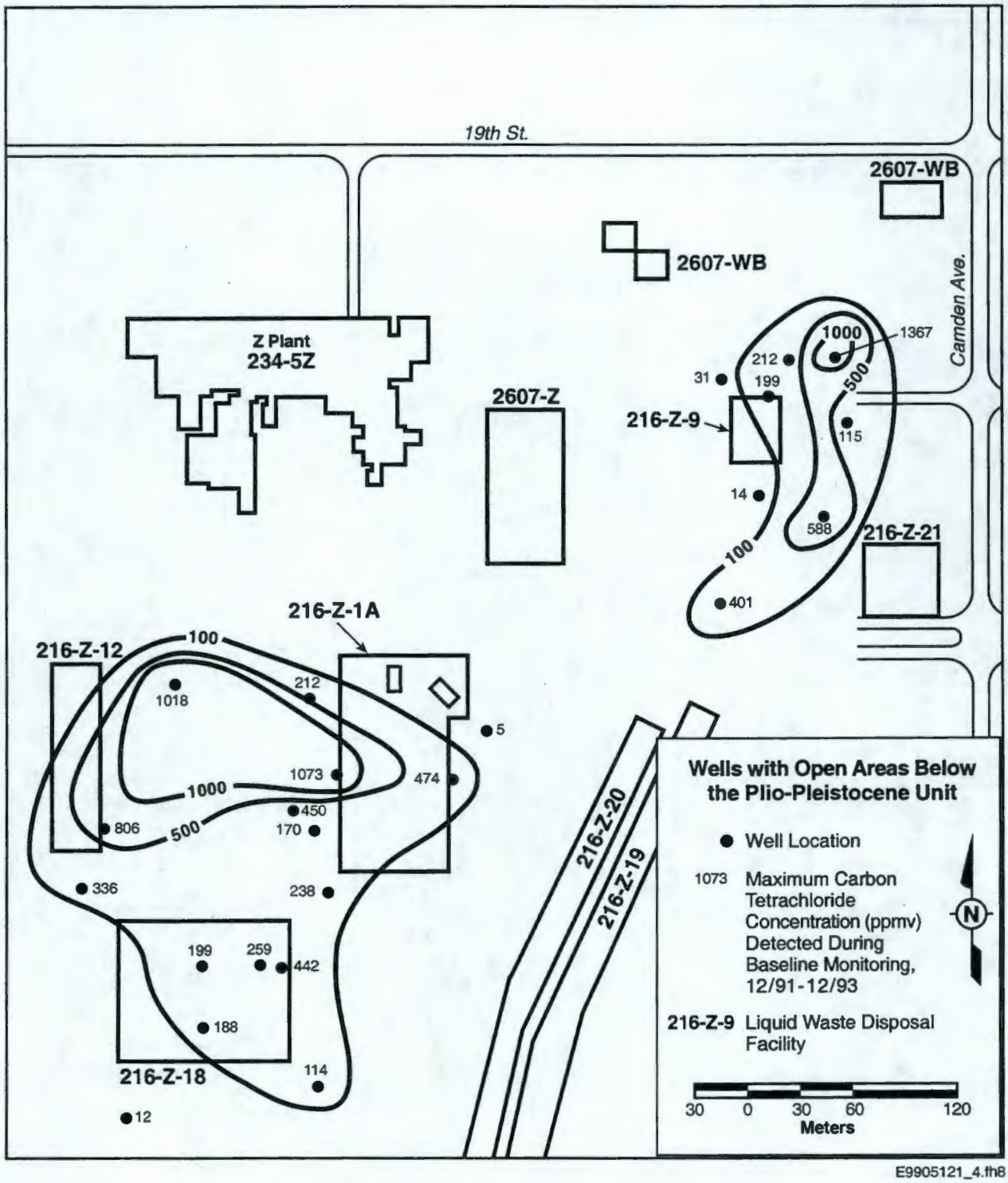


Figure 6-8a. Maximum Carbon Tetrachloride Rebound Concentrations Recorded at Wells and Deep Soil Vapor Probes Open Above the Plio-Pleistocene Unit, November 1996 Through July 1997.

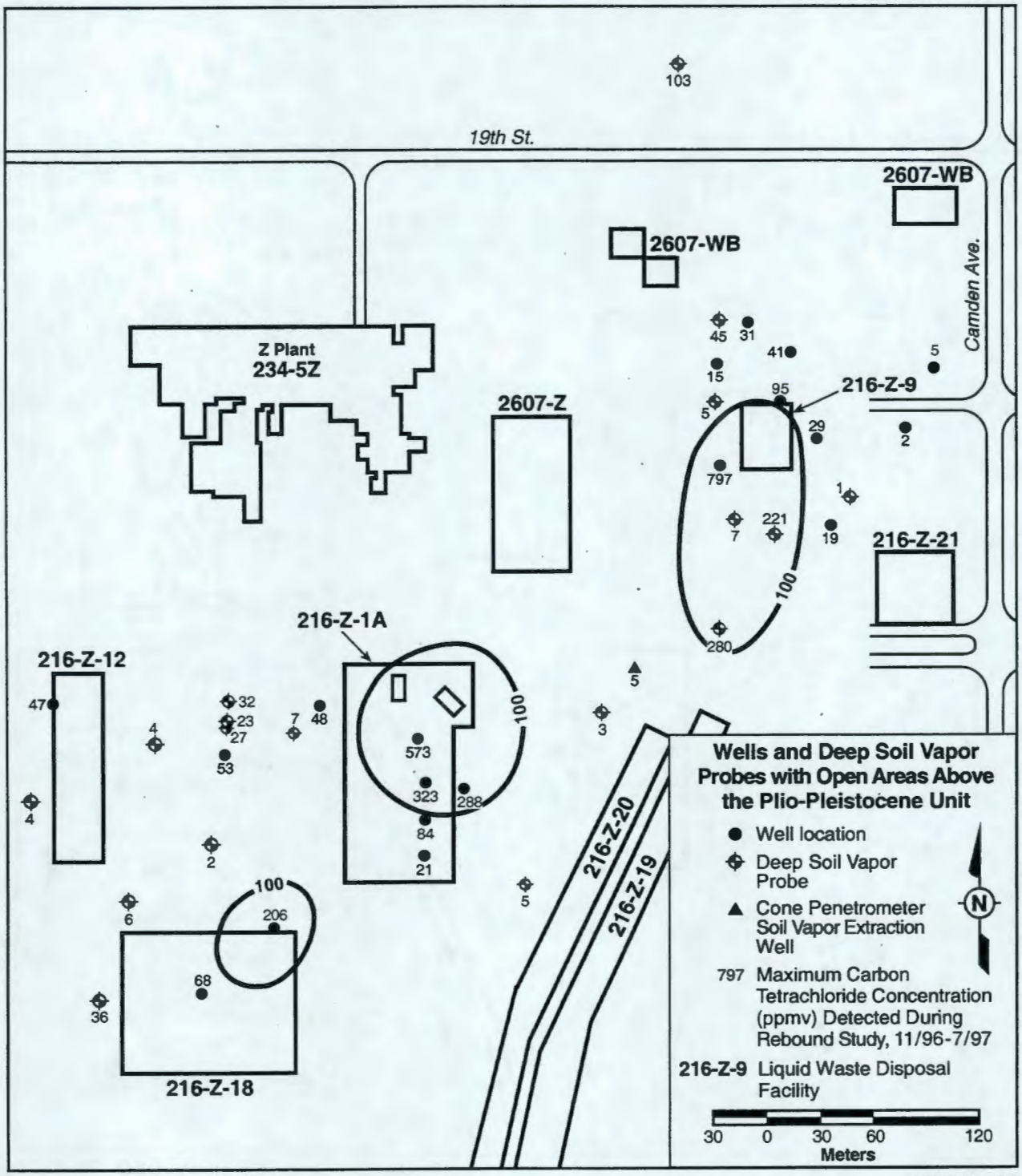
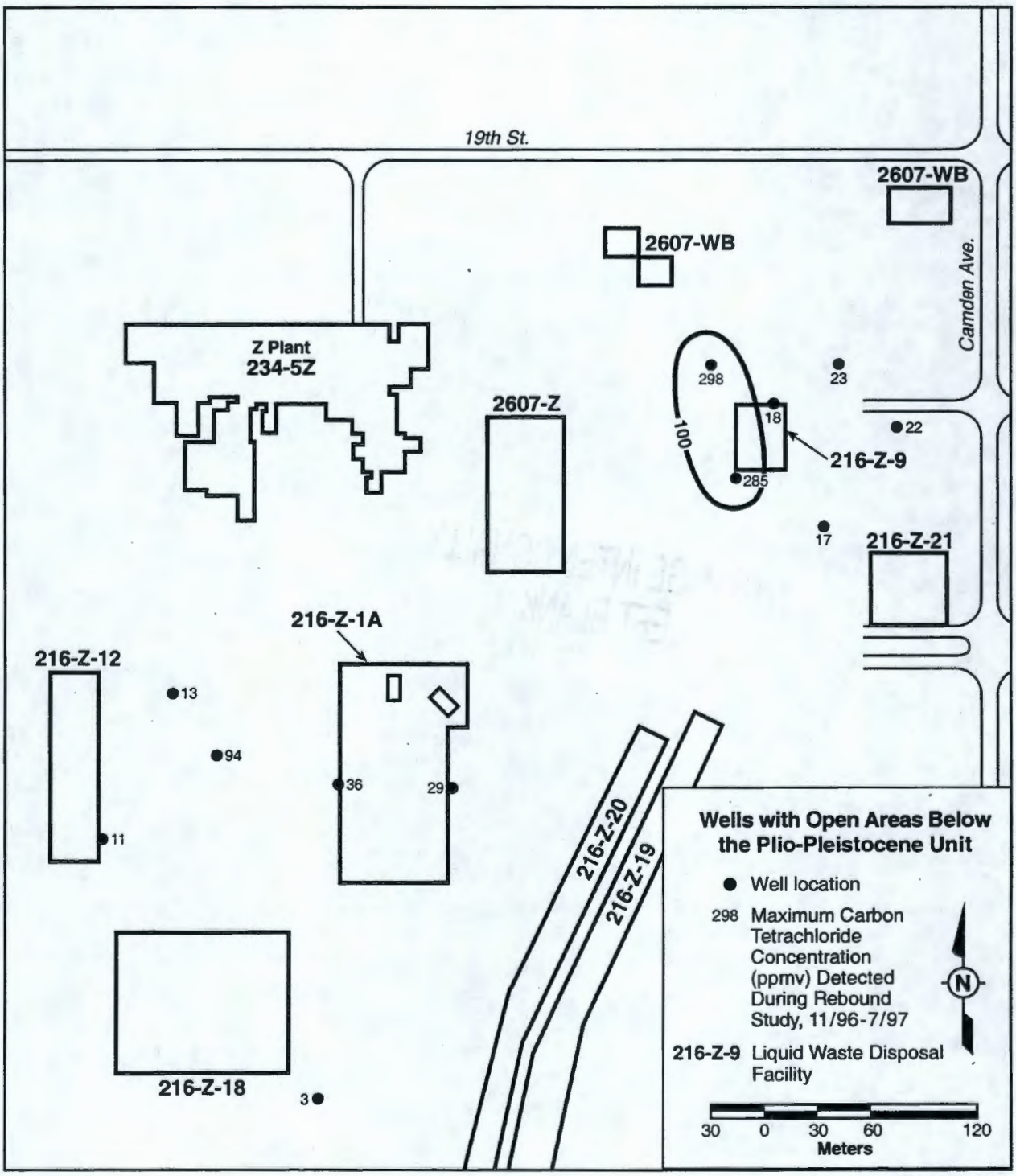


Figure 6-8b. Maximum Carbon Tetrachloride Rebound Concentrations Recorded at Wells Open Below the Plio-Pleistocene Unit, November 1996 Through July 1997.



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7.0 1998 CARBON TETRACHLORIDE CONCEPTUAL MODEL UPDATE

This section summarizes the current conceptual model as well as working hypotheses concerning the source term, environmental setting, vadose zone and groundwater contaminant distribution, and vadose zone and groundwater transport of carbon tetrachloride and associated contaminants in the 200 West Area. Additional details are provided in Appendix D. The conceptual model of the 200 West Area carbon tetrachloride plume has been continuously refined as additional site-specific data have been collected and as the understanding of dense nonaqueous-phase liquid (DNAPL) behavior in the subsurface has been developed by the scientific community. The conceptual model presented in this report provides an update to the conceptual models presented in Rohay and Johnson (1991), Last and Rohay (1991, 1993), Last et al. (1991), and Rohay et al. (1994).

Carbon tetrachloride contamination is present in multiple phases and at varying concentrations throughout the vadose zone and groundwater systems. Near the disposal sites, the soil vapor concentrations are much higher and are found throughout the vadose zone; the highest concentrations are associated with the Plio-Pleistocene layer. Farther away from the disposal sites, vapor concentrations are much lower and are usually found at the capillary zone or immediately beneath the Plio-Pleistocene layer. This implies that the farfield diffuse vapor plume may be the result of aquifer outgassing. Based on these observations, carbon tetrachloride contamination can be divided geographically into three main areas:

1. A higher concentration vadose zone vapor plume at the three primary disposal facilities: 216-Z-9, 216-Z-1A, and 216-Z-18 (approximately 0.2 km^2)

2. A higher concentration groundwater plume with the centroid located north-northwest of the three primary disposal facilities (although, because of recent pump-and-treat remediation efforts, the centroid has expanded and the eastern edge is nearer to the groundwater extraction wells) (Appendix D, Figure D-3) (DOE-RL 1999) (approximately 0.6 km^2)

3. A geographically large dissolved and diffuse groundwater plume (<1,000 μg/L) and vapor plume (approximately 11 km^2). The lateral extent of the vapor plume is not defined but, based on volatilization from groundwater, could be at a minimum coincident with the dissolved groundwater plume.

Possible transport mechanisms and distributions of contaminant phases for the high-concentration zone of the plume, which may also contain DNAPL/residual carbon tetrachloride, are depicted in Figure 7-1. Because of the differences in the sizes of the three primary disposal sites and the quantities of waste received at these disposal sites, one transport mechanism and resulting contaminant distribution (e.g., vapor phase and aqueous phase migration to groundwater) may be more appropriate for one or two disposal sites, and another transport mechanism and contaminant distribution (e.g., DNAPL and aqueous phase migration to groundwater) may be more appropriate for the other(s).

7.1 CONTAMINANT INVENTORY

Approximately 750,000 kg of carbon tetrachloride were discharged to the soil column from 1955 through 1973 (Table 2-1). Estimates of the current distribution of the original inventory are based on historical information, equilibrium partitioning calculations, site-specific characterization measurements, and remediation operating data (Table 7-1).

7.2 ENVIRONMENTAL SETTING

The 66-m-thick vadose zone can be broadly divided into an upper gravel and sand interval (Hanford formation) and a lower gravel and sand interval (Ringold Formation Unit E) separated by a finer grained, carbonate-cemented Plio-Pleistocene unit 35 m below land surface (7 m thick). The Plio-Pleistocene unit appears to have been an accumulation area for carbon tetrachloride. Disposed liquid wastes would have been impeded by this unit during movement through the vadose zone to the water table (Piepho 1996), and later during post-disposal drainage. Other fine-grained zones in both the upper and lower gravel and sand intervals may also be minor accumulation and spreading zones. Carbon tetrachloride may be in nonequilibrium sorption sites within intraparticle sediment pore spaces in these fine-grained units (Yonge et al. 1996).

Migration of fluids, both liquid and vapor, are influenced by the natural stratification and variability in these sediments. The surface of the Plio-Pleistocene unit generally slopes toward the south from the primary carbon tetrachloride disposal sites (Rohay et al. 1994). Areally, the character of the Plio-Pleistocene layer varies across the 200 West Area and includes locally less cemented, more permeable areas and fractures that allow more rapid fluid flow (Slate 1996).

The groundwater system in the area of the disposal sites can be broadly divided into three dominant hydrostratigraphic units: an upper, 66-m-thick unconfined (water table) aquifer (Ringold Formation Unit E); a confining unit/aquitard (Ringold lower mud); and a confined aquifer (from the lower mud to the top of basalt bedrock). This system is more complicated, however, when considered at a site-specific scale (tens of meters), because of spatial heterogeneities including lateral and vertical changes in grain size, changes in degree of cementation, and variably interbedded gravels, sands, silts and clays. Hydrologic properties within the same hydrostratigraphic unit vary spatially and directionally in the unconfined aquifer (Thorne and Newcomer 1992).

7.3 CONTAMINANT DISTRIBUTION

Carbon tetrachloride in the subsurface can exist as a vapor phase, as a dissolved aqueous phase, as an adsorbed phase on solid matrices, and as a separate organic phase (DNAPL). In the vadose zone, all of these phases have been detected except for DNAPL. In groundwater, only the dissolved phase has been detected.

7.3.1 Vadose Zone Concentrations

Carbon tetrachloride is found throughout the vadose zone within the 0.2-km^2 source area. Laterally, the highest concentrations are consistently located in the vicinity of the 216-Z-9 Trench. Vertically, the highest concentrations are associated with the finer grained, relatively less permeable units (e.g., the Plio-Pleistocene unit). The highest vapor and soil concentrations measured before and after SVE operations are summarized in Table 7-2.

Higher vapor concentrations (>12,000 ppmv) of carbon tetrachloride measured prior to SVE operations suggest the presence of DNAPL/residual carbon tetrachloride in the vadose zone (Appendix D). The 1997 rebound study and 1998 monitoring results now indicate that at most locations within the influence of the SVE systems, much of the readily available carbon tetrachloride has been removed. The lower permeability Plio-Pleistocene layer appears to be the most significant continuing source of carbon tetrachloride soil vapor (Rohay 1997).

In addition to the carbon tetrachloride contamination, plutonium and americium co-contaminants are distributed within the upper 30 m of the vadose zone (Price et al. 1979). The transuranic contamination at these sites may have been carried downward by a combination of acidic waste liquids and organic-complexant mixtures.

7.3.2 Groundwater Concentrations

The zone of highest groundwater concentrations (4,000 to 8,000 µg/L) still includes the 216-Z-9 Trench, suggesting that carbon tetrachloride discharged there has been providing a continuous source of contamination to the groundwater. The relatively low soil vapor concentrations monitored deep within the vadose zone during 1997 and 1998 suggest that the continuing groundwater source now resides within the aquifer. Based on dissolved phase concentrations in the upper 10 m of the unconfined aquifer in 1990, prior to pump-and-treat remediation, nearly 60% of the mass of carbon tetrachloride was contained within about 10% of the area of the plume (Rohay and Johnson 1991).

Although the magnitude and extent of contamination in the deep unconfined aquifer and confined aquifer is not well defined, recent data indicate that contamination is more extensive then previously thought. Contamination has been detected throughout the unconfined aquifer at the 216-Z-9 disposal site, west and north of Z Plant, near U Plant, and near T Plant (Appendix D). Dissolved carbon tetrachloride has also been observed within the deeper confined aquifer system at wells south and east of the 216-Z-9 disposal site and on the perimeter of the T-TY-TX tank farms (Appendix D).

In addition to disposal at the Z cribs and trenches, carbon tetrachloride may also have been disposed in the T Plant area and reached groundwater. Historically, carbon tetrachloride concentrations in the T Plant area have exceeded 1,000 µg/L, but recently have declined to less than 1,000 µg/L in this area (Hartman 1999).

If DNAPL is present in the groundwater, the most likely location would be near the 216-Z-9 Trench. Numerical modeling of vadose zone flow and transport indicates that both dissolved and nonaqueous-phase liquid carbon tetrachloride migrated through the vadose zone and reached the unconfined aquifer below the 216-Z-9 Trench (Piepho 1996).

7.4 CONTAMINANT TRANSPORT

7.4.1 Vadose Zone

Contaminated vapors can move downward and laterally by molecular diffusion and by advective flow. Vapors will diffuse along a chemical gradient from high-concentration areas to low areas in any direction (including upgradient with respect to the groundwater flow direction). The presence of a relatively low-permeability surface cover, such as a building foundation or soil horizon, can also enhance the lateral extent of diffusion. This might be significant in the area of Z Plant, where surface facilities could act as a barrier and promote lateral expansion of the vapor plume.

The density of saturated carbon tetrachloride vapor is greater than uncontaminated soil vapor. This contrast in densities can result in density-driven advective flow of vapors in the vadose zone. Within the vadose zone, carbon tetrachloride vapor may also flow in any direction along pressure gradients caused by barometric pressure fluctuations. Atmospheric pressure fluctuations appear to constitute a significant release mechanism for carbon tetrachloride vapor out of the vadose zone both through the soil surface and through boreholes (Table 7-1).

As nonaqueous-phase liquid carbon tetrachloride moves down through the soil column, some of the DNAPL will be held in the soil pores by capillary forces as residual contamination. Numerical modeling of vadose zone flow and transport indicates that 66% to 90% of the carbon tetrachloride discharged to the 216-Z-9 site was retained in the vadose zone (Piepho 1996). It should be noted, however, that DNAPL characteristically moves nonuniformly downward through the vadose zone (Cohen et al. 1993). The numerical modeling, therefore, may have overestimated the volume retained in the vadose zone.

Boreholes are also potential preferential pathways for movement of carbon tetrachloride vapor and liquid (both dissolved and DNAPL liquids and vapor). Most boreholes in the 200 West Area are capped but unsealed at the surface and therefore have the potential to draw carbon tetrachloride vapors horizontally along barometrically induced pressure gradients from the source area toward their open intervals. In addition, because most 200 West Area boreholes have no annular seal, the potential for vapor communication and transport of liquid also exists along the outside of the casing.

The presence of locally saturated or near-saturated vadose zone sediments underlying other aqueous waste disposal sites can inhibit the lateral extent of diffusion. The movement of vapor-phase contamination or DNAPL would be away from the hydraulic barrier.

As aqueous liquids from natural recharge or from artificial discharge to nearby disposal facilities migrate downward through the vadose zone, they may dissolve and transport carbon tetrachloride vapor and/or residual liquid phases.

The transport and inventory partitioning estimates presented in this discussion have been made using pure liquid-phase carbon tetrachloride properties. However, the carbon tetrachloride was not discharged as a pure liquid but as a mixture with other organics (tributyl phosphate [TBP], dibutyl butyl phosphate [DBBP], and lard oil). The organic composites (even the carbon tetrachloride:lard oil mixture) were found to be denser and more viscous than water (Last and Rohay 1993). Vapor pressure of the carbon tetrachloride:DBBP and carbon tetrachloride:lard oil mixtures is only half that of the pure carbon tetrachloride and the carbon tetrachloride:TBP mixture. The interfacial tension between the 50:50 carbon tetrachloride:lard oil mixture and a 5 M sodium nitrate solution was found to be low, suggesting that the fluids may be somewhat miscible, allowing them to mix and behave more as an aqueous fluid (Last and Rohay 1993) (Appendix D).

7.4.2 Capillary Fringe

The capillary fringe forms the interface between the vadose and groundwater zones. Because the capillary fringe does not contain a connected gas phase, transport of contaminants through this zone must occur in the aqueous or DNAPL phase. The three main mechanisms for aqueous contaminant migration through the capillary fringe are diffusion and dispersion, advection, and fluctuations in the elevation of the water table (Pankow and Cherry 1996). These processes of aqueous phase transport would produce a shallow (1 to 2 m thick) vertical distribution in the aquifer due to the relatively slow process of molecular diffusion. For this reason, the deeper distribution of carbon tetrachloride cannot be explained based on the exchange of vapor-phase carbon tetrachloride to the groundwater. However, transport and partitioning of carbon tetrachloride vapor between the groundwater and vadose zone may contribute to the large "low concentration halo" surrounding the high-concentration core of the groundwater plume (Appendix D).

Lateral spreading of contamination also occurs at the capillary fringe until sufficient hydraulic head builds up to displace air and water to move into the groundwater. Residual DNAPL would remain at this interface even after the main body of DNAPL contamination moved through. Water-level fluctuations at this interface could increase or decrease the amount of contamination dissolving from the residual mass. A relatively high water table occurred from 1965 to 1984 and may have resulted in carbon tetrachloride dissolving from the residual mass into the groundwater (Appendix D). The water table is now declining at a rate of about 0.45 m/yr in the area of the disposal sites, extending the depth of the vadose zone vapor plume. DNAPL has not been detected at the capillary fringe, but high soil vapor concentrations were detected at this depth at the 216-Z-9 site prior to SVE remediation (Table 7-2).

7.4.3 Groundwater Hydraulics

The hydraulic flow field during and after carbon tetrachloride waste disposal was characterized by an increase in the water table by 2 m (1965 to 1977). After discharges to the U Pond were discontinued in 1984, the water table began declining in the area of the disposal sites.

The U Pond produced a groundwater mound in the area of the disposal sites, creating a radial flow pattern in this area. Formerly, the flow direction was from west to east (Zimmerman et al. 1986, Newcomer 1990). This radial (up- or cross-gradient) flow direction probably pushed the high-concentration portion of the groundwater plume to the northwest. However, several other hypotheses might also account for the location of the plume center (centroid) to the northwest of the known disposal sites, including:

- Mounding of groundwater locally in the region of the carbon tetrachloride disposal sites, with a significant northwest trending hydraulic gradient.

- A continuous fine-grained stratigraphic unit dipping to the northwest that could have laterally diverted disposed liquids in this direction. The primary unit potentially affecting horizontal contaminant movement would be the Plio-Pleistocene unit. However, based on current geologic knowledge, this unit dips to the south, not to the northwest.

- Other undocumented sources of carbon tetrachloride from soil column disposal near the centroid.

- A vertical hydraulic barrier in the vadose zone from wastewater disposal at other facilities (e.g., the Z-20 Trench) to the south.

It should also be noted that there is no vadose zone data or groundwater data beneath the large area that the Z Plant surface facilities cover. Because of this, the plume center may not be positioned as far northwest of the 216-Z-9 Trench as previously thought. Plume contouring may be biased toward the higher well density to the northwest.

7.4.4 Groundwater

Numerical modeling of carbon tetrachloride flow and transport in the vadose zone indicates that depth of penetration of carbon tetrachloride (dissolved and nonaqueous liquid phases) into the aquifer primarily depends on the residual saturation in the vadose zone (Piepho 1996). Dissolved groundwater contamination may have reached 50 m below the water table and nonaqueous-phase liquid carbon tetrachloride about 25 m below the water table based on this modeling study.

Preliminary sitewide numerical modeling of carbon tetrachloride transport indicates that under nonretarded flow conditions contamination in excess of 5 μg/L will move significantly past the 200 East Area perimeter in 200 years with or without the current remediation activities (i.e., the pump-and-treat interim remedial measure does not affect the overall size and extent of the diffuse plume) (Chiaramonte et al. 1997). However, if a small retardation factor is included in the analysis, the movement of carbon tetrachloride will be significantly slowed, just reaching the eastern border of 200 East Area in 200 years. The extent of contamination is very sensitive to the carbon tetrachloride partitioning coefficient between the aquifer sediments and groundwater. However, values for the partitioning coefficient are not well defined. Other important factors that this modeling effort did not take into account were biodegradation and volatilization of

carbon tetrachloride during transport. These factors may reduce the extent of contamination over any comparable period of time.

Pump-and-treat extraction and injection operations have affected the distribution and concentration of carbon tetrachloride, moving the centroid position of the plume to the east and changing the groundwater flow field from west to east. The >4,000-µg/L contour interval has expanded in size: it now extends farther north and east toward the extraction wells and may be slightly reduced in the southwest (Appendix D). Injection of treated groundwater at the upgradient location is beginning to dilute the carbon tetrachloride plume in this area and displace it to the east. The increase in size of the 4,000-µg/L contour and the concomitant steady or increasing concentrations in the interior wells may imply more than just aqueous-phase carbon tetrachloride movement toward the extraction wells, e.g., the presence of DNAPL, residual carbon tetrachloride, or a higher partitioning coefficient than previously estimated. Approximately 2,100 kg of carbon tetrachloride have already been removed with no apparent reduction in concentrations in the high-concentration area. Therefore, the mass of carbon tetrachloride within the treatment area may be greater or distributed differently than what was assumed prior to pump-and-treat remediation.

7.5 DATA GAPS

The nature and extent of the carbon tetrachloride plume have been partially defined, but several key data gaps currently exist. The data gaps are identified in this report to help describe some uncertainties in the existing database being used to formulate the conceptual model.

1. The lateral extent of the carbon tetrachloride plume in the vadose zone and vertical extent of the carbon tetrachloride plume in the groundwater need to be better defined. These data would help define the extent of the contamination and therefore the expected magnitude of the remediation efforts.

2. Data are needed to determine the extent of the nonequilibrium sorption in the vadose zone and groundwater. This information would help account for the inventory and help define remediation needs.

3. The partitioning coefficient (Kd) for carbon tetrachloride on site sediments and its variation across the site needs to be quantified. This information would help refine the predictions of carbon tetrachloride transport rates using numerical models.

4. The location, amount, and properties of DNAPL carbon tetrachloride within the subsurface need to be quantified. This information would help focus and define the remediation needs.

5. The residual saturation of carbon tetrachloride (i.e., the carbon tetrachloride held in vadose zone sediments that is no longer mobile except through partitioning to pore water that is still migrating) needs to be quantified. This information would help account for inventory between the vadose and groundwater zones, help refine the estimates of flux from the vadose zone to the groundwater, and help refine the numerical modeling

estimates of the depth of carbon tetrachloride in the aquifer. Because SVE operations have modified the distribution of subsurface carbon tetrachloride and possibly soil moisture beneath the disposal sites, part of this task would be identification of suitable locations for data collection and measurements.

6. The inventory mass balance should be reevaluated based on more recent studies and data from current remedial actions in the groundwater and the vadose zone. This information would help define the source term.

7. The hydraulic flow fields during and after the carbon tetrachloride disposal should be reevaluated to determine if the distribution of the relatively high concentrations of carbon tetrachloride to the northwest, the low concentration lobes of carbon tetrachloride to the south, and the concentrations of carbon tetrachloride near T Plant are reasonable based on the hydraulics alone. Results of this evaluation potentially may identify other contributing carbon tetrachloride disposal areas.

Figure 7-1. Schematic Illustration of Carbon Tetrachloride and Wastewater Migration Beneath the 216-Z-9 Trench in the Higher Concentration Portion of the Plume.

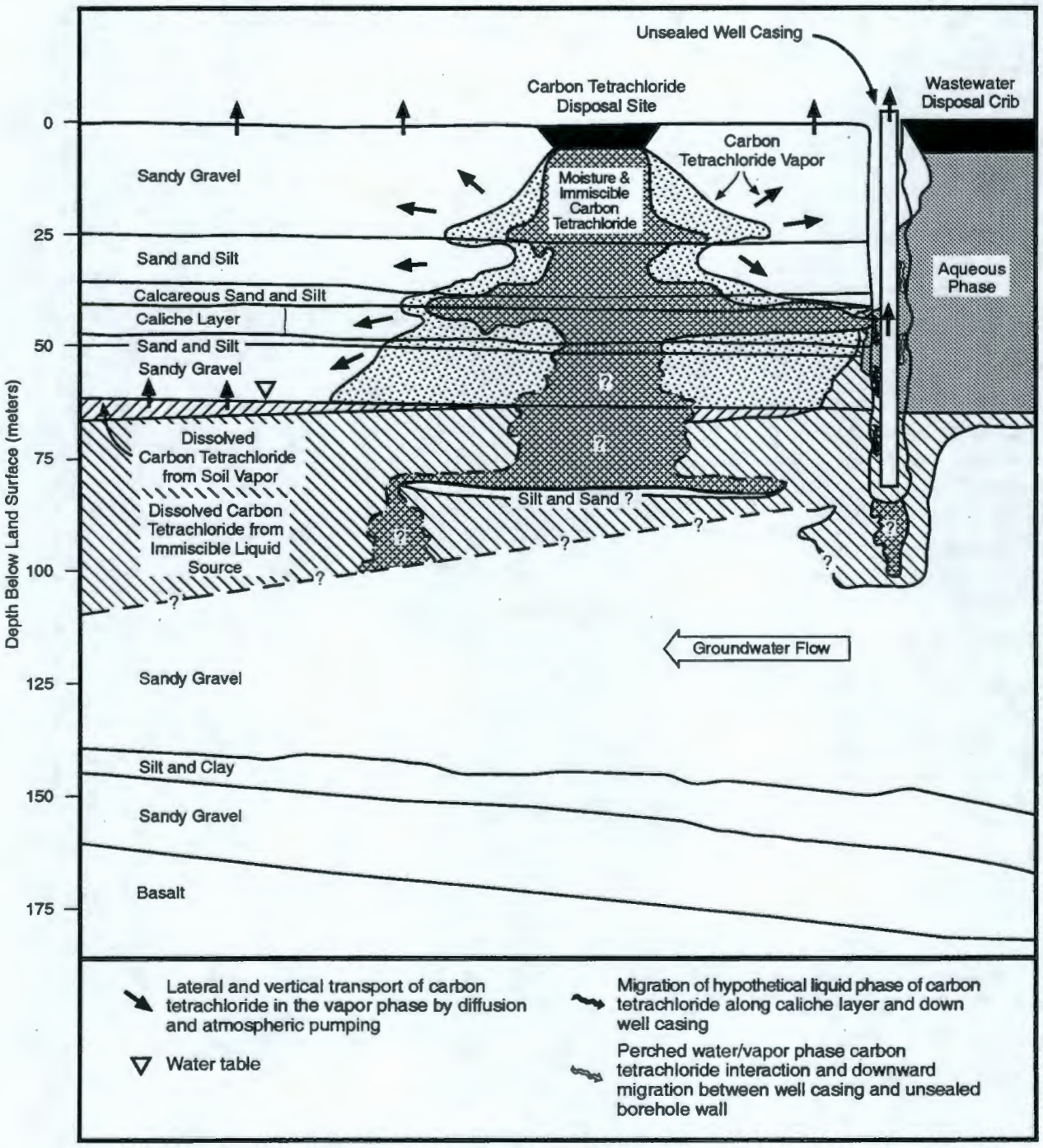

Table 7-1. Disposition of Carbon Tetrachloride Inventory Discharged to the Soil Column.

Carbon Tetrachloride Disposition	Percent of Estimated Original Carbon Tetrachloride Inventory (Average 750,000 kg)	Estimated Mass of Carbon Tetrachloride (kg)	Reference
Estimated using pre-remediation data			
Equilibrium partitioning within vadose zone into vapor, dissolved, and adsorbed phases	12	91,000	WHC 1993
Lost to atmosphere	21	159,000	WHC 1993
Biodegraded	1	8,000 (4,385 for Z-9 only)	Hooker et al. 1996
Dissolved in upper 10 m of unconfined aquifer (assuming 30% porosity and no partitioning to aquifer solids)	1-2	5,250 – 15,740	Rohay and Johnson 1991, BHI problem statement
DNAPL/residual in vadose and/or unconfined aquifer	65	484,000	WHC 1993
Measured using remediation data			
Removed from vadose zone using soil vapor extraction (1992-1998)	10	76,000	Table 4-1
Removed from unconfined aquifer using pump and treat (1994-1998)	0.3	2,100	DOE-RL 1999

Table 7-2. Carbon Tetrachloride Concentrations Measured in the Vadose Zone.

Location/Type	Facility	Geologic Unit	Year	Maximum Carbon Tetrachloride Concentration
Soil vapor survey	All three sites	Near surface	1991	72 ppmv
Wellheads/deep soil vapor probes	216-Z-9	Above PP	1991-93	>10,000 ppmv (estimated)
Wellheads/deep soil vapor probes	216-Z-1A/Z-18	Above PP	1991-93	1,000 ppmv
Wellhead vapor	All three sites	Below PP	1991-93	1,000 ppmv
Sediment samples	216-Z-9	PP	1992-93	37.8 ppm
Sediment sample	216-Z-1A/Z-18	PP	1992-93	6.6 ppm
In situ soil vapor	216-Z-9	PP	1993	21,000 ppmv
In situ soil vapor	216-Z-9	Capillary fringe	1993	10,000 ppmv
In situ soil vapor	216-Z-1A/Z-18	PP	1993	1,400 ppmv
SVE inlet	216-Z-9	Above PP	1993	30,000 ppmv
SVE inlet	216-Z-1A/Z-18	Above PP	1992	1,500 ppmv
Wellheads/deep soil vapor probes	216-Z-9	Above PP	1997	797 ppmv
Wellheads/deep soil vapor probes	216-Z-1A	Above PP	1997	573 ppmv
Wellhead vapor	216-Z-9	Below PP	1997	298 ppmv
Wellhead vapor	216-Z-1A	Below PP	1997	94 ppmv

PP = Plio-Pleistocene

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8.0 RECOMMENDATIONS

8.1 STATUS OF FY 1997 RECOMMENDATIONS

The status of recommendations regarding future SVE operations that were based on the FY 1997 rebound study, operating experience, and data evaluation (Rohay 1997) is as follows:

- **FY 1997 Recommendation**: Implement cyclic operations of the SVE systems using a minimum of 4 to 8 weeks of operation followed by 8 to 16 weeks of rebound to optimize the carbon tetrachloride mass removal efficiency (in terms of mass of carbon tetrachloride removed per volume of soil vapor extracted).

  Status: At the conclusion of the rebound study, the three SVE systems were operated for 11 weeks (July 1997-September 1997). During FY 1998, one SVE system was operated for 12 weeks (April 1998–June 1998) at the 216-Z-1A/Z-18/Z-12 site following 26 weeks of rebound (October 1997-March 1998), and then operated for 12 weeks (July 1998-September 1998) at the 216-Z-9 site following 39 weeks of rebound (October 1997-June 1998). Cyclic operations are also planned for FY 1999.

