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1. Enclosed is the final report "2-Phase Extraction Innovative Technology Evaluation Report Supplement." Comments received to the draft document have been incorporated in this final report.

2. This report documents a comparison of 2-Phase Extraction with conventional groundwater extraction and soil vapor technologies and will be included in the U. S. Environmental Protection Agency "2-Phase Extraction Innovative Technology Evaluation Report." This document is not listed as part of the Deliverable Status Report.

3. If you have any questions or concerns, please contact Mr. Tim Chapman at (916) 643-1739 or Mr. Craig Burnett at (916) 643-3672 ext. 327.

Philip H Mook Jr

PHILIP H. MOOK, JR., P.E.
Sr. Technical Advisor
Environmental Restoration Division
Environmental Management Directorate

Attachment:
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2-PHASE™ INNOVATIVE TECHNOLOGY EVALUATION REPORT – SUPPLEMENT

FINAL

for

McCLELLAN AFB/EM
McCLELLAN AFB, CALIFORNIA 95652-1389

29 APRIL 1997

CONTRACT NO. 68-W9-0054/WA NO. 54-40-9341
URS SUBCONTRACT NO. SC-96-F-0597

This supplement has been prepared by the staff of Radian International LLC. The interpretation of these data and the conclusions drawn were governed by our experience and professional judgment.

Gordon B. Kingsley

Gordon B. Kingsley, P.E.

Registered Chemical Engineer, #3503

State of California

1.0 SUMMARY

The United States Air Force at McClellan Air Force Base (AFB), in coordination with United States Environmental Protection Agency (EPA) Superfund Innovative Technology Evaluation (SITE) Program initiated this study to supplement information contained in the Draft Innovative Technology Evaluation Report (ITER) (EPA, 1995) and other reports prepared for evaluating the application of 2-Phase Extraction™ (2PE), soil vapor extraction (SVE) and pump and treat (PT) technologies. Groundwater is contaminated with trichloroethene (TCE), tetrachloroethene (PCE) and Freon® 113 and lesser quantities of other volatile organic compounds (VOCs). A SITE demonstration of 2PE was conducted at McClellan AFB over a six-month period from August 1994 through January 1995. The demonstration was conducted in an existing well previously used for extracting contaminated groundwater using a PT system. An SVE system was later implemented in nearby vapor extraction wells. The purpose of this report is to present evaluation of each of these technologies so that the lessons learned can be applied to similar sites requiring remediation. Included in this report are models of the zone of vacuum influence of SVE and 2PE, models of the groundwater cone of depression of PT and 2PE, and cost estimates for implementation of these technologies.

The results of this study indicate that:

- 2PE groundwater extraction rates in extraction well (EW) 233 averaged 5.4 gallons per minute (gpm) over the six-month demonstration test. Contaminant removal was estimated at 1,600 pounds (lbs) VOC over six months or an average of 9 pounds per day (lbs/day). Soil vapor concentrations varied from 100 to 460 parts per million by volume (ppmv). Groundwater concentrations varied from 500 micrograms per liter (μg/L) to 3,300 μg/L. EW-233 is located outside the source area.
- PT averaged 3.1 gpm of groundwater extracted from EW-233 over a three-month period commencing in January 1994. Approximately 4 pounds per month (lbs/mo) or an average of 0.1 lbs/day of VOC were removed. Groundwater VOCs concentrations averaged 4,000 μg/L.
- SVE rates from vapor well 1 (VW-1) averaged 370 standard cubic feet per minute (scfm) of soil gas over 738 hours and removed approximately 2,300 pounds of VOC or approximately 75 lbs/day (URS, 1996a). Soil vapor total VOC concentrations varied from 140 to 950 ppmv. VW-1 is located within the contaminant source area.
- 2PE dewatered approximately 20,000 to 80,000 more cubic feet (cf) of vadose zone than PT.
- 2PE vacuum influence in EW-233 was 1 inch of water at a 170-foot radius at a flow rate of 100 scfm (URS, 1996b). SVE vacuum influence in VW-1 was 3 inches of water at a 200-foot radius at a flow of 360 scfm.

In general, the most significant findings are that 2PE and SVE produced orders of magnitude increases in chemicals removed from the subsurface in the same vicinity as compared to PT. Additionally, 2PE increased the production of groundwater from EW-233, providing greater hydraulic control. Higher VOCs mass removal would be achieved by 2PE if EW-233 were located in the source area. Soil gas concentrations measured at VW-1 were approximately double those measured at EW-233. Locating EW-233 within the source area, however, would not provide as effective plume containment. Mass removal goals must be balanced with groundwater plume containment in determining optimum well location(s).

Estimated costs per pound of total VOCs removed and assumed flow rates are as follows:

- 2PE at 100 scfm soil vapor and 5.5 gpm groundwater: $28/lb;
- SVE at 100 scfm soil vapor: $24/lb; and
- PT at 3 gpm groundwater: $807/lb.

The results are based on measurements taken during operation of PT, 2PE and SVE systems at McClellan AFB, Operable Unit (OU) B, Investigation Cluster (IC) 1 over a period from October 1993 to April 1995. Cost estimates are based on assumptions contained in the ITER, and evaluation of test data from McClellan AFB.

It is important to note that 2PE, SVE and PT each has a different application. 2PE is often applied in low permeability formations in which both soil vapor and groundwater contaminant removal is desired. 2PE will remediate the capillary fringe and saturated zones, but may not be as effective in the shallow vadose zone. SVE is effective for soil vapor contaminant removal throughout the vadose zone especially in medium and high permeability soils formations. PT is commonly used as a means of plume containment, especially in medium and high permeability formations often characterized by gravels and sands. SVE and PT can be accomplished in the same well by screening through both the saturated and vadose zones. This technique is commonly known as dual phase extraction (DPE). Like 2PE, a greater cone of depression is produced increasing the size of the vadose zone and often enhancing removal of contaminants. Increasing the cone of depression does not necessarily ensure higher VOC removal rates. Complex variables including preferential flow paths, air and liquid flow in soils, and soil moisture content can dramatically affect VOC removal. VOC removal rates are limited by diffusion. Pilot tests over extended periods and varying flow rates are often necessary to determine the effect of depressing the water table and optimize mass removal of VOCs. The selection of PT, 2PE, or DPE is contingent upon specific site conditions, lithology, contaminants and mass, and costs. Additional tests of 2PE and DPE are being conducted to demonstrate the effectiveness of these technologies and provide information to allow selection, design, and implementation for remediating similar sites.

2.0 BACKGROUND

2.1 Location and Site History

McClellan AFB, located in Sacramento County, California, has been in operation since 1936 and is on the National Priority List of contaminated sites. McClellan AFB has also been selected as a Department of Defense National Test

Site for remediation technologies. Operable Unit (OU) B at McClellan AFB covers approximately 325 acres in the southwest portion of the base. OU B formerly housed a number of industrial operations such as a wash rack, painting facility, an industrial wastewater treatment plant, and a plating shop (Figure 1). This site was selected for 2PE and SVE testing based on the nature and distribution of contamination and similarity to other sites.

2.2 Contaminant Distribution

Site characterization activities identified concentrations of TCE and PCE in the subsurface soil, soil gas, and groundwater. IC 1, located in the central portion of OU B, is contaminated primarily with TCE and PCE in soil vapor with concentrations up to 7,000,000 parts per billion by volume (ppbv). Groundwater contaminated with TCE and PCE, with concentrations up to 9,500 parts per billion (ppb), has migrated from IC 1, approximately 1,200 feet, to the base boundary and off the base to the southwest.

Referring to Figure 1, it should be noted that VW-1 is located in the source area whereas EW-233 is located outside this area.

2.3 Geology

Four laterally continuous units of silt and three units of sand/silty sand have been identified throughout most of the contaminated area of IC 1. Silt units appear to be of greater horizontal continuity and are located at approximately 40, 18, 5 and -20 feet mean sea level (msl). Moderate and high permeable (0.1 to 1.7 darcies) layers are located at 50, 13, and -8 feet msl. Lithologically, the sediment is approximately 30% sand, 51% silt, and 15% silty sand. The remaining 4% is associated with sediments that are generally found at or near ground surface (e.g., fill material).

2.4 Hydrology

Data collected basewide indicated that groundwater from 100 to 450 feet below ground surface (BGS) beneath McClellan AFB is one hydraulic system. There are local variations within the system (for example, confining layers and differences in hydraulic behavior between adjacent waterbearing zones) that suggest multiple hydraulic systems are present. However, across McClellan AFB, hydraulic responses and vertical contaminant migration indicate that only one system can be defined. The system has been divided into five monitoring zones (A, B, C, D and E, from shallowest to deepest) on the basis of lithologic and geophysical characteristics. The zones are useful in tracking the horizontal migration of contaminants and monitoring local variations in hydraulic gradient. Fine-grained deposits used to define the zones are not continuous and allow groundwater leakage and contaminant migration between zones.

The A zone is unconfined. Groundwater in the A zone beneath IC 1 occurs at approximately 108 feet BGS and flows generally south to southwest. The local groundwater gradient is approximately 0.026 feet/foot to the south/southwest, and is influenced by the pumping of Base Well 18 and EW-233. Base Well 18 is approximately 900 feet southwest of EW-233.

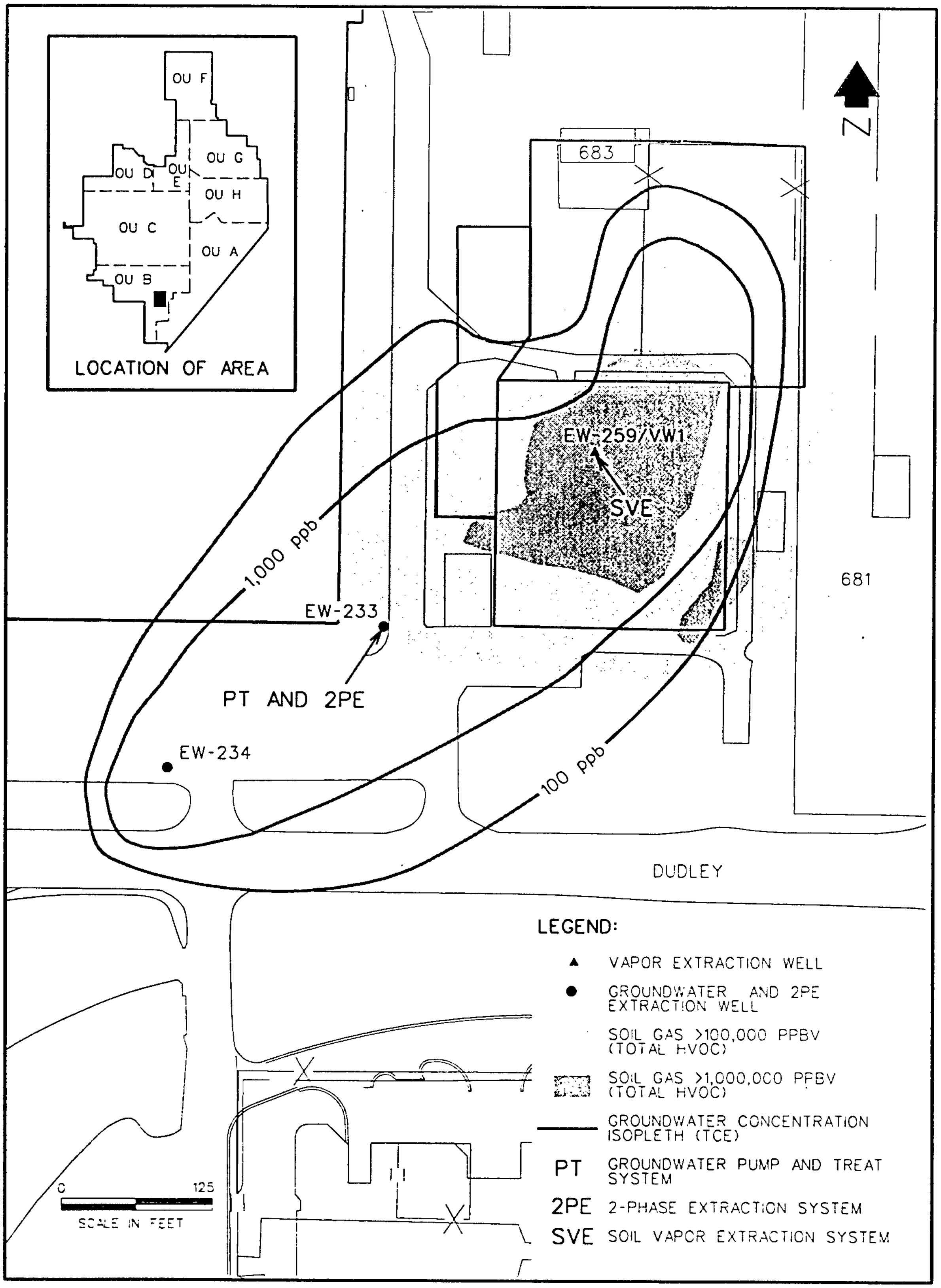


Figure 1. Site Location

2.5 Removal Action

In 1991, EW-233 and EW-234 and a liquid phase carbon treatment system were installed to control the migration of VOCs from IC 1. From 1991 to 1994, this system removed an average of 129 pounds of contaminant per year and provided limited hydraulic control.