- **FY 1997 Recommendation**: Implement carbon tetrachloride vapor monitoring during future periods of nonoperation of the SVE systems to confirm that groundwater quality and atmospheric emissions are not being negatively impacted.

  Status: Carbon tetrachloride vapor monitoring was conducted at both the 216-Z-1A/Z-18/Z-12 site and the 216-Z-9 site from October 1997-March 1998 during the 26 weeks of nonoperation of the SVE system. While the SVE system was operated at 216-Z-1A/Z-18/Z-12 from April 1998-June 1998, vapor monitoring was focused at 216-Z-9, and while the SVE system was operated at 216-Z-9 from July 1998-September 1998, vapor monitoring was focused at 216-Z-1A/Z-18/Z-12. Based on the monitoring, nonoperation of the SVE system appears to have caused no additional degradation of groundwater quality and minimal detectable vertical transport of carbon tetrachloride through the soil surface to atmosphere. Vapor monitoring during periods of nonoperation of the SVE system is also planned for FY 1999.

- **FY 1997 Recommendation**: Repeat the measurement of carbon tetrachloride rebound in the first 4 to 8 weeks following SVE operations at 216-Z-1A planned from April through June 1998 and following SVE operations at 216-Z-9 planned from July through September 1998

  Status: The first carbon tetrachloride rebound measurements were made at the 216-Z-1A site 6.5 weeks (August 1998) after SVE operations ceased at that site (June 1998). The first carbon tetrachloride rebound measurements were made at the 216-Z-9 site 5 weeks (November 1998) after SVE operations ceased at that site (September 1998). Rebound measurements were continued monthly at both sites. This frequency of rebound monitoring is also planned for FY 1999.

- **FY 1997 Recommendation**: Consider implementation of passive SVE, also known as barometric pumping, as an alternative to active SVE operations.

  Status: Plans to implement passive SVE were included in the detailed planning for FY 1999. Passive SVE is scheduled to begin in July 1999.

- **FY 1997 Recommendation**: Update the carbon tetrachloride site conceptual model, including the estimate of the current distribution of the original carbon tetrachloride inventory and the nature and magnitude of the exchange of carbon tetrachloride between the vadose zone and groundwater.

  Status: Plans to update the carbon tetrachloride site conceptual model were included in the detailed planning for FY 1998. The site conceptual model is included in this performance evaluation report. The University of Washington, through the Consortium for Risk Evaluation and Stakeholder Participation, is reevaluating the estimate of the current distribution of the original carbon tetrachloride inventory; the evaluation combines field data with a numerical model that simulates subsurface vapor transport. Results are anticipated in March 2000. Investigation of the exchange of carbon tetrachloride between the vadose zone and groundwater was not implemented in FY 1998 and will be carried forward as a FY 1998 recommendation in this report.

8.2 FISCAL YEAR 1998 RECOMMENDATIONS

- Investigate the nature and magnitude of the exchange of carbon tetrachloride between the vadose zone and groundwater. This information will be required in the future to address the interdependency of the vadose zone-groundwater system in achieving remediation of the 200 West Area subsurface carbon tetrachloride contamination.

- Continue cyclic SVE operations. However, consider one or more of the following modifications:

  - In FY 1999, return the 14.2-m^3/min SVE system to a position closer to the 216-Z-1A Tile Field, where carbon tetrachloride concentrations are higher, to improve extraction efficiency from that site by allowing more wells to be online simultaneously. From its position in FY 1998 at the 216-Z-18 Crib, the 14.2-m^3/min SVE system could not extract from all 216-Z-1A/Z-18/Z-12 wells simultaneously.

  - Extend the length of the operating period at the 216-Z-1A/Z-18/Z-12 site to allow additional time to cycle between sets of wells.

- Continue carbon tetrachloride vapor monitoring during future periods of nonoperation of the SVE systems to confirm that groundwater quality is not being negatively impacted. Consider discontinuing the near-surface (1.5 m depth) monitoring for atmospheric emissions based on sporadic and low concentration detected in FY 1997 and FY 1998.

- Repeat the measurement of carbon tetrachloride rebound in the first 4 to 8 weeks following SVE operations at 216-Z-9 planned from April through June 1999 and following SVE operations at 216-Z-1A planned from July through September 1999.

- Consider application of one or more innovative technologies to significantly enhance characterization and/or remediation of carbon tetrachloride in the vadose zone and/or groundwater. An Innovative Treatment Remediation Demonstration program, funded through the DOE's EM-50 Office of Technology Development, has been implemented to evaluate appropriate technologies to address the Hanford Site 200 Area carbon tetrachloride plume. Treatability testing of the characterization and/or remediation strategy recommended by the Innovative Treatment Remediation Demonstration program is scheduled to begin in January 2000 and implementation is scheduled for September 2000.

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APPENDIX A

200-ZP-2 FLOW RATE ESTIMATION METHODOLOGY

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APPENDIX A

200-ZP-2 FLOW RATE ESTIMATION METHODOLOGY

The memorandum included in this appendix describes the methodology used to estimate the flow rates and cumulative volume of vapor extracted from each individual extraction well. The memorandum was prepared in July 1996 to support preparation of Revision 1 of this report, and the results it presents are now out-of-date. The results have been updated using the same methodology to support preparation of Revision 2 and are presented in Table 5-5 of this report.

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INTERNATIONAL TECHNOLOGY CORPORATION

Memorandum

To: Rhett Tranbarger, Virginia Rohay

Date: July 16, 1996

From: Kirk W. Hudson KWH

MEMO:0021-96

Subject: **200-ZP-2 Flow Rate Estimation Methodology and Results**

This letter report documents the review of the Soil Vapor Extraction (SVE) system data and flow rate estimates for the 200-ZP-2 system. The purpose of this work was to: 1) develop a spreadsheet that estimates the flow rates at extraction wells based on the flow rates at the header; and 2) estimate cumulative flow from each extraction well to date; and 3) plot estimated flow rates and carbon tetrachloride concentrations versus time for selected wells for comparison. This report documents the methodology used to estimate the flow rates and the results.

The 200-ZP-2 SVE system consists of three separate well fields (Z-18, Z-1A, and Z-9) with respective 500 cubic feet per minute (cfm), 1,000 cfm, and 1,500 cfm flow rate capacities. The systems are configured in such a manner that real-time flow rates, cumulative volume removed, and vacuums are indicated at a common header. The individual extraction wells are not equipped with vacuum gauges or flow meters. However, a truck-mounted flow meter and vacuum gauge are used periodically (scheduled once per quarter) to record vacuum and flow meter readings at individual extraction wells during system operation.

METHODOLOGY

Three methods were identified to estimate the flow rates from each extraction well based on the vacuum and flow measurements at the headers.

METHOD 1:

Using the Johnson Equation [Johnson 1990]:

$$Q = H \times \pi \times \left(\frac{k}{\mu}\right) \times P_w \times \frac{1 - \left(\frac{P_{atm}}{P_w}\right)^2}{\ln\left(\frac{R_w}{R_I}\right)}$$

44-8-85

Where: Q = vapor flow rate (scfs)
P_{atm} = absolute atmospheric pressure (psf)
P_w = absolute wellhead vacuum (P_{atm} - wellhead vacuum) (psf)
H = length of screened interval in vadose zone (ft)
k = soil permeability (sq. ft.)
μ = viscosity of air (lb-sec/sq. ft.)
R_w = radius of the well screen (in.)
R_I = vapor radius of influence (assumed 20 meters) (in.)

If P_{atm}, μ, and R_I are assumed constant throughout the site, and P_w, H, and R_w are given for each well, then the only missing factor is k. If all the variables are the same for two given wells (i.e., upper and lower nested wells) then k can be estimated (proportionally). Therefore, a factor can be developed for each well to proportion the flow contribution from each well to the total flow measured at the header. The permeability and the factor can then be adjusted accordingly to calibrate to the characterization data.

Use of this equation is based on the following assumptions:

- Radial flow and equal velocity distribution throughout screened interval
- Radius of influence is consistent from well to well at the site (assumed 20 meters)
- Viscosity of air (temperature) is the same from well to well
- Wells are screened in the vadose zone

METHOD 2:

Using a ratio of the open area (screened or jet perforated) of the wells.

For example:

Wells A, B, and C have ten, twenty, and thirty square inches of open area, respectively and are being used as extraction wells with a flow rate at the system header of 1000 cfm. The flow rates are proportioned out as follows:

$$\text{Well A flow rate} = 1000 \times \frac{10}{10 + 20 + 30} = 1000 \times \frac{10}{60} = 167\ cfm$$

$$\text{Well B flow rate} = 1000 \times \frac{20}{60} = 333\ cfm$$

Well C flow rate = $1000 \times \frac{30}{60} = 500\ cfm$

Use of this method is based on the following assumptions:

- The flow rates from individual wells are directly proportional to the open areas of the well screens.
- The soil permeabilities are the same for every well.
- Friction losses from the well head to the system are the same for every well.
- Well losses are the same for each well.

METHOD 3:

Using a ratio of estimated permeabilities for different lithologic layers where wells are screened to proportion flow rates amongst wells.

For example:

System header flow rate = 500 cfm and,

Well A is screened in the Hanford Lower Coarse layer from 50 - 60 feet below grade.

Well B is screened in the Plio-Pleistocene layer from 125 - 140 feet below grade.

If the permeability in the Hanford Lower Coarse layer is estimated to be two times that in the Plio-Pleistocene layer then the flow rate from Well A is twice that of Well B.

Well A flow rate = $500 \times \frac{2}{2+1} = 500 \times \frac{2}{3} = 333\ cfm$

Well B flow rate = $500 \times \frac{1}{2+1} = 500 \times \frac{1}{3} = 167\ cfm$

The permeabilities for different lithologies are estimated based on the flow rate ratio (from characterization data) from wells screened in different zones.

Use of this method is based on the following assumption:

- The screen length, well vacuum, radius of well, and radius of influence in the Johnson Equation (Method 1) combine to form a constant. This constant does not change significantly from well to well with the variations in screen length, well

vacuum, radius of well, and radius of influence. Therefore, the most significant parameter is the variation in soil permeability from well to well.

EVALUATION OF METHODOLOGY

Characterization data was used to evaluate the three methods. Characterization data was used for comparison purposes only if it was more recent than June 1995. Prior to June 1995, wells were characterized on an individual basis as opposed to on a system basis where all wells in operation are characterized. Based on this criterion, two characterization data events were determined to be useable from the Z-18 system. One characterization data event was determined to be useable from the Z-1A system. Two characterization data events were determined to be useable from the Z-9 system. Table 1 presents a summary of the characterization data events that were determined to be useable.

TABLE 1
USEABLE CHARACTERIZATION DATA SUMMARY

SYSTEM	DATE	EXTRACTION WELLS IN OPERATION	TOTAL NUMBER OF EXTRACTION WELLS IN SYSTEM	HEADER FLOW RATE (scfm)	SUM OF INDIVIDUAL WELL FLOW RATES (scfm)
Z-18	8/3/95	12, 246U, 246L, 252U, 252L, 96	17	474	1,158
Z-18	11/16/95	152, 252L	17	227	210
Z-1A	8/4/95 - 8/7/95	7, 89, 248, 165, 174	34	801	773
Z-9	8/1/95 - 8/2/95	82, 9U, 84, 85, 217, 218L, 218U, 219L, 219U	20	1314	1328
Z-9	11/28/95 - 11/29/95	6L, 9U, 216L, 218L, 218U, 220L, 220U, 82, 86, 217, 219L, 219U	20	1448	1171

Based on the characterization data, Z-9 appeared to be the system with the most complete data as there was characterization data for 14 out of 20 wells and the summations of the individual flow rates were somewhat consistent with the header flow rate. Therefore, the three methods were used on both useable characterization data sets for Z-9 (Attachment 1).

The results of the estimated flow rates using each method are summarized in Table 2. Method 1 flow rate estimates are summarized by presenting the adjusted flow rates resulting from the average adjusted k values from both characterization data sets for Z-9.

TABLE 2 SUMMARY OF METHOD RESULTS							
WELL	MEASURED FLOW (scfm)	METHOD 1 ESTIMATED FLOW (scfm)	ERROR (%)	METHOD 2 ESTIMATED FLOW (scfm)	ERROR (%)	METHOD 3 ESTIMATED FLOW (scfm)	ERROR (%)
Characterization Data Set # 1							
82	172	146	-18%	167	-3%	164	-5%
9U	79	66	-20%	54	-46%	164	108%
84	420	226	-86%	167	-151%	164	-156%
85	166	105	-58%	167	1%	164	-1%
217	67	148	120%	152	126%	164	145%
218L	95	168	77%	152	60%	82	-16%
218U	175	272	56%	152	-15%	164	-7%
219L	71	73	3%	152	114%	82	16%
219U	83	111	34%	152	83%	164	98%
TOTAL	1,328						
Characterization Data Set #2							
6L	91	100	10%	121	33%	96	5%
9U	39	44	12%	50	27%	138	255%
216L	23	31	35%	93	303%	96	316%
218L	103	111	8%	139	35%	96	-8%
218U	194	181	-7%	139	-40%	138	-40%
220L	98	157	60%	139	42%	138	41%
220U	135	201	49%	139	3%	96	-41%
82	95	97	2%	153	61%	138	46%
86	190	306	61%	59	-220%	138	-37%
217	103	98	-5%	139	35%	138	34%
219L	35	49	39%	139	297%	96	173%
219U	65	74	13%	139	114%	138	113%
TOTAL	1,171						

The results of an error analysis for each well on each characterization data set are summarized in Table 3.

TABLE 3 ERROR ANALYSIS SUMMARY		
	CHARACTERIZATION DATA SET #1	CHARACTERIZATION DATA SET #2
METHOD	% ERROR RANGE	% ERROR RANGE
1	-86% to 120%	-7% to 61%
2	-151% to 126%	-220% to 303%
3	-156% to 145%	-41% to 316%

At first glance, it would appear that Method 1 is the most accurate approach. However, the accuracy of Method 1 depends heavily on the amount of characterization data in order to estimate and adjust the permeability to calibrate with the characterization data. In the absence of characterization data, it can be shown (Attachment 2) that the error range increases significantly (-185% to 260%) when estimated permeability values are used. This also holds true for Method 3 which relies heavily on characterization data to estimate relative permeabilities of different lithologies.

In conclusion, with the limited characterization data, Methods 1 and 3 do not appear to be any more accurate than Method 2 which does not rely on characterization data whatsoever. Furthermore, discrepancies in cumulative flow measurements (between the header flow rates and the total measured flow rates) from the characterization data (Table 1) present further questions about the confidence in the characterization data that were determined to be useable. Therefore, method 2 was used to estimate flow rates and cumulative flow from the wells.

SPREADSHEET DEVELOPMENT

One spreadsheet was developed for each well field. Each spreadsheet was set up so that each well in the well field has five columns associated with it. These columns consist of the following:

- Operation - ("on" is entered in this cell if this well was used as an extraction well on a particular date). Cell was left blank if the well was not being used as an extraction well.

- Flow - estimated flow rates are calculated for all wells with "on" entered in the operation column by multiplying the system flow rate by the ratio of that well's

open area to the sum of the open areas for all the wells in operation for that particular day.

- Volume Removed - estimated by multiplying the estimated well flow rate by the estimated duration of operation for that particular day.

- Cumulative Volume Removed - summation of the Volume Removed cells for individual wells.

- Carbon Tetrachloride Concentration - Individual well carbon tetrachloride concentrations are entered corresponding to the day monitored. These concentrations can be used for comparison with flow rates, cumulative flow, and time.

The only other individual well data entered was the estimated open areas (provided) of each well screen. Some of the wells have open areas which changed due to jet perforating. Therefore, the open areas of some wells may vary depending on the date with which the well was in operation. The dates of operation, duration of operation, and system flow rate columns were used as the reference to which all data were input and estimates were linked.

The assumptions and notes associated with these flow rate estimates are as follows:

- The flow rates of individual wells are directly proportional to the open areas of individual well screens.

- Wells that were used as part of other well fields were included in each system's spreadsheet. Flow rates, however, were only estimated in the system spreadsheet for the system which was extracting vapors from that well on a particular date.

- The screened areas for wells W15-223 and W18-167 were modified to reflect actual operating conditions. The flow rates based on the provided open areas were grossly over-estimated. The open area for well W15-223 was modified by using an estimated open area of 3.67 in^2/ft of well screen. At 20 feet of well screen, the open area was estimated at 73.4 in^2. The open area of well W18-167 was modified by ignoring the open bottom of the well. Therefore, an open area of 8.438 in^2 was used when operated on 4/22/94 and 4/26/94 and 23.562 in^2 was used for this well when operated from 8/10/95 to 4/24/96.

As a quality check on the spreadsheets, the system header flow rates were multiplied by the estimated duration of operation and summed. This estimated total system volume removed was compared and confirmed to be equivalent to the summation of the individual well cumulative volumes removed.

RESULTS

The results of the cumulative volume estimates are summarized in Attachment 3 for each well and corresponding system from the period 2/25/92 to 4/24/96. It should be noted that there are errors associated with this calculation as discussed in the Evaluation of Methodology section.

Two sample plots generated from the spreadsheets are included in Attachment 4. These plots include: 1) well W15-82 cumulative volume removed and carbon tetrachloride concentrations versus time; and 2) well W15-223 flow rate and carbon tetrachloride concentrations versus time. The well W15-82 plot indicates decreasing carbon tetrachloride concentrations with increasing cumulative volume removed. The well W15-223 plot indicates carbon tetrachloride concentrations' response to well operation (decreasing carbon tetrachloride concentrations with well operation and minor rebounding concentrations while well is not in operation).

SUMMARY AND CONCLUSIONS

The flow rate and cumulative volume estimates presented in this report were developed using methodologies presented in this report. The estimates are based on measured flow rates at each system header and proportioned to individual wells based on a ratio of open areas of the operating extraction wells' screened interval. This report acknowledges that there are several sources of error associated with these estimates. Nonetheless, these estimates do provide useful information with respect to analyzing operating conditions of the system (estimated flow rates, operational periods for individual wells and well combinations, and carbon tetrachloride concentration trends with respect to well operation).

REFERENCES

Johnson, P.C., M.W. Kemblowski, and J.D. Colthart, 1990, "Quantitative Analysis for the Cleanup of Hydrocarbon-Contaminated Soils by In-Situ Soil Venting", Groundwater, pp. 413-429.

KWH:mmz

attachment

ATTACHMENT 1

1500 CFM SYSTEM													
SYSTEM FLOW RATE =			1314	scfm									
AIR VISCOSITY =			3.76E-07	lb-sec/sq. ft.									
ATMOSPHERIC PRESSURE =			2116	psf									
RADIUS OF INFLUENCE			787	in									
METHOD 1 - CHARACTERIZATION DATA SET #1													
WELL	DIAM (in)	SCREEN LENGTH (ft)	AIR K (m/d)	AIR K ADJ	Pw (in. water)	FACTOR	FACTOR ADJ	Q ESTIMATED	Q ADJ	% ERROR			
82	8	15	0.36	7.74	80	10578	258159	8	152	-13%			
9U	4	25	4.15	2.26	72	201153	158076	145	93	18%			
84	8	15	0.36	15.12	60	14353	684243	10	402	-5%			
85	8	15	4.15	7.03	72	136530	262506	98	154	-8%			
217	4	15	4.15	2.73	62	141329	119203	102	70	5%			
218L	4	15	21.74	4.74	75	605291	169349	436	99	5%			
218U	4	15	4.15	8.07	70	124360	310496	90	182	4%			
219L	4	15	21.74	4.31	90	496605	126464	358	74	5%			
219U	4	15	4.15	5.07	90	94798	148576	68	87	5%			
					671			1314	1314				
METHOD 1 - CHARACTERIZATION DATA SET #2 (USING ADJUSTED FACTORS FOR REPEATED WELLS IN CALIBRATION CASE #1)													
SYSTEM FLOW RATE =			1448	scfm									
WELL	DIAM (in)	SCREEN LENGTH (ft)	AIR K (m/d)	AIR K ADJ	Pw (in. water)	FACTOR	FACTOR ADJ	Q ESTIMATED	Q ADJ	% ERROR			
6L	8	30	21.74	5.33	55	1897780	620857	459	179	97%			
9U	4	25	4.15	2.26	64	271996	213748	66	62	58%			
216L	4	10	21.74	6.33	75	403527	138762	98	40	74%			
218L	4	15	21.74	4.74	86	522026	146053	126	42	-145%			
218U	4	15	4.15	8.07	74	117216	292660	28	84	-130%			
220L	4	15	21.74	19.55	81	557175	843238	135	185	89%			
220U	4	15	4.15	25.47	76	113917	897598	28	259	92%			
82	8	15	0.36	7.74	71	12021	293367	3	85	-12%			
86	6	30	21.74	16.26	75	1298712	1366291	314	394	107%			
217	4	15	4.15	2.73	83	103584	87367	25	25	-309%			
219L	4	15	21.74	4.31	79	572430	145773	139	42	20%			
219U	4	15	4.15	5.07	76	113917	178542	28	51	-77%			
					885			1448	1448				

METHOD 1 - CHARACTERIZATION DATA SET #2 (READJUSTING ALL FACTORS)

SYSTEM FLOW RATE = 1448 scfm

WELL	DIAM (in)	SCREEN LENGTH (ft)	AIR K (m/d)	AIR K ADJ	Pw (in. water)	FACTOR	FACTOR ADJ	Q ESTIMATED	Q ADJ	% ERROR
6L	8	30	21.74	4.31	55	1897780	501608	459	116	27%
9U	4	25	4.15	2.46	54	271996	232483	66	54	37%
216L	4	10	21.74	5.12	75	403527	112272	85	26	12%
218L	4	15	21.74	17.73	86	622026	546591	126	126	22%
218U	4	15	4.15	28.39	74	117216	1029502	28	237	22%
220L	4	15	21.74	15.80	81	557175	520058	135	120	22%
220U	4	15	4.15	20.33	76	113917	716406	28	165	22%
82	8	15	0.36	11.76	71	12021	445654	3	103	8%
86	6	30	21.74	13.14	75	1298712	1104356	314	254	34%
217	4	15	4.15	17.05	83	103584	546591	25	126	22%
219L	4	15	21.74	5.49	79	572430	185735	139	43	22%
219U	4	15	4.15	9.79	76	113917	344936	28	79	22%
					885		6286191	1448	1448	

WELL SUMMARY (WITH AVERAGE K VALUES)

WELL	DIAM (in)	SCREEN LENGTH (ft)	AIR K (m/d)	AIR K ADJ	Pw (in. water)	FACTOR	FACTOR ADJ
82	8	15	0.36	9.75	80	10578	325165
84	8	15	0.36	15.12	60	14353	684243
85	8	15	4.15	7.03	72	136530	262506
86	6	30	21.74	13.14	75	1298712	1104356
217	4	15	4.15	9.89	62	141329	432485
216L	4	10	21.74	5.12	75	403527	112272
218L	4	15	21.74	11.23	75	605291	401562
218U	4	15	4.15	18.23	70	124360	701371
219L	4	15	21.74	4.90	90	496605	143798
219U	4	15	4.15	7.43	90	94798	217810
220L	4	15	21.74	15.80	81	557175	520058
220U	4	15	4.15	20.33	76	113917	716406
6L	8	30	21.74	4.31	55	1897780	501608
9U	4	25	4.15	2.36	72	201153	165004

METHOD 1 AND 2 TEST ON CHARACTERIZATION DATA SET #1 (WITH AVERAGE K VALUES)

WELL	DIAM (in)	SCREEN LENGTH (ft)	MEHTOD 1 AIR K (m/d)	AIR K ADJ	Pw (in. water)	FACTOR	FACTOR ADJ	Q ESTIMATED	Q ADJ	% ERROR	METHOD 2 Q AREA	% ERROR	AREA
82	8	15	0.36	9.75	75	11411	350754	8	146	-18%	167.179106	-3%	60.678
9U	4	25	4.15	2.36	75	193804	158976	133	66	-20%	54.0980544	-46%	19.635
84	8	15	0.36	15.12	75	11411	544000	8	228	-66%	167.179106	-151%	60.678
85	8	15	4.15	7.03	75	131542	252916	90	105	-58%	167.179106	1%	60.678
217	4	15	4.15	9.89	75	116283	355840	80	148	120%	151.672926	126%	55.05
218L	4	15	21.74	11.23	75	609152	404123	418	168	77%	151.672926	60%	55.05
218U	4	15	4.15	18.23	75	116283	655816	80	272	56%	151.672926	-15%	55.05
219L	4	15	21.74	4.90	75	609152	176387	418	73	3%	151.672926	114%	55.05
219U	4	15	4.15	7.43	75	116283	267173	80	111	34%	151.672926	83%	55.05
								1314	1314		1314		476.919

1500

METHOD 1 AND 2 TEST ON CHARACTERIZATION DATA SET #2 (WITH AVERAGE K VALUES)													
			METHOD 1								METHOD 2		
WELL	DIAM (in)	SCREEN LENGTH (ft)	AIR K (m/d)	AIR K ADJ	Pw (in. water)	FACTOR	FACTOR ADJ	Q ESTIMATED	Q ADJ	% ERROR	Q AREA	% ERROR	AREA
6L	8	30	21.74	4.31	56	1865501	493076	362	100	10%	121.172287	33%	48.03
9U	4	25	2.66	2.36	56	168146	215189	33	44	12%	49.5360786	27%	19.635
216L	4	10	21.74	5.12	56	549697	152940	107	31	35%	92.5884433	303%	36.7
218L	4	15	21.74	11.23	56	824546	547019	160	111	8%	138.882665	35%	55.05
218U	4	15	4.15	18.23	56	157399	887710	31	181	-7%	138.882665	-40%	55.05
220L	4	15	21.74	15.80	56	824546	769617	160	157	60%	138.882665	42%	55.05
220U	4	15	4.15	20.33	56	157399	989856	31	201	49%	138.882665	3%	55.05
82	8	15	0.36	9.75	56	15446	474780	3	97	2%	153.081242	61%	60.678
86	6	30	21.74	13.14	56	1769144	1504387	343	306	61%	59.4432943	-220%	23.562
217	4	15	4.15	9.89	56	157399	481663	31	98	-5%	138.882665	35%	55.05
219L	4	15	21.74	4.90	56	824546	238757	160	49	39%	138.882665	297%	55.05
219U	4	15	4.15	7.43	56	157399	361644	31	74	13%	138.882665	114%	55.05
								1448	1448		1448		573.955

Bold values are taken from the Characterization Data Set #1

1500

METHOD 3 TEST ON CHARACTERIZATION DATA SET #1				
WELL	FLOW (scfm)	LITHOLOGY	EST Q	% ERROR
82	172	Hf	164.25	-5%
9U	79	Hf	164.25	108%
84	420	Hf	164.25	-156%
85	166	Hf	164.25	-1%
217	67	Hf	164.25	145%
218L	95	Rge	82.125	-16%
218U	175	Hf	164.25	-7%
219L	71	Rge	82.125	16%
219U	83	Hf	164.25	98%
AVE	Rge	83	1314	
	Hf	166		
RATIO	2			

CHARACTERIZATION DATA SET #1 ERROR ANALYSIS			
WELL	METHOD 1	METHOD 2	METHOD 3
82	-18%	-3%	-5%
9U	-20%	-46%	108%
84	-86%	-151%	-156%
85	-58%	1%	-1%
217	120%	126%	145%
218L	77%	60%	-16%
218U	56%	-15%	-7%
219L	3%	114%	16%
219U	34%	83%	98%
AVE	12%	19%	20%
STD. DE	0.65963	0.87606617	0.69009225

METHOD 3 TEST ON CHARACTERIZATION DATA SET #2

WELL	FLOW (scfm)	LITHOLOGY	EST Q	% ERROR
6L	91	Rge	95.58	5%
9U	39	Hf	138.306977	255%
216L	23	Rge	95.58	316%
218L	103	Rge	95.58	-8%
218U	194	Hf	138.306977	-40%
220L	98	Hf	138.306977	41%
220U	135	Rge	95.58	-41%
82	95	Hf	138.306977	46%
86	190	Hf	138.306977	-37%
217	103	Hf	138.306977	34%
219L	35	Rge	95.58	173%
219U	65	Hf	138.306977	113%
AVE	Rge	77.4	1446	
	Hf	112		
RATIO	1.44703			

CHARACTERIZATION DATA SET #2 ERROR ANALYSIS

WELL	METHOD 1	METHOD 2	METHOD 3
6L	10%	33%	5%
9U	12%	27%	255%
216L	35%	303%	316%
218L	8%	35%	-8%
218U	-7%	-40%	-40%
220L	60%	42%	41%
220U	49%	3%	-41%
82	2%	61%	46%
86	61%	-220%	-37%
217	-5%	35%	34%
219L	39%	297%	173%
219U	13%	114%	113%
AVE	26%	57%	71%
STD. DE	0.2613	1.338236821	1.19036081

ATTACHMENT 2

1500

METHOD 1

CHARACTERIZATION DATA SET #2 (USING ADJUSTED K VALUES FOR REPEATED WELLS IN CHARACTERIZATION DATA SET #1 AND SIMILAR K VALUES FOR WELLS SCREENED AT SIMILAR DEPTHS

SYSTEM FLOW RATE = 1448 scfm

WELL	DIAM (in)	SCREEN LENGTH (ft)	AIR K (m/d)	AIR K ADJ	Pw (in. water)	FACTOR	FACTOR ADJ	Q ESTIMATED	Q ADJ	% ERROR
6L	8	30	21.74	4.74	55	1897780	551878	459	328	260%
9U	4	25	4.15	2.26	54	271996	213748	66	127	225%
216L	4	10	21.74	4.74	75	403527	103918	98	62	168%
218L	4	15	21.74	4.74	86	622026	146053	126	87	-19%
218U	4	15	4.15	8.07	74	117216	292660	28	174	-12%
220L	4	15	21.74	4.74	81	557175	155988	135	93	-6%
220U	4	15	4.15	2.26	76	113917	79658	28	47	-185%
82	8	15	0.36	7.74	71	12021	293367	3	174	83%
86	6	30	21.74	2.26	75	1298712	189877	314	113	-69%
217	4	15	4.15	2.73	83	103584	87367	25	52	-99%
219L	4	15	21.74	4.31	79	572430	145773	139	87	147%
219U	4	15	4.15	5.07	76	113917	178542	28	106	63%
					885			1448	1448	

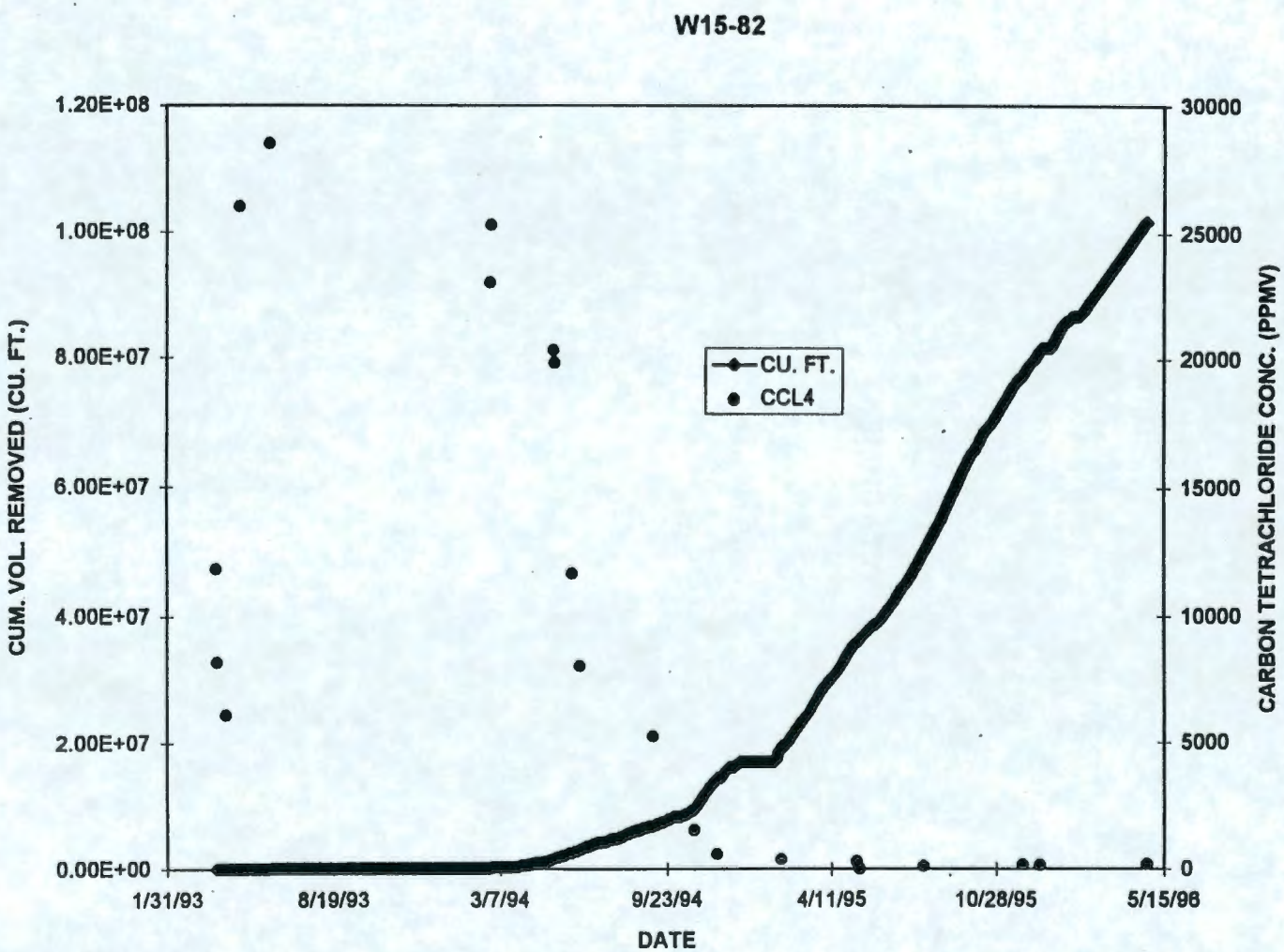
Bold values are taken from the Characterization Data Set #1

ATTACHMENT 3

CUMULATIVE VOLUME REMOVED (IN CUBIC FT.)										
	7.11									
Z-1A	~~1.42E+08~~	CU. FT. REMOVED FROM 2/25/92 TO 4/24/96								
WELLS	W18-150L	W18-150M	W18-150U	W18-175	W18-158L	W18-158M	W18-158U	W18-97	W18-10L	W18-10U
CU. FT.	7.46E+06	1.02E+06	1.02E+06	1.14E+07	2.29E+06	1.06E+03	1.77E+07	5.61E+06	1.26E+07	1.52E+07
	W18-171U	W18-165	W18-166	W18-252L	W18-252U	W18-248	W18-246L	W18-246U	W18-6L	W18-6U
	1.04E+07	3.70E+07	8.56E+06	2.11E+06	7.40E+06	3.50E+07	1.82E+05	2.38E+05	2.84E+07	7.34E+06
Z-9	8.15E+08	CU. FT. REMOVED FROM 3/31/93 TO 4/24/96								
WELLS	W15-82	W15-84	W15-85	W15-95	W15-217	W15-223	W15-216L	W15-216U	W15-219L	W15-219U
CU. FT.	1.02E+08	7.09E+07	5.12E+07	9.60E+06	9.93E+07	3.05E+07	2.04E+07	6.50E+04	6.68E+07	6.80E+07
Z-18	2.91E+08	CU. FT. REMOVED FROM 6/30/94 TO 4/24/96								
WELLS	W18-10L	W18-10U	W18-11L	W18-12	W18-246L	W18-246U	W18-249	W18-252L	W18-252U	W18-152
CU. FT.	6.22E+07	2.34E+07	7.38E+06	2.42E+07	2.91E+07	1.06E+07	1.82E+07	5.38E+07	1.92E+07	2.24E+07

CUMULATIVE VOLUME REMOVED (IN CUBIC FT.)										
Z-1A										
WELLS	W18-163L	W18-163M	W18-163U	W18-159	W18-168	W18-87L	W18-87M	W18-87U	W18-171L	W18-171M
CU. FT.	8.17E+05	3.19E+05	4.55E+05	2.09E+07	2.80E+07	8.07E+05	5.65E+05	8.87E+05	5.27E+06	9.24E+06
	W18-7	W18-174	W18-167	W18-89						
	2.09E+08	6.31E+07	2.66E+07	1.34E+08						
Z-9										
WELLS	W15-220L	W15-220U	W15-218L	W15-218U	W15-8	W15-9	W15-9L	W15-9U	W15-86	W15-6L
CU. FT.	3.08E+07	3.08E+07	8.51E+07	8.66E+07	0.00E+00	1.26E+04	8.42E+06	1.36E+07	9.97E+06	3.09E+07
Z-18										
WELLS	W18-93	W18-94	W18-96	W18-97	W18-98	W18-99				
CU. FT.	1.36E+04	7.55E+04	1.45E+07	7.15E+03	6.70E+04	5.53E+06				