In 1993, 2PE was proposed to enhance the removal of contaminants in the area. During June and July of 1993, a 2PE system was installed at IC 1 at extraction well EW-233 to remediate VOCs in the vadose zone and groundwater.

2.6 Technology Descriptions

2.6.1 2-Phase Extraction

The 2PE groundwater and soil vapor extraction technique was developed and patented by Xerox Corporation to address sites contaminated with VOCs in low permeability porous media. The technique is ideally suited for deposits having VOC contamination present in both the unsaturated (vadose) zone and groundwater. By using a high vacuum to withdraw soil gas and groundwater, this technology remediates contamination in soil and groundwater simultaneously. 2PE technology is generally not applicable for remediation of soil in the vadose zone if sands or other permeable materials are present due to the higher energy requirements necessary at high vapor flow rates.

The 2PE technique requires the use of a groundwater well that is screened above and below the water table. The 2PE process does not require a conventional water pump. An aboveground vacuum pump provides all the energy required to extract groundwater and soil vapor from the well. The high-vacuum system consists of an extraction or recovery wellhead and extraction pipe, a common liquid-air extraction line, a liquid knockout pot or pots and liquid transfer pump, a high vacuum pump and dehumidification components if used with vapor phase carbon emission control.

The typical 2PE system draws groundwater and air from the soil formation, at vacuums up to 25 inches of mercury. The recovery well is outfitted with a valved atmospheric inlet to assist in system startup. The extraction pipe is placed so the pipe tip is near the anticipated sustainable drawdown elevation. High vacuum within the extraction pipe draws soil vapor from the formation. Groundwater is entrained into the vapor at the tip of the extraction pipe. The combined water and air results in an aspirated or entrained flow condition. Water is then drawn up the extraction pipe along with air forming a turbulent and aspirated mixture. The aspiration allows VOCs and semivolatile organic compounds (SVOCs) to be "stripped" from the groundwater.

The entrained flow reaches the high-vacuum equipment unit where it passes through a knock-out pot or pots. The sudden expansion in the pot allows the entrained groundwater to drop out. The soil vapor, including the "stripped" compounds, pass out the top of the pot, through the vacuum pump, and intercooler, and is discharged to some form of emission control.

2.6.2 Groundwater Pump and Treat

Groundwater extraction wells are used to lift groundwater to the surface for ex-situ treatment and/or disposal. When pumped, the well creates a cone of depression around the well, inducing an artificial groundwater gradient. Depending on pumping rate, hydraulic conductivity, and confinement of the aquifer, the radius of influence can extend a few feet to several hundred feet from the well. The radius is smaller in the downgradient direction. In common installations, a number of wells are placed along the downgradient edge and/or within the contaminant plume. Wells along the downgradient edge of the plume help prevent further migration of the plume by forming an hydraulic depression into which the groundwater flows. Additional extraction wells located within the plume may remove more highly contaminated water in a shorter period of time.

The number and placement of extraction wells is an important factor in designing groundwater extraction systems to ensure contaminant plume capture. The number and placement of wells will depend on the natural groundwater gradient, soil permeability, transmissivity, and other site-specific hydrogeological factors.

Extraction wells are typically sized from 4 to 12 inches in diameter and each employs a single pump. Most groundwater recovery wells depend on submersible pumps to extract the water. The length and placement of the screen within the well depends on the type of contaminants being recovered and aquifer thickness. For unconfined aquifer conditions, including those with the presence of free product, the well screen will extend from a few feet above the water table to some depth within the aquifer.

Once the water is extracted from the aquifer and lifted to the surface, ex-situ treatment begins. Ex-situ treatment technologies use a variety of physical, chemical, and biological processes to concentrate, breakdown, degrade and/or chemically alter contaminants. The technologies may result in highly concentrated contamination requiring subsequent disposal, such as landfilling or thermal destruction, or they may reduce the contaminants to carbon dioxide, water, and non-toxic by-products.

Traditional groundwater PT does not remediate the vadose zone. A soil vapor extraction system can be added if the vadose zone requires technological remediation. As described previously, a combination of PT and SVE in the same well is the basic design of a DPE system.

2.6.3 Soil Vapor Extraction

Soil vapor extraction has become one of the most common technologies for the removal of VOCs from unsaturated soils in the vadose zone. Where contamination is present at greater depths in the vadose zone, or where excavation may be difficult due to structures, underground utilities, etc., SVE is the preferred treatment alternative. SVE is a physical removal process in which air is pulled through the contaminated soil to remove VOCs for subsequent collection or destruction. The primary components of the treatment system include extraction wells, manifolds, vacuum blowers, and soil vapor treatment. The process is operated by extracting soil gas from the vapor extraction wells completed in the contaminated soil. While wells are typically completed in the vadose zone, they may extend into the groundwater. The air extracted from the well induces air flow in the surrounding soil, causing air to be drawn downward from the ground surface, through the surrounding soil, and into the extraction well.

As air is drawn through the soil, VOCs are released into the air. The withdrawn air is usually treated by collection on activated carbon to remove the contaminants, passed through a thermal destruction unit, such as an incinerator or catalytic oxidation unit to destroy the contaminants, or passed through a condensation or synthetic resin system to allow product recovery. The rate at which the soil is cleaned up is primarily controlled by: (1) the rate at which air is drawn through the soil, (2) the volatility of the contaminants, (3) soil characteristics which control the rate at which VOCs can diffuse out of the soil particles, and (4) the layout of the vacuum and air inlet systems.

SVE does not directly remediate groundwater contamination. A groundwater extraction system can be added if required. This technology is provided in this document to illustrate the effectiveness of SVE in comparison to 2PE.

Figure 2 presents typical well configurations for 2PE, groundwater PT, SVE, and DPE systems.

2.6.4 Dual Phase Extraction

DPE is another technology available for groundwater remediation. This technology is a physical, in-situ extraction process that combines conventional groundwater pumping with vacuum SVE to simultaneously extract groundwater and soil vapor from a single extraction well screened in moderate to low permeability formations. The well may be screened above and below the unconfined water table and may include the vadose zone and saturated zone in the area of contamination. Soil vapor and groundwater are removed from the well via separate piping to their respective treatment systems. DPE systems typically focus SVE on the volume of soil dewatered in the groundwater cone of depression.

As the DPE system operates, the groundwater table is lowered by various pumping techniques while a vacuum is applied to the soil above the groundwater table. This allows a greater volume of soil to be exposed to the vacuum in the well. Conventional SVE induces a vacuum that can cause localized up-welling or mounding of the water table, especially if the SVE wells are screened close to the groundwater table. Continued pumping lowers the water table, over coming this effect, and previously saturated soil is exposed to the vacuum and opened to vapor flow. As the vacuum is applied to the newly dewatered region, liquid contaminants volatilize and contaminant vapors are drawn to the surface for treatment.

No data have been collected at this site to use in evaluating DPE in comparison with 2PE, groundwater PT or soil vapor extraction techniques because a DPE extraction system was not tested.

2.6.5 Pilot Tests

Pilot tests are recommended prior to full scale implementation of any cleaning technology, including 2PE, SVE, or DPE. Radian conducted "proof of concept" and extended pilot tests at three separate sites prior to implementation of a full scale 2PE system at IC 1. Proof of concept tests can often be conducted in one day, if site conditions allow.

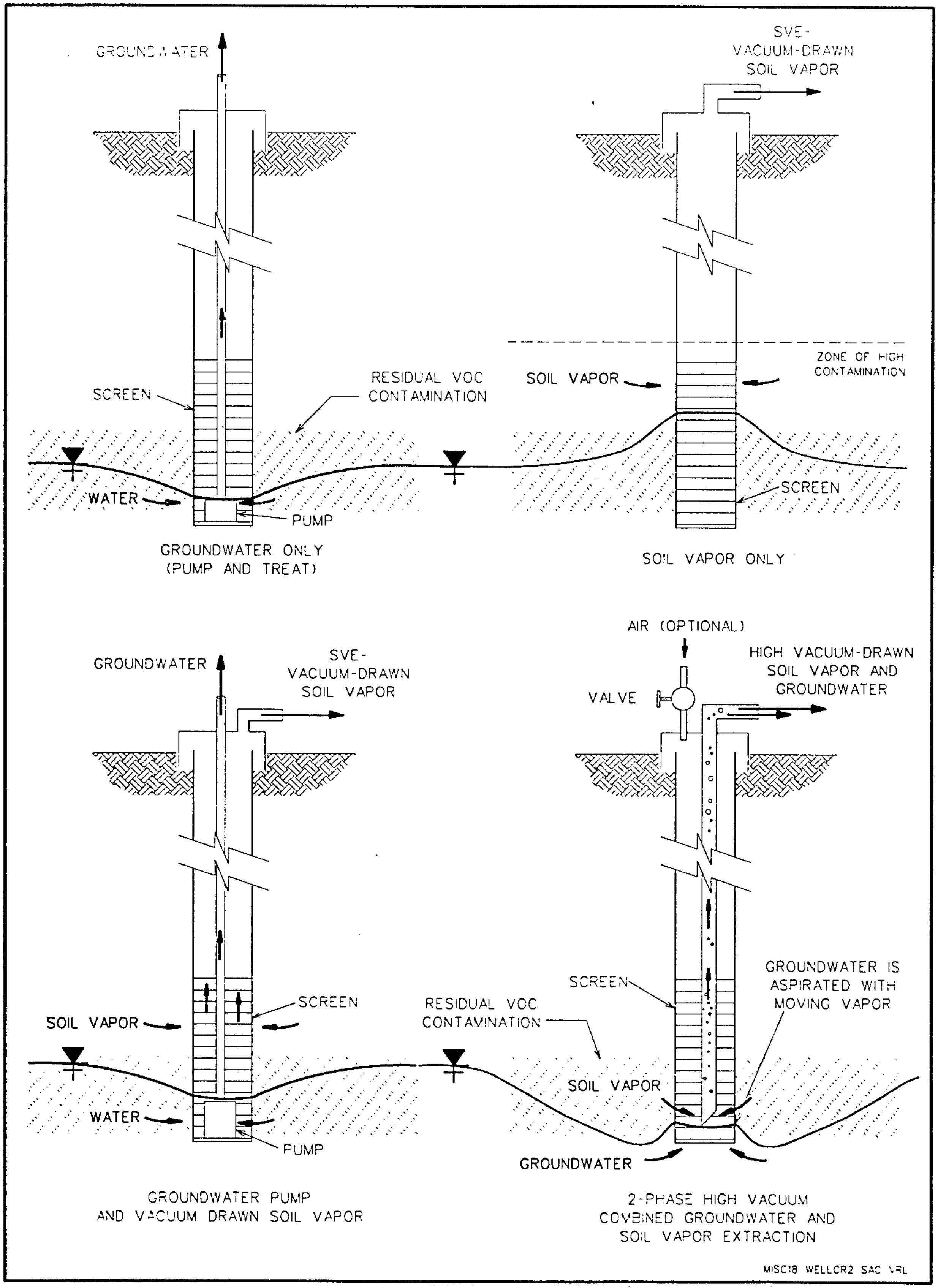


Figure 2. Examples of Conventional Groundwater Pump & Treat, Soil Vapor Extraction, Dual Phase Extraction, and 2-Phase Extraction Systems

A small (5 to 10 scfm) mobile packaged unit was brought to the site. Vapor and water samples were taken. An extraction tube was lowered to the groundwater table and connected at the surface to the 2PE pilot unit. The wellhead was sealed to prevent air from the surface entering the annular space. The system was then run long enough to determine water and vapor extraction rates—typically 4 hours—during which vapor and water samples were collected, flow rates and induced vacuum monitored, and electrical use determined. The pilot system was then shut down and the extraction tube and well head fittings were removed. Water and vapor samples were taken from the well. The equipment and fittings were decontaminated and equipment demobilized from the site. An extended test requires a longer period to gather data and monitor contaminant concentration trends. The minimum recommended time is 72 hours continuous operation with a larger (40 to 60 scfm) capacity pilot unit. This extended period is required to determine concentration trends, optimum extraction tube design, groundwater flow and characteristics, induced vacuum changes, and parameters needed for design of groundwater and soil vapor treatment. Extended testing at higher rates provides the engineer and scientist with data critical to complete the design. The increased efficiency of the full scale system often provides a short payback for the additional costs associated with the extended pilot tests. Similar pilot tests are recommended for SVE and DPE.