ATTACHMENT 4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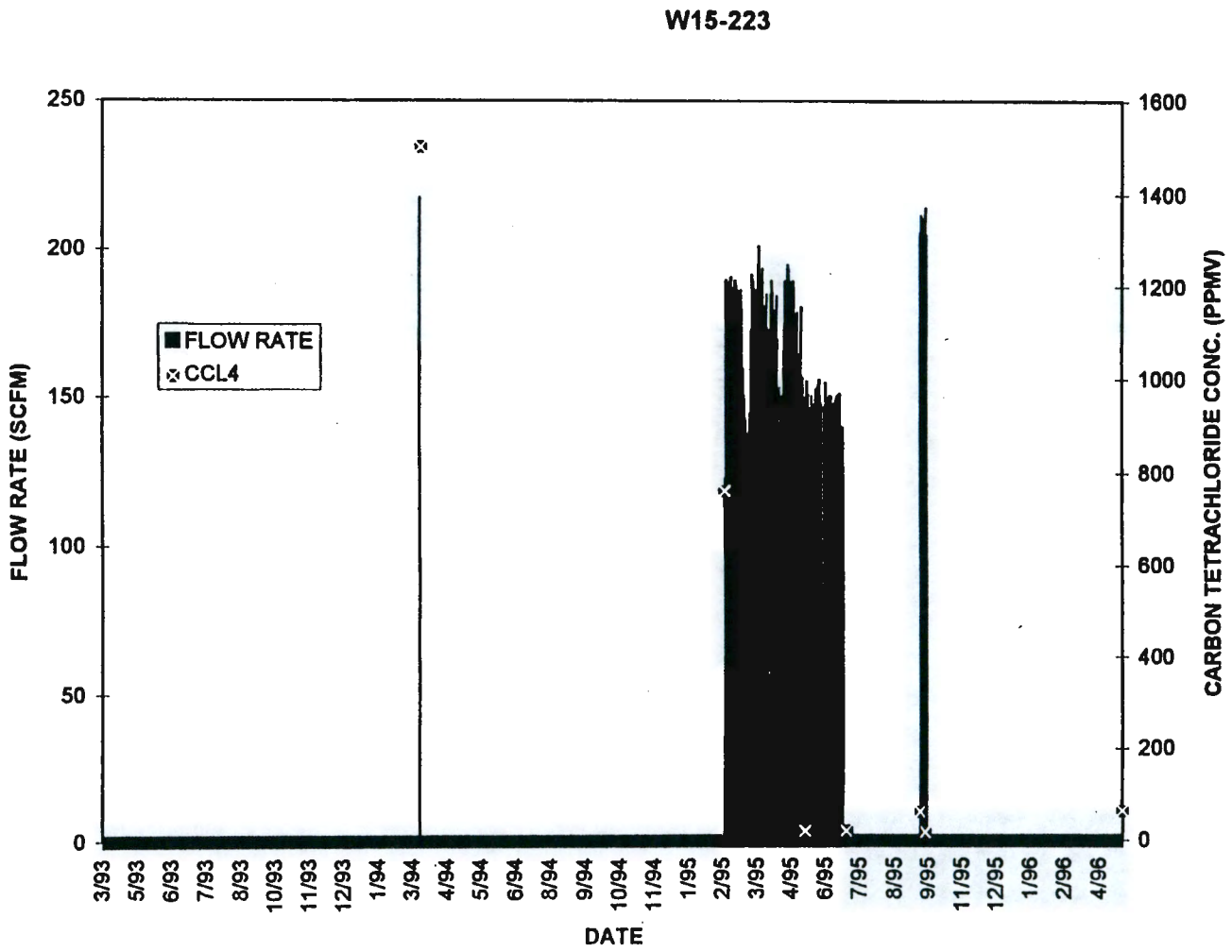
1.00E+08
8.00E+07
6.00E+07
4.00E+07
2.00E+07
0.00E+00
CUM. VOL. REMOVED (CU. FT.)
30000
25000
20000
15000
10000
5000
0
CARBON TETRACHLORIDE CONC. (PPMV)
CU. FT.
CCL4
1/31/93
8/19/93
3/7/94
9/23/94
4/11/95
10/28/95
5/15/96
DATE


W15-223
FLOW RATE
CCL4
FLOW RATE (SCFM)
CARBON TETRACHLORIDE CONC. (PPMV)
DATE
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150
200
250
0
200
400
600
800
1000
1200
1400
1600
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APPENDIX B

CHARACTERIZATION DATA

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Table B-1. Characterization Data for Individual Extraction Wells in the 216-Z-1A Wellfield, April 1992–September 1998. (6 Pages)

Date	Well & Interval	Vacuum* (kPa)	Flow (m3/min)	CCl4 (ppmv)	CCl4 Flux (kg/day)	CHCl3 (ppmv)	CH2Cl2 (ppmv)	MEK (ppmv)
05/02/94	299-W18-6L	22.2	10.5	304.0	0.891	0.0	4.0	0.0
06/20/94	299-W18-6L	21.4	11.0	525.0	1.609	0.0	7.0	0.0
11/22/94	299-W18-6L	26.7	9.7	199.0	0.540	0.0	0.0	0.0
02/07/95	299-W18-6L	24.9	11.8	161.0	0.529	0.0	1.0	0.0
09/06/95	299-W18-6L	5.7	1.2	73.5	0.024	0.0	1.3	0.0
05/09/96	299-W18-6L	5.2	0.9	54.4	0.013	0.0	0.0	0.0
05/14/96	299-W18-6L	11.2	2.5	30.0	0.021	0.0	0.0	0.0
09/18/96	299-W18-6L	3.2	1.4	19.6	0.008	2.2	0.0	0.0
10/29/96	299-W18-6L	3.5	2.4	15.8	0.010	0.0	0.0	0.0
07/21/97	299-W18-6L	1.5	0.5	26.8	0.004	3.7	0.0	0.0
07/24/97	299-W18-6L	2.0	0.5	24.4	0.004	2.9	0.0	0.0
07/28/97	299-W18-6L	1.9	0.4	30.9	0.004	3.8	0.0	0.0
07/31/97	299-W18-6L	2.1	0.5	8.6	0.001	2.0	0.0	0.0
03/30/98	299-W18-6L	6.0	0.0	25.6	0.000	0.6	0.0	0.0
04/08/98	299-W18-6L	0.8	0.0	0.1	0.000	0.4	0.0	0.0
04/10/98	299-W18-6L	0.0	0.0	33.4	0.000	1.1	0.0	0.0
04/16/98	299-W18-6L	1.5	0.1	0.1	0.000	0.6	0.0	0.0
04/29/98	299-W18-6L(f)	21.7	2.9	17.6	0.014	0.9	0.0	1.2
04/30/98	299-W18-6L	0.6	0.0	33.2	0.000	1.4	0.0	0.0
05/21/98	299-W18-6L	11.0	2.7	28.1	0.021	2.9	0.0	0.0
05/29/98	299-W18-6L	11.2	2.9	29.1	0.024	1.6	0.0	0.0
06/19/98	299-W18-6L	2.1	0.8	13.5	0.003	1.6	0.0	0.0
09/06/95	299-W18-6U	4.5	2.4	10.1	0.007	0.0	0.3	0.0
05/09/96	299-W18-6U	4.5	2.3	15.1	0.010	0.0	0.0	0.0
09/18/96	299-W18-6U	2.2	2.4	6.9	0.005	1.1	0.0	0.0
10/29/96	299-W18-6U	3.2	2.5	1.2	0.001	1.1	0.0	0.0
09/24/97	299-W18-6U	2.1	1.2	6.8	0.002	2.3	0.0	0.0
05/06/94	299-W18-7	23.9	6.1	209.0	0.359	0.0	3.0	0.0
06/21/94	299-W18-7	21.2	6.3	388.0	0.682	0.0	6.0	0.0
11/22/94	299-W18-7	24.4	5.1	197.0	0.282	0.0	0.0	0.0
02/01/95	299-W18-7	26.2	7.8	192.0	0.420	0.0	4.0	0.0
03/28/95	299-W18-7(e)	23.2	12.4	160.0	0.556	0.0	29.0	3.0
05/31/95	299-W18-7(e)	23.9	11.9	106.0	0.353	1.0	2.0	0.0
08/04/95	299-W18-7(e)	5.0	7.1	75.6	0.151	0.5	2.5	0.4
11/28/95	299-W18-7(e)	4.7	6.5	34.2	0.062	0.9	0.1	0.0
12/20/95	299-W18-7(e)	3.5		33.0		0.7	1.4	
05/02/96	299-W18-7(e)	5.0	6.6	31.0	0.057	0.0	0.0	0.0
05/14/96	299-W18-7(e)	6.5	9.9	43.2	0.120	0.0	0.0	0.0
07/17/96	299-W18-7(e)	2.5	5.4	16.5	0.025	2.6	0.0	0.0
09/16/96	299-W18-7(e)	3.7	5.9	17.7	0.029	1.7	0.0	0.0
10/29/96	299-W18-7(e)	3.0	2.8	0.0	0.000	0.0	0.0	0.0
07/21/97	299-W18-7(e)	2.5	2.8	30.8	0.024	6.1	0.0	0.0
07/24/97	299-W18-7(e)	2.0	3.5	3.9	0.004	3.3	0.0	0.0
07/28/97	299-W18-7(e)	2.0	3.5	9.8	0.009	2.7	0.0	0.0
07/31/97	299-W18-7(e)	2.5	3.6	26.6	0.027	3.2	0.0	0.0
03/30/98	299-W18-7(e)	1.2	0.7	14.8	0.003	0.7	0.1	0.0
04/09/98	299-W18-7(e)	0.6	0.7	0.9	0.000	0.0	0.1	0.0
04/10/98	299-W18-7(e)	0.4	1.7	26.8	0.013	1.2	0.0	0.0
04/16/98	299-W18-7(e)	1.0	0.0	0.0	0.000	1.1	0.0	0.0
04/30/98	299-W18-7(e)	0.5	0.0	0.3	0.000	0.1	0.1	0.0
06/05/98	299-W18-7(e)	2.0	3.5	24.6	0.024	2.1	0.0	0.0

Table B-1. Characterization Data for Individual Extraction Wells in the 216-Z-1A Wellfield, April 1992–September 1998. (6 Pages)

Date	Well & Interval	Vacuum* (kPa)	Flow (m3/min)	CCl4 (ppmv)	CCl4 Flux (kg/day)	CHCl3 (ppmv)	CH2Cl2 (ppmv)	MEK (ppmv)
06/11/98	299-W18-7(e)	1.8	3.1	25.7	0.023	2.6	0.0	0.0
02/03/93	299-W18-87	24.9	2.3	365.0	0.231			
06/02/93	299-W18-87	32.4	3.4	75.0	0.071			
11/16/93	299-W18-87	31.6	2.2	55.0	0.034	0.1	0.3	0.0
03/03/95	299-W18-87	offline						
07/26/94	299-W18-89	24.2	10.4	496.0	1.441	0.0	6.0	0.0
11/22/94	299-W18-89	25.4	9.9	123.0	0.341	0.0	0.0	0.0
08/04/95	299-W18-89	3.7	7.3	92.0	0.189	0.2	3.6	0.7
11/16/95	299-W18-89	5.0	8.2	34.0	0.078	0.5	0.0	0.0
12/20/95	299-W18-89	4.2		32.0		0.3	1.3	
05/01/96	299-W18-89	4.5	6.9	28.1	0.055	0.0	0.0	0.0
07/17/96	299-W18-89	2.5	4.9	30.6	0.042	1.5	0.0	0.0
09/18/96	299-W18-89	4.5	6.2	14.3	0.025	1.7	0.0	0.0
10/29/96	299-W18-89	3.2	3.4	20.8	0.020	0.0	0.0	1.1
09/24/97	299-W18-89	1.9	3.1	15.5	0.014	3.9	0.0	0.0
03/30/98	299-W18-89	1.2	0.4	28.1	0.003	0.7	0.2	0.0
04/08/98	299-W18-89	0.6	0.5	0.8	0.000	0.2	0.1	0.0
04/10/98	299-W18-89	0.5	1.6	25.9	0.012	0.7	1.0	0.0
04/16/98	299-W18-89	0.9	2.0	5.9	0.003	1.1	0.0	0.0
04/30/98	299-W18-89	0.5	1.9	28.5	0.015	1.3	0.0	0.0
05/08/98	299-W18-89	0.5	1.0	27.4	0.008	3.1	0.0	0.0
05/13/98	299-W18-89	0.5	1.0	27.7	0.008	1.7	0.0	0.0
06/19/98	299-W18-89	1.6	4.2	23.6	0.028	2.1	0.0	0.0
06/01/93	299-W18-150L	32.9	2.4	219.0	0.146			
11/15/93	299-W18-150L	32.1	1.4	243.0	0.096	0.1	2.7	1.1
11/15/93	299-W18-150L(b)	32.1	1.4			0.6	6.7	
04/15/94	299-W18-150L	31.6	1.5	150.0	0.063	0.4		0.2
11/22/94	299-W18-150L	25.9	1.1	82.0	0.025	0.0	0.0	0.0
02/01/95	299-W18-150L	24.4	1.2	10.0	0.003	0.0	1.0	0.0
06/01/93	299-W18-150M	32.9	0.8	157.0	0.035			
04/18/94	299-W18-150M	28.9	0.5	180.0	0.024	0.0		0.9
06/01/93	299-W18-150U	32.6	0.9	35.0	0.009			
04/18/94	299-W18-150U	30.1	0.6	181.0	0.029	0.0		1.3
05/25/95	299-W18-150	alpha						
04/30/92	299-W18-158L(a)	27.4	1.7	270.0	0.128			
09/22/92	299-W18-158L(a)	22.7	1.3	500.0	0.178			
06/01/93	299-W18-158L	32.6	1.1	144.0	0.046			
11/15/93	299-W18-158L	30.9	0.7	394.0	0.081	3.8	3.6	0.8
04/18/94	299-W18-158L	29.9	1.4	192.0	0.076	0.9		0.5
02/01/95	299-W18-158L	26.2	0.4	45.0	0.005	2.0	3.0	0.0
08/08/95	299-W18-158L	10.0	0.0					
07/30/96	299-W18-158L	3.7	1.2	76.5	0.026	0.0	9.4	0.0
09/16/96	299-W18-158L	8.2	0.0	0.2	0.000	0.4	0.0	0.0
10/29/96	299-W18-158L	3.5	0.0	77.6	0.000	0.0	0.0	6.5
09/24/97	299-W18-158L	3.7	0.0	0.0	0.000	2.4	0.0	0.0
06/01/93	299-W18-158M	32.6	1.1	91.0	0.029			
04/18/94	299-W18-158M(c)	31.1	0.8	106.0	0.023	0.6		0.8
06/01/93	299-W18-158U(c)	7.7	1.8	2.0	0.001			
04/18/94	299-W18-158U(c)	30.9	2.2	38.0	0.023	0.4		0.5
08/08/95	299-W18-158U(e)	7.5	1.8	248.0	0.124	0.0	10.8	0.0
11/29/95	299-W18-158U(e)	4.7	0.4	127.0	0.015	8.0	18.0	1.0

Table B-1. Characterization Data for Individual Extraction Wells in the 216-Z-1A Wellfield, April 1992–September 1998. (6 Pages)

Date	Well & Interval	Vacuum* (kPa)	Flow (m3/min)	CCl4 (ppmv)	CCl4 Flux (kg/day)	CHCl3 (ppmv)	CH2Cl2 (ppmv)	MEK (ppmv)
12/22/95	299-W18-158U(e)	3.7		124.0		0.0	12.0	
06/03/96	299-W18-158U(e)	5.0	1.9	99.8	0.052	0.0	7.8	0.0
09/16/96	299-W18-158U(e)	6.2	2.8	2.5	0.002	0.6	0.2	0.0
10/29/96	299-W18-158U(e)	2.5	1.4	0.0	0.000	1.3	0.0	0.0
09/24/97	299-W18-158U(e)	3.0	0.9	0.0	0.000	3.7	0.0	0.0
09/22/92	299-W18-159(a)	24.9	1.6	580.0	0.262			
06/01/93	299-W18-159	32.9	2.0	307.0	0.175			
04/15/94	299-W18-159	31.6	1.1	243.0	0.073	0.7		0.4
06/20/94	299-W18-159	24.2	1.1	238.0	0.073			
11/22/94	299-W18-159		0.0					
02/01/95	299-W18-159	26.2	0.8	150.0	0.033	0.0	7.0	0.0
05/31/95	299-W18-159(e)	24.9	11.1	77.0	0.239	0.0	3.0	0.0
06/13/96	299-W18-159(e)	6.2	3.8	9.7	0.010	2.5	1.3	0.0
07/30/96	299-W18-159(e)	3.0	3.9	8.1	0.009	3.1	0.0	0.0
09/18/96	299-W18-159(e)	3.7	3.1	5.6	0.005	1.4	1.4	0.0
10/29/96	299-W18-159(e)	3.5	3.1	11.7	0.010	0.0	0.0	2.1
09/24/97	299-W18-159(e)	2.5	0.8	3.1	0.001	3.6	0.0	0.0
09/22/92	299-W18-163L(a)	19.9	0.7	140.0	0.029			
06/01/93	299-W18-163L	30.9	0.2	5.0	0.000			
11/15/93	299-W18-163L	31.9	0.0					
04/18/94	299-W18-163L	29.9	0.0					
06/02/93	299-W18-163M	32.4	0.3	2.0	0.000			
04/18/94	299-W18-163M	29.1	0.0					
08/08/95	299-W18-163L(e)	7.5	1.8	80.6	0.040	2.0	2.5	0.0
05/10/96	299-W18-163L(e)	3.0	0.5	31.1	0.005	0.0	0.0	0.0
10/29/96	299-W18-163L(e)	2.0	0.5	1.7	0.000	0.0	0.0	0.0
09/24/97	299-W18-163L(e)	1.7	0.0	5.2	0.000	2.6	0.0	0.0
06/02/93	299-W18-163U	35.1	0.3	2.0	0.000			
04/18/94	299-W18-163U	29.6	0.0					
08/08/95	299-W18-163U(e)	6.2	4.0	72.1	0.082	0.1	9.1	0.0
06/13/96	299-W18-163U(e)	5.0	2.1	17.7	0.010	0.0	13.5	0.0
07/30/96	299-W18-163U(e)	1.7	2.1	27.5	0.016	0.0	13.9	0.0
10/29/96	299-W18-163U(e)	1.7	2.4	5.6	0.004	0.0	1.3	8.7
09/24/97	299-W18-163U(e)	1.5	1.0	14.8	0.004	1.5	2.4	0.0
04/20/94	299-W18-165	30.4	0.1	140.0	0.004			
05/31/95	299-W18-165(e)	24.9	6.7	150.0	0.281	0.0	5.0	0.0
08/07/95	299-W18-165(e)	14.9	6.2	91.9	0.159	2.2	4.0	0.0
11/29/95	299-W18-165(e)	5.0	1.4	29.4	0.012	2.0	4.0	0.4
12/22/95	299-W18-165(e)	3.7		25.0		0.0	0.0	
06/03/96	299-W18-165(e)	6.7	3.8	10.0	0.011	0.0	0.5	0.1
07/30/96	299-W18-165(e)	6.2	2.2	8.9	0.005	1.8	0.0	0.0
09/16/96	299-W18-165(e)	5.5	3.3	16.0	0.015	1.6	0.0	0.0
10/29/96	299-W18-165(e)	3.0	2.7	29.9	0.022	0.0	0.0	1.9
09/24/97	299-W18-165(e)	3.5	1.9	15.5	0.008	2.1	0.0	0.0
04/01/98	299-W18-165(e)	0.3	0.0	5.8	0.000	1.0	0.0	0.0
04/09/98	299-W18-165(e)	0.6	0.0	36.7	0.000	0.5	1.8	0.0
04/10/98	299-W18-165(e)	0.6	0.5	33.6	0.005	1.6	1.0	0.0
04/30/98	299-W18-165(e)	0.5	0.4	42.0	0.005	2.9	0.0	0.0
05/08/98	299-W18-165(e)	0.3	0.0	2.5	0.000	0.4	0.0	0.0
05/13/98	299-W18-165(e)	0.4	0.0	1.4	0.000	0.9	0.0	0.0
06/05/98	299-W18-165(e)	2.5	1.7	40.3	0.019	3.9	0.0	0.0

Table B-1. Characterization Data for Individual Extraction Wells in the 216-Z-1A Wellfield, April 1992–September 1998. (6 Pages)

Date	Well & Interval	Vacuum* (kPa)	Flow (m3/min)	CCl4 (ppmv)	CCl4 Flux (kg/day)	CHCl3 (ppmv)	CH2Cl2 (ppmv)	MEK (ppmv)
06/11/98	299-W18-165(e)	2.4	1.7	43.2	0.020	3.2	0.0	0.0
06/19/98	299-W18-165(e)	7.0	3.3	22.3	0.021	2.8	0.0	0.0
06/01/93	299-W18-166	32.4	0.5	82.0	0.010			
11/16/93	299-W18-166	31.9	0.1	70.0	0.002	0.3	0.7	0.0
04/18/94	299-W18-166	29.9	0.1	148.0	0.005	0.7		0.8
05/31/95	299-W18-166(e)	25.7	6.9	37.0	0.071	1.0	1.0	0.0
08/07/95	299-W18-166(e)	16.2	5.7	66.6	0.107	0.3	4.0	0.0
06/13/96	299-W18-166(e)	6.7	2.1	17.4	0.010	1.5	0.0	0.0
07/30/96	299-W18-166(e)	6.2	1.9	9.7	0.005	0.0	0.0	0.0
09/18/96	299-W18-166(e)	8.7	4.7	7.0	0.009	1.1	1.7	0.0
10/29/96	299-W18-166(e)	2.7	2.1	8.4	0.005	0.0	0.0	0.0
09/24/97	299-W18-166(e)	5.0	2.5	15.9	0.011	4.4	0.0	0.0
04/20/94	299-W18-167	29.9	1.6	180.0	0.083			
06/21/94	299-W18-167	21.7	0.6	191.0	0.030	0.0	3.0	0.0
03/28/95	299-W18-167(e)	20.7	12.9	51.0	0.183	1.0	22.0	3.0
08/08/95	299-W18-167(e)	2.5	6.4	208.0	0.374	0.8	5.8	0.0
11/29/95	299-W18-167(e)	3.7	7.1	34.4	0.068	3.4	7.0	0.6
12/22/95	299-W18-167(e)	3.7		27.0		0.0	3.0	
05/10/96	299-W18-167(e)	3.7	8.2	18.9	0.043	0.0	0.5	0.0
07/30/96	299-W18-167(e)	2.0	5.4	16.0	0.024	1.2	2.9	0.0
10/29/96	299-W18-167(e)	3.0	3.5	18.9	0.018	0.0	0.0	1.8
07/21/97	299-W18-167(e)	1.7	4.8	20.6	0.028	3.6	5.5	1.1
07/24/97	299-W18-167(e)	2.2	4.8	21.2	0.029	3.4	2.2	0.0
07/28/97	299-W18-167(e)	2.0	4.9	15.3	0.021	3.5	1.8	0.0
07/31/97	299-W18-167(e)	2.4	4.7	1.8	0.002	2.7	0.0	0.0
09/24/97	299-W18-167(e)	2.0	5.0	27.9	0.039	2.7	0.0	0.0
04/01/98	299-W18-167(e)	0.3	1.0	26.9	0.007	2.8	0.0	0.0
04/09/98	299-W18-167(e)	0.4	1.2	11.7	0.004	0.3	0.3	0.0
04/10/98	299-W18-167(e)	0.3	1.3	11.1	0.004	1.0	0.4	0.0
04/30/98	299-W18-167(e)	0.4	1.8	19.6	0.010	2.9	0.0	0.0
05/08/98	299-W18-167(e)	0.4	0.9	30.4	0.007	1.5	0.0	0.0
05/13/98	299-W18-167(e)	0.5	0.0	0.0	0.000	1.2	0.0	0.0
06/05/98	299-W18-167(e)	1.3	4.6	25.1	0.032	2.7	0.0	0.0
06/11/98	299-W18-167(e)	1.2	4.5	23.9	0.030	2.8	0.0	0.0
10/06/92	299-W18-168(a)	24.9	0.3	670.0	0.053			
06/01/93	299-W18-168	34.6	0.8	212.0	0.045			
11/16/93	299-W18-168	32.1	0.4	371.0	0.038	3.6	5.0	0.3
11/16/93	299-W18-168(b)	32.1	0.4				1.5	
04/18/94	299-W18-168	29.9	0.4	108.0	0.012	0.0		0.6
06/20/94	299-W18-168	22.2	0.2					
03/30/95	299-W18-168(e)	25.7	7.2	101.0	0.203	6.0	101.0	5.0
08/09/95	299-W18-168(e)	6.2	2.2	302.0	0.189	5.1	0.0	0.0
11/29/95	299-W18-168(e)	4.5	0.4	54.6	0.006	3.6	7.0	0.6
12/22/95	299-W18-168(e)	4.7		54.0		0.0	2.0	
05/10/96	299-W18-168(e)	4.7	0.9	42.3	0.011	0.0	0.0	0.0
10/29/96	299-W18-168(e)	2.5	0.8	2.8	0.001	1.3	0.0	0.0
09/24/97	299-W18-168(e)	3.7	1.4	27.2	0.011	2.1	0.0	0.0
04/01/98	299-W18-168(e)	0.4	0.0	1.3	0.000	0.7	0.0	0.0
04/09/98	299-W18-168(e)	0.5	0.0	0.3	0.000	0.1	0.0	0.0
04/10/98	299-W18-168(e)	0.4	0.0	2.4	0.000	1.1	0.0	0.0
04/29/98	299-W18-168(e)(f)	16.4	4.0	44.1	0.049	2.9	0.0	0.0

Table B-1. Characterization Data for Individual Extraction Wells in the 216-Z-1A Wellfield, April 1992–September 1998. (6 Pages)

Date	Well & Interval	Vacuum* (kPa)	Flow (m3/min)	CCl4 (ppmv)	CCl4 Flux (kg/day)	CHCl3 (ppmv)	CH2Cl2 (ppmv)	MEK (ppmv)
04/30/98	299-W18-168(e)	0.5	0.0	11.9	0.000	0.8	0.0	0.0
05/21/98	299-W18-168(e)	10.0	4.7	28.1	0.037	2.5	0.0	0.0
05/29/98	299-W18-168(e)	11.0	5.9	35.1	0.058	2.4	0.0	0.0
06/19/98	299-W18-168(e)	6.2	3.2	31.2	0.028	2.4	0.0	0.0
06/21/94	299-W18-169	22.4	0.0					
03/28/95	299-W18-169	23.7	1.2	266.0	0.088	0.0	54.0	6.0
09/06/95	299-W18-169(e)	3.7	3.7	15.6	0.016	1.4	1.4	0.1
05/10/96	299-W18-169(e)	3.5	4.1	11.5	0.013	0.0	0.3	0.0
09/25/96	299-W18-169(e)	5.0	4.4	4.1	0.005	1.6	0.0	0.0
10/29/96	299-W18-169(e)	3.5	3.7	0.0	0.000	0.0	0.0	0.0
09/24/97	299-W18-169(e)	2.5	1.8	4.2	0.002	2.2	0.0	0.0
02/03/93	299-W18-171	24.9	8.5	350.0	0.831			
06/02/93	299-W18-171	32.4	8.4	329.0	0.771			
11/12/93	299-W18-171(d)	32.4	8.2	29.0	0.067			
11/16/93	299-W18-171(d)	26.9	7.1	51.5	0.102	0.0	0.8	0.0
04/15/94	299-W18-171(d)	30.6	9.2	50.0	0.129	0.0		0.1
06/20/94	299-W18-171(d)	21.9	8.0	8.0	0.018	0.0	1.0	0.0
08/16/95	299-W18-171L	9.0	4.0	7.2	0.008	0.6	0.0	0.0
04/03/96	299-W18-171L	7.0	2.9	3.3	0.003	0.0	0.0	0.0
09/25/96	299-W18-171L	6.2	3.7	1.8	0.002	0.0	0.0	0.0
10/29/96	299-W18-171L	7.0	4.6	4.6	0.006	1.3	0.0	0.0
09/24/97	299-W18-171L	4.7	2.4	5.0	0.003	3.1	0.0	0.0
08/16/95	299-W18-171U	7.5	5.6	0.6	0.001	1.3	0.0	0.0
04/03/96	299-W18-171U	6.0	4.1	0.5	0.001	0.0	0.0	0.0
09/25/96	299-W18-171U	6.0	5.3	0.0	0.000	1.2	0.0	0.0
10/29/96	299-W18-171U	6.0	7.8	0.0	0.000	0.0	0.0	1.6
09/24/97	299-W18-171U	4.0	3.2	0.0	0.000	2.1	0.0	0.0
04/21/94	299-W18-174	29.9	3.5	199.0	0.195	0.0	4.0	0.0
06/20/94	299-W18-174	23.4	3.2	227.0	0.201	1.0	4.0	0.0
11/22/94	299-W18-174		0.0					
02/01/95	299-W18-174	25.4	0.0					
05/31/95	299-W18-174	24.9	2.9	82.0	0.067	1.0	3.0	0.0
08/07/95	299-W18-174	7.5	1.1	80.6	0.025	2.7	0.8	0.0
10/29/96	299-W18-174	1.0	0.0	0.0	0.000	0.0	0.0	0.0
07/21/97	299-W18-174	2.5	0.4	7.0	0.001	3.1	0.0	0.0
07/24/97	299-W18-174	2.5	0.4	2.9	0.000	1.4	0.0	0.0
07/28/97	299-W18-174	2.5	0.4	0.0	0.000	1.8	0.0	0.0
07/31/97	299-W18-174	3.2	0.4	4.0	0.000	1.9	0.0	0.0
09/24/97	299-W18-174	4.0	0.8	14.6	0.003	2.8	0.0	0.0
04/01/98	299-W18-174	0.4	0.0	7.7	0.000	0.8	0.0	0.0
04/09/98	299-W18-174	0.7	0.0	0.4	0.000	0.0	0.0	0.0
05/21/98	299-W18-174	10.5	2.5	15.2	0.010	2.1	0.0	0.0
05/29/98	299-W18-174	9.5	2.9	22.4	0.018	1.9	0.0	0.0
04/13/92	299-W18-175(a)	24.9	2.5	275.0	0.196			
09/22/92	299-W18-175(a)	22.4	1.7	605.0	0.287			
06/01/93	299-W18-175	32.9	1.9	490.0	0.264			
04/15/94	299-W18-175	30.9	0.9	576.0	0.151	0.0		1.6
06/20/94	299-W18-175	21.9	1.1	494.0	0.156	0.0	12.0	1.0
11/22/94	299-W18-175	25.2	0.8	193.0	0.043	0.0	0.0	0.0
02/01/95	299-W18-175	26.4	0.9	277.0	0.070	0.0	22.0	0.0
04/24/95	299-W18-175	alpha						

Table B-1. Characterization Data for Individual Extraction Wells in the 216-Z-1A Wellfield, April 1992–September 1998. (6 Pages)

Date	Well & Interval	Vacuum* (kPa)	Flow (m3/min)	CCl4 (ppmv)	CCl4 Flux (kg/day)	CHCl3 (ppmv)	CH2Cl2 (ppmv)	MEK (ppmv)
04/21/94	299-W18-248	29.9	0.8	142.0	0.034	0.0	1.0	0.0
06/21/94	299-W18-248	22.7	0.8	301.0	0.064	1.0	4.0	1.0
12/20/94	299-W18-248	26.4	0.7	137.0	0.028	0.0	3.0	0.0
02/07/95	299-W18-248	25.9	0.6	69.0	0.012	0.0	0.0	0.0
03/28/95	299-W18-248	24.7	2.0	263.0	0.146	0.0	37.0	4.0
05/31/95	299-W18-248	24.9	0.7	433.0	0.079	2.0	2.0	0.0
08/04/95	299-W18-248	0.0	0.1					
05/07/96	299-W18-248	12.5	0.5	277.0	0.035	0.0	0.0	0.0
07/17/96	299-W18-248	2.5	0.1	9.5	0.000	0.0	0.0	0.0
09/16/96	299-W18-248	8.7	0.6	62.3	0.010	2.2	0.0	0.0
10/29/96	299-W18-248	6.0	0.5	8.4	0.001	0.0	0.0	0.0
07/21/97	299-W18-248	3.2	0.1	59.3	0.001	3.7	0.0	0.0
07/24/97	299-W18-248	3.7	0.3	57.9	0.004	2.2	0.0	0.0
07/28/97	299-W18-248	3.5	0.3	2.7	0.000	2.9	0.0	0.0
07/31/97	299-W18-248	3.7	0.4	26.4	0.003	2.0	0.0	0.0
09/30/97	299-W18-248	3.7	0.0	4.8	0.000	2.5	0.0	0.0
03/30/98	299-W18-248	2.5	0.0	0.7	0.000	0.0	0.5	0.0
04/09/98	299-W18-248	0.9	0.0	0.0	0.000	0.2	0.0	0.0
04/10/98	299-W18-248	1.8	0.0	36.4	0.000	1.2	0.0	0.0
04/16/98	299-W18-248	1.8	0.0	0.0	0.000	0.6	0.0	0.0
04/30/98	299-W18-248	1.0	0.0	0.9	0.000	0.3	0.0	0.0
05/21/98	299-W18-248	11.2	0.5	47.0	0.007	2.3	0.0	0.0
05/29/98	299-W18-248	12.5	0.8	29.5	0.006	2.1	0.0	0.0

* After 6/15/95, all measurements made at the wellhead

(a) Odyssey analysis
(b) gas chromatograph analysis
(c) short circuiting
(d) packer broken ?
(e) after jet perforating
(f) only well on-line

CCl4 = Carbon Tetrachloride
CHCl3 = Chloroform
CH2Cl2 = Methylene Chloride
MEK = Methyl ethyl ketone

Table B-2. Characterization Data for Individual Extraction Wells in the 216-Z-18/Z-12 Wellfield, May 1992–September 1998. (4 Pages)

Date	Well & Interval	Vacuum* (kPa)	Flow (m3/min)	CCl4 (ppmv)	CCl4 Flux (kg/day)	CHCl3 (ppmv)	CH2Cl2 (ppmv)	MEK (ppmv)
06/05/92	299-W18-10L(a)	25.7	2.4	27.4	0.018			
06/09/92	299-W18-10L(a)	24.9	1.9	200.0	0.105			
06/12/92	299-W18-10L(a)	24.9	0.9	280.0	0.074			
06/15/92	299-W18-10L(a)	24.9	2.6	190.0	0.140			
02/03/93	299-W18-10L	26.9	1.8	210.0	0.106			
06/02/93	299-W18-10L	32.4	2.3	221.0	0.140			
11/16/93	299-W18-10L	32.4	1.3	342.0	0.125	4.7	6.0	0.8
04/15/94	299-W18-10L	30.9	1.4	267.0	0.104	0.0		0.2
07/26/94	299-W18-10U&L	24.9	2.3	149.0	0.094	1.3	1.0	0.8
11/02/94	299-W18-10U&L	25.2	2.0	43.0	0.024	1.0	0.0	0.0
05/10/95	299-W18-10L	24.4	1.5	18.0	0.008	2.0	3.0	0.0
04/04/96	299-W18-10L	18.7	1.0	11.5	0.003	0.0	0.0	0.0
05/14/96	299-W18-10L	19.4	0.9	7.0	0.002	0.1	0.0	0.0
09/23/96	299-W18-10L			4.0		0.0	0.0	0.0
04/04/96	299-W18-10U		0.0					
09/23/96	299-W18-10U	19.9	0.0					
07/14/94	299-W18-11U&L	25.2	0.9	54.1	0.014	0.0	1.0	1.8
05/10/95	299-W18-11L	24.7	0.8	8.0	0.002	1.0	2.0	0.0
06/07/95	299-W18-11L	24.7	0.8	27.0	0.006	1.0	0.0	0.0
04/04/96	299-W18-11L	19.2	0.3	1.7	0.000	0.0	0.0	0.0
09/19/96	299-W18-11L	18.9	0.9	1.1	0.000	0.5	1.4	0.0
04/04/96	299-W18-11U	17.9	0.8	2.0	0.000	0.0	0.0	0.0
09/19/96	299-W18-11U	18.2	1.2	1.2	0.000	1.0	0.0	0.0
04/10/95	299-W18-12(b)	25.7	7.1	82.0	0.162			
05/10/95	299-W18-12(b)	25.4	5.6	55.0	0.087	3.0	4.0	0.0
06/07/95	299-W18-12(b)	25.2	5.6	46.0	0.072	2.0	2.0	0.0
08/03/95	299-W18-12(b)	24.7	5.5	23.0	0.035	1.0	0.0	0.0
04/04/96	299-W18-12(b)	15.7	4.4	17.1	0.021	0.0	0.0	0.0
05/14/96	299-W18-12(b)	16.9	3.2	15.4	0.014	0.0	0.0	0.0
09/23/96	299-W18-12(b)	14.9	6.2	10.7	0.018	1.7	0.0	0.0
03/30/98	299-W18-12(b)	8.7	0.4	28.7	0.003	1.0	0.0	0.0
04/09/98	299-W18-12(b)	2.1	0.8	19.1	0.004	1.3	0.0	0.0
04/10/98	299-W18-12(b)	2.5	1.9	0.3	0.000	0.5	0.0	0.0
04/16/98	299-W18-12(b)	0.4	5.4	0.0	0.000	0.3	0.0	0.0
04/30/98	299-W18-12(b)	3.0	1.8	17.4	0.009	1.2	0.0	0.0
05/08/98	299-W18-12(b)	1.3	0.5	14.6	0.002	1.2	0.0	0.0
05/13/98	299-W18-12(b)	1.4	0.7	14.1	0.003	2.3	0.0	0.0
07/14/94	299-W18-93	24.9	4.8	25.8	0.035	0.0	1.8	1.0
04/04/96	299-W18-93	14.9	2.8	0.4	0.000	0.2	0.0	0.2
09/19/96	299-W18-93	15.9	3.5	0.1	0.000	1.4	0.0	0.0
07/25/94	299-W18-94	25.4	7.7	22.0	0.047	0.0	1.3	0.8
04/06/96	299-W18-94	13.2	6.1	0.5	0.001	0.0	0.0	0.0
09/19/96	299-W18-94	13.4	5.6	0.1	0.000	1.5	0.0	0.0
07/13/94	299-W18-96	24.9	7.2	103.0	0.209	0.7		0.3
11/02/94	299-W18-96	25.9	8.2	29.0	0.067	1.0	0.0	0.0
02/15/95	299-W18-96	24.4	9.4	121.0	0.317			
03/28/95	299-W18-96	25.2	9.3	120.0	0.314	1.0	0.0	0.0
04/10/95	299-W18-96	28.9	9.9	143.0	0.396			
05/10/95	299-W18-96	24.9	7.5	50.0	0.105	2.0	4.0	0.0
08/03/95	299-W18-96	24.7	7.2	13.0	0.026	1.0	0.0	0.0
04/09/96	299-W18-96	12.0	6.5	7.2	0.013	0.2	0.0	0.0

Table B-2. Characterization Data for Individual Extraction Wells in the 216-Z-18/Z-12 Wellfield, May 1992–September 1998. (4 Pages)

Date	Well & Interval	Vacuum* (kPa)	Flow (m3/min)	CCl4 (ppmv)	CCl4 Flux (kg/day)	CHCl3 (ppmv)	CH2Cl2 (ppmv)	MEK (ppmv)
09/23/96	299-W18-96	12.5	8.2	3.4	0.008	0.0	0.0	0.0
03/30/98	299-W18-96	9.2	1.6	16.2	0.007	0.6	0.0	0.0
04/09/98	299-W18-96	2.0	2.1	26.5	0.016	1.4	0.0	0.0
05/08/98	299-W18-96	1.4	1.8	14.2	0.007	0.9	0.0	0.0
05/13/98	299-W18-96	1.5	1.9	19.9	0.011	2.4	0.0	0.0
05/01/92	299-W18-97(a)	6.2	2.9	95.0	0.077			
05/05/92	299-W18-97(a)	5.5	3.2	70.0	0.063			
02/03/93	299-W18-97	27.1	7.5	355.0	0.745			
06/02/93	299-W18-97	33.4	8.8	23.0	0.057			
11/16/93	299-W18-97	31.9		95.0		0.0	0.0	0.0
04/15/94	299-W18-97	32.1	7.3	48.2	0.098	0.5		0.1
07/26/94	299-W18-97	25.4	8.4	12.0	0.028	0.0	1.9	0.7
04/06/96	299-W18-97	13.0	6.2	0.3	0.000	0.0	0.0	0.0
09/23/96	299-W18-97	13.2	7.6	0.0	0.000	1.3	0.0	0.0
07/12/94	299-W18-98	31.4	9.3	37.6	0.098	1.5	1.7	0.1
07/12/94	299-W18-98	25.2	7.5	39.0	0.082	0.0	3.8	0.5
04/04/96	299-W18-98	13.7	5.4	0.3	0.000	0.2	0.0	0.0
09/23/96	299-W18-98	13.9	7.1	0.0	0.000	1.0	0.0	0.0
06/30/94	299-W18-99	24.7	6.4	106.0	0.190	0.3	1.6	0.3
02/16/95	299-W18-99	25.4	7.8	11.0	0.024	0.0	2.0	0.0
03/28/95	299-W18-99	24.4	7.8	9.0	0.020	0.0	0.0	0.0
04/05/96	299-W18-99	23.7	5.4	0.7	0.001	0.0	0.0	0.0
09/24/96	299-W18-99	14.4	6.4	0.0	0.000	1.3	0.0	0.0
07/12/95	299-W18-152	24.9	6.6	362.0	0.671	13.0	20.0	3.0
11/16/95	299-W18-152	8.7	3.9	47.0	0.051	0.0	0.0	0.0
12/20/95	299-W18-152	8.5		38.9		0.7	0.7	
05/07/96	299-W18-152	14.7	6.9	31.7	0.061	0.0	0.0	0.0
07/17/96	299-W18-152	11.7	6.6	20.9	0.039	3.7	0.0	0.0
10/29/96	299-W18-152	2.2	1.0	11.4	0.003	1.7	0.0	0.0
09/24/97	299-W18-152	24.9	3.9	12.7	0.014	2.6	0.0	0.0
03/30/98	299-W18-152	6.5	0.4	20.8	0.002	0.7	0.0	0.0
04/09/98	299-W18-152	0.1	0.0	0.3	0.000	1.4	0.0	0.0
06/05/98	299-W18-152	5.0	4.4	18.3	0.022	2.1	0.0	0.0
06/11/98	299-W18-152	6.5	3.3	16.8	0.015	2.8	0.0	0.0
07/12/95	299-W18-153	24.9	10.0	52.0	0.146	2.0	2.0	0.0
05/07/96	299-W18-153	5.0	9.7	2.7	0.007	0.0	0.0	0.0
09/26/96	299-W18-153	11.5	10.6	0.7	0.002	1.7	0.0	0.0
10/29/96	299-W18-153	2.5	3.8	0.0	0.000	0.0	0.0	0.0
09/24/97	299-W18-153	5.7	0.0	2.2	0.000	2.4	0.0	0.0
07/12/95	299-W18-157	24.9	10.1	20.0	0.056	1.0	1.0	0.0
04/06/96	299-W18-157	6.2	8.1	6.5	0.015	0.2	0.0	0.0
09/26/96	299-W18-157	9.0	8.1	0.6	0.001	0.5	0.2	0.2
04/20/94	299-W18-246L	30.1	1.7	162.0	0.076	0.7	0.8	0.1
04/20/94	299-W18-246L	17.7	1.2	169.0	0.058	0.3	0.2	0.0
06/21/94	299-W18-246L	21.7	1.5	236.0	0.097	0.0	2.0	0.0
11/02/94	299-W18-246U&L	25.4	8.6	134.0	0.321	1.0	0.0	0.0
06/07/95	299-W18-246L	24.9	2.1	114.0	0.066	4.0	5.0	0.0
08/03/95	299-W18-246L	24.7	5.2	49.0	0.071	1.0	2.0	0.0
04/06/96	299-W18-246L	16.9	1.8	32.2	0.017	0.0	0.0	0.0
05/14/96	299-W18-246L	17.4	1.5	32.3	0.014	0.0	0.0	0.0
09/18/96	299-W18-246L	18.7	2.4	16.3	0.011	1.7	0.0	0.0

Table B-2. Characterization Data for Individual Extraction Wells in the 216-Z-18/Z-12 Wellfield, May 1992–September 1998. (4 Pages)

Date	Well & Interval	Vacuum* (kPa)	Flow (m3/min)	CCl4 (ppmv)	CCl4 Flux (kg/day)	CHCl3 (ppmv)	CH2Cl2 (ppmv)	MEK (ppmv)
10/29/96	299-W18-246L	7.5	1.4	6.9	0.003	2.0	0.0	0.0
04/19/94	299-W18-246U	29.1	5.4	271.0	0.412	0.2		0.4
06/21/94	299-W18-246U	22.4	4.4	125.0	0.154	0.0	3.0	0.0
08/03/95	299-W18-246U	25.2	5.4	48.0	0.072	2.0	2.0	0.0
04/06/96	299-W18-246U	16.9	4.2	27.9	0.033	0.0	0.0	0.0
07/17/96	299-W18-246U	14.9	5.2	9.8	0.014	1.2	0.0	0.0
09/18/96	299-W18-246U	13.9	5.7	29.7	0.048	1.2	0.0	0.0
10/29/96	299-W18-246U	5.5	11.6	9.0	0.029	0.0	0.0	0.0
03/30/98	299-W18-246U	8.7	1.2	29.7	0.010	0.8	0.0	0.0
04/08/98	299-W18-246U	1.8	1.6	15.2	0.007	0.8	1.3	0.0
05/08/98	299-W18-246U	1.4	1.2	22.4	0.008	1.5	0.0	0.0
05/13/98	299-W18-246U	1.6	1.1	23.4	0.007	2.0	0.0	0.0
05/08/96	299-W18-247L	17.9	1.4	2.9	0.001	0.0	0.0	0.0
09/19/96	299-W18-247L	16.9	2.5	1.4	0.001	1.6	0.0	0.1
05/08/96	299-W18-247U	20.4	0.4	5.2	0.001	0.0	0.0	0.0
09/19/96	299-W18-247U	19.9	0.0	4.7	0.000	1.7	0.1	0.0
07/11/94	299-W18-249	21.2	13.5	108.0	0.407	0.0	1.7	0.5
02/15/95	299-W18-249	18.4	14.2	93.0	0.369			
03/28/95	299-W18-249	17.4	14.2	32.0	0.127	0.0	0.0	0.0
04/05/96	299-W18-249	5.7	10.4	2.1	0.006	0.4	0.0	0.0
09/24/96	299-W18-249	11.5	9.1	15.7	0.040	1.3	0.0	0.0
03/30/98	299-W18-249	7.0	2.7	33.4	0.025	0.3	0.0	0.0
04/09/98	299-W18-249	1.1	3.2	20.2	0.018	1.0	0.0	0.0
05/08/98	299-W18-249	1.0	3.3	13.6	0.012	0.9	0.0	0.0
05/13/98	299-W18-249	1.1	3.1	15.9	0.014	2.9	0.0	0.0
03/07/94	299-W18-252L	30.4	2.7	618.0	0.470	4.3	6.0	0.2
08/03/95	299-W18-252L	25.7	3.0	97.0	0.082	4.0	5.0	0.0
11/16/95	299-W18-252L	11.2	2.0	35.0	0.020	0.0	0.0	0.0
12/20/95	299-W18-252L	11.2		28.2		0.4	0.2	
04/09/96	299-W18-252L	12.2	5.9	41.6	0.069	0.0	0.0	0.0
05/14/96	299-W18-252L	15.9	6.4	25.0	0.045	0.0	0.0	0.0
07/17/96	299-W18-252L	18.4	0.0					
09/18/96	299-W18-252L	13.4	4.2	13.9	0.017	1.6	0.0	0.0
10/29/96	299-W18-252L	9.0	14.2	14.6	0.058	0.0	0.0	0.0
03/30/98	299-W18-252L	12.0	0.5	28.9	0.004	0.6	0.0	0.0
04/09/98	299-W18-252L	2.5	0.0	11.7	0.000	1.5	0.0	0.0
04/10/98	299-W18-252L	2.5	1.2	23.3	0.008	0.7	0.0	0.0
04/16/98	299-W18-252L	2.5	1.2	25.6	0.009	0.9	0.0	0.0
04/30/98	299-W18-252L	2.5	1.4	24.7	0.010	1.4	0.0	0.0
05/08/98	299-W18-252L	1.9	0.7	29.1	0.005	1.7	0.0	0.0
05/13/98	299-W18-252L	1.7	0.9	11.9	0.003	1.6	0.0	1.0
01/05/94	299-W18-252U	22.9	4.2	97.0	0.114	0.6	1.2	0.2
01/06/94	299-W18-252U	31.6	6.7	527.0	0.985	3.6	5.8	0.1
01/20/94	299-W18-252U	31.6	6.7	500.0	0.930			
03/10/94	299-W18-252U	14.2	5.3					
03/10/94	299-W18-252U	18.4	5.8					
03/10/94	299-W18-252U	23.7	6.6					
03/10/94	299-W18-252U	28.4	7.3	547.0	1.113			
03/10/94	299-W18-252U	32.6	7.6					
05/16/94	299-W18-252U	24.2	6.7	368.0	0.685	0.0	0.0	0.0
05/17/94	299-W18-252U	23.9	6.8	440.0	0.833	0.0	4.0	0.0

Table B-2. Characterization Data for Individual Extraction Wells in the 216-Z-18/Z-12 Wellfield, May 1992–September 1998. (4 Pages)

Date	Well & Interval	Vacuum* (kPa)	Flow (m3/min)	CCl4 (ppmv)	CCl4 Flux (kg/day)	CHCl3 (ppmv)	CH2Cl2 (ppmv)	MEK (ppmv)
05/18/94	299-W18-252U	23.9	6.6	395.0	0.726	0.0	4.0	0.0
05/19/94	299-W18-252U	23.7	6.7	404.0	0.755	0.0	4.0	0.0
12/20/94	299-W18-252U	25.2	8.7	106.0	0.257	1.0		0.0
05/11/95	299-W18-252U	6.7	2.6					
05/11/95	299-W18-252U	8.7	4.0	143.0	0.162	0.0	0.0	
05/11/95	299-W18-252U	11.0	5.2	182.0	0.262	7.0	10.0	
05/11/95	299-W18-252U	13.7	6.2	239.0	0.413	9.0	13.0	
05/11/95	299-W18-252U	17.4	6.6	234.0	0.434	8.0	12.0	
05/11/95	299-W18-252U	21.2	7.3	235.0	0.482	9.0	13.0	
05/11/95	299-W18-252U	24.4	7.9	242.0	0.533	9.0	14.0	
05/11/95	299-W18-252U	28.1	8.4	241.0	0.569	9.0	14.0	
08/03/95	299-W18-252U	24.9	6.5	53.0	0.096	2.0	3.0	0.0
06/12/96	299-W18-252U	11.2	6.6	5.5	0.010	0.0	0.0	0.0
09/18/96	299-W18-252U	24.2	6.1	7.2	0.012	1.7	0.0	0.0
10/29/96	299-W18-252U	4.5	10.8	10.4	0.031	0.0	0.0	0.0
07/21/97	299-W18-252U	3.7	4.2	41.5	0.049	4.4	0.0	0.0
07/24/97	299-W18-252U	4.7	3.6	25.8	0.026	3.1	0.0	0.0
07/28/97	299-W18-252U	4.2	3.5	11.4	0.011	4.1	0.0	0.0
07/31/97	299-W18-252U	5.0	4.0	8.4	0.009	2.6	0.0	0.0
03/30/98	299-W18-252U	9.0	1.7	35.7	0.017	0.9	0.0	0.0
04/09/98	299-W18-252U	2.2	1.7	33.2	0.016	1.6	0.0	0.0
05/08/98	299-W18-252U	2.0	1.1	28.4	0.009	2.0	0.0	0.0
05/13/98	299-W18-252U	2.0	0.4	27.2	0.003	2.7	0.0	0.0

* After 6/15/95, all measurements made at the wellhead

(a) Odyssey analysis
(b) after jet perforating

CCl4 = Carbon Tetrachloride
CHCl3 = Chloroform
CH2Cl2 = Methylene Chloride
MEK = Methyl ethyl ketone

Table B-3. Characterization Data for Individual Extraction Wells in the 216-Z-9 Wellfield, March 1993–September 1998. (8 Pages)

Date	Well & Interval	Vacuum* (kPa)	Flow (m3/min)	CCl4 (ppmv)	CCl4 Flux (kg/day)	CHCl3 (ppmv)	CH2Cl2 (ppmv)	MEK (ppmv)
08/22/95	299-W15-6L(f)	21.2	3.5	79.6	0.078	1.0	4.6	0.1
11/28/95	299-W15-6L(f)	13.7	2.6	35.3	0.025	3.0	5.7	0.0
12/20/95	299-W15-6L(f)	21.7		30.5		0.3	4.9	
05/02/96	299-W15-6L(f)	16.9	2.8	24.4	0.019	0.0	2.3	0.0
05/14/96	299-W15-6L(f)	22.9	3.6	26.4	0.026	0.0	2.5	0.0
07/23/96	299-W15-6L(f)	17.9	3.3	15.3	0.014	1.2	1.1	0.0
09/10/96	299-W15-6L(f)	19.9	4.8	14.6	0.020	0.0	1.7	0.0
10/29/96	299-W15-6L(f)	8.7	2.5	14.2	0.010	0.0	2.0	0.0
07/18/97	299-W15-6L(f)	10.0	2.7	20.2	0.015	3.9	0.0	0.0
07/21/97	299-W15-6L(f)	8.0	2.4	20.3	0.014	2.9	1.3	0.0
07/24/97	299-W15-6L(f)	11.0	2.2	22.6	0.014	2.9	0.0	0.0
07/28/97	299-W15-6L(f)	12.5	3.0	20.6	0.017	3.8	0.0	0.0
07/31/97	299-W15-6L(f)	10.0	2.9	20.5	0.017	1.9	0.0	0.0
09/26/97	299-W15-6L(f)	10.5	2.0	16.5	0.009	3.4	0.0	0.0
07/30/98	299-W15-6L(f)	9.5	2.1	17.6	0.010	1.7	1.8	0.0
08/25/98	299-W15-6L(f)	10.5	2.9	18.1	0.015	0.9	1.2	0.0
09/03/98	299-W15-6L(f)	4.5	1.6	18.1	0.008	1.8	1.4	0.0
09/14/98	299-W15-6L(f)	4.5	1.7	17.0	0.008	0.8	1.5	0.0
09/22/98	299-W15-6L(f)	3.0	1.3	14.5	0.005	1.4	1.6	0.0
09/30/98	299-W15-6L(f)	2.5	1.4	17.9	0.007	0.6	2.1	0.0
08/22/95	299-W15-6U(f)	19.9	4.3	15.3	0.018	0.0	0.0	0.0
05/02/96	299-W15-6U(f)	16.2	3.2	1.8	0.002	0.0	0.0	0.0
09/12/96	299-W15-6U(f)	17.9	4.6	0.0	0.000	1.1	0.0	0.0
10/29/96	299-W15-6U(f)	7.5	2.4	0.0	0.000	0.0	0.0	0.0
12/02/94	299-W15-8L	24.9	1.5	119.0	0.049	5.0		0.0
02/01/95	299-W15-8L	26.4	0.7					
02/10/95	299-W15-8L	26.9	1.2	22.0	0.007	3.9	2.7	1.0
03/09/95	299-W15-8	alpha						
12/02/94	299-W15-9L	24.9	1.4	110.0	0.044	5.0		0.0
02/01/95	299-W15-9L	26.4	1.0					
02/10/95	299-W15-9L	27.6	1.0	93.0	0.027	5.7	4.9	1.0
07/10/95	299-W15-9L(f)	13.7	1.4	63.0	0.025	1.4	4.0	0.5
05/03/96	299-W15-9L(f)	17.4	1.6	14.2	0.006	0.0	0.0	0.0
05/14/96	299-W15-9L(f)	27.4	2.1	19.4	0.011	0.0	0.0	0.0
09/12/96	299-W15-9L(f)	19.7	2.4	11.4	0.008	1.3	0.0	0.0
10/29/96	299-W15-9L(f)	10.0	2.0	9.7	0.005	0.0	0.0	0.0
07/18/97	299-W15-9L(f)	16.2	1.7	19.8	0.009	2.2	0.0	0.0
07/21/97	299-W15-9L(f)	19.4	1.8	21.3	0.011	3.6	0.0	0.0
07/24/97	299-W15-9L(f)	21.2	2.1	21.0	0.012	1.4	0.0	0.0
07/28/97	299-W15-9L(f)	20.9	2.7	14.8	0.011	3.3	0.0	0.0
07/31/97	299-W15-9L(f)	19.4	2.4	14.5	0.010	3.7	0.0	0.0
09/26/97	299-W15-9L(f)	18.7	2.5	12.6	0.009	2.8	0.0	0.0
07/10/98	299-W15-9L(f)	19.4	2.3	16.7	0.011	2.5	0.0	0.0
07/30/98	299-W15-9L(f)	19.4	1.7	19.3	0.009	1.7	1.0	0.5
08/25/98	299-W15-9L(f)	17.7	2.0	15.0	0.008	1.5	0.0	0.0
09/03/98	299-W15-9L(f)	10.0	1.3	15.3	0.006	1.3	0.0	0.0
09/14/98	299-W15-9L(f)	10.0	1.4	13.4	0.005	1.3	0.0	0.0
09/22/98	299-W15-9L(f)	5.5	0.9	9.4	0.002	1.1	0.0	0.0
09/30/98	299-W15-9L(f)	5.5	0.9	12.1	0.003	1.4	0.0	0.0
08/02/95	299-W15-9U(f)	17.9	2.2	97.2	0.061	3.4	6.7	1.3
11/28/95	299-W15-9U(f)	13.4	1.1	26.0	0.008	1.1	0.1	0.0

Table B-3. Characterization Data for Individual Extraction Wells in the 216-Z-9 Wellfield, March 1993–September 1998. (8 Pages)

Date	Well & Interval	Vacuum* (kPa)	Flow (m3/min)	CCl4 (ppmv)	CCl4 Flux (kg/day)	CHCl3 (ppmv)	CH2Cl2 (ppmv)	MEK (ppmv)
12/22/95	299-W15-9U(f)	15.2		32.5		0.0	1.7	
05/03/96	299-W15-9U(f)	17.9	1.4	68.2	0.028	0.0	0.0	0.0
09/12/96	299-W15-9U(f)	21.7	1.6	48.9	0.021	1.6	0.0	0.0
10/29/96	299-W15-9U(f)	10.7	1.3	8.1	0.003	0.0	1.1	1.1
09/26/97	299-W15-9U(f)	19.7	1.4	8.4	0.003	1.7	0.0	0.0
07/10/98	299-W15-9U(f)	19.9	2.0	29.6	0.017	1.9	0.0	0.0
07/30/98	299-W15-9U(f)	18.4	2.0	33.5	0.019	1.9	0.0	0.5
08/25/98	299-W15-9U(f)	19.4	1.8	16.3	0.008	1.4	0.0	0.0
03/31/93	299-W15-82(a)(b)	31.9	0.7	11848.0	2.158			
04/01/93	299-W15-82(a)(c)		1.6	8208.0	3.575			
04/12/93	299-W15-82(a)(c)			6101.0				
04/28/93	299-W15-82	6.5	2.0	26000.0	14.411			
06/03/93	299-W15-82	17.2	7.2	28500.0	57.319			
02/23/94	299-W15-82	3.2	1.4	23000.0	9.288	113.0	114.0	3.9
02/23/94	299-W15-82(b)	3.2	1.4			16.1	24.6	
02/24/94	299-W15-82	3.2	1.4	25300.0	9.616	106.0	139.0	4.1
02/24/94	299-W15-82(b)	3.2	1.4			25.0	25.0	
05/10/94	299-W15-82	5.0		20300.0		102.0	115.0	2.4
05/11/94	299-W15-82	5.2		19800.0		99.2	118.0	2.8
06/01/94	299-W15-82	11.5		11700.0		69.8	74.7	2.0
06/10/94	299-W15-82	24.9		8040.0		68.3	61.6	2.0
09/06/94	299-W15-82	28.9	8.2	5240.0	11.949	56.3	28.8	1.3
10/26/94	299-W15-82	29.9	10.4	1550.0	4.492	59.7	81.9	5.8
11/22/94	299-W15-82	30.9	10.3	582.0	1.668	29.0		3.0
01/31/95	299-W15-82	25.7	9.1					
02/08/95	299-W15-82	25.2	9.1	378.0	0.964	20.9	22.5	3.6
05/12/95	299-W15-82	24.9	7.6	279.0	0.592	7.3	14.8	1.3
08/01/95	299-W15-82	19.9	4.9	94.5	0.129	3.3	6.3	1.2
11/29/95	299-W15-82	17.7	2.7	155.0	0.117	7.1	10.6	0.9
12/20/95	299-W15-82	19.7		143.0		1.0	1.2	
04/25/96	299-W15-82	23.9	2.3	180.0	0.114	0.0	0.0	0.0
07/19/96	299-W15-82	20.9	2.2	87.3	0.053	2.0	0.0	0.0
09/10/96	299-W15-82	24.9	3.2	43.9	0.040	0.0	0.0	0.0
10/29/96	299-W15-82	13.4	1.9	28.5	0.015	1.2	0.0	0.0
07/18/97	299-W15-82	15.9	1.6	106.0	0.046	2.8	6.7	0.0
07/21/97	299-W15-82	13.7	2.1	46.8	0.027	4.1	0.0	0.0
07/24/97	299-W15-82	16.9	1.9	170.0	0.090	4.2	0.0	0.0
07/28/97	299-W15-82	16.7	1.8	126.0	0.063	3.8	0.0	0.0
07/31/97	299-W15-82	18.4	1.8	116.0	0.058	4.0	0.0	0.0
09/26/97	299-W15-82	14.9	1.5	19.7	0.008	1.6	0.0	0.0
07/10/98	299-W15-82	17.4	2.1	196.0	0.116	3.5	11.0	0.0
07/30/98	299-W15-82	12.5	1.6	153.0	0.067	4.4	0.0	0.1
08/25/98	299-W15-82	12.7	1.6	89.9	0.041	2.1	0.0	0.0
09/03/98	299-W15-82	6.2	0.8	70.0	0.015	2.4	0.0	0.0
09/14/98	299-W15-82	6.5	0.9	40.7	0.010	1.7	0.0	0.0
09/22/98	299-W15-82	4.0	0.5	41.4	0.006	1.8	0.0	0.0
09/30/98	299-W15-82	3.7	0.5	56.7	0.009	1.3	0.0	0.0
04/02/93	299-W15-84(a)	31.9	0.0					
04/29/93	299-W15-84	5.0	2.1	8475.0	5.033			
03/01/94	299-W15-84	16.2	9.1	8230.0	21.049	51.7	58.8	1.6
03/01/94	299-W15-84(b)	16.2	9.1			32.8	6.0	

Table B-3. Characterization Data for Individual Extraction Wells in the 216-Z-9 Wellfield, March 1993–September 1998. (8 Pages)

Date	Well & Interval	Vacuum* (kPa)	Flow (m3/min)	CCl4 (ppmv)	CCl4 Flux (kg/day)	CHCl3 (ppmv)	CH2Cl2 (ppmv)	MEK (ppmv)
03/01/94	299-W15-84	10.0	2.7	7100.0	5.453	43.6	51.5	1.4
03/01/94	299-W15-84(b)	10.0	2.7			46.7	5.3	
03/02/94	299-W15-84	10.0	5.8	9910.0	16.165	57.4	69.2	2.2
03/02/94	299-W15-84(b)	10.0	5.8			64.8	6.8	
05/10/94	299-W15-84	5.0		17200.0		83.3	100.0	2.0
05/11/94	299-W15-84	5.2		16300.0		79.3	100.0	3.0
06/01/94	299-W15-84	11.5		5010.0		31.7	37.8	1.9
06/10/94	299-W15-84	24.9		4470.0		37.5	38.7	2.0
09/06/94	299-W15-84	25.2	12.5	444.0	1.547	7.4	6.9	0.5
10/26/94	299-W15-84	28.1	13.3	787.0	2.923	32.5	45.7	3.3
11/22/94	299-W15-84	26.4	13.5	348.0	1.317	17.0		1.0
01/31/95	299-W15-84	26.7	12.5					
02/08/95	299-W15-84	25.9	13.3	166.0	0.615	11.9	13.0	2.2
08/02/95	299-W15-84	14.9	11.9	54.7	0.182	2.0	4.5	0.6
04/25/96	299-W15-84	11.7	12.9	0.0	0.000	0.0	0.0	0.0
09/12/96	299-W15-84	6.7	7.0	0.0	0.000	1.6	0.0	0.0
10/29/96	299-W15-84	10.5	10.0	1.6	0.004	0.0	0.0	0.0
09/26/97	299-W15-84	18.7	0.7	20.8	0.004	2.4	0.0	0.0
09/03/98	299-W15-84	3.0	4.2	15.2	0.018	1.0	0.8	0.0
09/14/98	299-W15-84	4.2	4.6	13.3	0.017	1.9	0.0	0.0
09/22/98	299-W15-84	3.2	4.1	12.8	0.015	0.7	1.4	0.2
09/30/98	299-W15-84	2.2	4.2	39.0	0.046	1.5	5.1	0.0
04/02/93	299-W15-85(a)	32.4	0.0					
04/05/93	299-W15-85(a)	30.6	0.0					
04/30/93	299-W15-85	4.2	2.1	16700.0	9.917			
03/03/94	299-W15-85	22.9	6.5	10400.0	18.940	60.3	55.3	1.3
03/03/94	299-W15-85(b)	22.9	6.5			16.1	5.5	
03/03/94	299-W15-85	15.4	2.7	12600.0	9.578	59.1	76.6	2.2
03/03/94	299-W15-85(b)	15.4	2.7			12.9	6.4	
09/06/94	299-W15-85	28.6	6.1	256.0	0.438	4.8	1.0	0.3
10/26/94	299-W15-85	32.4	7.5	237.0	0.495	10.8	15.3	1.2
11/22/94	299-W15-85	29.9	7.4	111.0	0.229	5.0		0.0
01/31/95	299-W15-85	25.9	5.5					
02/08/95	299-W15-85	25.2	6.7	86.0	0.161	7.1	7.4	1.7
05/16/95	299-W15-85	25.9	8.6	41.1	0.099	0.6	2.7	1.0
08/02/95	299-W15-85	17.9	4.7	18.0	0.024	1.3	2.1	0.6
04/10/96	299-W15-85	22.4	8.6	47.5	0.115	0.0	0.0	0.0
07/19/96	299-W15-85	20.9	5.2	97.0	0.140	2.8	0.0	0.0
09/12/96	299-W15-85	23.4	6.6	64.4	0.119	1.2	0.0	0.0
10/29/96	299-W15-85	10.5	2.4	6.2	0.004	0.0	0.0	0.0
09/26/97	299-W15-85	17.4	5.4	22.0	0.033	2.6	0.0	0.0
09/22/98	299-W15-85	4.0	2.2	1.1	0.001	1.1	0.0	0.0
09/30/98	299-W15-85	3.2	3.5	0.8	0.001	1.4	0.0	0.0
08/22/95	299-W15-86(f)	18.7	8.6	215.0	0.519	4.9	10.9	0.7
11/29/95	299-W15-86(f)	18.7	5.4	59.7	0.090	4.1	6.8	0.6
12/22/95	299-W15-86(f)	22.4		49.0		0.5	2.9	
05/07/96	299-W15-86(f)	19.7	4.6	2.5	0.003	0.0	0.0	0.0
09/16/96	299-W15-86(f)	15.4	6.5	65.9	0.119	1.5	0.0	0.0
10/29/96	299-W15-86(f)	16.2	8.0	41.8	0.094	1.2	1.7	0.0
07/18/97	299-W15-86(f)	15.2	4.8	138.0	0.186	4.2	0.0	0.0
07/21/97	299-W15-86(f)	12.5	5.1	111.0	0.158	3.4	0.0	0.0

Table B-3. Characterization Data for Individual Extraction Wells in the 216-Z-9 Wellfield, March 1993–September 1998. (8 Pages)

Date	Well & Interval	Vacuum* (kPa)	Flow (m3/min)	CCl4 (ppmv)	CCl4 Flux (kg/day)	CHCl3 (ppmv)	CH2Cl2 (ppmv)	MEK (ppmv)
07/24/97	299-W15-86(f)	16.4	4.9	57.8	0.079	3.5	0.0	0.0
07/28/97	299-W15-86(f)	13.9	4.7	69.6	0.091	5.1	0.0	0.0
07/31/97	299-W15-86(f)	16.7	4.7	62.5	0.082	2.8	0.0	0.0
09/26/97	299-W15-86(f)	14.9	4.5	34.9	0.044	2.1	0.0	0.0
07/30/98	299-W15-86(f)	13.0	4.1	107.0	0.124	2.2	0.0	0.0
08/25/98	299-W15-86(f)	13.9	4.3	37.2	0.045	1.5	0.0	0.0
09/03/98	299-W15-86(f)	7.5	0.3	1.5	0.000	0.2	0.0	0.1
09/14/98	299-W15-86(f)	8.2	0.3	0.1	0.000	0.6	0.0	0.0
04/05/93	299-W15-95(a)	30.6	0.0					
04/13/93	299-W15-95(a)(c)		0.6	14320.0	2.268			
04/14/93	299-W15-95(a)(c)		0.6	6240.0	0.988			
04/28/93	299-W15-95	29.4	1.0	10700.0	2.881			
03/08/94	299-W15-95	26.2	0.6	11900.0	1.979	60.9	67.3	1.6
03/08/94	299-W15-95(b)	26.2	0.6			12.6	4.6	
05/18/94	299-W15-95	25.7	2.1	8740.0	5.121	44.9	49.6	0.0
06/01/94	299-W15-95	11.5		4530.0		21.9	30.3	0.6
06/10/94	299-W15-95	24.9		2110.0		14.1	18.4	1.3
09/06/94	299-W15-95	24.7	1.8	444.0	0.221	6.4	5.3	0.4
10/26/94	299-W15-95	28.1	2.3	330.0	0.212	14.5	19.6	1.6
11/22/94	299-W15-95	26.9	2.1	249.0	0.144	11.0		0.0
01/31/95	299-W15-95	27.9	1.5					
02/10/95	299-W15-95	29.4	1.6	211.0	0.094	10.9	12.4	1.4
05/02/96	299-W15-95(f)	14.9	9.9	1.7	0.005	0.0	0.0	0.0
09/11/96	299-W15-95(f)	15.9	9.1	1.0	0.003	1.4	0.0	0.0
10/29/96	299-W15-95(f)	9.5	3.3	0.0	0.000	1.6	0.0	0.0
09/26/97	299-W15-95(f)	19.9	2.4	33.6	0.022	3.4	0.0	0.0
09/03/98	299-W15-95(f)	5.5	5.0	6.9	0.010	1.2	0.0	0.0
09/14/98	299-W15-95(f)	6.5	4.8	0.4	0.001	1.3	0.0	0.0
03/17/94	299-W15-216L	26.4	2.4	878.0	0.598	3.9	6.9	0.7
03/17/94	299-W15-216L(b)	26.4	2.4			0.2	0.1	
02/02/95	299-W15-216L	28.1	2.0					
02/14/95	299-W15-216L	27.1	2.0	139.0	0.079	6.5	7.4	1.1
07/10/95	299-W15-216L	21.2	0.8	77.5	0.017	1.9	3.9	0.7
11/28/95	299-W15-216L	18.7	0.7	39.7	0.007	0.0	0.9	0.0
12/20/95	299-W15-216L	19.4		32.7		0.3	1.2	
04/19/96	299-W15-216L	23.2	1.4	17.8	0.007	0.0	0.0	0.0
05/14/96	299-W15-216L	22.4	0.8	27.3	0.006	0.0	0.0	0.0
09/11/96	299-W15-216L	18.7	1.6	9.5	0.004	2.0	0.0	0.0
10/29/96	299-W15-216L	14.4	1.4	11.3	0.004	0.0	0.0	0.0
09/30/97	299-W15-216L	14.9	1.7	5.5	0.003	5.6	0.0	0.0
09/22/98	299-W15-216L	4.7	1.1	5.3	0.002	1.0	0.0	0.0
09/30/98	299-W15-216L	4.5	1.1	5.7	0.002	0.2	0.0	0.0
03/18/94	299-W15-216U	26.7	5.6	1410.0	2.188	9.2	8.8	0.0
03/18/94	299-W15-216U(b)	26.7	5.6			4.4	0.2	
02/02/95	299-W15-216U	23.9	7.2					
02/14/95	299-W15-216U	25.4	7.6	40.0	0.086	3.9	2.5	0.9
07/10/95	299-W15-216U	19.9	8.1	24.0	0.054	0.1	0.6	0.0
04/19/96	299-W15-216U	18.4	6.5	14.9	0.027	0.0	0.0	0.0
07/23/96	299-W15-216U	20.2	6.1	4.7	0.008	1.4	0.0	0.0
09/11/96	299-W15-216U	16.2	7.0	7.1	0.014	1.7	0.0	0.0
10/29/96	299-W15-216U	8.7	5.7	12.0	0.019	0.0	0.0	0.0

Table B-3. Characterization Data for Individual Extraction Wells in the 216-Z-9 Wellfield, March 1993–September 1998. (8 Pages)