2.7 Data Collection

2.7.1 Groundwater Data

The groundwater PT system was in operation for three years before it was shut down and replaced with the 2PE system. Groundwater level data were collected at the groundwater PT system from July 1991 through mid-June 1994 and at the 2PE system from August 1993 through January 1995.

Historical Water Level Elevations

Basewide historical water level elevations were reviewed to determine if the water table had increased or decreased during the period between the two system operations. Within the last 10 years, water levels in the A monitoring zone have been declining at a rate of approximately 1.25 to 2 feet per year. Water level data collected from monitoring wells in the vicinity of IC 1 within the A zone indicated a decline of approximately 1 foot between 1993 and 1994. Table 1

Table 1. Historical Water Level Elevations at IC 1

		Recorded Elevations[a]				Difference
Well No	Zone	September 1993	September 1994	October 1993	August 1994	Between Water Elevations (ft)
MW-153	A			-45.17	-46.03	0.86
MW-282	A	-45.78	-46.93			1.15
MW-283	A	-41.64	-42.86			1.22
MW-285	A	-45.13	-46.44			1.31
MW-287	A	-45.42	-46.46			1.04
MW-288	A			-45.29	-46.07	0.78

[a] Elevations are recorded in feet mean sea level.

summarizes the historical water level data from wells outside the zone of influence from the treatment systems and the differences in water level elevation between 1993 and 1994 measurements.

Groundwater Pump and Treat

From July 1991 through 13 June 1994, groundwater was extracted from EW-233 and EW-234 and treated with activated carbon. EW-234 was shut down in September 1993 because extraction rates had decreased to less than 1 gpm. Water level measurements were collected on a monthly basis from these extraction wells and adjacent monitoring wells throughout the operation of PT activities. Figure 3 shows the extraction well and associated monitoring well locations.

To illustrate a representative groundwater cone of depression for the PT system (to be used for comparison to the 2PE groundwater cone of depression), the extraction rate, extraction well operation duration, the number of extraction wells on-line, and the season during which the data were collected were taken into account. 2PE was operated using only one extraction well, EW-233, during the period between August 1994 and January 1995. Therefore, only groundwater PT data collected after the shutdown of extraction well EW-234 and between the months of August and January were reviewed.

EW-233 was redeveloped in May 1993 to improve the well's extraction rate which had degraded from 6 gpm to approximately 2 gpm over a one-year period. After May and before September 1993, EW-233 operated at an average extraction rate of 4.7 gpm. After August 1993, EW-233 extraction rate decreased, averaging 3.0 to 3.3 gpm. By the time EW-233 was shut down in June 1994, the well was pumping at only 2.5 gpm. This decrease in production rate is often observed, especially where a fine screen well is installed in the well. Groundwater data collected on 30 August 1993 from the PT system were therefore selected. This data set was selected because extraction well EW-233 was operating at 4.5 gpm, the well had been online for approximately 104 consecutive days, and operation took place in the fall prior to the rainy season.

Figure 4 illustrates the difference in the groundwater cone of depression between the August 1993 data set when EW-233 was operating at 4.5 gpm and the January 1994 data set when EW-233 was operating at 3.3 gpm. Table 2 summarizes the wells and data for the groundwater PT system presented in Section 3.0.

2-Phase Extraction

Three piezometer nests (PN1, PN2 and PN3) and two companion wells (CW1 and CW2) were installed in July 1994 to monitor flow of groundwater and vacuum around EW-233 during a six-month 2PE demonstration test conducted from August 1994 through January 1995. Six additional monitoring wells located in the A zone were also used to monitor groundwater conditions. The well and piezometer placement are shown in Figure 5.

Groundwater levels from companion wells and piezometer nests associated with the 2PE demonstration project (CW1, CW2, PN1, PN2, and PN3) were measured periodically from startup on 1 August 1994 through January 1995. The data set collected on 29 August 1994 was used to be representative of the groundwater

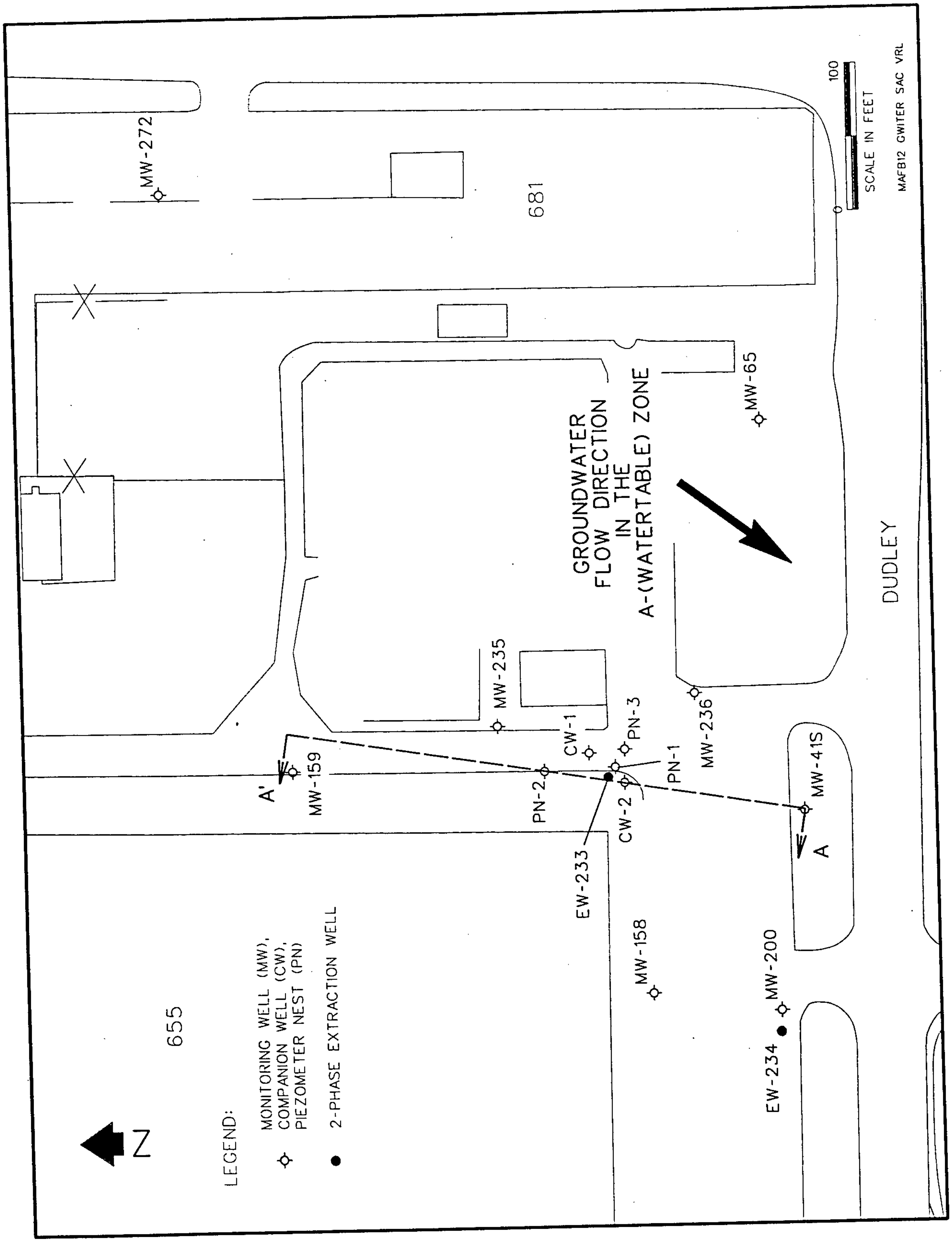
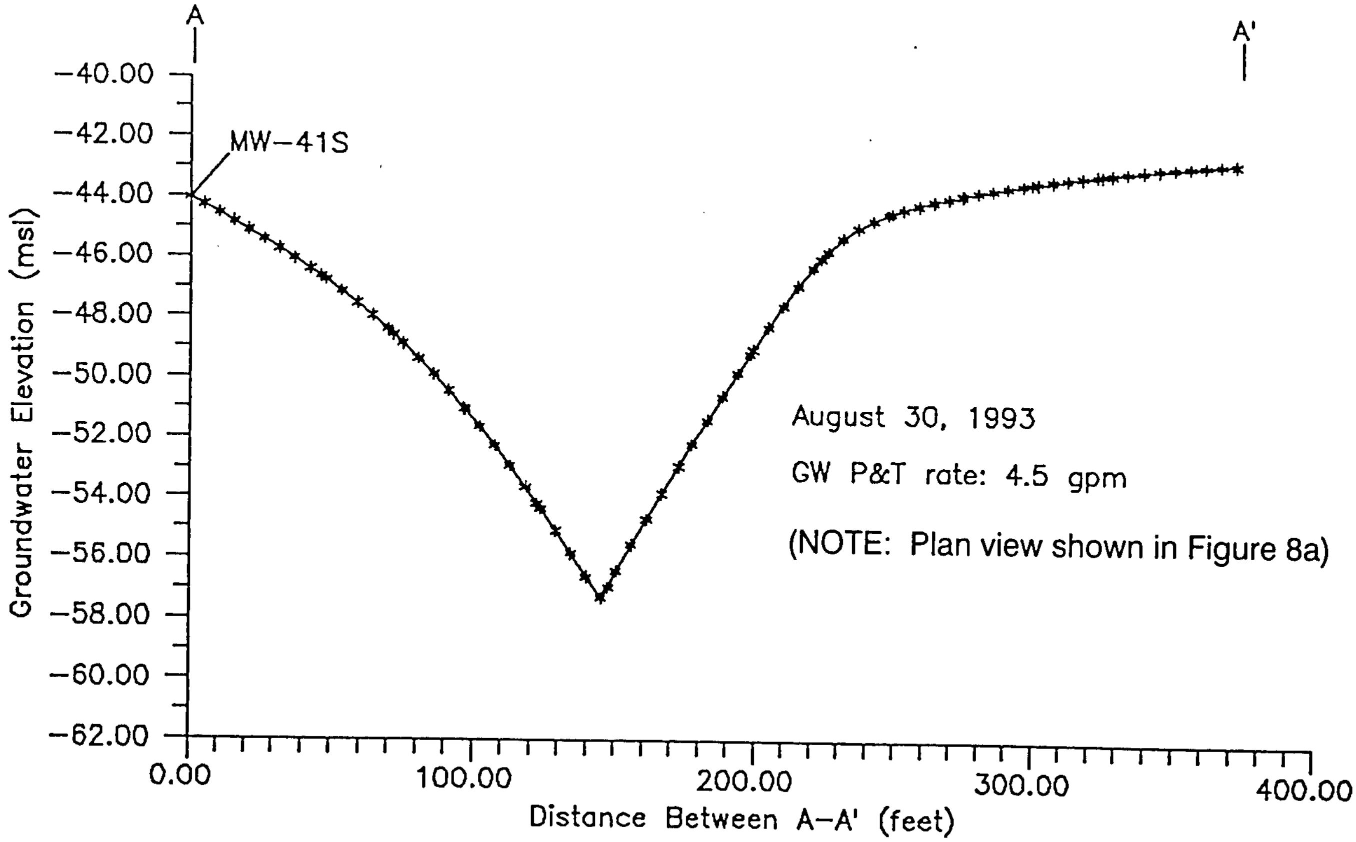


Figure 3. Groundwater Monitoring and 2-Phase Extraction Well Locations

Cross Section A-A' (August 30, 1993)



Cross Section A-A' (January 26, 1994)