Date	Well & Interval	Vacuum* (kPa)	Flow (m3/min)	CCl4 (ppmv)	CCl4 Flux (kg/day)	CHCl3 (ppmv)	CH2Cl2 (ppmv)	MEK (ppmv)
09/30/97	299-W15-216U	13.9	1.9	3.2	0.002	4.3	0.0	0.0
09/22/98	299-W15-216U	3.2	2.7	6.5	0.005	1.2	0.0	0.0
09/30/98	299-W15-216U	3.0	2.8	4.8	0.004	0.6	0.0	0.0
05/04/93	299-W15-217	15.4	2.1	18200.0	10.808			
05/05/93	299-W15-217	32.4	4.4	23800.0	29.587			
05/10/93	299-W15-217	29.6	5.3	23000.0	33.874			
05/11/93	299-W15-217	23.7	5.0	25500.0	35.940			
03/04/94	299-W15-217	7.0	1.1	15500.0	4.909	76.0	88.9	2.9
03/04/94	299-W15-217(b)	7.0	1.1			15.1	3.5	
03/04/94	299-W15-217	10.2	2.1	16300.0	9.680	74.4	96.7	3.9
03/04/94	299-W15-217(b)	10.2	2.1			24.7	3.7	
03/04/94	299-W15-217	15.2	2.7	20300.0	15.270	93.2	112.0	3.9
03/04/94	299-W15-217(b)	15.2	2.7			18.5	3.0	
03/04/94	299-W15-217	18.2	2.8	21400.0	16.945	104.0	122.0	3.7
03/04/94	299-W15-217(b)	18.2	2.8			17.3	2.9	
05/10/94	299-W15-217	5.0		7070.0		44.5	47.1	1.9
05/11/94	299-W15-217	5.2		7000.0		42.9	48.4	1.8
06/01/94	299-W15-217	11.5		10600.0		60.3	67.1	2.1
06/10/94	299-W15-217	24.9		6800.0		59.1	53.5	1.7
09/06/94	299-W15-217	28.4	4.5	1420.0	1.777	20.6	11.0	0.8
10/26/94	299-W15-217	32.4	5.7	1430.0	2.299	57.6	77.5	5.5
11/22/94	299-W15-217	30.6	5.2	1131.0	1.648	44.0		3.0
01/31/95	299-W15-217	28.4	5.3					
02/10/95	299-W15-217	28.9	5.0	690.0	0.967	28.9	36.0	4.3
05/16/95	299-W15-217	26.2	5.8	150.0	0.242	1.0	4.6	1.0
08/02/95	299-W15-217	15.4	1.9	63.0	0.033	0.0	0.2	0.1
11/29/95	299-W15-217	20.7	2.9	104.0	0.085	5.9	10.1	0.8
12/22/95	299-W15-217	23.4		102.0		0.9	2.8	
04/25/96	299-W15-217	23.9	3.3	27.2	0.025	0.0	0.0	0.0
07/19/96	299-W15-217	21.7	3.8	2.8	0.003	0.0	0.0	0.0
09/10/96	299-W15-217	23.7	5.7	2.1	0.003	0.0	0.0	0.0
10/29/96	299-W15-217	16.9	7.9	71.7	0.158	0.0	2.6	0.0
07/18/97	299-W15-217	15.7	4.7	256.0	0.336	3.5	0.5	0.0
07/21/97	299-W15-217	12.5	5.8	86.3	0.140	4.1	0.0	0.0
07/24/97	299-W15-217	17.4	3.8	164.0	0.174	3.6	2.7	0.0
07/28/97	299-W15-217	14.7	3.8	129.0	0.137	5.3	0.0	0.0
07/31/97	299-W15-217	17.4	3.8	131.0	0.139	3.5	0.0	0.0
09/26/97	299-W15-217	14.9	4.0	26.0	0.029	1.8	0.0	0.0
07/10/98	299-W15-217	14.9	4.4	135.0	0.167	2.7	5.8	0.0
07/30/98	299-W15-217	12.5	4.0	50.4	0.057	1.8	1.1	0.2
08/25/98	299-W15-217	10.5	2.8	5.9	0.005	1.4	0.0	0.0
03/24/94	299-W15-218L	24.7	4.3	808.0	0.979	4.9	7.4	0.3
03/24/94	299-W15-218L(b)	24.7	4.3			1.2	< 0.1	
09/07/94	299-W15-218L	27.4	2.9	595.0	0.490	8.8	8.8	0.5
10/26/94	299-W15-218L	30.1	4.4	319.0	0.397	16.4	26.4	1.7
11/22/94	299-W15-218L	28.9	4.8	175.0	0.237	9.0		0.0
02/02/95	299-W15-218L	26.9	4.2					
02/14/95	299-W15-218L	27.9	4.2	127.0	0.148	9.4	12.7	1.6
05/16/95	299-W15-218L	25.7	5.2	17.2	0.025	0.4	3.7	0.9
08/02/95	299-W15-218L	18.7	2.7	42.5	0.032	1.3	4.8	0.5
11/28/95	299-W15-218L(g)	21.4	2.9	26.1	0.021	2.8	5.5	0.4

Table B-3. Characterization Data for Individual Extraction Wells in the 216-Z-9 Wellfield, March 1993–September 1998. (8 Pages)

Date	Well & Interval	Vacuum* (kPa)	Flow (m3/min)	CCl4 (ppmv)	CCl4 Flux (kg/day)	CHCl3 (ppmv)	CH2Cl2 (ppmv)	MEK (ppmv)
12/20/95	299-W15-218L(g)	21.9		23.4		0.5	4.1	
04/10/96	299-W15-218L	24.9	3.8	24.2	0.026	0.0	2.5	0.0
05/14/96	299-W15-218L	23.2	3.7	19.8	0.020	0.0	1.8	0.0
07/19/96	299-W15-218L	24.4	3.8	15.0	0.016	1.1	1.6	0.0
09/11/96	299-W15-218L	15.4	4.1	16.1	0.018	1.1	1.6	0.0
10/29/96	299-W15-218L	8.0	1.6	13.7	0.006	0.0	1.8	0.0
07/18/97	299-W15-218L	19.9	3.0	20.3	0.017	3.0	0.3	0.0
07/21/97	299-W15-218L	12.7	2.4	21.9	0.015	2.7	1.6	0.2
07/24/97	299-W15-218L	15.9	2.4	20.0	0.013	2.5	0.0	0.0
07/28/97	299-W15-218L	14.9	2.4	20.0	0.013	2.4	0.0	0.0
07/31/97	299-W15-218L	16.2		12.4		1.9	0.0	0.0
09/26/97	299-W15-218L	18.7	2.9	16.2	0.013	2.1	1.9	0.0
03/25/94	299-W15-218U	24.7	2.8	14800.0	11.484	65.2	82.7	0.0
03/25/94	299-W15-218U(b)	24.7	2.8			12.0	0.7	
09/07/94	299-W15-218U	29.1	3.7	424.0	0.433	7.6	4.2	0.1
10/26/94	299-W15-218U	31.6	6.3	339.0	0.601	17.5	28.5	1.9
11/22/94	299-W15-218U	29.1	5.0	181.0	0.251	9.0		0.0
02/02/95	299-W15-218U	26.9	4.2					
02/14/95	299-W15-218U	27.4	4.2	143.0	0.168	7.6	7.8	1.2
05/16/95	299-W15-218U	24.7	5.1	57.4	0.082	0.4	7.5	1.2
05/16/95	299-W15-218U,L	25.9	8.6	37.7	0.091	1.2	5.3	1.3
08/02/95	299-W15-218U	17.4	5.0	56.8	0.079	1.7	6.6	0.5
11/28/95	299-W15-218U(g)	18.4	5.5	25.6	0.039	2.4	5.2	0.2
12/20/95	299-W15-218U(g)	19.2		23.8		0.2	4.3	
04/10/96	299-W15-218U	24.9	3.8	24.3	0.026	0.0	2.1	0.0
07/19/96	299-W15-218U	24.9	2.4	8.8	0.006	2.1	0.0	0.0
09/11/96	299-W15-218U	17.9	2.4	6.9	0.005	1.1	0.0	0.0
10/29/96	299-W15-218U	7.0	2.9	15.6	0.013	0.0	2.5	0.0
07/18/97	299-W15-218U	17.4	6.0	21.1	0.036	1.9	0.9	0.0
07/21/97	299-W15-218U	11.5	4.6	21.8	0.028	2.0	1.5	0.0
07/24/97	299-W15-218U	13.7	4.2	21.1	0.025	4.8	0.0	0.0
07/28/97	299-W15-218U	12.7	4.2	22.0	0.026	2.7	0.0	0.0
07/31/97	299-W15-218U	16.2	3.3	19.1	0.018	3.4	0.0	0.0
09/26/97	299-W15-218U	12.5	5.4	15.0	0.023	2.6	0.0	0.0
07/30/98	299-W15-218U	12.0	2.4	5.7	0.004	1.1	0.0	0.2
03/21/94	299-W15-219L	27.9	3.8	2360.0	2.485	13.3	20.1	0.3
03/21/94	299-W15-219L(b)	27.9	3.8			3.2	0.1	
09/07/94	299-W15-219L	27.6	3.5	450.0	0.442	6.4	8.0	0.3
10/26/94	299-W15-219L	29.9	3.6	341.0	0.340	16.6	26.5	1.7
11/22/94	299-W15-219L	28.1	4.1	192.0	0.220	10.0		0.0
02/02/95	299-W15-219L	26.2	3.3					
02/13/95	299-W15-219L	27.6	3.4	172.0	0.163	10.4	15.8	1.5
05/16/95	299-W15-219L	26.2	3.8	38.0	0.041	0.6	4.4	0.7
08/02/95	299-W15-219L	22.4	2.0	26.3	0.015	2.0	2.2	0.1
11/29/95	299-W15-219L	19.7	1.0	23.2	0.006	3.5	5.8	0.7
04/19/96	299-W15-219L(g)	22.4	2.4	25.1	0.017	0.0	0.1	0.0
05/14/96	299-W15-219L	23.9	2.5	20.6	0.015	0.0	1.4	0.0
09/11/96	299-W15-219L	20.2	3.3	5.2	0.005	0.0	0.0	0.0
10/29/96	299-W15-219L	13.9	2.6	12.8	0.009	0.0	2.9	0.0
09/30/97	299-W15-219L	15.4	2.4	10.8	0.007	3.4	0.0	0.0
09/03/98	299-W15-219L	4.7	1.0	18.3	0.005	1.3	1.0	0.1

Table B-3. Characterization Data for Individual Extraction Wells in the 216-Z-9 Wellfield, March 1993–September 1998. (8 Pages)

Date	Well & Interval	Vacuum* (kPa)	Flow (m3/min)	CCl4 (ppmv)	CCl4 Flux (kg/day)	CHCl3 (ppmv)	CH2Cl2 (ppmv)	MEK (ppmv)
09/14/98	299-W15-219L	4.7	1.0	16.8	0.005	1.4	1.5	0.0
09/22/98	299-W15-219L	3.0	1.0	12.4	0.003	0.8	1.5	0.2
09/30/98	299-W15-219L	2.7	1.0	12.6	0.003	0.8	0.8	0.0
03/22/94	299-W15-219U	27.1	4.3	9710.0	11.763	42.2	59.1	0.0
03/22/94	299-W15-219U(b)	27.1	4.3			6.8	0.2	
09/07/94	299-W15-219U	28.1	3.5	490.0	0.481	8.4	7.0	0.3
10/26/94	299-W15-219U	30.6	4.2	430.0	0.507	20.6	29.7	2.2
11/22/94	299-W15-219U	27.9	4.2	93.0	0.110	4.0		0.0
02/02/95	299-W15-219U	26.2	4.4					
02/13/95	299-W15-219U	26.9	4.0	72.0	0.080	5.0	5.4	0.8
05/16/95	299-W15-219U	26.4	4.7	16.1	0.021	1.1	2.3	0.7
05/16/95	299-W15-219U,L	25.2	6.8	27.0	0.051	0.8	2.5	0.3
08/02/95	299-W15-219U	22.4	2.4	21.0	0.014	0.7	2.1	0.4
11/29/95	299-W15-219U	18.9	1.8	13.0	0.007	2.3	3.4	0.4
12/22/95	299-W15-219U	21.4		6.8		0.4	1.6	
04/24/96	299-W15-219U(g)	22.4	4.1	24.1	0.028	0.0	1.1	0.0
07/23/96	299-W15-219U	19.4	2.2	4.0	0.002	0.0	0.0	0.0
09/11/96	299-W15-219U	22.4	3.0	13.6	0.011	1.1	0.0	0.0
10/29/96	299-W15-219U	13.7	4.0	0.0	0.000	0.0	0.0	0.0
09/30/97	299-W15-219U	15.9	2.5	10.2	0.007	2.0	0.0	0.0
03/23/94	299-W15-220L	25.9	4.2	589.0	0.695	3.0	3.8	0.3
03/23/94	299-W15-220L(b)	25.9	4.2			0.3	< 0.1	
02/13/95	299-W15-220L	27.6	4.2	190.0	0.223	9.9	11.6	1.5
08/21/95	299-W15-220L	14.9	2.7	74.8	0.056	0.9	2.3	0.2
11/28/95	299-W15-220L	20.2	2.8	32.6	0.025	0.0	0.7	0.0
12/20/95	299-W15-220L	22.7		23.2		0.7	0.8	
04/19/96	299-W15-220L(g)	26.2	2.7	16.8	0.013	0.0	0.0	0.0
05/14/96	299-W15-220L	23.2	3.0	17.4	0.015	0.0	0.0	0.0
09/11/96	299-W15-220L	19.4	3.9	10.6	0.012	1.2	0.0	0.0
10/29/96	299-W15-220L	11.2	3.2	12.1	0.011	1.2	0.0	0.0
09/26/97	299-W15-220L	13.4	2.1	13.5	0.008	3.0	0.0	0.0
09/22/98	299-W15-220L	2.5	1.1	9.7	0.003	0.9	0.0	0.1
09/30/98	299-W15-220L	2.5	1.1	10.2	0.003	0.9	0.0	0.0
03/23/94	299-W15-220U	23.2	4.5	2740.0	3.428	13.3	19.6	0.0
03/23/94	299-W15-220U(b)	23.2	4.5			1.0	< 0.1	
02/13/95	299-W15-220U	26.2	5.1	231.0	0.329	10.5	12.3	1.5
08/21/95	299-W15-220U	19.9	4.5	108.0	0.135	1.5	3.2	0.1
11/28/95	299-W15-220U	18.9	3.8	42.1	0.045	0.0	0.6	0.0
12/20/95	299-W15-220U	20.4		29.4		0.6	0.5	
04/19/96	299-W15-220U(g)	26.4	4.8	21.5	0.029	0.0	0.0	0.0
07/23/96	299-W15-220U	18.7	3.5	11.4	0.011	1.4	0.0	0.0
09/10/96	299-W15-220U	18.7	5.8	0.0	0.000	0.0	0.0	0.0
10/29/96	299-W15-220U	10.0	3.8	8.1	0.009	1.2	0.0	0.0
09/26/97	299-W15-220U	12.7	2.7	0.0	0.000	2.6	0.0	0.0
03/16/94	299-W15-223	22.7	5.9	1500.0	2.482	8.4	11.3	0.1
03/16/94	299-W15-223(b)	22.7	5.9			2.1	0.1	
02/01/95	299-W15-223	27.6	8.1					
02/14/95	299-W15-223	30.1	4.7	761.0	1.006	28.7	35.1	4.1
05/15/95	299-W15-223	24.7	8.9	21.3	0.053	1.6	0.7	0.9
06/30/95	299-W15-223	16.2	5.9	21.9	0.036	1.5	4.4	0.8
09/19/95	299-W15-223	13.0	5.1	62.7	0.089			

Table B-3. Characterization Data for Individual Extraction Wells in the 216-Z-9 Wellfield, March 1993–September 1998. (8 Pages)

Date	Well & Interval	Vacuum* (kPa)	Flow (m3/min)	CCl4 (ppmv)	CCl4 Flux (kg/day)	CHCl3 (ppmv)	CH2Cl2 (ppmv)	MEK (ppmv)
09/26/95	299-W15-223			18.3				
05/01/96	299-W15-223	12.5	6.4	64.1	0.114	0.0	0.0	0.0
09/12/96	299-W15-223	14.4	8.4	58.5	0.138	2.1	0.0	0.0
10/29/96	299-W15-223	9.0	3.9	10.0	0.011	2.7	0.0	0.0
09/26/97	299-W15-223	16.2	6.6	0.0	0.000	2.8	0.0	0.0
06/03/93	CPT-8	23.9	0.3	54	0.005			
05/27/93	CPT-12	25.2	1.8	74.0	0.038	3.4		

* After 6/15/95, all measurements made at the wellhead

(a) before perforating well casing
(b) gas chromatograph analysis
(c) Odyssey analysis
(d) Benzene
(e) Methyl isobutyl ketone (MIBK)
(f) after jet perforating
(g) packer deflated

CCl4 = Carbon Tetrachloride
CHCl3 = Chloroform
CH2Cl2 = Methylene Chloride
MEK = Methyl ethyl ketone

APPENDIX C

FISCAL YEAR 1998 SOIL VAPOR MONITORING DATA

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Table C-1. Carbon Tetrachloride Concentrations Monitored at the 216-Z-1A/Z-18 Wellfield During Nonoperation of the SVE System, October 1997 Through September 1998. (4 Pages)

216-Z-1A/Z-18/Z-12 SITE										
Sample Location	Depth (m bgs)	Zone	Sample Date Time	Differential Pressure (kPa)	CCl4 (ppmv)	CHCl3 (ppmv)	MEK (ppmv)	CH2Cl2 (ppmv)	Water (ppmv)	Comment
79-01/ 5 ft	2	1	8/14/98 0:00							destroyed or not found
79-03/ 5 ft	2	1	9/29/98 8:00	0.000	0.0	0.0	0.0	0.0	11,000	substituted for 79-01
79-11/ 5 ft	2	1	12/1/97 13:55	-0.010	0.0	0.0	0.0	0.0	8,280	
79-11/ 5 ft	2	1	1/10/98 12:08	-0.010	0.0	0.0	0.0	0.0	4,860	
79-11/ 5 ft	2	1	1/29/98 10:16	-0.007	0.0	0.0	0.0	0.0	8,170	
79-11/ 5 ft	2	1	2/26/98 11:44	-0.002	0.0	0.0	0.0	0.0	7,120	
79-11/ 5 ft	2	1	3/24/98 8:06	-0.002	0.0	0.0	0.0	0.0	9,050	
79-11/ 5 ft	2	1	8/14/98 10:47	0.017	0.0	0.0	0.0	0.0	9,830	analyzed on 8/15/98
79-11/ 5 ft	2	1	9/29/98 10:53	0.005	0.0	0.0	0.0	0.0	16,600	
87-01R/ 5 ft	2	1	12/1/97 13:18	-0.007	0.0	0.0	0.0	0.0	8,430	
87-01R/ 5 ft	2	1	1/10/98 14:40	-0.012	0.0	0.0	0.0	0.0	5,050	
87-01R/ 5 ft	2	1	1/29/98 11:46	-0.005	0.0	0.0	0.0	0.0	8,380	
87-01R/ 5 ft	2	1	2/26/98 13:01	-0.032	0.0	5.0	1.4	0.0	6,940	
87-01R/ 5 ft	2	1	3/24/98 10:23	0.000	0.0	0.0	0.0	0.0	9,540	
87-01R/ 5 ft	2	1	8/14/98 7:34	0.002	0.0	1.1	0.0	0.0	9,780	partially destroyed. analyzed on 8/15/98
87-03/ 5 ft	2	1	9/29/98 10:03	0.002	0.0	0.0	0.0	0.0	13,300	substituted for 87-01R
87-05/ 5 ft	2	1	8/14/98 10:04	0.010	0.0	1.0	0.0	0.0	9,750	analyzed on 8/15/98
87-05/ 5 ft	2	1	9/29/98 10:09	0.002	0.0	0.0	0.0	0.0	12,700	
87-09/ 5 ft	2	1	12/1/97 13:44	-0.085	0.0	0.0	0.0	0.0	8,120	
87-09/ 5 ft	2	1	1/10/98 12:00	-0.010	0.0	0.0	0.0	0.0	4,700	
87-09/ 5 ft	2	1	1/29/98 10:00	-0.010	0.0	0.0	0.0	0.0	7,840	
87-09/ 5 ft	2	1	2/26/98 11:17	-0.007	0.0	0.0	0.0	0.0	6,360	
87-09/ 5 ft	2	1	3/24/98 7:53	-0.002	0.0	0.0	0.0	0.0	8,970	
87-09/ 5 ft	2	1	8/14/98 11:27	0.017	0.0	0.0	0.0	0.0	9,770	analyzed on 8/15/98
87-09/ 5 ft	2	1	9/29/98 11:17	0.007	1.5	0.0	0.0	0.0	18,800	
N-6/ 5 ft	2	1	12/1/97 14:20	-0.102	0.0	0.0	0.0	0.0	8,520	
N-6/ 5 ft	2	1	1/10/98 0:00							sample tube clogged
N-6/ 5 ft	2	1	1/29/98 0:00							unable to sample
N-6/ 5 ft	2	1	2/5/98 8:15							sample tube clogged
N-6/ 5 ft	2	1	2/26/98 0:00							could not pull a sample
N-6/ 5 ft	2	1	3/24/98 12:25	0.017	0.0	0.0	1.1	0.0	13,800	

Table C-1. Carbon Tetrachloride Concentrations Monitored at the 216-Z-1A/Z-18 Wellfield During Nonoperation of the SVE System, October 1997 Through September 1998. (4 Pages)

216-Z-1A/Z-18/Z-12 SITE										
Sample Location	Depth (m bgs)	Zone	Sample Date Time	Differential Pressure (kPa)	CCl4 (ppmv)	CHCl3 (ppmv)	MEK (ppmv)	CH2Cl2 (ppmv)	Water (ppmv)	Comment
CPT-13A/ 9 ft	3	2	12/1/97 14:00	-0.007	0.0	0.0	0.0	0.0	8,270	
CPT-13A/ 9 ft	3	2	1/10/98 12:15	-0.010	0.0	0.0	0.0	0.0	4,940	
CPT-13A/ 9 ft	3	2	1/29/98 10:23	-0.012	0.0	0.0	0.0	0.0	8,260	
CPT-13A/ 9 ft	3	2	2/26/98 11:36	-0.002	0.0	0.0	0.0	0.0	7,000	
CPT-13A/ 9 ft	3	2	3/24/98 12:15	0.007	0.0	0.0	1.4	0.0	11,100	
CPT-13A/ 9 ft	3	2	4/30/98 7:41	-0.010	0.0	0.0	1.1	0.0	8,980	
CPT-13A/ 9 ft	3	2	5/26/98 6:47	0.005	0.0	0.0	0.0	0.0	8,070	
CPT-13A/ 9 ft	3	2	6/29/98 7:16	-0.007	0.0	3.3	0.0	0.0	13,500	
CPT-13A/ 9 ft	3	2	8/14/98 10:55	0.017	0.0	0.0	0.0	0.0	9,810	analyzed on 8/15/98
CPT-13A/ 9 ft	3	2	9/29/98 10:59	0.007	0.0	0.0	0.0	0.0	17,100	
CPT-31/ 25 ft	8	2	12/1/97 14:54	-0.022	0.0	0.0	0.0	0.0	7,900	
CPT-31/ 25 ft	8	2	1/10/98 14:20	-0.100	0.0	0.0	0.0	0.0	4,980	
CPT-31/ 25 ft	8	2	1/29/98 11:22	0.000	0.0	0.0	0.0	0.0	8,760	
CPT-31/ 25 ft	8	2	2/26/98 12:51	-0.007	0.0	0.0	0.0	0.0	7,030	
CPT-31/ 25 ft	8	2	3/24/98 10:00	-0.002	0.0	0.0	0.0	0.0	9,480	
CPT-31/ 25 ft	8	2	8/14/98 8:51	0.007	0.0	0.0	0.0	0.0	9800	analyzed on 8/15/98
CPT-31/ 25 ft	8	2	9/29/98 9:23	-0.010	0.0	0.0	0.0	0.0	12,300	
CPT-32/ 25 ft	8	2	12/1/97 14:26	-0.007	0.0	0.0	0.0	0.0	8,220	
CPT-32/ 25 ft	8	2	1/10/98 14:30	-0.010	0.0	0.0	0.0	0.0	5,430	
CPT-32/ 25 ft	8	2	1/29/98 11:15	-0.010	5.1	0.0	0.0	0.0	8,640	
CPT-32/ 25 ft	8	2	2/26/98 12:44	-0.007	6.6	0.0	0.0	0.0	6,950	
CPT-32/ 25 ft	8	2	3/24/98 10:06	-0.010	9.1	0.0	0.0	1.1	9,630	
CPT-32/ 25 ft	8	2	8/14/98 10:16	0.012	0.0	1.2	1.2	0.0	9850	analyzed on 8/15/98
CPT-32/ 25 ft	8	2	9/29/98 10:14	0.000	0.0	0.0	0.0	0.0	15,000	
CPT-7A/ 32 ft	10	2	12/1/97 14:42	-0.010	0.0	0.0	0.0	0.0	8,050	
CPT-7A/ 32 ft	10	2	1/10/98 14:50	-0.010	0.0	0.0	0.0	0.0	5,590	
CPT-7A/ 32 ft	10	2	1/29/98 9:53	-0.012	1.9	0.0	0.0	0.0	7,830	
CPT-7A/ 32 ft	10	2	2/26/98 11:02	-0.002	2.3	0.0	0.0	0.0	6,390	
CPT-7A/ 32 ft	10	2	3/24/98 7:46	-0.007	2.2	0.0	0.0	0.0	9,070	
CPT-7A/ 32 ft	10	2	8/14/98 11:46	0.032	1.4	1.0	0.0	0.0	9720	analyzed on 8/15/98
CPT-7A/ 32 ft	10	2	9/29/98 11:22	-0.005	1.7	0.0	0.0	0.0	17,000	

Table C-1. Carbon Tetrachloride Concentrations Monitored at the 216-Z-1A/Z-18 Wellfield During Nonoperation of the SVE System, October 1997 Through September 1998. (4 Pages)

216-Z-1A/Z-18/Z-12 SITE										
Sample Location	Depth (m bgs)	Zone	Sample Date Time	Differential Pressure (kPa)	CCl4 (ppmv)	CHCl3 (ppmv)	MEK (ppmv)	CH2Cl2 (ppmv)	Water (ppmv)	Comment
CPT-1A/ 35 ft	11	2	12/1/97 15:13	-0.012	0.0	0.0	0.0	0.0	8,190	
CPT-1A/ 35 ft	11	2	1/10/98 14:35	-0.012	0.0	0.0	0.0	0.0	5,500	
CPT-1A/ 35 ft	11	2	1/29/98 11:40	0.000	0.0	0.0	0.0	0.0	8,010	
CPT-1A/ 35 ft	11	2	2/26/98 13:08	-0.002	0.0	0.0	0.0	0.0	6,530	
CPT-1A/ 35 ft	11	2	3/24/98 10:18	0.000	1.2	0.0	0.0	0.0	9,220	
CPT-1A/ 35 ft	11	2	4/30/98 7:35	-0.017	1.2	0.0	0.0	0.0	8,760	
CPT-1A/ 35 ft	11	2	5/26/98 6:40	0.002	1.3	0.0	0.0	0.0	7,970	
CPT-1A/ 35 ft	11	2	6/29/98 7:10	-0.020	0.0	3.5	0.0	0.0	13,100	
CPT-1A/ 35 ft	11	2	8/14/98 7:55	0.005	1.4	0.0	0.0	0.0	9,750	analyzed on 8/15/98
CPT-1A/ 35 ft	11	2	9/29/98 7:53	-0.012	1.1	0.0	0.0	0.0	10,700	
CPT-33/ 40 ft	12	2	12/1/97 15:00	-0.017	0.0	0.0	0.0	0.0	7,960	
CPT-33/ 40 ft	12	2	1/10/98 14:04	-0.017	1.8	0.0	0.0	0.0	5,390	
CPT-33/ 40 ft	12	2	1/29/98 11:32	-0.007	1.8	0.0	0.0	0.0	8,230	
CPT-33/ 40 ft	12	2	2/26/98 12:57	-0.002	1.3	0.0	0.0	0.0	6,870	
CPT-33/ 40 ft	12	2	3/24/98 9:35	0.002	1.4	0.0	0.0	0.0	9,320	
CPT-33/ 40 ft	12	2	8/14/98 8:40	0.007	1.1	0.0	0.0	0.0	9810	analyzed on 8/15/98
CPT-33/ 40 ft	12	2	9/29/98 9:15	-0.012	2.0	0.0	0.0	0.0	12,100	
CPT-34/ 86 ft	26	2	8/14/98 8:12	0.000	4.5	2.1	1.3	0.0	9800	analyzed on 8/15/98
CPT-34/ 86 ft	26	2	9/29/98 8:11	-0.075	5.9	0.0	0.0	0.0	10,900	
CPT-4A/ 91 ft	28	2	8/14/98 9:53	0.050	6.9	0.0	1.1	6.5	9770	analyzed on 8/15/98
CPT-4A/ 91 ft	28	2	9/29/98 9:55	-0.105	7.7	0.0	0.0	5.5	13,000	
W18-252SST/ 100 ft	30	2	8/14/98 9:18	0.040	8.9	0.0	0.0	0.0	9,640	analyzed on 8/15/98
W18-252SST/ 100 ft	30	2	9/29/98 9:31	-0.112	17.8	0.0	0.0	0.0	11,400	
W18-152/ 102 ft	31	2	8/14/98 7:44	0.005	11.1	1.4	0.0	0.0	9,670	analyzed on 8/15/98
W18-152/ 102 ft	31	2	9/29/98 7:43	-0.072	0.0	0.0	0.0	0.0	10,600	
W18-167/ 106 ft	32	3	8/14/98 0:00							no access
W18-167/ 106 ft	32	3	9/29/98 8:56	-0.082	79.7	1.6	0.0	3.2	11,200	
CPT-4F/ 109 ft	33	2	8/14/98 9:41	0.040	6.3	2.6	1.0	1.2	9790	analyzed on 8/15/98
CPT-4F/ 109 ft	33	2	9/29/98 9:43	-0.070	13.8	0.0	0.0	0.0	12,500	
W18-174/ 117 ft	36	3	8/14/98 0:00							not in service
W18-174/ 117 ft	36	3	9/29/98 0:00							not in service

Table C-1. Carbon Tetrachloride Concentrations Monitored at the 216-Z-1A/Z-18 Wellfield During Nonoperation of the SVE System, October 1997 Through September 1998. (4 Pages)

216-Z-1A/Z-18/Z-12 SITE										
Sample Location	Depth (m bgs)	Zone	Sample Date Time	Differential Pressure (kPa)	CCl4 (ppmv)	CHCl3 (ppmv)	MEK (ppmv)	CH2Cl2 (ppmv)	Water (ppmv)	Comment
W18-158L/ 120 ft	36	3	8/14/98 0:00							no access
W18-158L/ 120 ft	36	3	9/29/98 8:47	-0.082	143.0	0.0	7.7	165.0	11,100	
W18-249/ 130 ft	39	3	8/14/98 0:00							not in service
W18-249/ 130 ft	39	3	9/29/98 8:33	-0.095	20.4	2.0	1.1	4.8	10,900	
W18-248/ 131 ft	40	3	8/14/98 11:20	0.072	7.1	2.2	0.0	0.0	9,810	analyzed on 8/15/98
W18-248/ 131 ft	40	3	9/29/98 11:12	-0.075	86.3	2.3	0.0	1.5	14,300	
W18-7/ 197 ft	60	6	12/1/97 0:00							not in service
W18-7/ 197 ft	60	6	1/10/98 14:45	0.095	12.6	0.0	0.0	0.0	6,180	
W18-7/ 197 ft	60	6	1/29/98 10:09	0.767	14.4	0.0	0.0	0.0	8,130	
W18-7/ 197 ft	60	6	2/26/98 11:25	-0.516	15.7	0.0	0.0	1.5	6,580	
W18-7/ 197 ft	60	6	2/26/98 11:25	-0.516	15.7	0.0	0.0	1.5	6,550	duplicate
W18-7/ 197 ft	60	6	3/24/98 7:59	0.144	15.8	0.0	0.0	1.5	9,020	
W18-7/ 197 ft	60	6	8/14/98 11:09	0.035	0.0	2.3	1.2	0.0	9710	analyzed on 8/15/98
W18-7/ 197 ft	60	6	9/29/98 11:06	-0.192	17.2	1.2	0.0	0.0	14,400	duplicate
W18-7/ 197 ft	60	6	9/29/98 11:06	-0.192	17.3	0.0	0.0	0.0	14,500	
W18-12/ 198 ft	60	6	8/14/98 12:50	0.391	1.2	2.3	1.0	2.0	9,730	analyzed on 8/15/98
W18-12/ 198 ft	60	6	9/29/98 10:31	-0.214	3.8	0.0	0.0	9.0	12,200	
W18-6L/ 208 ft	63	6	12/1/97 0:00							not in service
W18-6L/ 208 ft	63	6	1/10/98 13:50	0.139	24.0	0.0	0.0	2.0	4,700	
W18-6L/ 208 ft	63	6	1/29/98 11:05	0.687	25.8	0.0	0.0	1.9	8,350	
W18-6L/ 208 ft	63	6	2/26/98 12:30	-0.456	31.3	1.0	0.0	1.2	6,830	
W18-6L/ 208 ft	63	6	3/24/98 10:11	0.167	0.0	3.1	2.3	1.6	9,850	(a)
W18-6L/ 208 ft	63	6	8/14/98 10:36	0.252	4.3	1.6	0.0	0.0	9560	analyzed on 8/15/98
W18-6L/ 208 ft	63	6	8/14/98 10:36	0.252	4.2	1.6	0.0	0.0	9,560	analyzed on 8/15/98
W18-6L/ 208 ft	63	6	9/29/98 10:21	-0.214	14.5	1.0	0.0	2.2	12,600	

(a) sampling tube removed, SVE wellhead adaptor installed prior to sampling;
sampled from wellhead after well had been open to atmosphere for wellhead assembly changeout.