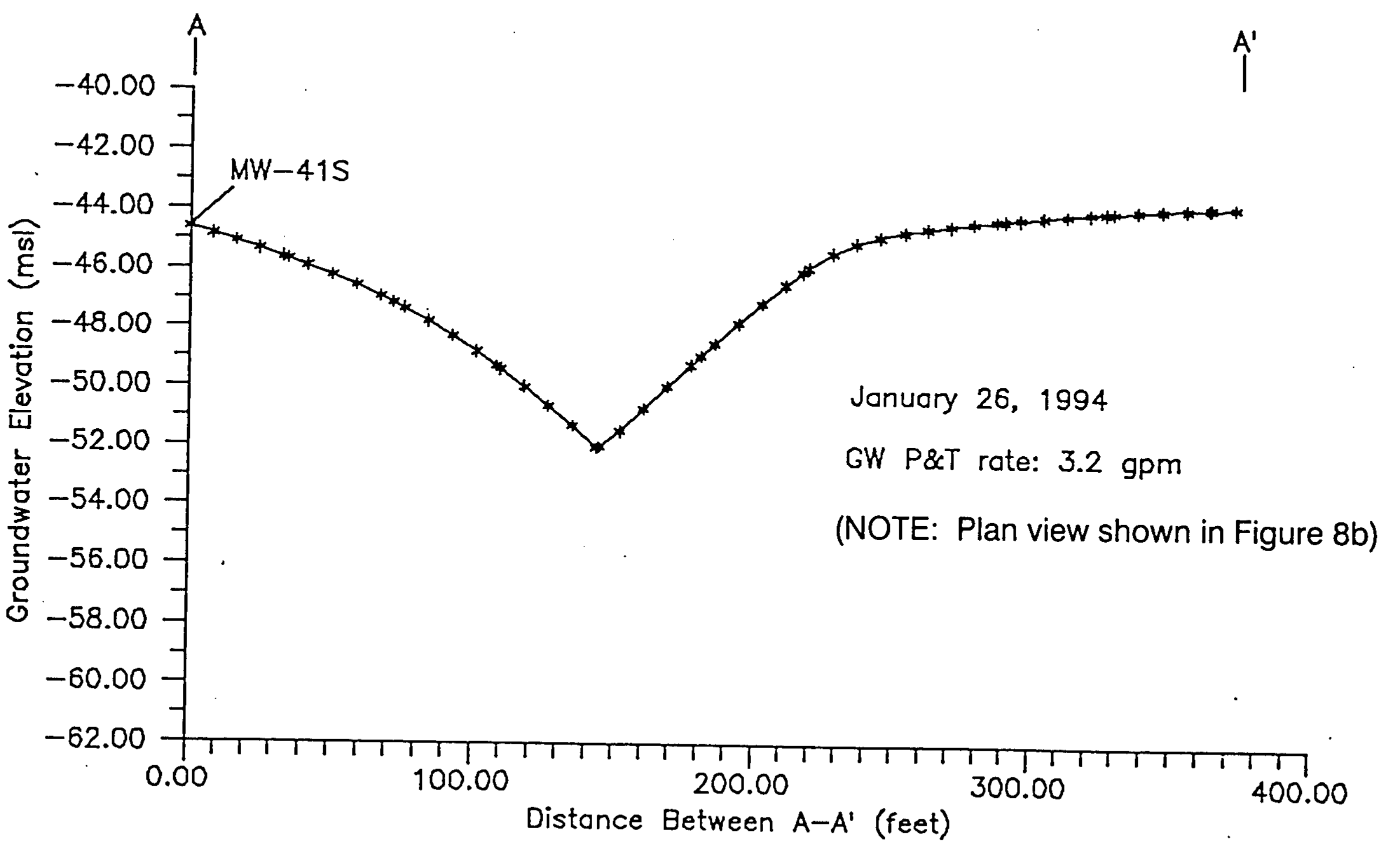


Figure 4. Cross Sections Showing the Extent of Drawdown for Groundwater Pump and Treat August 30, 1993 and January 26, 1994

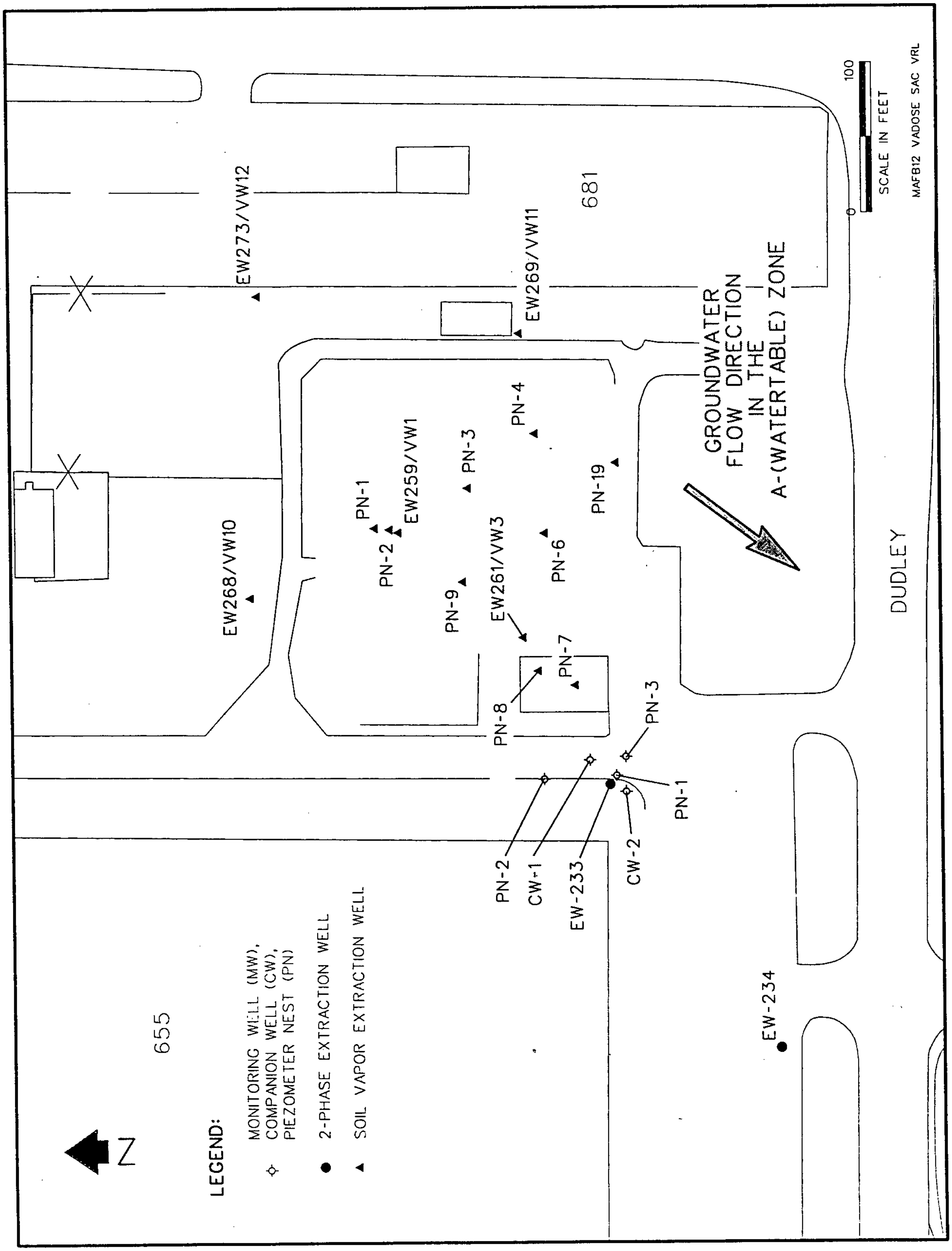


Figure 5. SVE AND 2PE Well Locations

Table 2. Water Level Elevations Measured at IC 1 During System Operation (feet msl)

	Groundwater Pump & Treat		2-Phase Extraction	
Well No.	August 1993	January 1994	August 1994	October 1994
EW-233	-57.43	-52.20	-48.30	-61.10
CW-1	—	—	—	-48.08
CW-2	—	—	—	-46.35
PN1	—	—	—	-53.39
PN2	—	—	—	-47.47
PN3	—	—	—	-47.59
MW-158	-44.06	-44.82	-46.03	-46.37
MW-159	-42.90	-43.65	-45.15	-44.90
MW-235	-44.03	-44.56	-46.05	-45.85
MW-236	-44.26	-44.71	-46.53	-46.06
MW-41S	-44.03	-44.63	-46.28	-46.10
MW-65	-43.78	-47.09	-46.19	-46.50

cone of depression created by the 2PE system. This data set was selected because the 2PE system had been operating at an ideal flow (5 to 8 gpm estimated flow rate using well EW-233 only) for six weeks and water levels from monitoring wells beyond CW1, CW2, PN1, PN2 and PN3 were also available on this date. After October 1994, flow was reduced to less than 5 gpm to prevent carbon breakthrough. Table 2 summarizes the wells and data used in presenting the groundwater cone of depression for the 2PE system presented in Section 3.0.

2.7.2 Induced Vacuum Data

Induced vacuum measurements for the SVE system were collected on 25 and 26 April 1995 from VPN2, VPN3, VPN4, VPN7, VPN9, VPN10, VPN14 and VPN19. During this two-day data collection event, the SVE system was shut down after 2 to 8 hours of operation. The data collected around 1630 hours on 26 April 1995 was used because the system had been operating for 8 hours (using VW-1 only) without shutdown and was considered the best data available. The SVE system was operating at an average rate of 360 to 380 scfm at EW-259/VW1. The 2PE system was also operational during this time.

Induced vacuum measurements for the 2PE system were collected periodically from August 1994 through January 1995 from PN1, PN2, PN3, PN7, PN8, and PN9. The 2PE system operated at a flow rate of 100 to 110 scfm between 12 August and 4 November 1994 and 5 December 1994 and 31 January 1995. The flow rate was lowered from 50 to 60 scfm between 4 November 1995 and 5 December 1995.

3.0 GROUNDWATER CONE OF DEPRESSION MODELING

3.1 Methodology

The groundwater cones of depression for the PT and 2PE technologies were modeled using SURFER®, a grid-based contouring and three dimensional surface plotting graphics program on the Microsoft Windows 3.1® platform.

SURFER® interpolates irregularly spaced horizontal coordinates and elevation data onto a regularly spaced grid. The data are used to produce contour maps and surface plots. Water level elevations measured during PT and 2PE operation were contoured. The contour maps present a planar view of the groundwater cones of depression. SURFER® also produced a slice through the simulated contour map for a cross-sectional view of the cone of depression (from A to A'). These cross-sectional views were imported into the graphics program (GRAPHER™) to produce graphs of groundwater elevation in feet msl plotted on the Y axis and the distance between A to A' in feet plotted on the X axis.

3.2 Groundwater Cone of Depression

3.2.1 Pump and Treat

A PT system was operated over a three-year period from May 1991 through mid-June 1994 to confine contaminated water to IC 1. EW-233 extracted approximately 6 million gallons and averaged 3.9 gpm during this period. Contaminant removal is estimated at approximately 50 pounds per year. A cone of depression was created in the groundwater table estimated to be 210,000 cf at an extraction rate of 4.5 gpm and150,000 cubic feet at 3.3 gpm. This depression provided a hydraulic gradient that influenced groundwater over a distance of at least 270 feet at 4.5 gpm and 250 feet at 3.2 gpm. MW-41S static water level was used as a baseline. Over time the groundwater flowrate declined from 7 gpm to as low as 2 gpm. Cleaning and backflushing the well screen on a periodic basis helped improve production; however, over time a flow rate decay pattern became evident. A second well EW-234 operated from May 1991 through September 1992. Approximately 1 million gallons of water was extracted at an average rate of 1.7 gpm over this period. Eventually the flow rate was too low to economically maintain the pump and the well was taken out of service. It therefore was decided to test and demonstrate 2PE as a means of elevating groundwater extraction rates and providing a technology that combined the benefits of SVE with increased mass removal.

Figure 6 illustrates the plan view and cross section showing extent of drawdown for PT on 30 August 1993.

3.2.2 2-Phase Extraction

Over the six-month span of the 2PE demonstration test, August through January 1995, 1.4 million gallons of groundwater were extracted at an average rate of 5.4 gpm from EW-233. A cone of depression was created in the groundwater table estimated to be 230,000 cf at an extraction rate of 5.1 gpm. This depression provided a hydraulic gradient that influenced groundwater over a distance of at least 270 feet at 5.1 gpm. Approximately 20,000 to 80,000 cf of additional vadose zone was created by 2PE compared to PT. In part the additional dewatering and increased volume can be attributed to the extraction tube extending 4 feet lower than the water depth measured for PT. The 2PE cone of depression presented in Figure 7 shows a drawdown to an elevation of -61.1 feet msl. This drawdown is 4 feet deeper than the PT maximum drawdown depth. Also, during startup of 2PE, fine particulate was observed in the groundwater and on associated filter elements. After the first week of startup particulate,

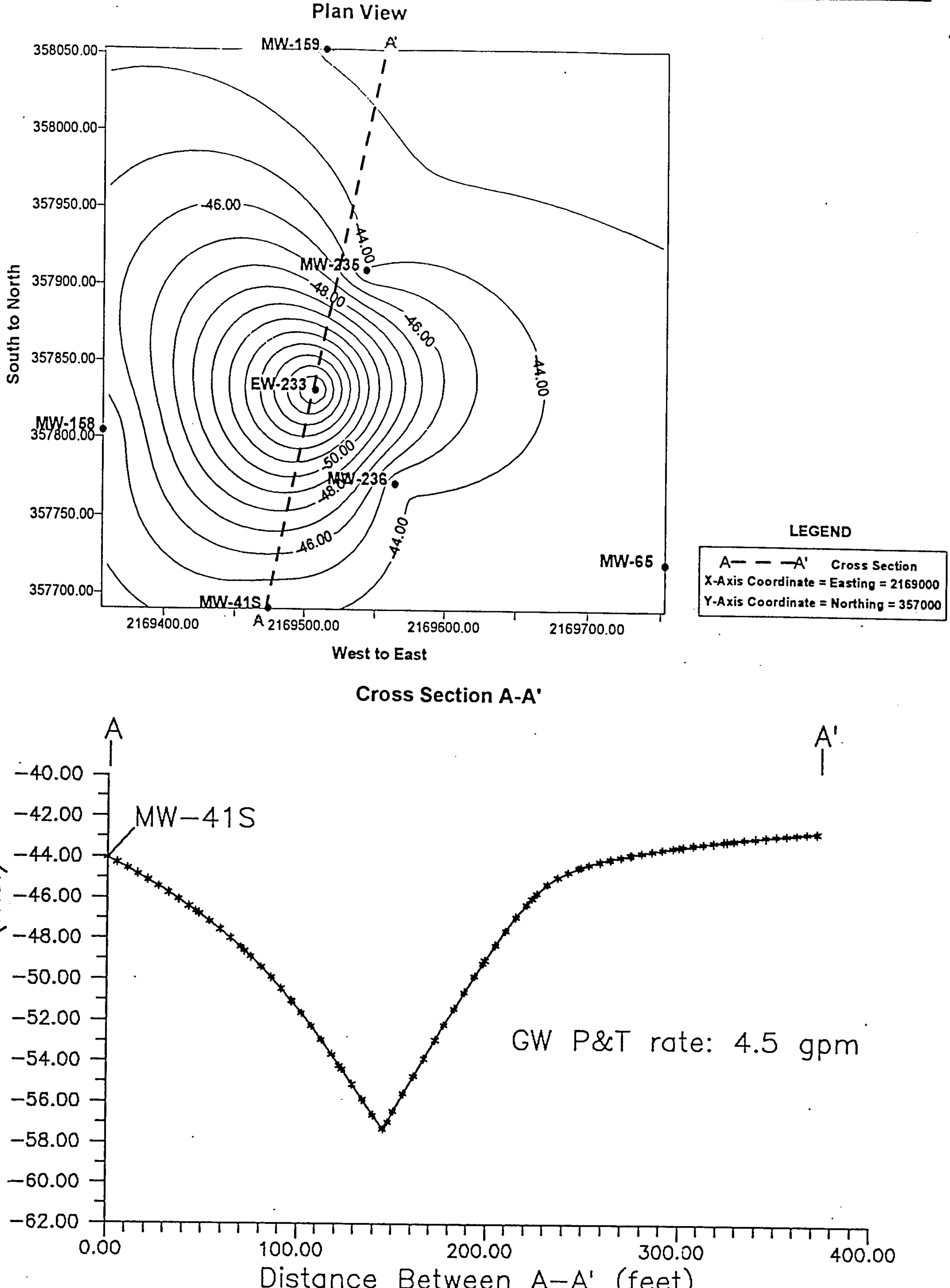


Figure 6. Plan View and Cross Section Showing the Extent of Drawdown for Groundwater Pump and Treat on August 30, 1993

concentration declined. One explanation is that particulate had built up around the sand pack and well screen during operation of PT restricting flow. The high vacuum produced by 2PE may have dislodged this particulate, opening up flow paths for flow of groundwater, thereby increasing the rate. One of the inherent advantages of 2PE is that because there are no moving parts below grade, clogging of the sand pack and well screen by fine silts is minimized or eliminated. Figure 7 is included for illustration only and should not be compared directly to Figure 6. The data points are different. See volume calculations below for explanation.

The drawdown is dependent on the size and design of the system. The 2PE straw was sized to extract 5 to 10 gpm groundwater and 100 scfm soil vapor. The bottom tip of the extraction tube extended to within 1 foot of the bottom of the well. The PT pump, on the other hand, required a higher water depth to facilitate installation of the pump and prevent cavitation.

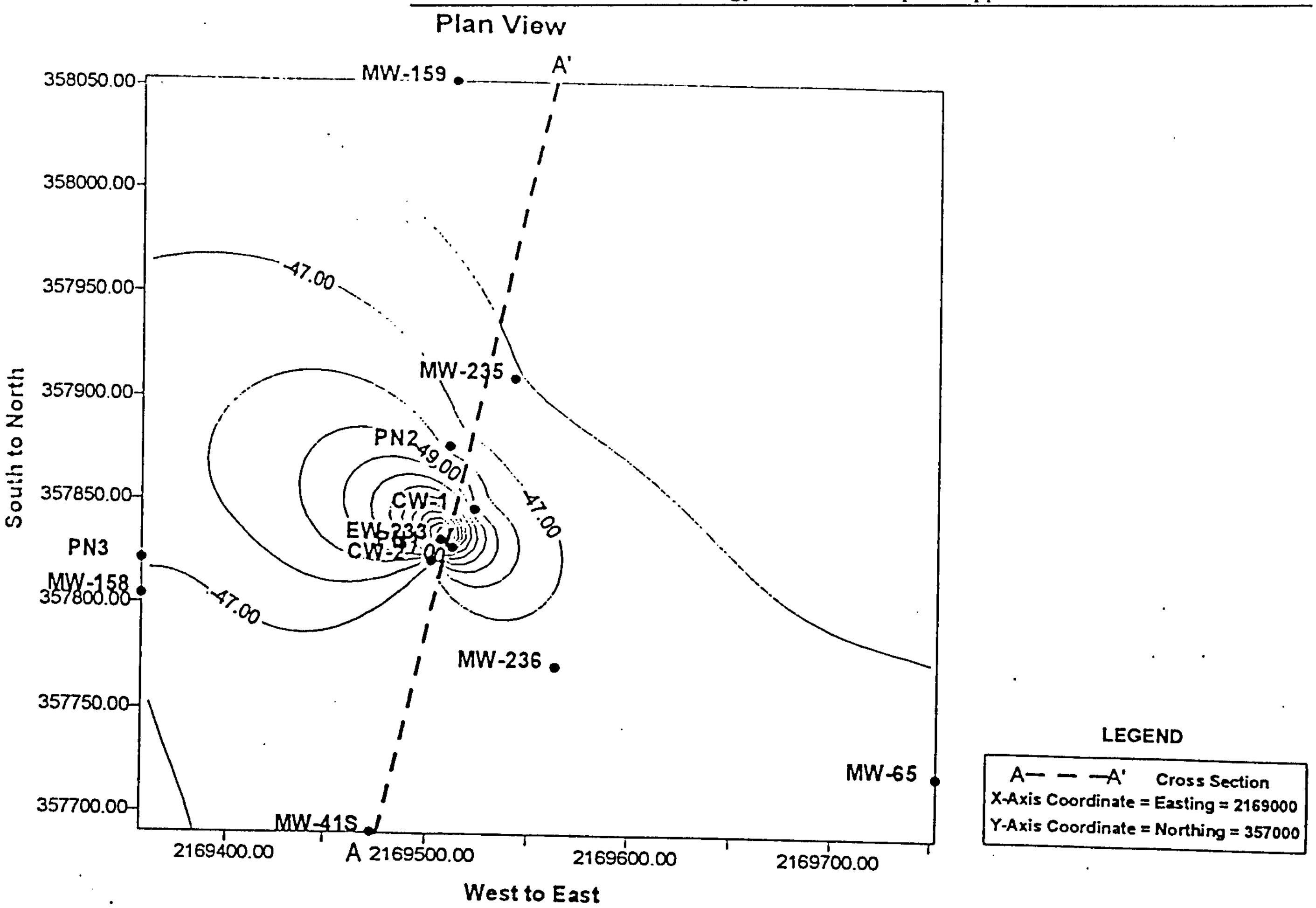
The increase in vadose zone increases mass removal. The diffusion and removal of VOCs from soil in the gas phase is orders of magnitude greater than in the water phase (EPA, 1991). Therefore, exposing additional vadose zone increases the mass removal making 2PE and DPE effective groundwater and soil remediation technologies.

3.3 Volume Calculations

Volume calculations were performed on three cones of depression using SURFER®. Because the groundwater PT system had limited data points for creating water level contour plots and associated cross sections showing extent of drawdown, data points in the 2PE model, which were not available for the PT model were deleted (CW1, CW2, PN1, PN2 and PN3). This allows for comparison between the two systems using similar data points at the time measurements were taken for PT and 2PE. However, by deleting data points in the 2PE data set and the lack of data points for the PT data set, the cones of depression are larger in each of the models because there is less definition close to EW-233. Consequently, the volumes presented here are for comparison purposes only. Actual volumes would likely be less. Volume calculations are reported by SURFER® as Positive Volume (Cut), Negative Volume (Fill), and Net Volume (Cuts minus Fills). Positive Volumes (Cuts) are the volumes of material above the plane defined as Z. Negative Volumes (Fills) are the volumes of material below the plane defined as Z. Z was defined as the water level elevation from well MW-41S for each time period calculated for volume. The volume of the groundwater cone of depression is the negative volume (fill) calculated by SURFER®.

Planar area was also calculated during the volume calculation process in SURFER®. SURFER® projects the cut and fill portions onto a plane and calculates the area of projection. The fill planar area would be defined by the Z value used in the volume calculation, which was equal to the groundwater elevation at MW-41S for each data set calculated.

Using MW-41S as the criterion for the extent of influence of extraction well EW-233, the planar area for the 2PE was smaller than the PT; however, the volume of soil dewatered by the 2PE was larger than PT. This volume increase



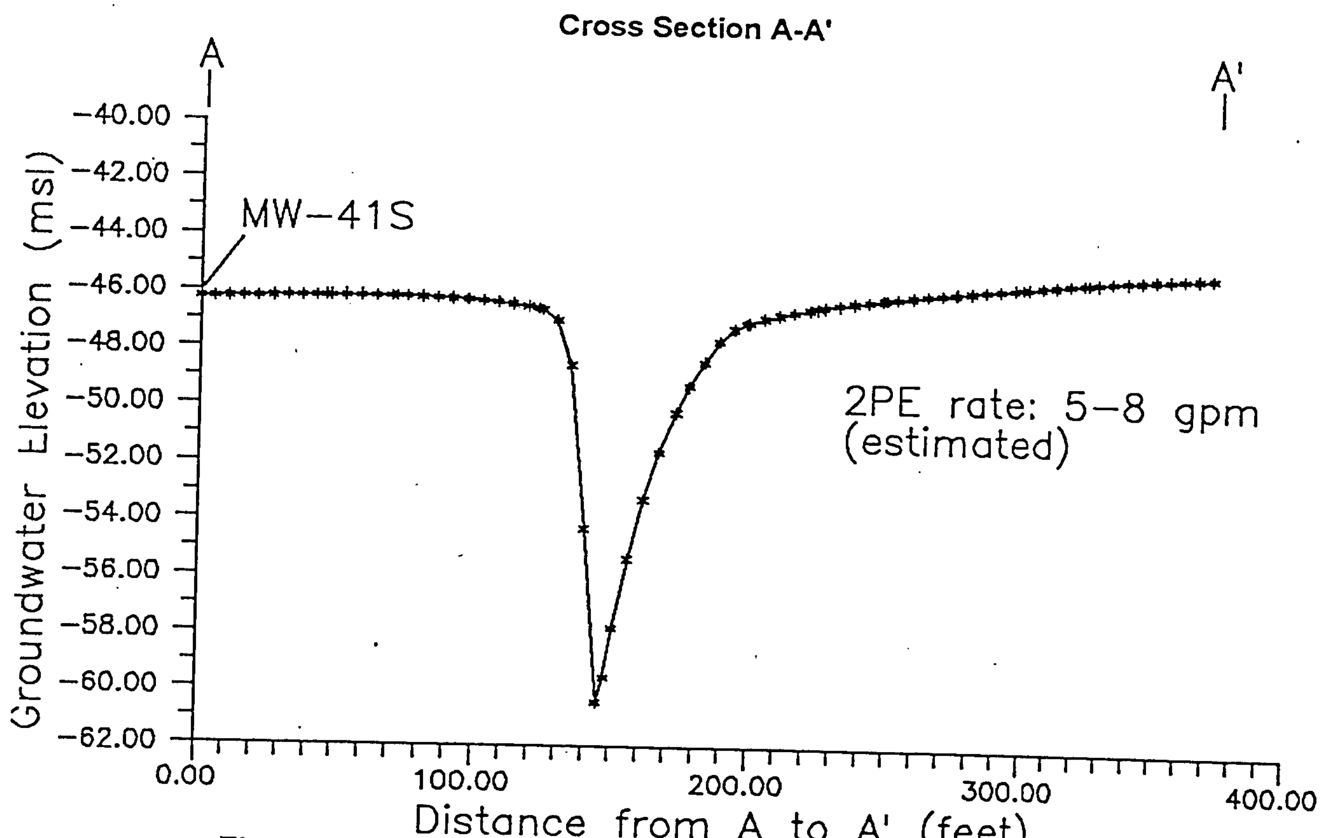


Figure 7. Plan View and Cross Section Showing the Extent of Drawdown for 2-Phase Extraction on August 29, 1994

for the 2PE occurred in part because the drawdown depth for the 2PE was 4 feet deeper than the PT drawdown.