Table C-2. Carbon Tetrachloride Concentrations Monitored at the 216-Z-9 Wellfield During Nonoperation of the SVE System, October 1997 Through September 1998. (5 Pages)

216-Z-9 SITE										
Sample Location	Depth (m bgs)	Zone	Sample Date Time	Differential Pressure (kPa)	CCl4 (ppmv)	CHCl3 (ppmv)	MEK (ppmv)	CH2Cl2 (ppmv)	Water (ppmv)	Comment
86-06/ 5 ft	2	1	12/1/97 12:07	-0.005	0.0	0.0	0.0	0.0	7,340	
86-06/ 5 ft	2	1	1/10/98 9:08	-0.010	0.0	0.0	0.0	0.0	4,150	
86-06/ 5 ft	2	1	1/29/98 8:20	0.005	0.0	0.0	0.0	0.0	7,300	
86-06/ 5 ft	2	1	2/26/98 8:42	-0.010	0.0	0.0	0.0	0.0	5,460	
86-06/ 5 ft	2	1	3/24/98 13:00	0.007	0.0	0.0	0.0	0.0	11,000	
86-06/ 5 ft	2	1	4/30/98 11:06	0.002	0.0	0.0	0.0	0.0	13,100	
86-06/ 5 ft	2	1	5/26/98 9:10	0.005	0.0	0.0	0.0	0.0	8,410	
86-06/ 5 ft	2	1	6/29/98 11:42	0.010	0.0	0.0	0.0	1.6	23,800	
94-09/ 5 ft	2	1	12/1/97 12:35	-0.007	1.3	0.0	0.0	0.0	7,460	
94-09/ 5 ft	2	1	1/10/98 9:22	-0.012	0.0	0.0	0.0	0.0	4,110	
94-09/ 5 ft	2	1	1/29/98 8:40	-0.007	0.0	0.0	0.0	0.0	7,340	
94-09/ 5 ft	2	1	2/26/98 9:02	-0.007	1.3	0.0	0.0	0.0	5,720	
94-09/ 5 ft	2	1	3/24/98 11:51	0.002	0.0	0.0	0.0	0.0	10,600	
94-09/ 5 ft	2	1	4/30/98 11:12	0.007	0.0	0.0	0.0	0.0	13,500	
94-09/ 5 ft	2	1	5/26/98 9:17	-0.002	0.0	0.0	0.0	0.0	8,510	
94-09/ 5 ft	2	1	6/29/98 9:23	0.007	0.0	2.2	0.0	0.0	20,000	
94-09/ 5 ft	2	1	8/14/98 12:08	0.017	0.0	1.3	0.0	0.0	9,750	analyzed on 8/15/98
94-09/ 5 ft	2	1	9/29/98 11:35	0.007	0.0	1.5	0.0	0.0	21,200	
95-11/ 5 ft	2	1	12/1/97 12:57	-0.007	0.0	0.0	0.0	0.0	7,730	
95-11/ 5 ft	2	1	1/10/98 10:07	-0.010	0.0	0.0	0.0	0.0	4,140	
95-11/ 5 ft	2	1	1/29/98 9:08	0.000	0.0	0.0	0.0	0.0	7,360	
95-11/ 5 ft	2	1	2/26/98 10:22	-0.005	0.0	0.0	0.0	0.0	6,040	
95-11/ 5 ft	2	1	3/24/98 11:27	0.000	1.2	0.0	0.0	0.0	10,000	
95-11/ 5 ft	2	1	4/30/98 9:09	0.005	0.0	0.0	0.0	0.0	9,710	
95-11/ 5 ft	2	1	5/26/98 7:36	0.002	2.1	0.0	0.0	0.0	8,440	
95-11/ 5 ft	2	1	6/29/98 7:59	0.005	1.8	1.4	0.0	0.0	15,300	
95-12/ 5 ft	2	1	12/1/97 13:10	-0.007	0.0	0.0	0.0	0.0	7,600	
95-12/ 5 ft	2	1	1/10/98 11:25	-0.010	0.0	0.0	0.0	0.0	4,390	
95-12/ 5 ft	2	1	1/29/98 9:17	-0.010	0.0	0.0	0.0	0.0	7,380	
95-12/ 5 ft	2	1	2/26/98 10:27	-0.005	0.0	0.0	0.0	0.0	6,030	
95-12/ 5 ft	2	1	3/24/98 11:16	0.000	0.0	0.0	0.0	1.3	9,880	
95-12/ 5 ft	2	1	4/30/98 8:25	0.002	1.4	0.0	0.0	1.3	9,240	
95-12/ 5 ft	2	1	5/26/98 7:20	-0.042	1.5	0.0	0.0	0.0	8,400	
95-12/ 5 ft	2	1	6/29/98 7:45	0.000	1.2	2.2	0.0	0.0	16,000	

Table C-2. Carbon Tetrachloride Concentrations Monitored at the 216-Z-9 Wellfield During Nonoperation of the SVE System, October 1997 Through September 1998. (5 Pages)

216-Z-9 SITE										
Sample Location	Depth (m bgs)	Zone	Sample Date Time	Differential Pressure (kPa)	CCl4 (ppmv)	CHCl3 (ppmv)	MEK (ppmv)	CH2Cl2 (ppmv)	Water (ppmv)	Comment
CPT-16/ 10 ft	3	2	12/1/97 12:50	-0.100	0.0	0.0	0.0	0.0	7,980	
CPT-16/ 10 ft	3	2	1/10/98 9:32	-0.020	0.0	0.0	0.0	0.0	4,200	
CPT-16/ 10 ft	3	2	1/29/98 8:46	-0.012	0.0	0.0	0.0	0.0	7,300	
CPT-16/ 10 ft	3	2	2/26/98 9:09	-0.017	0.0	0.0	0.0	0.0	5,770	
CPT-16/ 10 ft	3	2	3/24/98 11:46	0.012	0.0	0.0	0.0	0.0	11,100	
CPT-16/ 10 ft	3	2	4/30/98 10:41	0.002	0.0	0.0	0.0	0.0	12,700	
CPT-16/ 10 ft	3	2	5/26/98 8:40	0.007	0.0	0.0	0.0	0.0	8,340	
CPT-16/ 10 ft	3	2	6/29/98 9:11	0.002	0.0	0.0	0.0	0.0	16,400	
CPT-17/ 10 ft	3	2	12/1/97 13:17	-0.005	0.0	0.0	0.0	0.0	7,750	
CPT-17/ 10 ft	3	2	1/10/98 11:32	-0.010	0.0	0.0	0.0	0.0	4,500	
CPT-17/ 10 ft	3	2	1/29/98 9:22	-0.020	0.0	0.0	0.0	0.0	7,660	
CPT-17/ 10 ft	3	2	2/26/98 10:33	-0.002	0.0	0.0	0.0	1.4	6,430	
CPT-17/ 10 ft	3	2	3/24/98 11:13	0.005	1.2	0.0	0.0	1.5	10,400	
CPT-17/ 10 ft	3	2	4/30/98 8:21	0.002	3.6	0.0	0.0	1.8	9,170	
CPT-17/ 10 ft	3	2	5/26/98 7:17	0.005	4.2	1.1	0.0	0.0	8,320	
CPT-17/ 10 ft	3	2	6/29/98 7:41	-0.002	4.1	1.0	0.0	0.0	14,900	
CPT-18/ 15 ft	5	2	12/1/97 13:04	-0.007	0.0	0.0	0.0	0.0	7,830	
CPT-18/ 15 ft	5	2	1/10/98 10:30	-0.010	0.0	0.0	0.0	0.0	4,320	
CPT-18/ 15 ft	5	2	1/29/98 9:03	0.002	0.0	0.0	0.0	0.0	7,510	
CPT-18/ 15 ft	5	2	2/26/98 10:18	-0.007	0.0	0.0	0.0	0.0	5,890	
CPT-18/ 15 ft	5	2	3/24/98 11:30	0.005	0.0	0.0	0.0	0.0	10,600	
CPT-18/ 15 ft	5	2	4/30/98 9:06	0.005	1.0	0.0	0.0	0.0	9,470	
CPT-18/ 15 ft	5	2	5/26/98 7:31	0.012	4.3	0.0	0.0	0.0	8,410	
CPT-18/ 15 ft	5	2	6/29/98 7:56	0.000	6.5	1.7	0.0	0.0	14,900	
CPT-28/ 40 ft	12	2	12/1/97 13:33	-0.010	17.0	0.0	0.0	0.0	7,970	
CPT-28/ 40 ft	12	2	1/10/98 11:48	-0.012	19.1	0.0	0.0	0.0	4,590	
CPT-28/ 40 ft	12	2	1/29/98 9:38	-0.040	21.6	0.0	0.0	0.0	7,810	
CPT-28/ 40 ft	12	2	1/29/98 9:38	-0.040	21.8	0.0	0.0	0.0	7,820	duplicate
CPT-28/ 40 ft	12	2	2/26/98 10:50	-0.010	19.2	0.0	0.0	1.4	6,250	
CPT-28/ 40 ft	12	2	3/24/98 12:40	0.032	11.7	0.0	0.0	0.0	13,700	
CPT-28/ 40 ft	12	2	4/30/98 7:50	-0.035	13.3	0.0	0.0	0.0	8,490	

Table C-2. Carbon Tetrachloride Concentrations Monitored at the 216-Z-9 Wellfield During Nonoperation of the SVE System, October 1997 Through September 1998. (5 Pages)

216-Z-9 SITE										
Sample Location	Depth (m bgs)	Zone	Sample Date Time	Differential Pressure (kPa)	CCl4 (ppmv)	CHCl3 (ppmv)	MEK (ppmv)	CH2Cl2 (ppmv)	Water (ppmv)	Comment
CPT-21A/ 45 ft	14	2	12/1/97 13:25	-0.022	18.5	0.0	0.0	1.4	8,040	
CPT-21A/ 45 ft	14	2	1/10/98 11:40	-0.010	30.5	0.0	0.0	2.0	4,600	
CPT-21A/ 45 ft	14	2	1/29/98 9:29	-0.027	37.1	0.0	0.0	1.9	7,750	
CPT-21A/ 45 ft	14	2	2/26/98 10:40	-0.037	21.5	0.0	0.0	1.5	6,370	
CPT-21A/ 45 ft	14	2	3/24/98 11:06	0.042	43.0	0.0	0.0	2.3	11,000	duplicate
CPT-21A/ 45 ft	14	2	3/24/98 11:06	0.042	42.9	0.0	0.0	2.2	10,900	
CPT-21A/ 45 ft	14	2	4/30/98 8:11	-0.045	41.4	0.0	0.0	2.6	9,140	
CPT-21A/ 45 ft	14	2	5/26/98 7:07	0.057	52.7	1.3	0.0	2.1	8,270	
CPT-21A/ 45 ft	14	2	6/29/98 7:33	-0.067	33.7	2.1	0.0	1.0	14,700	
CPT-28/ 60 ft	18	2	5/26/98 6:52	0.015	1.3	0.0	0.0	0.0	8,100	substituted for CPT-28/40 ft
CPT-28/ 60 ft	18	2	6/29/98 7:23	-0.012	0.0	3.3	0.0	0.0	14,900	substituted for CPT-28/40 ft
CPT-28/ 60 ft	18	2	8/14/98 11:54	0.027	1.3	0.0	0.0	0.0	9,750	substituted for CPT-28/40 ft; analyzed on 8/15/98
CPT-28/ 60 ft	18	2	9/29/98 11:28	0.000	1.5	0.0	0.0	0.0	17,400	substituted for CPT-28/40 ft
CPT-9A/ 60 ft	18	2	12/1/97 12:25	-0.012	35.8	0.0	0.0	2.3	7,310	
CPT-9A/ 60 ft	18	2	12/1/97 12:25	-0.012	35.8	0.0	0.0	2.6	7,300	duplicate
CPT-9A/ 60 ft	18	2	1/10/98 15:00	-0.040	37.5	0.0	0.0	2.1	5,580	
CPT-9A/ 60 ft	18	2	1/10/98 15:00	-0.040	37.9	0.0	0.0	2.4	5,620	duplicate
CPT-9A/ 60 ft	18	2	1/29/98 8:30	0.010	39.1	0.0	0.0	2.3	7,330	
CPT-9A/ 60 ft	18	2	2/26/98 8:54	-0.052	40.9	0.0	0.0	2.8	5,510	
CPT-9A/ 60 ft	18	2	3/24/98 12:03	0.037	38.9	0.0	0.0	2.6	11,000	
CPT-9A/ 60 ft	18	2	4/30/98 11:19	0.007	39.1	0.0	0.0	2.3	13,700	
CPT-9A/ 60 ft	18	2	5/26/98 9:24	0.065	38.8	0.0	0.0	3.7	8,360	
CPT-9A/ 60 ft	18	2	6/29/98 9:30	0.000	38.0	1.3	0.0	1.8	20,200	
CPT-9A/ 60 ft	18	2	8/14/98 12:20	0.080	30.4	0.0	0.0	2.2	9,660	analyzed on 8/15/98
CPT-9A/ 60 ft	18	2	9/29/98 11:41	0.007	41.1	0.0	0.0	1.0	17,700	
CPT-24/ 70 ft	21	2	4/30/98 10:28	-0.005	1.8	0.0	0.0	0.0	13,800	substituted for CPT-24/ 95 ft
CPT-24/ 70 ft	21	2	5/26/98 7:42	0.112	3.2	0.0	0.0	1.7	8,420	substituted for CPT-24/ 95 ft
CPT-24/ 70 ft	21	2	6/29/98 8:04	-0.060	2.9	0.0	0.0	0.0	15,400	substituted for CPT-24/ 95 ft
CPT-21A/ 86 ft	26	2	4/30/98 8:15	-0.087	169.0	1.5	0.0	3.1	9,220	
CPT-21A/ 86 ft	26	2	5/26/98 7:12	0.115	168.0	0.0	0.0	3.6	8,230	
CPT-21A/ 86 ft	26	2	6/29/98 7:36	-0.127	206.0	7.5	2.7	3.1	14,500	

Table C-2. Carbon Tetrachloride Concentrations Monitored at the 216-Z-9 Wellfield During Nonoperation of the SVE System, October 1997 Through September 1998. (5 Pages)

216-Z-9 SITE										
Sample Location	Depth (m bgs)	Zone	Sample Date Time	Differential Pressure (kPa)	CCl4 (ppmv)	CHCl3 (ppmv)	MEK (ppmv)	CH2Cl2 (ppmv)	Water (ppmv)	Comment
W15-95/ 87 ft	26	2	4/30/98 9:44	-0.022	11.9	0.0	0.0	0.0	12,000	sampled from wellhead without tubing after 3 minute purge
W15-95/ 87 ft	26	2	5/26/98 8:21	0.144	15.0	0.0	0.0	1.5	8,520	sampled from wellhead without tubing after 3 minute purge
W15-95/ 87 ft	26	2	6/29/98 8:45	-0.075	15.3	1.7	0.0	0.0	19,000	sampled from wellhead without tubing after 3 minute purge
CPT-28/ 87 ft	27	2	4/30/98 8:04	-0.087	229.0	1.6	0.0	2.4	9,050	
CPT-28/ 87 ft	27	2	5/26/98 7:00	0.110	229.0	1.8	0.0	1.7	8,160	
CPT-28/ 87 ft	27	2	6/29/98 7:26	-0.130	230.0	2.8	0.0	1.3	14,500	
W15-82/ 88 ft	27	2	4/30/98 10:51	0.007	0.0	0.0	0.0	0.0	13,000	sampled from wellhead without tubing after 3 minute purge
W15-82/ 88 ft	27	2	5/26/98 8:50	0.137	5.5	0.0	0.0	5.5	8,450	sampled from wellhead without tubing after 3 minute purge
W15-82/ 88 ft	27	2	6/29/98 11:33	0.015	0.0	0.0	0.0	2.3	19,000	sampled from wellhead without tubing after 3 minute purge
CPT-9A/ 91 ft	28	2	4/30/98 11:24	0.002	27.6	0.0	0.0	1.9	10,500	
CPT-9A/ 91 ft	28	2	5/26/98 9:29	0.067	34.5	0.0	0.0	3.2	8,190	
CPT-9A/ 91 ft	28	2	6/29/98 9:35	-0.045	33.6	0.0	0.0	1.7	15,800	
W15-218U/ 106 ft	32	3	4/30/98 10:03	0.080	0.0	0.0	0.0	1.1	12,900	sampled from wellhead without tubing after 3 minute purge
W15-218U/ 106 ft	32	3	4/30/98 10:10	0.080	0.0	0.0	0.0	0.0	12,400	sampled from wellhead without tubing after 10 minute purg
W15-218U/ 106 ft	32	3	5/26/98 8:06	0.229	0.0	0.0	0.0	0.0	8,300	sampled from wellhead without tubing after 3 minute purge
W15-218U/ 106 ft	32	3	5/26/98 8:11	0.229	0.0	0.0	0.0	0.0	8,270	sampled from wellhead without tubing after 10 minute purg
W15-218U/ 106 ft	32	3	6/29/98 8:36	-0.227	0.0	1.9	0.0	0.0	18,000	sampled from wellhead without tubing after 3 minute purge
W15-223/ 110 ft	34	3	4/30/98 10:22	0.010	0.0	0.0	0.0	0.0	15,000	sampled from wellhead without tubing after 3 minute purge
W15-223/ 110 ft	34	3	5/26/98 7:55	0.154	2.2	0.0	0.0	0.0	8,340	sampled from wellhead without tubing after 3 minute purge
W15-223/ 110 ft	34	3	6/29/98 8:25	-0.085	0.0	0.0	0.0	0.0	12,900	sampled from wellhead without tubing after 3 minute purge
W15-217/ 114 ft	35	3	3/24/98 11:22	0.077	95.7	0.0	0.0	0.0	9,510	sampled from wellhead without tubing after 3 minute purge
W15-217/ 114 ft	35	3	4/30/98 8:52	-0.057	18.8	0.0	0.0	0.0	8,880	sampled from wellhead without tubing after 3 minute purge
W15-217/ 114 ft	35	3	4/30/98 8:59	-0.057	25.4	1.0	0.0	0.0	8,770	sampled from wellhead without tubing after 10 minute purg
W15-217/ 114 ft	35	3	5/26/98 7:25	0.174	630.0	5.2	0.0	0.0	8,480	tubing installed 5/19/98
W15-217/ 114 ft	35	3	5/26/98 7:25	0.174	458.0	5.3	0.0	1.4	8,480	duplicate
W15-217/ 114 ft	35	3	6/29/98 7:50	-0.157	504.0	4.2	0.0	1.2	14,400	
CPT-24/ 118 ft	36	3	4/30/98 9:30	-0.080	37.7	1.6	1.6	2.9	10,200	
CPT-24/ 118 ft	36	3	4/30/98 9:30	-0.080	38.0	1.7	1.6	2.6	9,710	
CPT-24/ 118 ft	36	3	5/26/98 7:48	0.224	36.5	0.0	0.0	2.7	8,420	
CPT-24/ 118 ft	36	3	6/29/98 8:08	-0.172	37.8	1.9	1.4	2.3	15,700	duplicate
CPT-24/ 118 ft	36	3	6/29/98 8:08	-0.172	37.5	1.8	1.2	3.0	15,700	

Table C-2. Carbon Tetrachloride Concentrations Monitored at the 216-Z-9 Wellfield During Nonoperation of the SVE System, October 1997 Through September 1998. (5 Pages)

216-Z-9 SITE										
Sample Location	Depth (m bgs)	Zone	Sample Date Time	Differential Pressure (kPa)	CCl4 (ppmv)	CHCl3 (ppmv)	MEK (ppmv)	CH2Cl2 (ppmv)	Water (ppmv)	Comment
W15-9L/ 176 ft	53	6	12/1/97 0:00							not in service
W15-9L/ 176 ft	53	6	1/10/98 15:10	0.050	13.3	0.0	0.0	1.3	5,680	
W15-9L/ 176 ft	53	6	1/29/98 0:00							unable to sample; radiological concern
W15-9L/ 176 ft	53	6	2/5/98 8:00	-0.740	14.6	0.0	0.0	1.3	7,940	
W15-9L/ 176 ft	53	6	2/5/98 8:00	-0.740	14.6	0.0	0.0	1.1	7,970	duplicate
W15-9L/ 176 ft	53	6	2/26/98 9:34	-0.543	8.7	0.0	0.0	1.2	5,810	
W15-9L/ 176 ft	53	6	3/24/98 11:35	0.204	14.6	0.0	0.0	1.7	9,780	
W15-9L/ 176 ft	53	6	4/30/98 9:52	0.092	14.0	0.0	0.0	1.6	10,900	
W15-9L/ 176 ft	53	6	5/26/98 8:27	0.254	15.0	0.0	0.0	2.4	8,420	
W15-9L/ 176 ft	53	6	6/29/98 8:51	-0.249	8.6	2.0	0.0	0.0	18,800	
W15-216L/ 180 ft	55	5	12/1/97 0:00							not in service
W15-216L/ 180 ft	55	5	1/10/98 8:54	-0.095	14.1	0.0	0.0	0.0	4,190	
W15-216L/ 180 ft	55	5	1/29/98 8:11	0.177	15.5	0.0	0.0	0.0	7,380	
W15-216L/ 180 ft	55	5	2/26/98 8:33	-0.568	15.0	0.0	0.0	1.2	5,630	
W15-216L/ 180 ft	55	5	3/24/98 12:52	0.291	17.3	0.0	0.0	0.0	13,400	
W15-216L/ 180 ft	55	5	4/30/98 11:00	0.012	15.0	1.1	1.0	0.0	14,100	
W15-216L/ 180 ft	55	5	5/26/98 8:59	0.120	15.3	0.0	0.0	1.6	8,480	
W15-216L/ 180 ft	55	5	6/29/98 11:38	-0.012	12.8	3.4	1.9	4.1	21,500	
W15-6L/ 182 ft	55	6	12/1/97 0:00							not in service
W15-6L/ 182 ft	55	6	1/10/98 9:52	-0.067	15.2	0.0	0.0	1.9	5,620	
W15-6L/ 182 ft	55	6	1/29/98 8:53	0.807	16.1	0.0	0.0	2.2	7,490	
W15-6L/ 182 ft	55	6	2/26/98 9:20	-0.545	16.1	0.0	0.0	2.8	5,860	
W15-6L/ 182 ft	55	6	3/24/98 11:40	0.214	16.3	0.0	0.0	2.0	11,100	
W15-6L/ 182 ft	55	6	4/30/98 10:36	0.095	16.4	0.0	0.0	2.3	14,400	
W15-6L/ 182 ft	55	6	5/26/98 8:34	0.252	17.8	0.0	0.0	2.2	8,470	
W15-6L/ 182 ft	55	6	6/29/98 8:57	-0.252	17.6	1.6	0.0	2.5	18,200	

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APPENDIX D

1998 CARBON TETRACHLORIDE CONCEPTUAL MODEL UPDATE

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APPENDIX D
1998 CARBON TETRACHLORIDE CONCEPTUAL MODEL UPDATE

Virginia Rohay and Craig Swanson

This appendix presents the current conceptual model as well as working hypotheses concerning the source term, environmental setting, vadose zone and groundwater contaminant distribution, vadose zone and groundwater transport, atmospheric losses, and biological degradation of carbon tetrachloride and associated contaminants in the 200 West Area. The conceptual model of the 200 West Area carbon tetrachloride plume has been continuously refined as additional site-specific data have been collected and as the understanding of dense nonaqueous-phase liquid (DNAPL) behavior in the subsurface has been developed by the scientific community. The conceptual model presented in this report provides an update to the conceptual models presented in Rohay and Johnson (1991), Last and Rohay (1991, 1993), Last et al. (1991), and Rohay et al. (1994a).

Carbon tetrachloride contamination comprises two relatively distinct zones: a higher concentration zone in the source area and a lower concentration zone surrounding the source area. Possible transport mechanisms and distributions of contaminant phases for the high-concentration portion of the plume, which may also contain DNAPL/residual carbon tetrachloride, are depicted in Figure D-1. Because of the differences in the sizes of the three primary disposal sites and the quantities of waste received at these disposal sites, it may be that one transport mechanism and resulting contaminant distribution (e.g., vapor phase and aqueous phase migration to groundwater) is more appropriate for one or two disposal sites and that another transport mechanism and contaminant distribution (e.g., DNAPL and aqueous phase migration to groundwater) is more appropriate for the other(s).

D.1 SOURCE TERM

Between 1955 and 1973, a total of 363,000 to 580,000 L (577,000 to 922,000 kg) of liquid carbon tetrachloride, in mixtures with other organic and aqueous, actinide-bearing liquids, was discharged to the soil column at three subsurface disposal facilities (216-Z-9 Trench, 216-Z-1A Tile Field, and 216-Z-18 Crib) near Z Plant in the 200 West Area (Figure 2-1). The organic solutions consisted of 50% to 85% by volume carbon tetrachloride mixed with either tributyl phosphate (TBP), dibutyl butyl phosphonate (DBBP), or lard oil (Table D-1). The solvent that was discharged to the soil column also contained dibutyl phosphate (DBP), a degradation product of TBP. These organic solutions made up only approximately 4% to 8% of the total volume of liquid waste discharged to the disposal facilities. The predominant wastes discharged were acidic, high-salt (sodium nitrate), aqueous wastes containing the above organic solutions in saturated amounts (<1%). The organic solutions were periodically discharged to the predominantly water-wetted soil column in small (100- to 200-L) batches. Thus, carbon tetrachloride was introduced to the vadose zone as an aqueous phase and also as a DNAPL.

Three other sites in the vicinity of Z Plant also received some carbon tetrachloride wastes: the 216-Z-12 Crib, the 216-Z-19 Ditch, and the 216-T-19 Crib (Figure 2-1). 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, which included carbon tetrachloride (Kasper 1982). 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 and/or accidentally released to this ditch (e.g., as a result of steam and/or cooling water coil leaks) because heavy organic was noted in the outfall (Rohay and Johnson 1991). Between 1973 and 1976, aqueous waste saturated with carbon tetrachloride was sent to the 242-T Evaporator; during that time, the 216-T-19 Crib received approximately 1,400 kg (880 L) of carbon tetrachloride in the overhead condensate discharged from this evaporator (Rohay et al. 1993).

D.2 ENVIRONMENTAL SETTING

The vadose zone underlying the carbon tetrachloride disposal sites ranges in thickness from 64 m to 69 m and consists primarily of unconsolidated to partially consolidated gravel-, sand-, and silt-dominated deposits of the Pleistocene Hanford and late Miocene to Pliocene Ringold formations (Table D-2). Between these two units, the relatively less permeable Plio-Pleistocene unit, typically containing an increase in calcium carbonate content ("caliche layer"), occurs at approximately 34 to 39 m below the ground surface and ranges in thickness from 2 to 11 m (Table D-3). The field moisture content is typically higher in the Plio-Pleistocene unit (Table D-2). The permeability of the vadose zone is horizontally and vertically variable in the carbon tetrachloride disposal area: horizontal intrinsic permeabilities range from approximately 10^{-13} to 10^{-10} m^2; corresponding air conductivities range from 0.05 to 25 m/day (equivalent hydraulic conductivities range from 0.5 to 231 m/day) (Rohay and McMahon 1996) (Table D-2). The natural organic carbon content (f_{oc}) of the vadose zone sediments is low (0.11% in silty sand collected from 40- to 43-m depth in well 299-W15-31) (Ford 1996). The soil grain surface area is higher for the silty sand (26.8 m^2/g) than for a commercially available silica sand (0.32 m^2/g) (Ford 1996). Perched groundwater has been encountered at the Plio-Pleistocene zone, and airflow through it has been observed to be significantly impeded (Rohay et al. 1994b). Clastic dikes, which cross-cut the generally horizontal sedimentary layers, contain sediments that may be more permeable than the host sediments and enhance vertical migration of contaminants. However, the clay skins that typically line the margins of the dikes may be less permeable and inhibit horizontal migration across the dike margins (Fecht et al. 1999).

The wastewater discharges at cribs and ditches near the carbon tetrachloride disposal sites may have created vertical hydraulic barriers for liquid and vapor migration within the vadose zone. For example, liquid discharges to the 216-Z-1/Z-11/Z-19/Z-20/U-14 ditch system south and east of the disposal sites may have formed a hydraulic "curtain," preventing carbon tetrachloride-laden fluid and vapor migration to the south and east through the locally saturated soil column and thereby driving contaminant migration locally to the north and west. Ponded surface water and perched water may have created horizontal hydraulic barriers for vapor migration. Before the 216-Z-21 Pond was built southeast of the 216-Z-9 site in the 1980's to receive relatively clean storm drain and cooling water, this water was discharged to a low spot on the ground

surface on the north and east sides of the 216-Z-9 Trench (this may have been only a short-lived temporary discharge site). Water from the 216-Z-21 Pond is believed to be the source of the perched water encountered at the Plio-Pleistocene unit near the 216-Z-9 Trench 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 299-W15-220 in 1993 (Rohay et al. 1992, 1993). The 216-Z-21 Pond is 40 m southeast of W15-216 and received approximately 9.8 x 10^7 L of water per year until 1995, when liquid discharges to the ground ceased.

Natural recharge from precipitation is estimated to be greater than 100 mm/yr in the carbon tetrachloride disposal area (Fayer and Walters 1995). Recharge from precipitation is higher in the coarse-textured soils with little or no vegetation, as are found in the 200 West Area (Hartman 1999). Natural recharge may be enhanced at the 216-Z-1A Tile Field, which is approximately 1.5 m below grade and was covered with a gravel layer in 1993, although the tile field was covered with a sheet of 0.05-cm-thick polyethylene in 1964 prior to reactivation. The 216-Z-9 Trench is 2.5 m lower than the ground surface on its west and south sides.

The uppermost aquifer beneath the 200 West Area is unconfined and lies within an unconsolidated to semi-indurated gravel and sand sequence. The base of the unconfined aquifer is the Ringold lower mud unit. The unconfined aquifer is approximately 66 m thick underlying the carbon tetrachloride disposal sites (Auten and Reynolds 1997). The horizontal hydraulic conductivity in the aquifer ranges from approximately 10^{-3} cm/s to approximately 10^{-6} cm/s. Anisotropy within a sedimentary unit has not been measured at the disposal sites but elsewhere generally ranges from 6:1 to 16:1. The lateral and vertical variability in hydraulic conductivities is illustrated at the carbon tetrachloride disposal site by the production rates of the six pump-and-treat extraction wells, which range from 63 L/min to 310 L/min for similarly completed and configured wells (DOE-RL 1999b). It also appears that hydraulic conductivity decreases with depth in the unconfined aquifer.

Wastewater discharges since 1943 have created local groundwater mounds; the locations and heights of the mounds have changed as wastewater discharge locations and rates have changed. The presence of the mounds has affected both the direction of groundwater movement, causing radial flow from the discharge areas, and the rate of groundwater movement, causing increased hydraulic gradients. With the cessation of liquid discharges, the elevations of both the regional water table and the local groundwater mounds have been declining, resulting in (1) a concomitant increase in the thickness of the vadose zone, and (2) changes in flow directions and rates that affect the distribution of contaminants in the groundwater and the local definitions of "upgradient" and "downgradient" (DOE-RL 1999a).

In the early years of carbon tetrachloride discharges, the primary groundwater mound occurred north of Z Plant at T Pond, causing southward net flow until the late 1950's. From the late 1950's through the present, the primary groundwater mound influencing flow directions has been at U Pond and its associated ditches and cribs in the southern half of 200 West Area. The current groundwater flow directions underlying the carbon tetrachloride disposal sites are also influenced by the groundwater pump-and-treat system, which has been operating at full scale since 1996. The current regional hydraulic gradient is low (0.001 m/m) and the current regional groundwater flow rate is low (approximately 0.15 m/day) across the site (DOE-RL 1999b);

groundwater flow rates and contaminant movement are expected to continue to slow as the groundwater mound subsides and regional water table declines. The current rate of water table decline is approximately 0.45 m/yr under the carbon tetrachloride site (DOE-RL 1999b).

The elevation of the unconfined aquifer water table fluctuates up to 0.2 m/day in response to fluctuations in barometric pressure (Rohay et al. 1993). This water table response, which is more typical for a confined aquifer, is most likely caused by the presence of the overlying, less permeable Plio-Pleistocene layer and the relatively thick vadose zone.

Between 1965 and 1977, the net water table rise was approximately 2 m at the 216-Z-9 site; by 1987 (after U Pond discharges were terminated), the water table had declined to a lower elevation than the level measured in 1965 (Rohay and Johnson 1991). As a result, the location of the pre-1965 capillary fringe beneath the disposal sites was gradually covered with 2 m of saturated soils and then later re-exposed to unsaturated conditions. The thickness of the vadose zone also changed as the water table position changed.

Because of residual U Pond mounding, hydraulic head decreases with depth in the southern portion of the 200 West Area. Vertical groundwater gradients are downward from the unconfined to the confined system, with hydraulic head differences across the Ringold lower mud becoming more pronounced into the basalt aquifer (Spane and Webber 1995). Some wells extending below this hydraulic barrier may have permitted the movement of contamination between the unconfined and confined aquifers (e.g., Auten and Reynolds 1997).

The suprabasalt confined aquifer, composed of interbedded sands and gravels, extends from the Ringold lower mud to the top of basalt bedrock. The basalt confined aquifer system is composed of relatively higher conductivity, water-producing interflow/interbed zones separated by lower conductivity basalt flow interiors.

D.3 CARBON TETRACHLORIDE DISTRIBUTION

D3.1 Mass Balance Calculations

The original inventory of carbon tetrachloride discharged to the three primary disposal sites averaged 750,000 kg. After discharge to the soil column, the carbon tetrachloride in the dissolved and DNAPL phases could partition into soil vapor, soil moisture and groundwater, and sorbed solid phases. Concentrations of carbon tetrachloride measured in groundwater and soil vapor in 1990 prior to remediation were used with equilibrium partitioning relationships to account for approximately 35% of the total carbon tetrachloride inventory discharged to the soil column (WHC 1993) (Table D-4). However, a later laboratory-based study using carbon tetrachloride and site-specific soils concluded that calculation of carbon tetrachloride soil concentrations using measured vapor phase concentrations and either empirical relationships or adsorption isotherms to estimate the soil partitioning coefficient can lead to significant error (Yonge et al. 1996). In particular, these relationships do not account for the nonequilibrium partitioning of carbon tetrachloride within soil particles (the apparent "irreversible" adsorption).

Therefore, the remaining 65% of the original inventory is believed to be in residual saturation and nonequilibrium sorption sites within the vadose zone and groundwater.

Based on the equilibrium partitioning relationships and the 1990 soil vapor data, 12% of the original inventory was estimated to be in the vadose zone: 4% in soil vapor, 2% in soil moisture, and 6% sorbed to solids (WHC 1993). Based on more recent studies, a significant mass of carbon tetrachloride is believed to be in nonequilibrium sorption sites within the vadose zone soils (Cameron 1997). The extent and magnitude of nonequilibrium sorption has not been determined.

Numerical modeling of vadose zone flow and transport at the 216-Z-9 site indicates that 66% to 90% of the carbon tetrachloride discharged to the 216-Z-9 site was retained in the vadose zone, even under the most conservative bounding conditions of very small residual saturation and large source term (Piepho 1996). In this model, the term "residual saturation" refers to the immovable carbon tetrachloride liquid, including sorbed and entrapped phases. Because the natural organic carbon content in the soils is very small, low values (0.01 and 0.0001) of residual saturation were used in the simulations (Piepho 1996). Larger values of residual saturation would have resulted in less carbon tetrachloride transport to groundwater. The results of this modeling indicate that the rate and amount of carbon tetrachloride transport to groundwater is sensitive to the value of residual saturation assumed for the vadose zone and groundwater.

Evaporation and barometric pumping of carbon tetrachloride is estimated to have removed 21% of the original carbon tetrachloride inventory from the vadose zone between 1955 and 1990 (WHC 1993).

Based on the mass of the carbon source (lard oil and butyl phosphates) and nitrate (electron acceptor) co-disposed with the carbon tetrachloride, Hooker et al. (1996) estimated that 1% of the carbon tetrachloride could have been transformed to chloroform by microbial dechlorination during initial discharge stages (Hooker et al. 1996). The chloroform levels observed in the vadose zone and aquifer correspond to a reductive dechlorination of 1% of the carbon tetrachloride. Biodegradation is probably no longer occurring within the vadose zone and groundwater because the naturally-occurring total organic carbon in the soil is insufficient to fuel the process.

The mass of carbon tetrachloride in the upper 10 m of the unconfined aquifer in 1990 was estimated to be 5,250 to 15,740 kg, accounting for 1% to 2% of the original inventory, depending on the value of porosity assumed (Rohay and Johnson 1991) (Table D-5a). The mass of carbon tetrachloride in the aquifer calculated using the smoothed 1996 groundwater contours for comparable conditions (i.e., 10-m aquifer thickness, 30% porosity, no sorption) was 12,203 kg, also accounting for 1% to 2% of the original inventory (Table D-5b). For the 1990 estimate, a soil partitioning distribution coefficient (K_d) of 0.2 mL/g would result in an additional 2% to 8% of the carbon tetrachloride inventory sorbed to aquifer solids (Rohay et al. 1994a). The 1996 calculations evaluated the effect of two different K_d values (0.05 mL/g and 0.114 mL/g) for partitioning carbon tetrachloride between water and solid phases (Table D-5b).

Approximately 78,000 kg of carbon tetrachloride have been removed from the subsurface (vadose zone and groundwater) since remediation of the site began in 1992. Between February 1992 and September 1998, soil vapor extraction (SVE) removed approximately 76,000 kg of carbon tetrachloride from the vadose zone (Table 4-1). Between August 1994 and December 1998, pump and treat removed approximately 2,000 kg from the unconfined aquifer (DOE-RL 1999b).

D.3.2 Distribution within Atmosphere

Global background air concentrations of carbon tetrachloride are approximately 0.15 ppb (Shaw et al. 1996).

D.3.3 Distribution within Vadose Zone

Carbon tetrachloride is found throughout the vadose zone within the 0.2-km^2 source area. Laterally, the highest concentrations of carbon tetrachloride are consistently located in the vicinity of the 216-Z-9 Trench. Vertically, the highest concentrations are associated with the finer grained, relatively less permeable units (the Hanford lower fine and Plio-Pleistocene units). Carbon tetrachloride is present in the vadose zone as vapor, dissolved, and adsorbed phases.

The highest near-surface vapor concentration measured during a soil-vapor survey prior to remediation was 72 ppmv carbon tetrachloride just north of the 216-Z-9 Trench (Rohay et al. 1992). Maximum vapor concentrations observed at wellheads and deep soil vapor probes, which were measured twice a week for 25 months from 1991 through 1993, exceeded an estimated 10,000 ppmv (the instrument was calibrated up to 2,000 ppmv) total volatile organic compounds at monitoring locations above the Plio-Pleistocene unit and immediately north of the 216-Z-9 Trench (Fancher 1994). At similar depth intervals above the Plio-Pleistocene unit in the 216-Z-1A/Z-18/Z-12 area, maximum concentrations were an order of magnitude lower. However, maximum concentrations from monitoring ports below the Plio-Pleistocene unit were approximately 1,000 ppmv at both the 216-Z-9 and Z-1A/Z-18/Z-12 locations (Fancher 1994).

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 a well at the 216-Z-9 Trench (Rohay et al. 1994a). Carbon tetrachloride concentrations exceeded 10 ppm in samples from two other wells in the 216-Z-9 area. In contrast, the highest carbon tetrachloride concentration in a sediment sample from the 216-Z-1A/Z-18 area was 6.6 ppm from a well inside the 216-Z-1A Tile Field. At both locations, all of the maximum carbon tetrachloride sediment concentrations are associated with the interbedded sands and silts of the Hanford formation lower fine unit, laminated silts of the Plio-Pleistocene unit, and/or the top of the caliche. No sediment samples from the source zone area have been available for analysis following remediation.

The highest carbon tetrachloride concentrations in the in situ soil vapor samples collected during drilling were 17,000 to 21,000 ppmv from the Plio-Pleistocene unit in a well at the 216-Z-9 Trench and 10,000 ppmv from the same well at the capillary fringe; the highest in situ soil vapor sample measured from a 216-Z-1A/Z-18 well was 1,400 ppmv (Rohay 1997). Maximum carbon tetrachloride concentrations in soil vapor extracted using the SVE systems were approximately

30,000 ppmv from intervals above the Plio-Pleistocene unit at the 216-Z-9 Trench and 1,500 ppmv from intervals above the Plio-Pleistocene unit at the 216-Z-1A/Z-18 site.

Soil that is saturated with liquid carbon tetrachloride will have an associated equilibrium soil vapor concentration of 120,000 ppmv at 20 °C (Rohay and Johnson 1991). As a rule-of-thumb, for soils saturated with an organic contaminant, standard SVE will produce a gas stream containing one-tenth to one-half the equilibrium soil vapor concentration (Johnson 1993a). Therefore, vapor extraction concentrations greater than 12,000 ppmv of carbon tetrachloride may indicate that the soil near the extraction well is saturated with a nonaqueous-phase liquid. Initial soil vapor concentrations extracted from the 216-Z-9 site were approximately 30,000 ppmv, suggesting that a carbon tetrachloride DNAPL was present above the Plio-Pleistocene layer prior to remediation. The high in situ soil vapor concentrations of 17,000 to 21,000 ppmv observed prior to remediation during drilling also suggest the presence of DNAPL at the 216-Z-9 site.

The high vapor concentration (>10,000 ppmv) observed in the in situ soil vapor sample collected at the capillary fringe at the 216-Z-9 site suggests that DNAPL reached the aquifer. Whether a DNAPL penetrates the capillary fringe and enters the aquifer is dependent on contaminant density, interfacial relationships, grain sizes, soil packing, and degree of cementation. The DNAPL will accumulate at the capillary fringe until it develops sufficient head that it can break through (overcome entry pressure) into the aquifer as fingers of preferential flow.

The high carbon tetrachloride concentrations measured during baseline monitoring from 1991 through 1993 prior to remediation may also suggest the presence of DNAPL. As a rule-of-thumb, "full-scale OVA readings of 1,000 to 2,000 ppmv are probably a reasonable indication of the presence of DNAPL" (Pankow and Cherry 1996, p. 416). Fancher (1994) recorded maximum OVA measurements of approximately 1,000 ppmv at the Z-1A/12 site and exceeding 2,000 ppmv at the Z-9 site, above the lower permeability Plio-Pleistocene layer, and maximum OVA measurements of approximately 1,000 ppmv at the Z-1A/12 and Z-9 sites below the Plio-Pleistocene layer.

The locations of the maximum carbon tetrachloride rebound in the vadose zone following SVE operations were the same in 1997 and 1998. The persistence of these rebound locations may indicate the locations of DNAPL and/or residual carbon tetrachloride. The 1997 rebound study and 1998 monitoring indicated that at most locations within the influence of the SVE systems, much of the readily available carbon tetrachloride has been removed. The lower permeability Plio-Pleistocene layer, however, appears to be a continuing source of carbon tetrachloride soil vapor (Rohay 1997, Section 6.0 of this report). The SVE system is able to draw air through the higher permeability sands and gravels but not effectively through the lower permeability silts and carbonate-cemented sandy gravel of the Hanford lower fine and Plio-Pleistocene units.