To confirm that the data set collected on 29 August 1994 from the 2PE system represents a maximum drawdown scenario after 30 days of operation compared to 60 days of operation, data collected from the 31 October 1994 event was contoured and sliced. The October 1994 cone of depression was comparable to the 29 August 1994 cone of depression, showing a slightly smaller cone of depression. This difference may be a response to a rainfall event on 4 October 1993. The hydrographs within the ITER report (EPA, 1995) indicated that the outer well (MW-159) had reached a maximum drawdown within 30 days of operation.

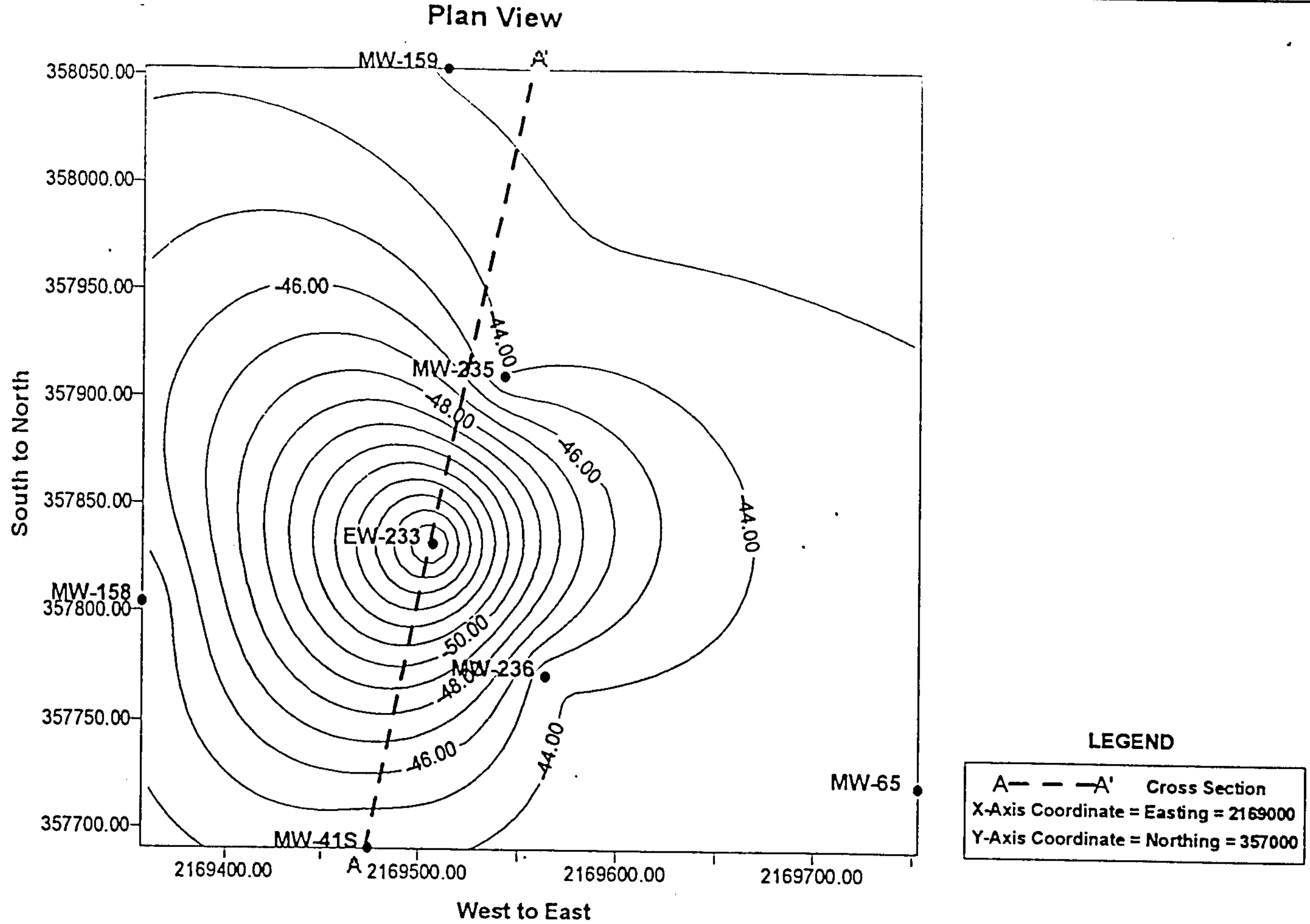
Table 3 summarizes the results of the SURFER® calculated fill volumes and planar areas for the 2PE limited data set collected on 29 August 1994 and for the PT data sets collected on 30 August 1993 and 27 January 1994. Two data sets for the PT system were used in calculating volumes to illustrate the effect different extraction rates have on total volume dewatered. Figures 8a, 8b, and 8c illustrate the area defined as the fill volume and the Z value for each calculated data set. Volume computation reports for each data set time period are provided in Appendix A.

Table 3. Volume Results

	Pump & Treat		2-Phase Groundwater
	30-Aug-93 (4.5 gpm)	27-Jan-94 (3.3 gpm)	29-Aug-94 (5-8 gpm)
Level Surface defined by Z (ft msl)	-44.03	-44.63	-46.28
Fill Volume (cubic feet)	211,840	152,559	227,630
Fill Planar Area (cubic feet)	75,040	108,344	74,350

4.0 VADOSE ZONE OF INFLUENCE MODELING

Models of induced vacuum show a greater influence by SVE than 2PE. The greater influence is attributable in large part to a higher soil gas flow rate for SVE of 360 to 380 scfm in comparison to 2PE of 100 scfm. In addition, differences in stratigraphy and well screen intervals have an effect on vacuum influence. SVE well VW-1 is screened over most of the vadose zone over an interval of 80 feet. 2PE well EW-233 is only screened in the lower 20 feet. Vacuums of 0.8 to 1.4 inches water at 158 feet distance for 2PE and 3.5 to 4.0 inches of water at 166 feet distance for SVE were measured. Induced vacuum measurements were collected during the operation of the 2PE system 17 October 1994 and the SVE system 26 April 1995. Figures 9 and 10 are diagrams of vacuum readings at 4 to 6 depth intervals plotted over distance from EW-233 or EW-259/VW-1 for the 2PE and SVE systems, respectively. Figure 11 graphically presents the vacuum data versus distance for comparison between the two systems. The highest vacuum measured was 8.3 inches of water within 10 feet of EW-259/VW-1 and 8.3 inches of water within 10 feet of EW-233. Vacuum decreased rapidly at the 2PE system at a depth of 90 to 110 feet,



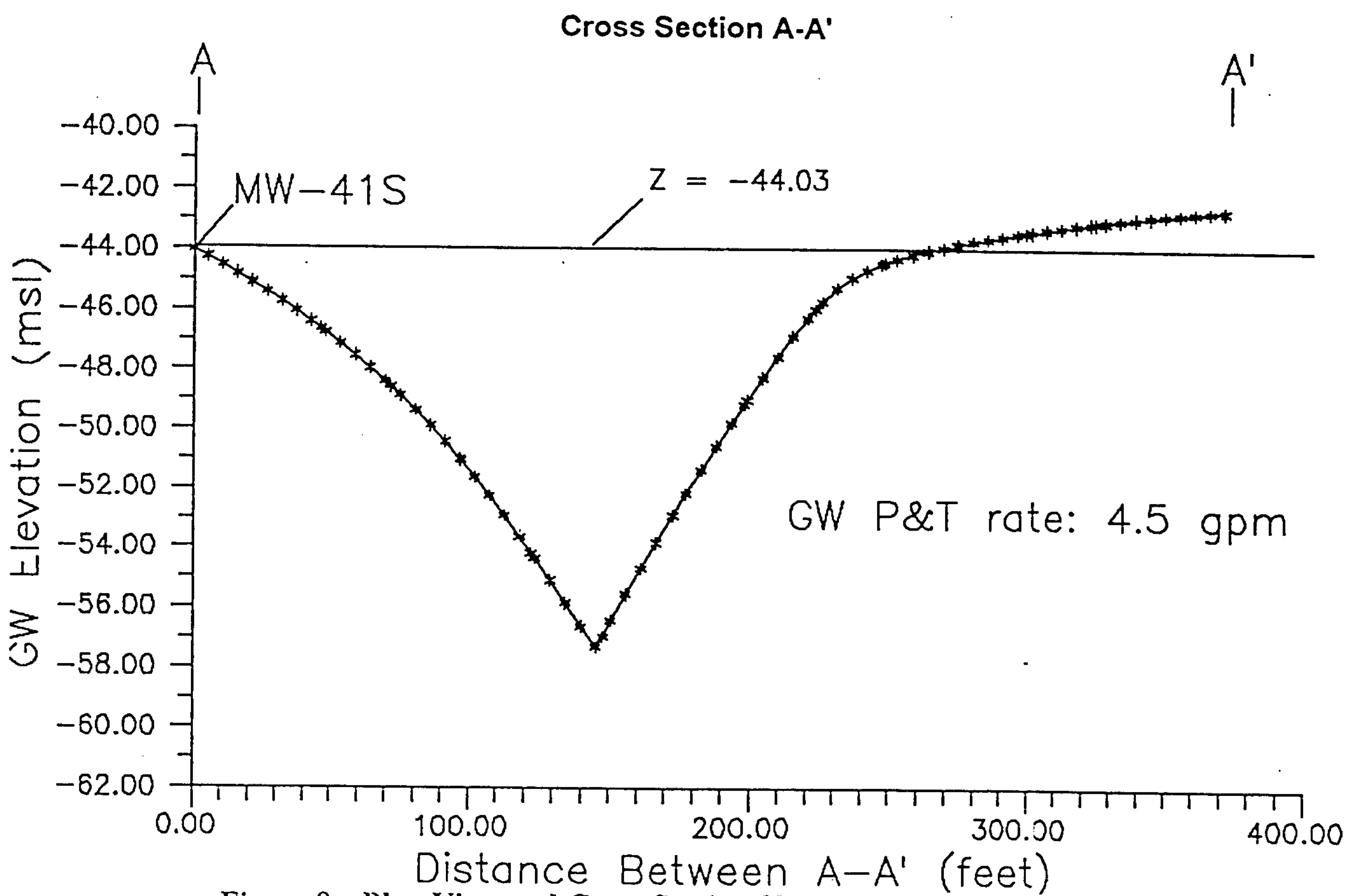
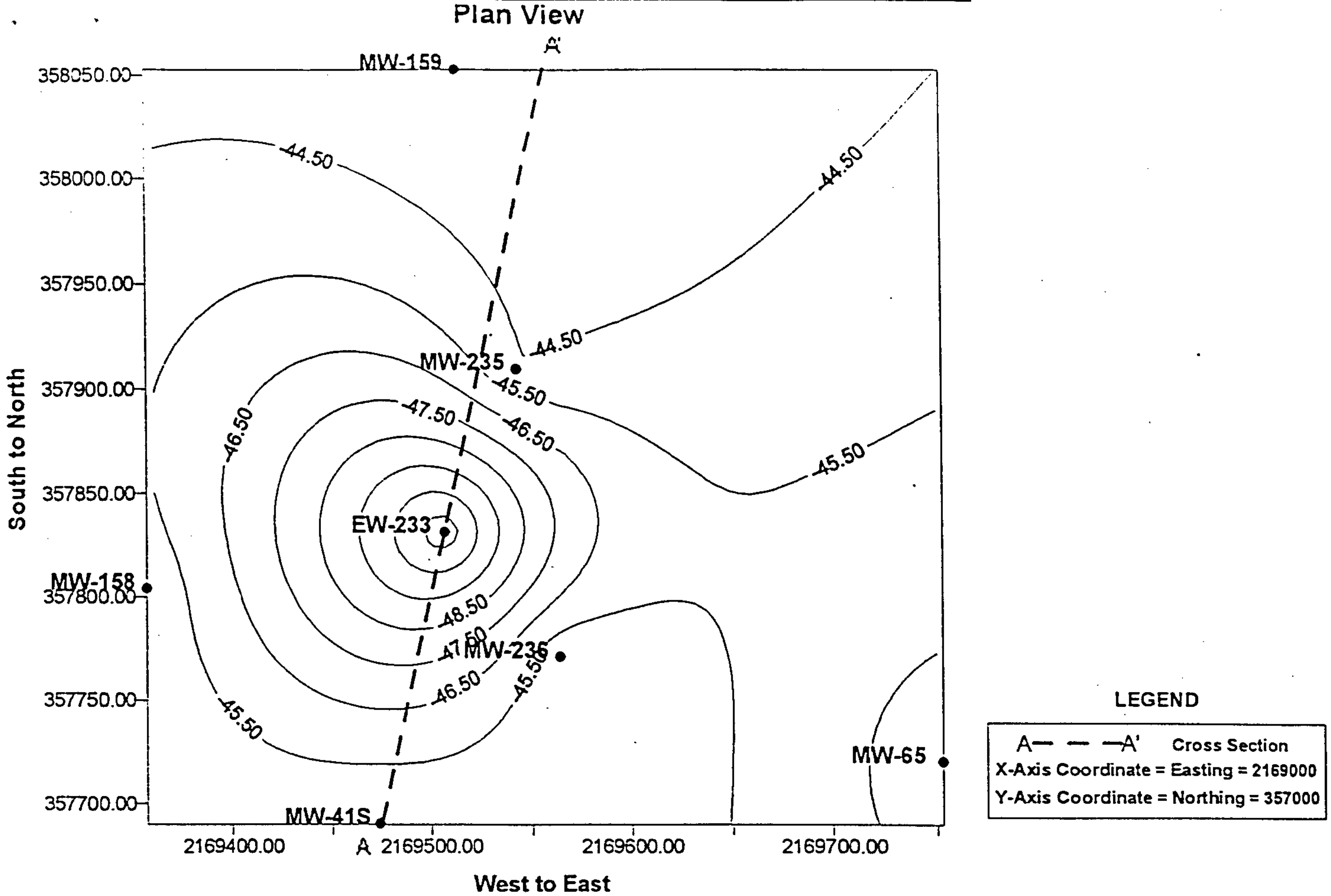