Nonaqueous-phase liquid carbon tetrachloride has not been observed in the vadose zone.

The spacing and various open intervals of the current SVE extraction and monitoring wells do not provide full coverage of the contaminated vadose zone in the disposal site area. Thus, some readily available carbon tetrachloride contaminant in relatively permeable sediments may still

remain in the vadose zone soils that are not currently impacted by the SVE system operations (Cameron 1997, Rohay 1997).

The limited number of monitoring locations, especially below the Plio-Pleistocene layer, and difficulty in predicting contaminant migration pathways from the surface disposal sites contribute to the uncertainty in describing the overall contaminant distribution in the vadose zone.

In the farfield, carbon tetrachloride vapor has been detected in wells under construction throughout much of the 200 West Area since 1987 (Rohay and Johnson 1991). Most of the reported detections have been from below the Plio-Pleistocene layer, often in the capillary fringe just above the water table. The distribution of wells with detections below the Plio-Pleistocene layer matches fairly well with the distribution of carbon tetrachloride dissolved in the groundwater, suggesting that the source of the vapor may be volatilization from groundwater. However, some wells, notably those approximately 300 m west of the 216-Z-18/Z-12 disposal sites, also had detections above the Plio-Pleistocene layer, suggesting that carbon tetrachloride may have migrated laterally from the disposal sites. (These detections of carbon tetrachloride occurred prior to vadose zone remediation using SVE.)

Plutonium and americium co-contaminants are distributed within the upper 30 m of the vadose zone (20-30 m below crib bottom), based on characterization of the 216-Z-1A Tile Field in 1976 (Price et al. 1977). The transuranic (TRU) contamination at the carbon tetrachloride sites may have been carried downward through a combination of acidic waste liquids and organic-complexant mixtures (Price et al. 1979, Johnson and Hodges 1997).

D.3.4 Distribution Within Groundwater

The plume of dissolved carbon tetrachloride extends over 11 km^2 in the unconfined aquifer underlying the 200 West Area (Hartman 1999) (Figure D-2). The zone of highest concentrations (4,000 to 8,000 µg/L) still includes the 216-Z-9 Trench, suggesting that the carbon tetrachloride discharged may be providing a continuous source of contamination to the groundwater. Based on dissolved phase concentrations in the upper 10 m of the unconfined aquifer in 1990, prior to remediation, nearly 60% of the groundwater mass of carbon tetrachloride was contained within about 10% of the area of the plume (Rohay and Johnson 1991) (Table D-5a).

Although the centroid of the plume has not migrated significantly under natural driving forces, the perimeter of the plume appears to be migrating laterally to the south and north (Hartman 1999). Dissolved concentrations measured in well 699-39-79 at the western perimeter of the plume increased by an order of magnitude between March 1987 and August 1988, suggesting the arrival of the plume at that time (Dresel et al. 1993). (Concentrations at well 699-39-79 have recently been impacted by injection of treated water at the nearby pump-and-treat injection wells, Figure D-2.)

The shape of the groundwater plume for the high-concentration area (>4,000 µg/L) lends itself to at least three explanations (Figure D-3). First, the location of the high-concentration area northwest of the 216-Z-9 disposal site implies that the groundwater mound created at the U Pond

produced a hydraulic flow field that moved contamination this direction. Recreating the development of the mound and disposal and migration of carbon tetrachloride contamination using a numerical computer model or other analytical tools would help determine if this type of movement is reasonable.

It should be noted that the groundwater plume map for 1996, prior to substantial remediation efforts, may not truly represent the baseline plume shape at that time because of the lack of monitoring locations northwest of 216-Z-9 between wells 299-W15-32 and 299-W25-31A. The centroid of the plume may in fact be located closer to 216-Z-9, easterly or southeasterly, beneath the Z Plant surface facilities. If this hypothesis is true, then the highest groundwater concentrations would be expected at this location. This explanation is supported by the increasing and high concentrations measured at wells 299-W15-31A (from 3,260 μg/L in 1996 to 6,500 μg/L in 1999) and 299-W15-1 (1,180 μg/L to about 6,350 μg/L in 1999). Both of these wells are in the induced flow path under Z Plant to extraction wells 299-W15-33 and 299-W15-34 (Figure D-3).

A second possible explanation for the current shape of the groundwater plume is that the movement of contamination was influenced to the northwest by relatively continuous lower permeability sediment units. The Plio-Pleistocene unit would be a prime candidate for this explanation. However, based on current geologic information, this unit dips to the south in the area of the disposal sites.

A third possible explanation for the distribution pattern of the groundwater plume is that one or more additional, as yet undocumented, source of carbon tetrachloride may have contributed to the groundwater contamination. The zone of highest concentrations includes the 216-Z-9 Trench, which is a known source, but it also includes the area northwest of Z Plant (Plutonium Finishing Plant [PFP]), where no sources are documented. Possible sources of this carbon tetrachloride contamination northwest of Z Plant include carbon tetrachloride discharges to the 216-Z-12 Crib that were higher than originally estimated (Kasper 1982) and that contributed directly to groundwater, saturated flow conditions under the 216-Z-12 Crib (which was not a specific retention crib), leaking of carbon tetrachloride-contaminated liquids from the 216-Z-12 head end pipe, and/or other undocumented sources of carbon tetrachloride from soil column disposal within or near PFP.

The 216-Z-7 Crib east of the 231-Z Building (Figure 2-1) may be a potential source of carbon tetrachloride contamination. Continuous measurements of carbon tetrachloride concentrations in air for 87 days in 1995 at a monitoring station north of the 216-Z-9 site indicated that the 216-Z-7 Crib was a source of the carbon tetrachloride (Shaw et al. 1996). At this monitoring station, an air sample was drawn alternately from each of two heights (0.88 and 2.65 m) every 10 minutes and analyzed for carbon tetrachloride concentrations as part of a determination of carbon tetrachloride flux to the atmosphere. The concentrations were compared to wind directions at the time of sampling to identify locations of carbon tetrachloride sources.

The source of the secondary maximum in groundwater near the T-TX-TY Tank Farms and T Plant is unknown (Figure D-2). One hypothesis is that it migrated from the 216-Z-9 area, i.e., it was hydraulically driven north because of mounding at U Pond. There may have been another

source of carbon tetrachloride near T Plant. Carbon tetrachloride discharges to the 216-T-19 Crib may have contributed to this portion of the groundwater plume. A computer modeling effort would help evaluate the reasonableness of these hypotheses.

The source of the low-concentration lobe of the carbon tetrachloride plume southwest of the former U Pond is also uncertain (Figure D-2). If the source of this contamination was from early years of carbon tetrachloride disposal, when the groundwater flow was to the south, and if concentrations were much higher then, the low concentrations might reflect displacement and dilution by the huge volume of U Pond discharges. However, if concentrations were not much higher originally, the U Pond discharges presumably should have displaced this hypothetical early plume. Contamination in this part of the aquifer may be a result of vapor transport from the source cribs or vapor cycling (carbon tetrachloride volatilizing from contaminated groundwater, diffusing through the vadose zone, and then contaminating clean groundwater).

Carbon tetrachloride has been detected at or less than 1% of its theoretical solubility limit in water (800,000 µg/L). Chlorinated hydrocarbon solvents are commonly observed to be at concentration levels in groundwater well below their aqueous solubility limits, even when the aquifer is believed to contain separate phase liquid (Anderson et al. 1992). Possible explanations proposed by Anderson et al. (1992) include the preferential formation of thin flat pools rather than vertical fingers of DNAPL, which would reduce the cross-sectional contact area between the oncoming groundwater and the DNAPL; dilution of small aqueous plumes by dispersion downgradient from the source; and dilution of thin and/or narrow aqueous plumes by uncontaminated water in monitoring wells screened over lengths of several meters, large relative to the dimensions of the plume. In addition, the wells monitor the top of the aquifer and may not sample carbon tetrachloride present at depth. In the 200 West Area, the wells are sampling an increasingly smaller portion of the top of the unconfined aquifer as the water table elevation declines.

As a rule-of-thumb, "dissolved concentrations that exceed 1% of the effective solubility should probably be cause for serious consideration of the presence of a DNAPL phase" (Pankow and Cherry 1996). Dissolved concentration of approximately 8,000 µg/L have been observed at an extraction well (299-W15-32) adjacent to the 216-Z-9 Trench. Numerical modeling of vadose zone flow and transport at the 216-Z-9 site indicates that liquid carbon tetrachloride reached the aquifer at that location (Piepho 1996). The continuing presence of relatively high, dissolved concentrations in groundwater in the immediate vicinity of the 216-Z-9 Trench also suggests that a DNAPL is slowly dissolving within the aquifer or continuing to migrate from the vadose zone. If, as the numerical modeling suggests, carbon tetrachloride reached the aquifer in the first 7 years of discharge and ponded at the capillary fringe present in 1962, the carbon tetrachloride may have been trapped and dissolving while it was buried for 25 years within the saturated zone as a result of the elevated water table from 1965 to 1987.

The rebound of carbon tetrachloride concentrations in groundwater following pump-and-treat operations might indicate the presence of DNAPL. However, concentrations at the extraction wells are still increasing and the plume is spreading; rebound testing has not been conducted.

The movement of the 4,000-µg/L contour from southwest of PFP to PFP in 2 years of pump-and-treat operations indicates that DNAPL is not present in the aquifer southwest of PFP (Figure D-4). This change can be explained by the changes in the hydraulic flow field produced by the groundwater extraction and injection wells (DOE-RL 1999b).

The mass of carbon tetrachloride dissolved in the aqueous wastewater discharges to the soil column was 10,500 kg (13.2×10^6 L x 800,000 µg/L at solubility limit x 1 kg/10^9 µg = 10,520 kg) (Rohay and Johnson 1991). This value is the same order of magnitude as the inventory calculated for the upper 10 m of the aquifer (5,250 to 15, 740 kg) (Table D-5a). Thus, solely aqueous-phase carbon tetrachloride could be the primary source of groundwater contamination; a DNAPL source would not be required to produce the groundwater inventory in the upper 10 m, assuming no sorption of carbon tetrachloride to aquifer solids. (This calculation assumes that the total volume of liquid discharged to each site was all aqueous phase containing carbon tetrachloride at its solubility limit. These quantities of carbon tetrachloride – Z-9 = 3,300 kg; Z-1A = 4,200 kg; Z-18 = 3,100 kg -- represent approximately 2% of the carbon tetrachloride discharged to these sites.)

DNAPL has never been observed directly in groundwater. The probability of actually intersecting DNAPL is very low given the behavior of DNAPL in the subsurface, the tendency of residual DNAPL to remain in the sediment pore spaces, and the small number of groundwater wells in the disposal area. There is a much higher likelihood of finding DNAPL in the vadose zone, given the higher well density. However, DNAPL has not been directly observed in the vadose zone, either.

Numerical modeling of vadose zone flow and transport indicates that at lower residual saturation values, dissolved and nonaqueous-phase liquid carbon tetrachloride can penetrate deeply into the flowing groundwater but will likely not reach the bottom of the unconfined aquifer (Piepho 1996). The depth of penetration depends on the level of residual saturation assumed in the vadose zone and the groundwater flow rate.

Dissolved carbon tetrachloride has been observed deep within the unconfined aquifer (between 10 m below the water table and the base of the unconfined aquifer) at the 216-Z-9 site (wells 299-W15-6 and 299-W15-5) (Rohay and Johnson 1991, Auten and Reynolds 1997); west and north of PFP (wells 299-W15-17, 299-W15-7, 299-W15-10, and 699-39-79) (Hartman 1999; BHI 1997, 1998); near U Plant (well 299-W19-34) (Ford 1995); and near T Plant (well 299-W11-32) (Newcomer et al. 1995). Dissolved carbon tetrachloride has also been observed within the confined aquifer system (i.e., in the gravels below base of unconfined aquifer) at wells south of the 216-Z-9 site (well 299-W15-5; well probably served as preferential pathway) (Auten and Reynolds 1997), east of the Z-9 site (well 299-W14-9) (DOE-RL 1999b), and near the T-TY-TX tank farms (wells 299-W10-24 and 299-W14-14) (Hartman 1999).

The observed distribution of dissolved carbon tetrachloride in the high-concentration portion of the groundwater plume is inconsistent with a vapor phase source. A vapor phase source should result in a shallow (1-2 m thick) vertical distribution in the aquifer due to the relatively slow process of molecular diffusion, the process by which the carbon tetrachloride vapor enters the

groundwater (Pinder and Abriola 1986). However, carbon tetrachloride contamination is found at depths greater than 30 m below the water table.

The groundwater pump-and-treat system is containing carbon tetrachloride within the 2,000-µg/L contour (DOE-RL 1999b). Since 1994, the system has removed 2,100 kg of carbon tetrachloride, which is 33 to 99% of the mass initially estimated to be contained within the 2,000-µg/L contour (Table D-5). The persistence of the carbon tetrachloride concentrations implies that the initial mass calculation was incorrect (for example, because of greater depth distribution), that the K_d is greater than assumed, and/or possibly the presence of a continuing source of carbon tetrachloride (residual or DNAPL).

Low (<10 pCi/L) plutonium-239/240 and americium-241 activities were detected in well 299-W15-8 adjacent to the 216-Z-9 Trench on two sampling dates (May 7, 1990 and November 13, 1991). The well went dry sometime after January 1992 and can no longer be sampled (Hartman 1999). The plutonium and americium contamination observed in groundwater at the 216-Z-9 site in 299-W15-8 may signify soil column breakthrough or a preferential pathway in the well. Followup sampling of groundwater extracted by the pump-and-treat system at 216-Z-9 did not detect mobile species indicative of TRU (Hartman 1999). "Extraction well 299-W15-32, located next to the 216-Z-9 Trench, has been sampled for plutonium isotopes for the last several years and for neptunium-237 and americium-241 in FY 1998, without detecting any plutonium, neptunium, or americium. However, because this well draws water from a considerable area, the samples may not be representative of contaminant activities directly under the trench" (Hartman 1999).

D.4 CARBON TETRACHLORIDE TRANSPORT

D.4.1 Vadose Zone/Atmosphere Interface

Atmospheric pressure fluctuations appear to constitute a significant release mechanism for carbon tetrachloride vapor out of the vadose zone both through the soil surface and through boreholes perforated or otherwise open to the vadose zone. The soil-surface flux of carbon tetrachloride measured at the ground surface in the vicinity of the 216-Z-9 site in 1992 and 1993 using the EMFLUX soil vapor technology ranged from 0 to 923 ng/m^2/min (0 to 485 kg/yr for a 1-km^2 area) (Rohay et al. 1994a). The average soil-surface flux for the area overlying the groundwater plume in 1990 was estimated to be 285 ng/m^2/min, or 1,800 kg/yr, assuming carbon tetrachloride partitions from groundwater according to Henry's Law, diffuses from groundwater to 1 m below ground surface, and then is barometrically swept out (WHC 1993). The 1994-1995 flux of carbon tetrachloride to the atmosphere from a 1-km^2 area that includes the carbon tetrachloride discharge sites was 1,200 kg/yr, based on site specific mass balance and tracer-ratio measurements (includes soil and wells) (Shaw et al. 1996).

It is estimated that, between 1955 and 1990, 18% of the total carbon tetrachloride inventory was lost to the atmosphere through natural soil flux at the ground surface (WHC 1993). The depth over which carbon tetrachloride is removed by barometric pumping was estimated in 1992 to be 1 m (WHC 1993). In 1992, barometric pressure fluctuations averaged 1.4% of the average

barometric pressure. Assuming that a 1.4% pressure increase results in a 1.4% volume decrease in the soil vapor, on an annually averaged basis barometric pumping would sweep out air in the pores of the top 1.4% of the vadose zone (1.4% of 64 m) half of the time.

The 2-m rise of the water table between 1965 and 1977 would have displaced contaminated soil vapor from the vadose zone to the atmosphere. This effect was not included in the 1990 estimates of vadose zone losses.

The wells "breathe" in response to atmospheric pressure changes and other meteorological phenomena. The carbon tetrachloride released from wells in the vicinity of the cribs between 1955 and 1990 was estimated to be 22,200 kg, or 3% of the discharged inventory (WHC 1993). Thus, an estimated 21% of the total carbon tetrachloride inventory may have been lost to the atmosphere via the soil surface and borehole flux since soil column disposal was initiated (WHC 1993).

D.4.2 Vadose Zone

Once discharged to the crib, the liquid wastes infiltrated into the underlying soils and migrated predominantly downward. An average infiltration rate or recharge rate into the soil column can be estimated for each crib from the area of the crib bottom and average annual discharges. These range from 1 to 10 L/m^2/day (Table D-6). Average infiltration rates from percolation tests in the 216-Z-20 and 216-Z-21 Crib areas have been reported as ranging from 1,900 to 2,850 L/m^2/day (Last and Rohay 1993). Thus, the field-measured infiltration rate of the soil column far exceeds the estimated recharge rate from the cribs. Assuming that the behavior of the liquid wastes discharged was similar to that of water used in the percolation tests, it is doubtful that the soil column ever became fully saturated or that the cribs exceeded the infiltration capacity, at least for any appreciable period of time. Crawley (1969), however, did report that a buildup of liquid waste was suspected in the head end of the 216-Z-1A Tile Field. This suggests that the infiltration capacity of the first one-third of the crib had been exceeded by the discharge volumes, perhaps as a result of plugging of the soil pores by fine particulates or other solids. It should also be noted that the 216-Z-1A Tile Field had received other liquid wastes from 1949 to 1959, so the soil column was already partially saturated.

As a first approximation, the likelihood that carbon tetrachloride in an aqueous or nonaqueous phase reached the groundwater can be estimated by comparing the total volume discharged to the column pore volume beneath each crib (i.e., bottom area of the crib multiplied by depth to water multiplied by porosity, assuming 30% porosity). Results of such calculations indicate that the 216-Z-1A and 216-Z-18 waste disposal facilities received only 12% and 29% of their estimated column pore volumes, respectively, while the 216-Z-9 Trench received 142% of its column pore volume (Table D-6). It must be noted that these are only rough estimates and that the wastes were discharged over periods of years rather than at one time. Additional drainage would also have occurred under unsaturated conditions, after discharges were terminated. If the porosity were smaller or if the entire column pore volume were not used (e.g., if the wastes migrated down preferential pathways such as unsealed wells or if the wastes did not spread out evenly over the crib floor), the values would be higher. Conversely, if the waste plume spread out laterally, increasing its column pore volume, these values would be smaller. In any case, the

216-Z-9 Trench is more likely to have had waste fluids containing carbon tetrachloride reach the groundwater strictly by downward percolation.

Numerical modeling of vadose zone flow and transport indicates that both dissolved and nonaqueous-phase liquid carbon tetrachloride migrated through the vadose zone and reached the unconfined aquifer below the 216-Z-9 Trench (Piepho 1996). In the simulations, the flux of carbon tetrachloride from the vadose zone into the aquifer primarily depends on the amount of carbon tetrachloride held in residual saturation in the vadose zone (Piepho 1996). However, for both values (0.01 and 0.001) of residual saturation used in the simulations, the numerical modeling results indicate that carbon tetrachloride continues to enter the aquifer for a long time (at least 38 years and likely for longer in the simulations) after the initial discharge to surface disposal sites (Piepho 1996). In addition to assuming potential values for residual saturation, several simplifications were applied and the physical properties of pure carbon tetrachloride were used rather than those of the carbon tetrachloride organic mixtures.

Numerical simulations of wastewater migration beneath the 216-Z-9 Trench suggest some horizontal spreading of the aqueous plume may have occurred at the Hanford coarse-grained unit/fine-grained unit boundary, but that little lateral spreading may have occurred below that (Last and Rohay 1993). Piepho (1996) indicates that greatest horizontal spreading of the aqueous phase in the vadose zone appears to be in the Plio-Pleistocene unit; in these numerical simulations, the ratio of the horizontal to vertical saturated hydraulic conductivity was 10. In these simulations, there is essentially no lateral spreading of the liquid carbon tetrachloride phase (Piepho 1996). Wright et al. (1994) inferred a near-vertical moisture plume beneath the carbon tetrachloride cribs, with some spreading occurring only on the Hanford formation lower fine/Plio-Pleistocene unit surfaces. Field measurements indicate that the lateral spread of radionuclides beyond the perimeter of the 216-Z-1A Tile Field was limited to a 9-m-wide zone (Price et al. 1979), suggesting that the spread of waste liquids was minimal or that the plutonium was filtered in that distance. In conclusion, the aqueous-phase carbon tetrachloride infiltrates predominantly downward from the near-surface discharge sites; any lateral spreading is primarily associated with coarse/fine layer contacts.

Because liquid carbon tetrachloride is relatively immiscible in water and the soil column is assumed to be water-wetted, the carbon tetrachloride would move under its own hydraulic gradient. Wright et al. (1994) concluded, based on their measurements, that the hydraulic conductivity of liquid carbon tetrachloride through the subsurface soil samples was much higher than that of water or of an aqueous carbon tetrachloride solution, and that the differences were greater in the finer grained sample.

As nonaqueous-phase liquid carbon tetrachloride moves down through the soil column, some of the liquid carbon tetrachloride will be held in the soil pores by capillary forces as residual liquid. Based on studies of carbon tetrachloride hydraulic conductivities in soil samples, Conca et al. (1992) concluded that the retention of liquid-phase carbon tetrachloride was about half that of water or an aqueous-phase carbon tetrachloride solution. Thus, if the field moisture content of the soil were 5% under a given unsaturated flow condition, it can be estimated to retain 2.5% carbon tetrachloride under the same conditions. It should be noted that these are strictly empirically derived estimates, based on two samples, and should be viewed with some caution

(Rohay et al. 1994). In addition to immobilization by capillary forces, some of the discharged carbon tetrachloride was retained in the vadose zone through mechanisms such as equilibrium (reversible) and nonequilibrium (nonreversible) sorption to soil and entrapment of DNAPL/dissolved liquids in dead-end pore spaces. Through all these mechanisms, residual saturation of contaminated aqueous-phase and nonaqueous-phase liquids will be left along the contaminant migration path.

A rough estimate of how far the organic nonaqueous-phase liquid may have traveled downward through the soil column as a continuous organic liquid phase (i.e., at saturations greater than the residual) can be calculated by assuming a single residual saturation of 2.5% for the entire pore column volume and by assuming that the organic was evenly distributed across the crib bottom area. Table D-7 lists the relative depth of nonaqueous-phase liquid migration for each facility. Note that the migration depth calculated for the 216-Z-9 Trench is over an order of magnitude greater than that of the other two cribs and is potentially below the water table. It also seems plausible that much of the organic nonaqueous-phase liquid may have been retained in the soil column because of the residual saturation. Numerical modeling of vadose zone flow and transport indicates that 66% to 90% of the carbon tetrachloride discharged to the 216-Z-9 site was retained in the vadose zone (Piepho 1996). It should be noted, however, that DNAPL characteristically moves nonuniformly downward through the vadose zone (Cohen et al. 1993), so this estimate is probably high. The distribution of plutonium and americium to 30-m depth beneath the 216-Z-1A Tile Field suggests that these estimates are minimum values.

Another potential indicator of the distribution of the organic phase is the distribution of the associated radionuclide co-contaminants. Transuranics (primarily plutonium-239 and americium-241) discharged to the disposal sites may have been carried in association with the organic-complexant liquid phase. The behavior of the transuranics in such a mixture as the DNAPL moves through the soil is unknown. Typically, when plutonium and americium are released as solutes, they are retained in the upper few meters of the soil column (Johnson 1993b). However at the 216-Z-1A Tile Field, these radionuclides were discharged as co-contaminants with the DNAPL-complexant mixture and are found at depths up to 30 m below the bottom of the tile field (Price et al. 1979). This behavior has been previously attributed to the destruction of the sorptive capacity of the soils by the acidic waste stream. However, the abundant amounts of calcium carbonate in the soil column could have easily neutralized the acid. For example, at a pH of 1 (0.1 M), which is more acidic than the discharged aqueous waste stream (pH of 2.5), the total volume of aqueous waste discharged to the 216-Z-1A Tile Field would have contained approximately 500 kmol of acid. Assuming a calcium carbonate content of 1%, the first meter of the soil column beneath this crib contains 588 kmol of calcium carbonate, which is more than enough calcium carbonate to neutralize this amount of acid (Johnson 1993b). Thus, it seems more probable that the greater depth distribution of transuranics in this crib is due to migration with the solvent-complexant phase. Beneath the 216-Z-1A Tile Field, increases in concentrations of plutonium and americium with depth are generally associated with an increase in the silt content of the sediments or with boundaries between sedimentary units. Because similar solvent-chemical conditions existed for disposal at the other carbon tetrachloride sites, similar depth distributions of significant transuranic concentrations could be encountered at these other sites.

Volatilization of carbon tetrachloride from aqueous- and nonaqueous-phase liquids within the disposal cribs and the vadose zone results in vapor phase carbon tetrachloride in soil pores. Contaminated vapor can move downward and laterally by molecular diffusion and by advective flow. Vapors can diffuse along a chemical gradient from high concentration to low in any direction (including upgradient with respect to the groundwater flow direction). The presence of a relatively low-permeability surface cover, such as a building foundation or soil horizon can also enhance the lateral extent of diffusion. The presence of locally saturated or near-saturated vadose zone sediments underlying other aqueous waste disposal sites can inhibit the lateral extent of diffusion.

Due to the high molecular weight of carbon tetrachloride compared to air, the density of saturated carbon tetrachloride vapor is greater than uncontaminated vapor in the vadose zone (Table D-8). This contrast in densities can result in density-driven advective flow, which would move carbon tetrachloride vapor downward and laterally from the disposal facilities. Numerical modeling studies show that in high permeability soils, density-induced advection can be a significant transport mechanism that equals or exceeds the effect of diffusion; large density gradients may cause downward advection with velocities on the order of meters per day (Pankow and Cherry 1996). The threshold soil permeability above which density-induced advection becomes important for the chlorinated solvents appears to be on the order of 10E-11 m^2 (equivalent to a hydraulic conductivity of 10E-2 cm/sec, which is typical for medium-coarse clean sand and gravel) (Pankow and Cherry 1996, Freeze and Cherry 1979). In experiments with TCE, which has a relative vapor density (1.35) similar to that of carbon tetrachloride (1.62), density-driven flow was found to be very important in a pea gravel but played only a minor role in a medium sand (Pankow and Cherry 1996). Pankow and Cherry (1996) note that the vapor source must be maintained at a high concentration in order to maintain high-density gradients and that the greater the thickness of the vadose zone, the greater the advective effects due to density gradients. Density-driven advective vapor flow may have contributed to the high vapor-phase carbon tetrachloride concentrations above the Plio-Pleistocene layer prior to remediation.

Within the vadose zone, carbon tetrachloride vapor may also flow in any direction along pressure gradients caused by barometric pressure fluctuations, which are damped and delayed as they propagate through the subsurface. The fluctuations are increasingly damped and delayed in the subsurface as the cumulative relative permeability of the overlying materials decreases. The pressure gradients may be vertical as a result of the pressure contrast between the subsurface and the surface or between soils above and below a lower permeability layer, or the pressure gradients may be horizontal between a location in the subsurface (e.g., open borehole) that communicates instantaneously with surface pressure changes and another location in the subsurface that communicates more slowly through the interconnected pore space in the vadose zone (Rohay 1996). Because most boreholes in the 200 West Area are (or for many years were) capped but unsealed at the surface, each borehole has the potential to draw carbon tetrachloride vapors horizontally from the source area toward its open interval. Because most boreholes have no annular seal or have an annular seal designed to prevent water migration, the potential for vapor communication and transport also exists along the outside of the casing.

As the contaminated vapor moves into uncontaminated areas in the vadose zone, it may partition into the soil moisture and adsorbed phases. The carbon tetrachloride vapor may also provide a

continuous source of contamination to groundwater. In the vadose zone, carbon tetrachloride vapors which equilibrate with perched water, with wastewater from other sources, and/or with infiltrating natural recharge water may then be transported to the water table in dissolved form. These aqueous transport mechanisms can also affect the soil moisture and adsorbed phases contaminated by vapor.

Carbon tetrachloride may volatilize from the dissolved groundwater plume. The contaminant vapors would then move upward by diffusion but may become temporarily trapped below the Plio-Pleistocene layer. The distribution of carbon tetrachloride vapor below the Plio-Pleistocene layer throughout much of the 200 West Area underlain by the groundwater plume suggests that these vapors may have volatilized from the dissolved groundwater plume throughout the 200 West Area.

Vapor transport, although still occurring, is expected to have been significantly reduced by removal of vapor since 1992 using SVE.

Older, poorly sealed wells, which penetrate either the Plio-Pleistocene unit and/or the water table, may provide a vertical conduit for fluids. Nonaqueous-phase liquid carbon tetrachloride, aqueous-phase dissolved carbon tetrachloride, and vapor phase carbon tetrachloride that intercept the borehole in the subsurface may migrate downward along the outside casing of the well. In addition, these fluids may be channeled along natural preferential pathways, such as fractures, clastic dikes, and large, interconnected pores, within the vadose zone.

Migration of fluids, both liquid and vapor, are influenced by the natural stratification and variability of the sediments. The Plio-Pleistocene paleosurface is a relatively continuous, lower permeability barrier to vertical movement of fluids in the vadose zone. This layer most likely diverted carbon tetrachloride liquid and/or vapor laterally away from primary carbon tetrachloride disposal sites until a sufficient amount accumulated to force the liquid or vapor through the lower permeability layer (Rohay and Johnson 1991). The surface of the Plio-Pleistocene unit generally slopes toward the south from the primary carbon tetrachloride disposal sites (Rohay et al. 1994a). For example, DNAPL may have migrated from 216-Z-1A to the south toward the 216-Z-18 site, where carbon tetrachloride was detected during drilling of monitoring wells 299-W18-9, W18-10, and W18-11 in 1968, before the crib was placed into service. The character of the Plio-Pleistocene layer varies across the 200 West Area and includes locally less-cemented, more permeable areas and fractures that allow more rapid fluid flow (Slate 1996).

Due to its low dielectric constant, carbon tetrachloride can theoretically increase the permeability of the subsurface materials and thereby strongly influence its own migration pathway. Solutions with high dielectric constants, such as water (Table D-8), will cause alumino-silicate clays to swell. A liquid with a low dielectric constant, such as carbon tetrachloride, causes clays to shrink and thereby increases the permeability of the soil through the introduction of cracks and fissures. Clay-sized particles that include alumino-silicate clay minerals occur throughout the vadose zone but are typically more abundant in the Plio-Pleistocene unit (Wright et al. 1994). Alumino-silicate clay minerals are also a component of the bentonite commonly used in annular seals for boreholes. However, permeation of water-wet clays (which describes nearly all

subsurface clays) by aqueous solutions containing nonaqueous-phase chlorinated solvents at concentrations at or below their solubility limits does not influence the permeability of clays because the low concentrations of these organic chemicals do not decrease the dielectric constant of the aqueous solution sufficiently (Pankow and Cherry 1996). Furthermore, nonaqueous-phase organic liquids apparently do not chemically increase the permeability of water-wet clay soils through changes to intracrystalline swelling because (1) the flow of the nonaqueous-phase liquid is restricted to pre-existing macro-pores or fractures in the clay, (2) the film of water separating the organic liquid and the clay surface prevents the organic liquid from contacting or entering the clay other than in dissolved form, and (3) the solubility of the nonaqueous-phase liquid is too low to significantly affect the dielectric constant of the water (Pankow and Cherry 1996). Based on the evaluation presented in Pankow and Cherry (1996), it appears that exposure to nonaqueous-phase liquids is unlikely to cause permeability increases in natural clay-rich soils. And if such chemically-induced increases did occur, the confining stresses due to the overburden would likely cause compaction of the clay-rich layer, preventing the increase in permeability (Pankow and Cherry 1996).

Carbon tetrachloride may become "irreversibly" adsorbed within intraparticle sediment pore spaces. Intraparticle porosity refers to the very small pores and associated surfaces within a particle of soil. Intraparticle pore sizes range from macropores (pores with diameters greater than 500 Å) to micropores (cylindrical or slit-shapes pores with diameters less than 20 Å) (Yonge et al. 1996). As summarized by Yonge et al. (1996), Farrell and Reinhard (1994) have demonstrated that adsorption in micropores contributes significantly to sorbate uptake and contributes to isotherm non-linearity on solids with low natural organic matter. They further note that hysteresis between adsorption and desorption may result from the fact that the nature of the micro-environment has been changed due to the initial adsorption. They state that the rate of desorption from soils with a high amount of intraparticle porosity is controlled by desorption from the intraparticle spaces and once external contaminant is removed, the internal contaminant may require months or even years to desorb completely. Because the approximate molecular diameter of carbon tetrachloride is 5 Å, it would have access to micropores (Yonge et al. 1996). The adsorption of carbon tetrachloride would be higher in the silty sands, which have a significantly higher amount of surface area than the sands (Ford 1996). The adsorption of carbon tetrachloride would also increase with time (Wilson et al. 1994).

Based on laboratory studies using carbon tetrachloride and site-specific soils, Yonge et al. (1996) estimated that SVE can remove only 10% to 15% of the initial mass of carbon tetrachloride (excluding any nonaqueous liquid phases) in contaminated zones through which flow is passing directly. Based on laboratory testing where carbon tetrachloride removal was dictated by diffusion from a zero velocity field to areas where flow was occurring, they describe four phases in the concentration-time profile: initial pore gas evacuation, free product removal, vapor diffusion from low velocity fields (transitional phase), and finally desorption-controlled removal (tailing phase). In field situations, which involve a complex heterogeneous subsurface, Yonge et al. (1996) expect that a relatively rapid concentration decrease followed by at least one slower rate of concentration decrease would be observed. They point out that when the rate of decrease reaches an asymptotic level and the contaminant collection yield reaches a perceived minimum, higher flows will probably not enhance removal. This is the region of removal controlled by desorption kinetics, and Yonge et al. conclude, based on their study, that even though a relatively

high-concentration gradient exists with regard to known adsorption characteristics, mass transfer is extremely slow (Yonge et al. 1996). Based on the carbon tetrachloride SVE and rebound data, Cameron (1997) believes that most of the vapor extraction site has passed through the first two phases and that some of the site is in the transitional phase and some is in the tailing phase.

D.4.3 Vadose Zone/Groundwater Interface

The capillary fringe forms the interface between the vadose and groundwater zones. Because the capillary fringe does not contain a connected gas phase, transport of contaminants through this zone must occur in the aqueous or DNAPL phase. The three main mechanisms for aqueous contaminant migration through the capillary fringe are diffusion and dispersion, advection, and fluctuations in the elevation of the water table (Pankow and Cherry 1996). These processes of aqueous-phase transport would produce a shallow groundwater plume (Pankow and Cherry 1996).

At the top of the capillary fringe, vapor-phase contaminants partition into the aqueous phase, and transport through the capillary fringe occurs by dispersion and diffusion along the aqueous-phase concentration gradient (Pankow and Cherry 1996). A vapor phase source should result in a shallow (1-2 m thick) vertical distribution in the aquifer due to the relatively slow process of molecular diffusion, the process by which the carbon tetrachloride vapor enters the groundwater (Pinder and Abriola 1986). Pankow and Cherry (1996) point out that because molecular diffusion and dispersion are weak processes, advective transport due to infiltrating water is likely to be a more significant mechanism for transporting contaminants downward through the capillary fringe. At the carbon tetrachloride disposal sites, an infiltrating water mechanism would have been more viable during operations when large volumes of water were artificially recharging the groundwater.

The elevation of the water table can change in response to barometric pressure fluctuations, regional water table decline, and pump-and-treat operations. Each of these may influence carbon tetrachloride migration. The water table below the carbon tetrachloride source cribs fluctuates daily in response to barometric pressure fluctuations. Over a 20-year period (1965-1985), the elevation of the water table rose and then declined 2 m; it is currently declining 0.45 m/yr. As the water table drops, contaminated vapors are drawn deeper into the expanded vadose zone and can partition into the newly exposed soil moisture. When the water table rises, the contaminated soil moisture will be incorporated into the groundwater system (Pankow and Cherry 1996). At the carbon tetrachloride site, the 2-m rise from 1965 to 1977 probably incorporated the carbon tetrachloride in that zone. The gradual but continual water table decline since 1977 would minimize additional contamination of the groundwater, but the daily fluctuations create a mixing zone that may continue to incorporate carbon tetrachloride. Temporary cessation of pump-and-treat operations at individual extraction wells would cause the water table to rise locally, incorporating carbon tetrachloride that migrated downward into the cone of depression. However, cessation of operations occurs infrequently and this mechanism may be insignificant with respect to degradation of groundwater quality.

Transport and partitioning of carbon tetrachloride vapor between the groundwater and vadose zone may contribute to the large "low concentration halo" surrounding the high-concentration core of the groundwater plume.

As a DNAPL moves into the tension-saturated portion of the capillary zone, it must displace water if continued downward migration is to occur. Since it is generally a nonwetting fluid with respect to water, there must be a sufficient buildup of capillary pressure to allow the organic liquid to overcome the entry pressure of the nearly water-saturated medium (Pankow and Cherry 1996). DNAPL may also spread laterally at the top of the capillary fringe. DNAPL that reached the 216-Z-9 capillary fringe prior to 1965 was probably incorporated into the groundwter by the rise of the water table between 1965 and 1977.

Potentially, a continued source of carbon tetrachloride to the groundwater in the area below the 216-Z-9 site exists because the centroid of the groundwater plume still includes the area underlying the disposal sites. The carbon tetrachloride source may be within the vadose zone and/or within the aquifer. Numerical modeling of vadose zone flow and transport indicates that both dissolved and nonaqueous-phase carbon tetrachloride reached the groundwater beneath the 216-Z-9 Crib and may have continued to enter the aquifer for many years. This potential vadose zone source has been mitigated by SVE operations that began in 1992.