Figure 8a. Plan View and Cross Section Showing the Extent of Drawdown for Groundwater Pump and Treat on August 30, 1993



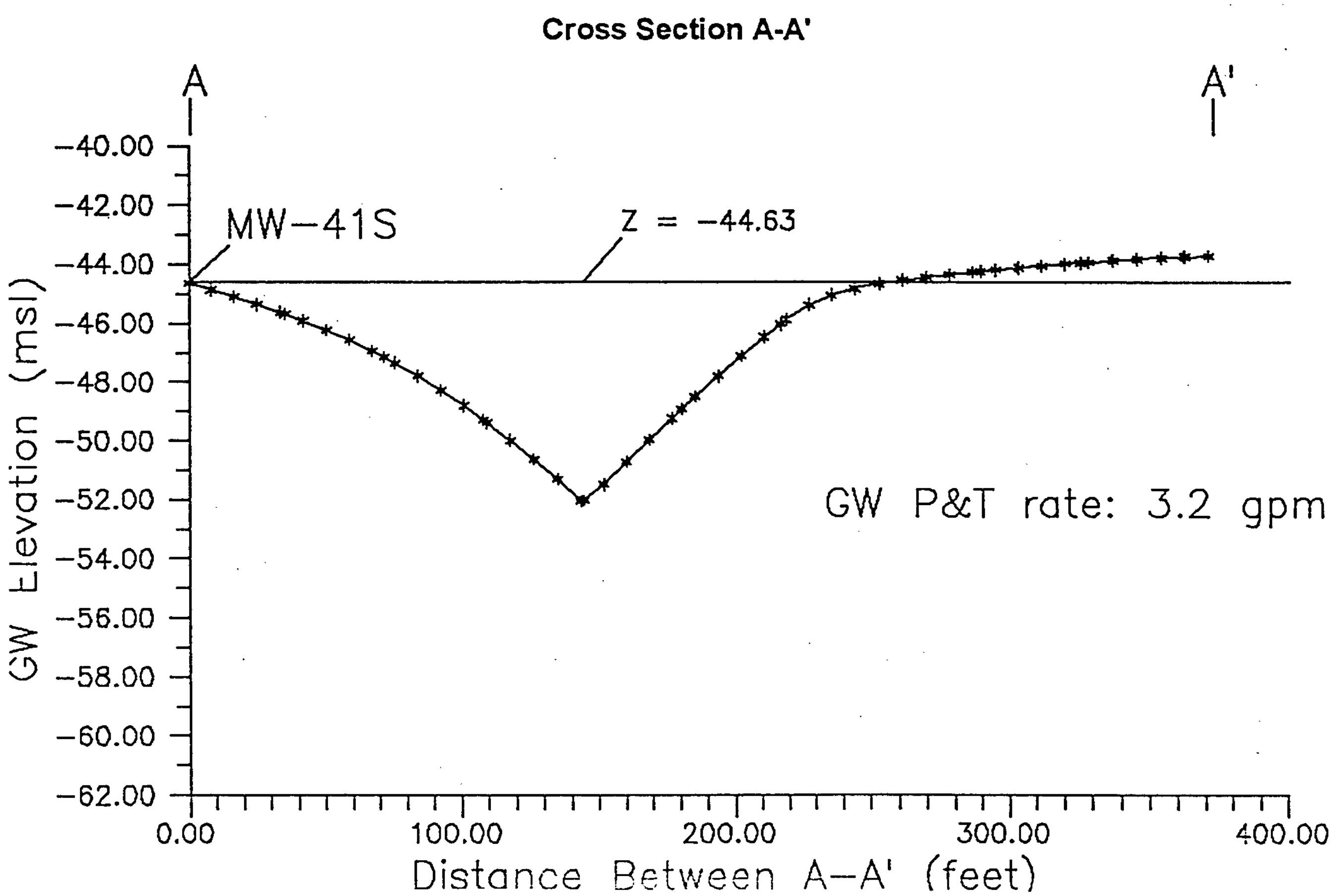


Figure 8b. Plan View and Cross Section Showing the Extent of Drawdown for Groundwater Pump and Treat on January 26, 1994

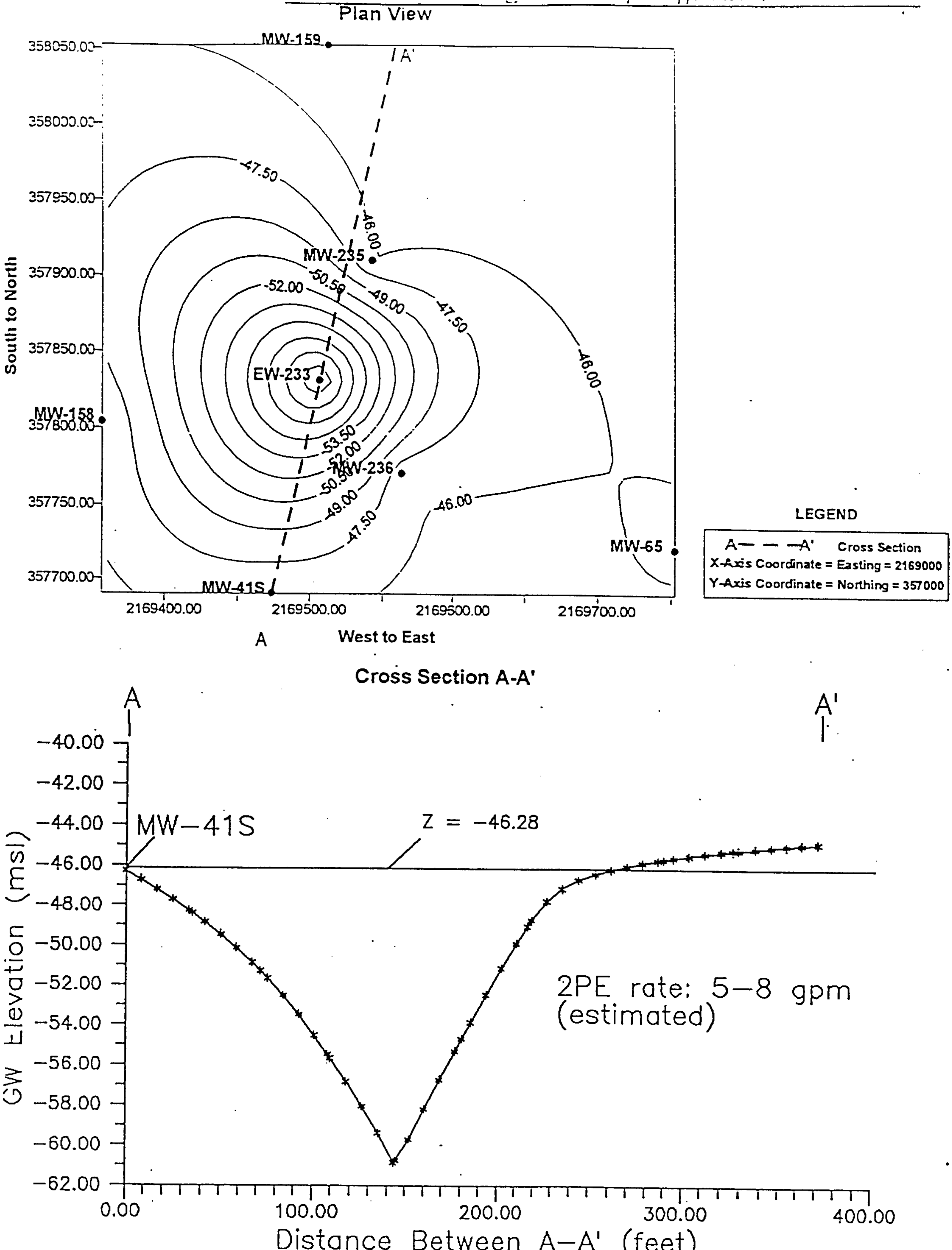


Figure 8c. Plan View and Cross Section Showing the Extent of Drawdown for Groundwater Pump and Treat on August 29, 1994

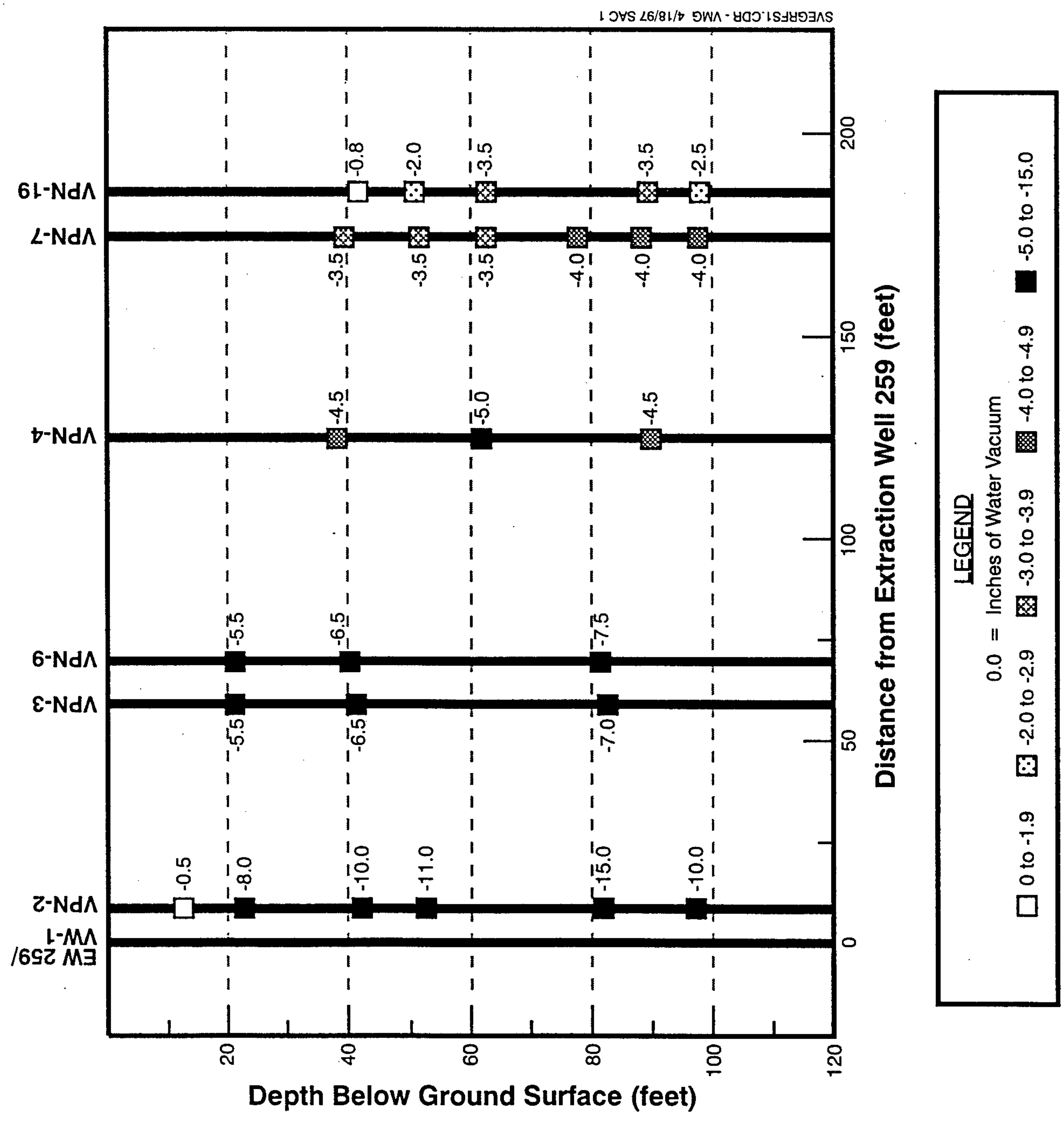


Figure 9. Soil Vapor Extraction Test Extraction Well 259 Vacuum Influence - April 26, 1995