D.4.4 Groundwater

Numerical modeling of carbon tetrachloride flow and transport in the vadose zone indicates that the depth of penetration of carbon tetrachloride (dissolved and nonaqueous phases) into the aquifer depends on the residual saturation in the vadose zone, which affects the flux to the aquifer, and the groundwater flow rate, which affects the lateral to vertical flux within the aquifer (Piepho 1996). For the higher value of residual saturation (0.01) used in the modeling, dissolved carbon tetrachloride reached approximately 20 m below the water table and nonaqueous-phase carbon tetrachloride reached approximately 10 m below the water table. For the lower value of residual saturation (0.0001) used in the modeling, dissolved carbon tetrachloride reached approximately 50 m below the water table and nonaqueous-phase carbon tetrachloride reached approximately 25 m below the water table. [Note: The nonaqueous phase case for a residual saturation of 0.0001 was not shown in Piepho (1996); the 25-m depth was estimated by analogy to higher residual saturation case.]

Preliminary sitewide numerical modeling of carbon tetrachloride transport in the aquifer indicates that under nonretarded flow conditions contamination in excess of 5 μg/L will move significantly past the 200 East Area perimeter in 200 years with or without the current remediation activities (i.e., the pump-and-treat interim remedial measure does not affect the overall size and extent of the diffuse plume) (Chiaramonte et al. 1997). However, if a small retardation factor is included in the analysis, the movement of carbon tetrachloride will be significantly slowed, just reaching the eastern border of 200 East Area in 200 years. The extent of contamination is very sensitive to the carbon tetrachloride partitioning coefficient between the aquifer sediments and groundwater. However, values for the partitioning coefficient are not well defined. Other important factors that this modeling effort did not take into account were

biodegradation and volatilization of carbon tetrachloride during transport. These factors may reduce the extent of contamination over any comparable period of time.

Partitioning of carbon tetrachloride to aquifer sediments is assumed to be low (or zero) and may be variable across the site. Site-specific measurements of the partitioning coefficient (K_d) magnitude and spatial distribution have not been published. However, a distribution coefficient (K_d) of 0.0 to 0.2 mL/g was suggested as likely for carbon tetrachloride aqueous solutions on Hanford soil based on batch K_d experiments (Last and Rohay 1993). A literature estimate for soil distribution of carbon tetrachloride is 0.114 mL/g (Chiaramonte et al. 1997). To calculate the inventory of carbon tetrachloride sorbed to vadose zone soils in 1990, a K_d value of 0.192 mL/g was estimated using the method of Thibodeaux et al. (1990) (WHC 1993). This K_d value falls within the range discussed for partitioning of carbon tetrachloride to aquifer sediments.

Pump-and-treat extraction and injection operations may be spreading or smearing a DNAPL aquifer source, if present. Pump-and-treat extraction and injection operations have affected the distribution and concentrations of carbon tetrachloride in the centroid portion of the plume. The >4,000-µg/L contour interval has expanded in size and now extends more northerly and easterly to near the extraction wells, although it may be slightly reduced in the southwest (Figure D-4). Injection of treated groundwater at the upgradient location is beginning to dilute the carbon tetrachloride plume in this area. The increase in size of the 4,000-µg/L contour and the concomitant steady or increasing concentrations in the interior wells may imply more than just aqueous-phase movement (dissolved carbon tetrachloride) toward the extraction wells, e.g., the presence of DNAPL, residual carbon tetrachloride, or a higher partitioning coefficient than previously estimated. Approximately 2,100 kg of carbon tetrachloride have already been removed with no apparent reduction in concentrations in the high-concentration area. Therefore, the mass of carbon tetrachloride within the treatment area may be greater or distributed differently than what was assumed prior to pump-and-treat remediation.

D.5 ORGANIC CO-CONTAMINANTS

The ratio of chloroform (a carbon tetrachloride biodegradation breakdown product) to carbon tetrachloride concentrations in vapor extracted using the SVE system is linear (Figure 5-26). For carbon tetrachloride concentrations greater than 1,000 ppmv, chloroform concentrations are approximately 0.005 that of carbon tetrachloride concentrations.

The 1989 Essential Material Specification for carbon tetrachloride states that the carbon tetrachloride must be 99% pure. Based on the process used to manufacture carbon tetrachloride, it is believed that the carbon tetrachloride used earlier in Z Plant operations was also relatively pure. The other 1% would typically be long chain alcohols used by industry as additives to prevent light degradation of the product.

The transport and inventory partitioning estimates presented in this discussion have been made using pure liquid-phase carbon tetrachloride properties. However, the carbon tetrachloride was not discharged as a pure liquid but as a mixture with other organics (TBP, DBBP, and lard oil).

The liquid properties (density, viscosity, interfacial tension, and vapor pressure) of three representative mixtures, 85:15 carbon tetrachloride:TBP, 50:50 carbon tetrachloride:DBBP, and 50:50 carbon tetrachloride:lard oil, are presented in Table D-8. The organic composites (even the carbon tetrachloride:lard oil mixture) were found to be denser and more viscous than water (Last and Rohay 1993). Vapor pressure of the carbon tetrachloride:DBBP and carbon tetrachloride:lard oil mixtures is only half that of the pure carbon tetrachloride and the carbon tetrachloride:TBP mixture. The interfacial tension between the 50:50 carbon tetrachloride:lard oil mixture and a 5 M sodium nitrate solution was found to be low, suggesting that the fluids may be somewhat miscible, allowing them to mix and behave more as an aqueous fluid (Last and Rohay 1993).

An 85:15 carbon tetrachloride:TBP ratio was used to make up the organic solution used in the plutonium recovery process. However, with exposure to ionizing radiation and nitric acid, the TBP within the solvent would gradually degrade to DBP. DBP has a much greater affinity for plutonium than TBP and would not work in the process because of its poor stripping properties. It was the degraded solvent that was discharged to the soil column.

The major organic co-contaminants TBP, DBP, and DBBP associated with the carbon tetrachloride solvent waste streams were not analyzed in groundwater samples collected during the 1991 characterization activities. However, existing data for TBP and DBP acquired for other programs between 1987 and 1990 are available. Results for samples from several wells in the vicinity of the Z cribs, as well as from wells within the core of the 200 West Area carbon tetrachloride plume, were all below detection limits for TBP and DBP. DBBP has not been previously analyzed. The apparent absence of TBP and DBP in 200 West Area groundwater is attributed to biodegradation of these organic constituents and/or because they have a moderate affinity for sediments (Ames and Serne 1991, Rohay and Johnson 1991). Soil and groundwater samples collected during drilling in 1992 were analyzed for TBP. TBP was detected in only one sample from the vadose zone (well 299-W15-217, 24.6-m depth), and the result was below the limit of quantitation (Rohay et al. 1994a). Analyses for DBP and DBBP were not conducted. The lack of TBP in vadose soils suggests that TBP degrades relatively quickly. The lack of TBP detected in groundwater suggests that carbon tetrachloride might have been a relatively pure phase when it reached groundwater. However, the differential partitioning and biodegradation of the components of these organic mixtures in Hanford Site sediments has not been determined.

Vadose zone sampling of soil and soil vapor in the source area has also detected methylene chloride, chloroform, TCE, tetrachloroethylene (PCE), trans-1,2-DCE, 1,1-DCA, 1,2-DCA, cis-1,2-DCE, 1,1,1-TCA, benzenes, xylenes, and toluene (Rohay et al. 1994a).

Groundwater sampling within and beyond the source area has also detected chloroform, methylene chloride, TCE, and PCE (Rohay et al. 1994a, DOE-RL 1999b).

Tetrachloroethylene (PCE) and tetrabromoethane were used at different times in combination with carbon tetrachloride as a diluent for TBP or for cleaning agents (Smith 1973, with respect to the wastes discharged to 216-Z-9).

Nitrate in the aqueous wastes discharged to the carbon tetrachloride source cribs has also produced an extensive groundwater plume (Figure D-5). Because nitrate and carbon tetrachloride were co-contaminants in the aqueous phase-discharges, comparison of the distribution of the two groundwater plumes may help in understanding the major factors affecting plume movement. For example, although the K_d for carbon tetrachloride is not well known, the K_d for nitrate is known to be zero (i.e., nitrate is not retarded in groundwater). The maximum extent of the carbon tetrachloride (defined by the 5-µg/L contour) and nitrate (defined by the 20-mg/L contour) plumes is similar to the north and northeast of the Z Plant area, suggesting that carbon tetrachloride has behaved as a nonretarded contaminant in groundwater (Figures D-3 and D-5). However, the carbon tetrachloride plume extends farther to the west (upgradient) than the nitrate plume, suggesting that the groundwater contamination in this area was controlled by a mechanism other than the hydraulic flow field. The absence of nitrate and presence of carbon tetrachloride to the southwest of the former U Pond site suggests that the carbon tetrachloride lobe is not a result of southerly flow during the initial period of discharge.

D.6 DATA GAPS

The nature and extent of the carbon tetrachloride plume have been partially defined, but several key data gaps currently exist. The data gaps are identified in this report to help describe some uncertainties in the existing database being used to formulate the conceptual model.

1. The lateral extent of the carbon tetrachloride plume in the vadose zone and vertical extent of the carbon tetrachloride plume in the groundwater need to be better defined. These data would help define the extent of the contamination and therefore the expected magnitude of the remediation efforts.

2. Data are needed to determine the extent of the nonequilibrium sorption in the vadose zone and groundwater. This information would help account for the inventory and help define remediation needs.

3. The partitioning coefficient (Kd) for carbon tetrachloride on site sediments and its variation across the site needs to be quantified. This information would help refine the predictions of carbon tetrachloride transport rates using numerical models.

4. The location, amount, and properties of DNAPL carbon tetrachloride within the subsurface need to be quantified. This information would help focus and define the remediation needs.

5. The residual saturation of carbon tetrachloride (i.e., the carbon tetrachloride held in vadose zone sediments that is no longer mobile except through partitioning to pore water that is still migrating) needs to be quantified. This information would help account for inventory between the vadose and groundwater zones, help refine the estimates of flux from the vadose zone to the groundwater, and help refine the numerical modeling estimates of the depth of carbon tetrachloride in the aquifer. Because SVE operations have modified the distribution of subsurface carbon tetrachloride and possibly soil

moisture beneath the disposal sites, part of this task would be identification of suitable locations for data collection and measurements.

6. The inventory mass balance should be reevaluated based on more recent studies and data from current remedial actions in the groundwater and the vadose zone. This information would help define the source term.

7. The hydraulic flow fields during and after the carbon tetrachloride disposal should be reevaluated to determine if the distribution of the relatively high concentrations of carbon tetrachloride to the northwest, the low concentration lobes of carbon tetrachloride to the south, and the concentrations of carbon tetrachloride near T Plant are reasonable based on the hydraulics alone. Results of this evaluation potentially may identify other contributing carbon tetrachloride disposal areas.

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Figure D-1. Schematic Illustration of Carbon Tetrachloride and Wastewater Migration Beneath the 216-Z-9 Trench in the Higher Concentration Portion of the Plume.

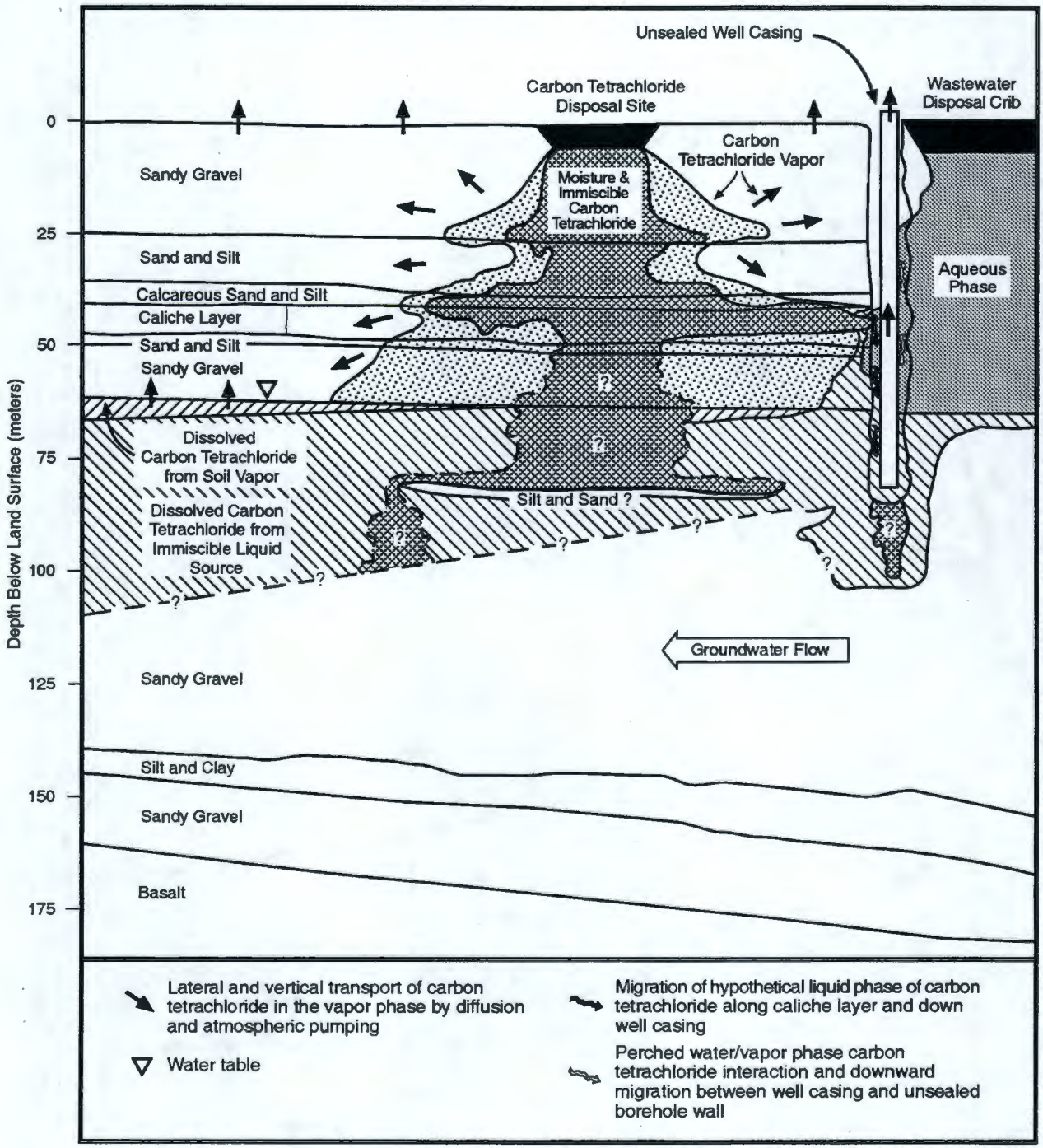

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Figure D-2. Average Carbon Tetrachloride Concentrations in the 200 West Area, Top of Unconfined Aquifer (from Hartman 1999).

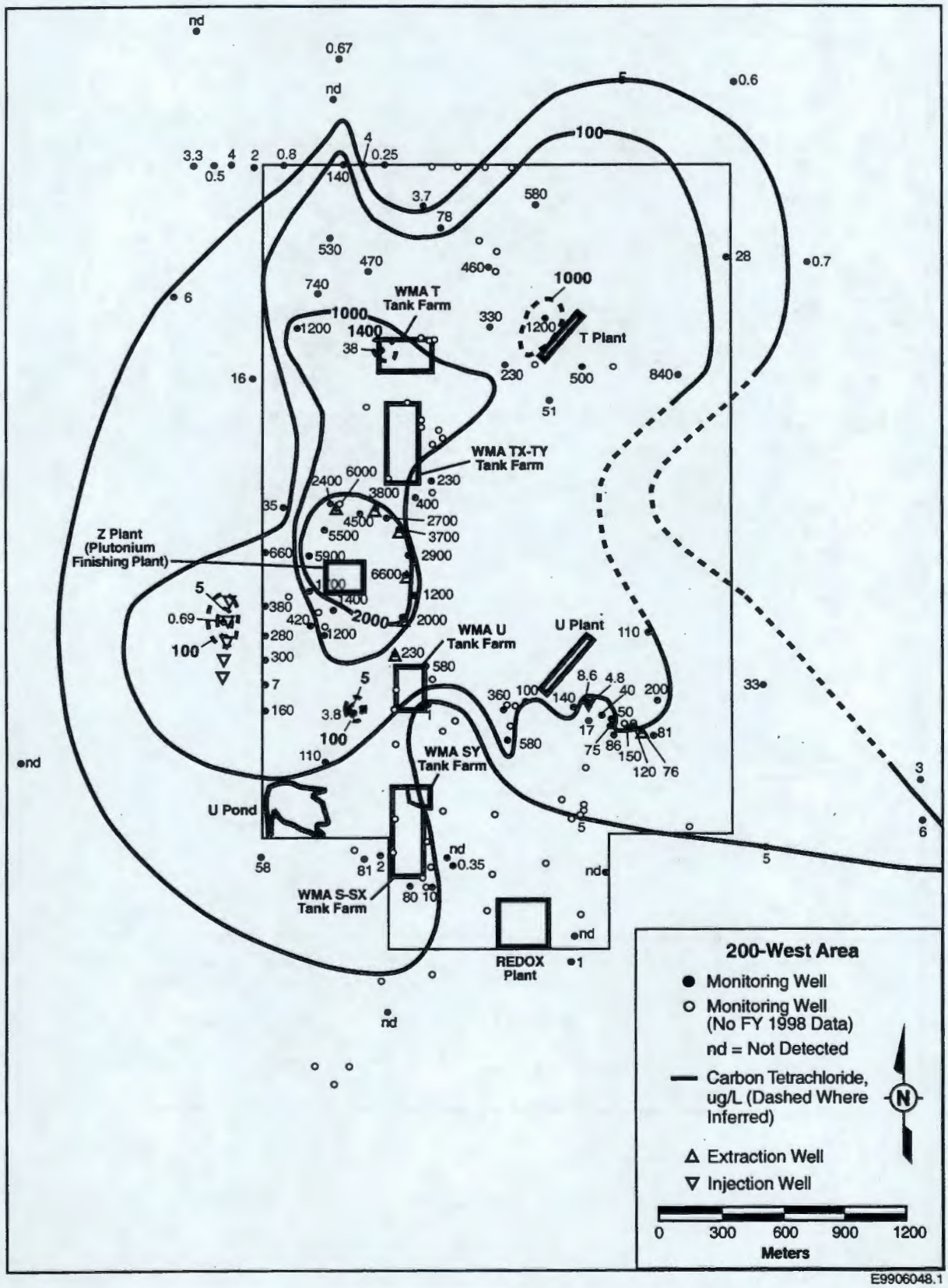

Figure D-3. Carbon Tetrachloride Concentrations in Pump-and-Treat Remediation Area, June 1996 and September 1998 (DOE-RL 1999b).

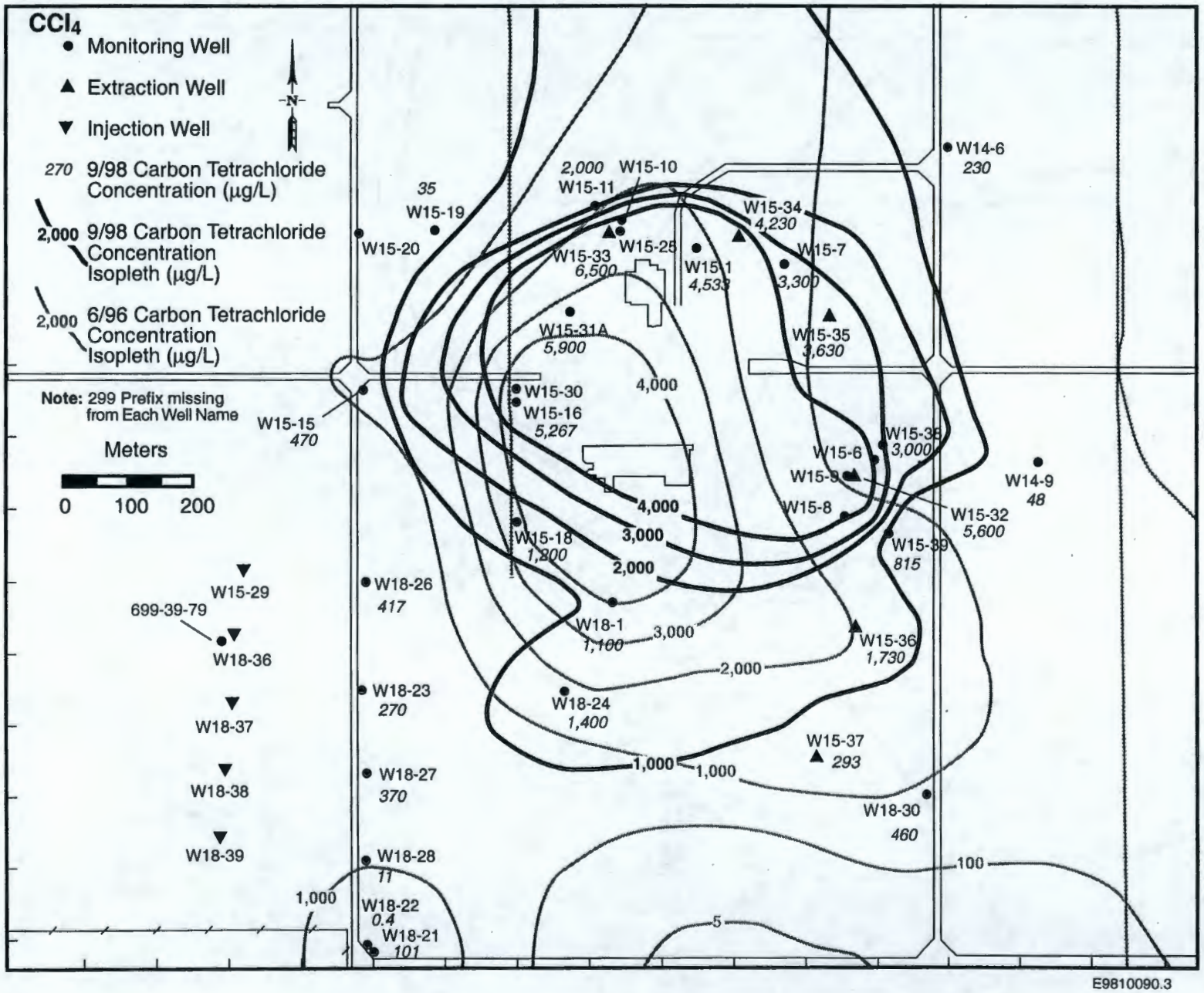

Figure D-4. Average Nitrate Concentrations in the 200 West Area (from Hartman 1999).

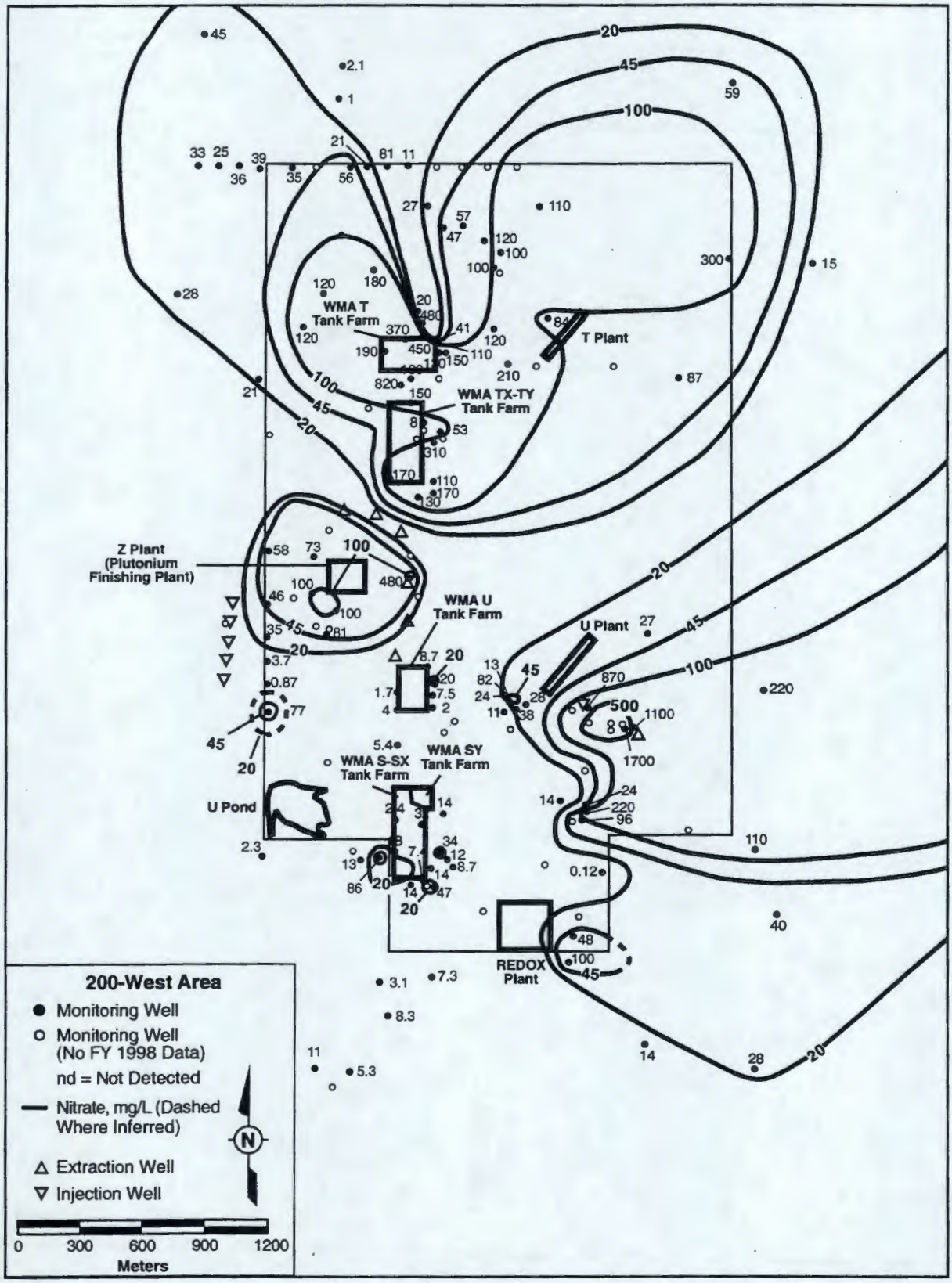

Table D-1. Waste Constituent Inventory Summary for the Three Primary Carbon Tetrachloride Disposal Facilities (from Rohay et al. 1994a).

Facility	Operating Dates	Total Volume (L)	Plutonium (kg)	Americium (kg)	Carbon Tetrachloride (kg)	Carbon Tetrachloride (L)	TBP (L)	DBBP (L)	Lard Oil (L)
216-Z-9	1955 to 1962[a]	4.09E+06	106[c]	2.5	130,000 – 480,000	83,000 – 300,000	27,900	46,500	9,300
216-Z-1A	1949 to 1959[b]	1.00E+06	0.05	ND	ND	ND	ND	ND	ND
	1964 to 1969	5.20E+06	57	1	270,000	170,000	23,900	27,500	11,000
216-Z-18	1969 to 1973	3.86E+06	23	0.4[d]	170,000	110,000	16,400	19,100	ND
Total	1955 to 1973	1.42E+07	186[c]	3.9	570,000 – 920,000	363,000 – 580,000	68,200	93,100	20,300

ND = no available data
TBP = tributyl phosphate
DBBP = dibutyl butyl phosphonate
[a]The Recuplex operation that used carbon tetrachloride was discontinued after a criticality incident in April 1962 and was replaced in 1964 by the Plutonium Reclamation Facility (DOE-RL 1991).
[b]From 1949 to 1959, the 216-Z-1A Tile Field received slightly basic, aqueous waste via overflow from associated 216-Z-1, -2, and –3 cribs prior to disposal of carbon tetrachloride waste (Price et al. 1979). From 1964 to 1969, carbon tetrachloride wastes were discharged directly to 216-Z-1A.
[c]58 kg were later removed (Ludowise 1978).
[d]Based on ratio of 1 kg americium to 57 kg plutonium for 216-Z-1A.

Table D-2. General Characteristics of the Vadose Zone Underlying the Carbon Tetrachloride Disposal Sites.

Geologic Unit	Geologic Material	Depth (m below ground surface)	Thickness (m)	Intrinsic Permeability (m^2)[a]	Field Moisture Content[b] (vol%)	Air Conductivity[a] (m/day)	Equivalent Hydraulic Conductivity[a] (m/day)
Hanford upper fine (H_{uf})	Gravelly sand and sand	0 – 6	6	1.6 E-11	5.5	1	9.0
Hanford upper coarse (H_{uc})	Gravel	6 – 16	10	4.1 E-10	4.6 – 5.7	25	231.4
Hanford fine (H_f)	Sand	16 – 31	15	1.6 E-11	1.5 – 19.7	1	9.0
Hanford lower coarse (H_{lc})[c]	Sandy gravel	31 – 34	3	3.3 E-10	5.1 – 5.3	20	186.3
Hanford lower fine (H_{lf})[c]	Interbedded silt and fine sand	34 – 38	4	1.6 E-12	6.1 – 11.8	0.1	0.9
Plio-Pleistocene (P-P)	Fine sandy silt/carbonate-cemented sandy gravel ("caliche")	38 – 45	7	8.2 E-13	8.1 – 38.5	0.05	0.5
Ringold Unit E (R_{ge})	Gravel	45 – 66	21	1.3 E-10	3.4 – 17.6	8	73.4

[a] Calibrated values based on numerical airflow model (Rohay and McMahon 1996).
[b] Based on samples collected during drilling at the carbon tetrachloride sites in 1992 and 1993 (Wright et al. 1994).
[c] Not present underlying the 216-Z-9 Trench.

Table D-3. Configuration of the Plio-Pleistocene Unit Underlying the Carbon Tetrachloride Disposal Sites.

Plio-Pleistocene Unit	216-Z-9 Site	216-Z-1A/Z-18/ Z-12 Site	Both Sites
Minimum Depth to Top[a] (m bgs)	31	36	--
Maximum Depth to Top[a] (m bgs)	35	45	--
Average Depth to Top[a] (m bgs)	34	39	38
Minimum Depth to Bottom[a] (m bgs)	35	42	--
Maximum Depth to Bottom[a] (m bgs)	45	54	--
Average Depth to Bottom[a] (m bgs)	38	48	45
Minimum Thickness[b] (m)	2	4	--
Maximum Thickness[b] (m)	6	11	--
Average Thickness[b] (m)	4	7	6

[a]Based on 11 wells at 216-Z-9 and 42 wells at 216-Z-1A/Z-18/Z-12
[b]Based on 8 wells at 216-Z-9 and 18 wells at 216-Z-1A/Z-18/Z-12

Table D-4. Disposition of Carbon Tetrachloride Inventory Discharged to the Soil Column.

Carbon Tetrachloride Disposition	Percent of Estimated Original Carbon Tetrachloride Inventory (Average 750,000 kg)	Estimated Mass of Carbon Tetrachloride (kg)	Reference
Estimated using pre-remediation data			
Equilibrium partitioning within vadose zone into vapor, dissolved, and adsorbed phases	12	91,000	WHC 1993
Lost to atmosphere	21	159,000	WHC 1993
Biodegraded	1	8,000 (4,385 for Z-9 only)	Hooker et al. 1996
Dissolved in upper 10 m of unconfined aquifer (assuming 30% porosity and no partitioning to aquifer solids)	1-2	5,250 – 15,740	Rohay and Johnson 1991, BHI problem statement
DNAPL/residual in vadose and/or unconfined aquifer	65	484,000	WHC 1993
Measured using remediation data			
Removed from vadose zone using soil vapor extraction (1992-1998)	10	76,000	Table 4-1
Removed from unconfined aquifer using pump and treat (1994-1998)	0.3	2,100	DOE-RL 1999b

Table D-5a. Mass Estimate of Carbon Tetrachloride Contained in Groundwater Plume in 1990 (from Rohay and Johnson 1991).

Contour Interval (µg/L)	Area (m^2)	Median Concentration (µg/L)	Calculated Mass (kg)[a]		Percent of Total	Cumulative Percent
			Porosity = 10%	Porosity = 30%		
10-100	8.34 E+06	55	460	1,380	8.75	8.75
100-1,000	3.09 E+06	550	1,700	5,100	32.39	41.14
1,000-2,000	0.64 E+06	1,500	970	2,900	18.44	59.58
2,000-3,000	0.30 E+06	2,500	760	2,280	14.49	74.07
>3,000	0.27 E+06	5,000	1,360	4,080	25.93	100.00
Total	12.65 E+06		5,250	15,740	100.00	

[a]Assuming a depth of 10 m.

Table D-5b. Mass Estimate of Carbon Tetrachloride Contained in Groundwater Plume in 1996 (from BHI Carbon Tetrachloride Problem Statement).

Contour Interval (µg/L)	Volume (m^3)[a]	Average Aqueous Concentration (µg/L)	Aquifer Mass			Sorbed Mass for K_d = 0.05 L/mg (kg)[b]	Sorbed Mass for K_d = 0.114 L/mg (kg)[b]
			kg[b]	Percent of Total	Cumulative Percent		
5 - 100	19,462,500	38.45	748	6.13	6.13	227	518
100 - 250	8,647,500	157.74	1364	11.18	17.31	414	943
250 - 500	5,092,500	357.40	1820	14.91	32.22	552	1259
500 - 750	2,700,000	615.44	1662	13.62	45.84	504	1149
750 - 1000	1,860,000	868.65	1616	13.24	59.08	490	1117
1000 - 1250	1,275,000	1092.70	1393	11.42	70.50	423	964
1250 - 2000	832,500	1554.88	1294	10.60	81.10	393	895
2000 - 3000	330,000	2452.79	809	6.63	87.73	246	560
3000 - 4000	232,500	3527.29	820	6.72	94.45	249	567
> 4000	157,500	4299.37	677	5.55	100.00	205	468
Total	40,590,000		12203	100.00		3703	8440

[a]Assuming a depth of 10 m.

[b]Assuming a porosity of 30%.

Table D-6. Pore Column Volume Estimates for the Carbon Tetrachloride Cribs.

Waste Disposal Facility	North-South Length (m)	East-West Length (m)	Bottom Area (m^2)	Depth to Water (m)	Average Annual Discharge (L)	Infiltration Rate ($L/m^2/day$)	Porosity (%)	Column Pore Volume (L)	Total Discharge Volume (L)	% Pore Volume
216-Z-1A	84	35	2,940	57	1.15E+06	1.07	30	5.03E+07	6.21E+06	12
216-Z-9	18.3	9.1	167	57.6	6.08E+05	10.00	30	2.88E+06	4.09E+06	142
216-Z-18	63	12	756	59	9.74E+05	3.53	30	1.34E+07	3.86E+06	29

Table D-7. Estimated Depth of Organic Migration Beneath the Carbon Tetrachloride Cribs (from Rohay et al. 1994a).

Waste Disposal Facility	North-South Length (m)	East-West Length (m)	Bottom Area (m^2)	Depth to Water (m)	Total Organic Discharge (L)	Residual Saturation (%)	Depth of Migration (m)
216-Z-1A	84	35	2,940	57	1.75E+05	2.5	2
216-Z-9	18.3	9.1	167	57.6	8.30E+05 to 3.00E+05	2.5	20 to 72
216-Z-18	63	12	756	59	1.10E+05	2.5	6

Table D-8. Physical Properties of Carbon Tetrachloride (from Last and Rohay 1993).

Property	Units	Pure Carbon Tetrachloride	85% Carbon Tetrachloride, 15% TBP by volume	50% Carbon Tetrachloride, 50% DBBP by volume	50% Carbon Tetrachloride, 50% Lard Oil by Volume	Water
Liquid density	g/mL at 20°C	1.59[b,c]				1.00[b,c]
	g/mL at 25°C		1.51[d]	1.27[d]	1.25[d]	
Absolute viscosity	centipoise at 24°C		5.75[d]	4.50[d]	10.50[d]	
	centipoise at 20°C	0.97[b,c]				1.00[b]
Interfacial tension with air	dynes/cm at 24°C		31.0[d]	32.0[d]	33.0[d]	
Interfacial tension with water	dynes/cm at 24°C		23[d]	11[d]	18[d]	
	dynes/cm at 20°C	45.0[b]				
Interfacial tension with 5 M sodium nitrate	dynes/cm at 24°C		11[d]	19[d]	7[d]	
Vapor pressure	cm H_2O at 24°C, 30.1 in. Hg	130[d]	100[d]	52[d]	60[d]	
	25°C	109[c]				
	20°C	90[b]				
Saturated vapor concentration	mg/L at 20°C	754[a]				
	ppmv at 20°C	120,000[a]				
Saturated vapor density	g/L at 25°C, 1 atm	6.29[b]				Dry air = 1.204[b]
Relative vapor density (dry air)	Saturated at 25°C and 1 atm	1.62[c]				
Relative vapor density (moist air)	Saturated at 20°C and 1 atm	1.51[b]				
Air diffusion coefficient	cm^2/s at 20°C	0.0797[b]				
Henry's Law constant	atm-m^3/mol at 25°C	0.0302[b] 0.0298[c]				
Solubility in water	mg/L at 20°C, 1 atm	800[a,b]				
Dielectric constant		2.2[a,c]				78.5(a) 80.4(c)

[a]Rohay and Johnson (1991).
[b]Cohen et al. (1993).
[c]Pankow and Cherry (1996).
[d]Last and Rohay (1993).
DBBP = dibutyl butyl phosphonate
TBP = tributyl phosphate

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