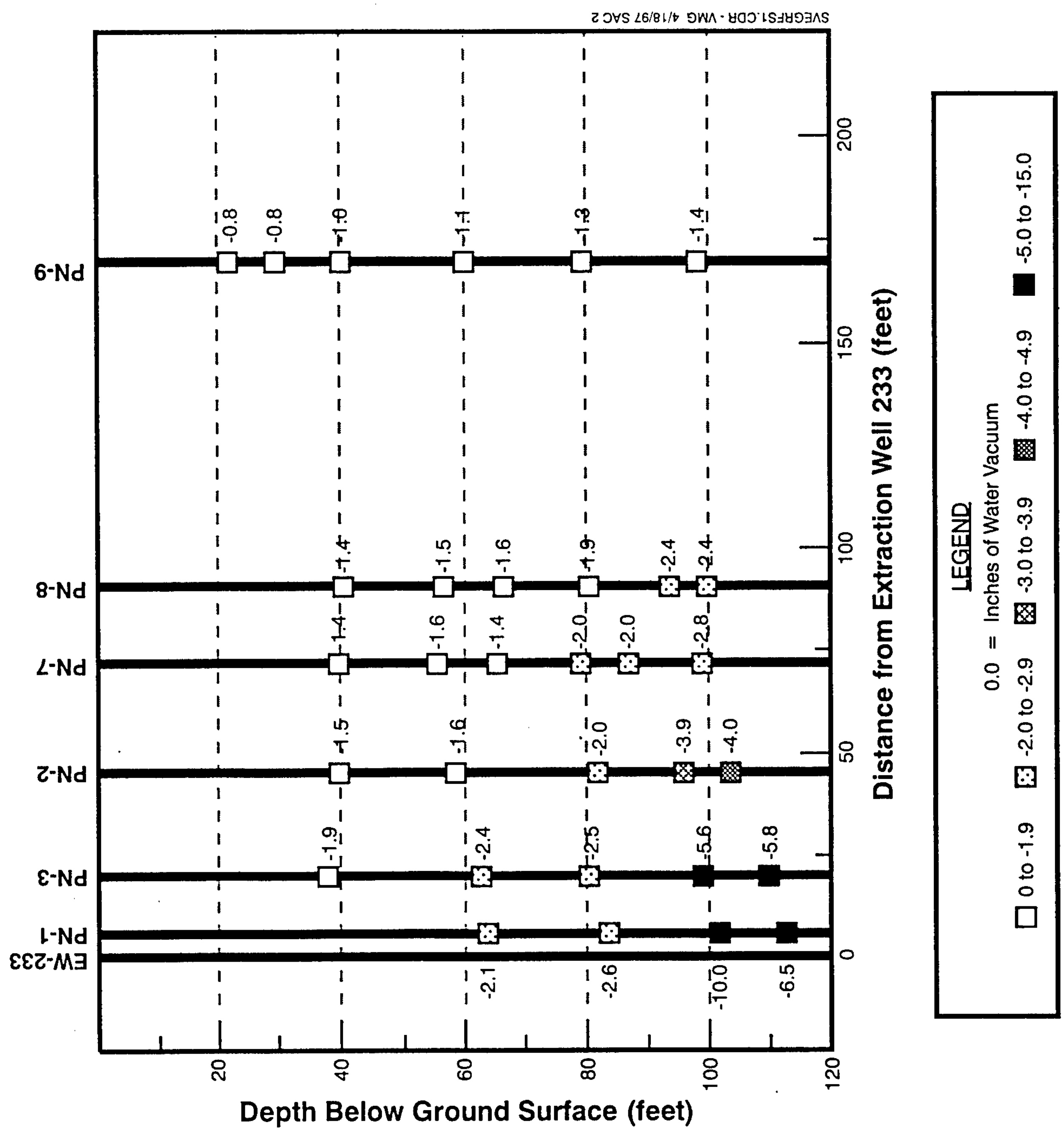
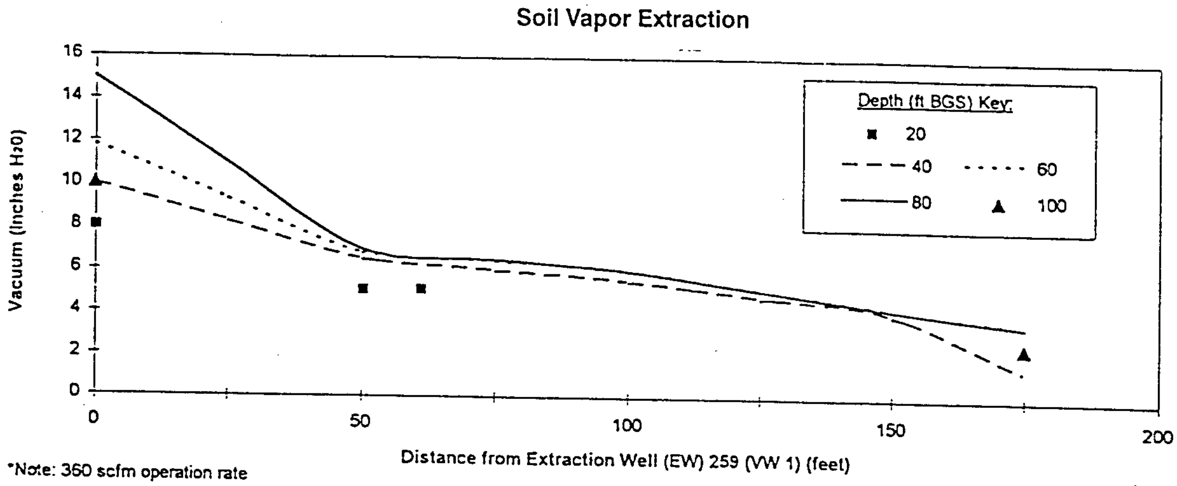
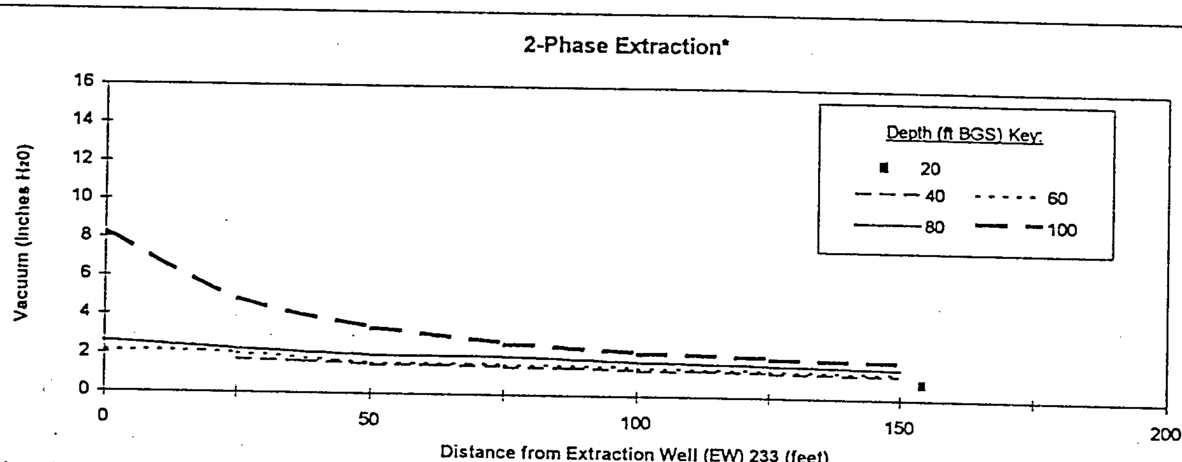


Figure 10. 2-Phase Extraction Test Extraction Well 233 Vacuum Influence - October 17, 1994



*Note: 360 scfm operation rate

Depth (ft. BGS)	Distance (feet from EW-259)					
	0	50	60.5	116	166	176
20	-8	-5.5	-5.5			
40	-10	-6.5	-6.5	-4.5	-3.5	-1.4
60	-11.8	-6.8	-7	-5	-3.5	-3.5
80	-15	-7	-7.5	-4.5	-4	-3.5
100	-10				-4	-2.5



*Note:100 scfm operation rate

Depth (ft. BGS)	Distance (feet from EW-233)					
	0	12.45	37.5	67.5	83	158
20						-0.8
40		-1.9	-1.5	-1.4	-1.4	-1
60	-2.1	-2.4	-1.6	-1.5	-1.55	-1.1
80	-2.6	-2.5	-2	-2	-1.9	-1.3
100	-8.25	-5.7	-3.95	-2.8	-2.4	-1.4

Figure 11. Soil Vapor Extraction and 2-Phase Extraction Vacuum Profiles

eventually flattening out at a distance of 80 feet, whereas vacuum decreased rapidly at the SVE system at 20 to 80 and remained stable beyond a distance of 50 feet.

5.0 COST ESTIMATION

The costs and removal rates for 2PE are based on Section 3 Economic Analysis presented in the ITER report (EPA, 1995). A two-dimensional SVE model was used to simulate removal of 25,500 pounds of TCE from a well screened over its entire length and located in the center of the source area (former Building 666, McClellan AFB). The estimated time to remove 99% of the TCE is approximately 3 years. The model is based on diffusion of TCE in moist, low permeability clay lenses. Vapor flow rate is assumed to be 100 scfm. Groundwater flow and concentrations are based on observations during the demonstration of 2PE. Other parameters including domain, porosity, and VOC physical and chemical constants are summarized in Section 3 of the ITER report (EPA, 1995).

Tables 4 and 5 summarize costs and VOC mass removal rates for 2PE in comparison with SVE and 2PE in comparison with PT. The actual cost is expected to fall in a range from 70% to 150% of this estimate. Identical soil gas flows and concentrations are assumed. The 2PE system ran at 100 scfm during the demonstration test and is used as a basis in the ITER report (EPA, 1995). SVE systems can be designed and operated at this low rate and recent investigations indicate that higher rates per well do not necessarily shorten cleanup time (Bohn, 1997). Twelve separate categories are presented consistent with costs provided in the ITER (EPA, 1995). In Table 4 the estimated costs for 2PE are $721,000 and $28 per pound of VOC as compared to SVE at $623,000 and $24 per pound of VOC. VOC removal is 8,500 pounds per year. Over half these costs are related to treatment of VOCs based on using activated carbon. SVE and 2PE treatment costs are approximately equal. Given the cost sensitivity—70% to 150%—a wide range of off-gas treatment options may be more cost effective than activated carbon. Thermal destruction, biological, and ultraviolet technologies should also be considered. Equipment, site preparation,

Table 4. Cost Comparison Hypothetical Site 2-Phase Extraction and Soil Vapor Extraction

Cost Category	2 PE $/pound	2PE Total $	SVE $/pound	SVE Total $
Site Preparation	1.17	30,000	0.90	23,000
Permitting and Regulatory	0.79	20,000	0.47	12,000
Equipment	2.02	52,000	0.27	7,000
Startup & Fixed	4.14	106,000	4.14	106,000
Operating	2.09	53,000	2.09	53,000
Supplies	0.22	6,000	0.22	6,000
Consumables	.55	14,000	.16	4,000
Effluent Treatment	15.45	393,000	15.41	392,000
Analytical	0.79	20,000	0.39	10,000
Residuals and Waste	0.20	5,000	0.16	4,000
Maintenance	0.70	18,000	0.08	2,000
Site Demobilization	0.16	4,000	0.16	4,000
Total Costs ($/pound)	28.28	0.00	24.45	0.00
Total Costs ($)		721,000		623,000
Mass Removal (pounds/yr)	8,500		8,500	

Table 5. Cost Comparison Hypothetical Site 2-Phase Extraction and Pump and Treat				
Cost Category	**2PE $/pound**	**2PE Total $**	**PT $/pound**	**PT Total $**
Site Preparation	1.17	30,000	100	15,000
Permitting and Regulatory	0.79	20,000	67	10,000
Equipment	2.02	52,000	33	5,000
Startup & Fixed	4.14	106,000	73	11,000
Operating Costs	2.09	53,000	354	53,000
Supplies	0.22	6,000	20	3,000
Consumables	.55	14,000	7	1,000
Effluent Treatment	15.45	393,000	33	5,000
Analytical	0.79	20,000	67	10,000
Residuals and Waste	0.20	5,000	27	4,000
Maintenance	0.70	18,000	13	2,000
Site Demobilization	0.16	4,000	13	2,000
Total Costs ($/pound)	28.28	0.00	807	
Total Costs ($)		721,000		121,000
Mass Removal (pounds/yr)	8,500		50	

electrical utilities, analytical, residuals and wastes and maintenance costs are higher for 2PE than SVE. In Table 5 the estimated costs for 2PE are the same as Table 4 and PT costs are estimated to be $121,000 over three years and $807 per pound of VOC extracted. The higher cost per pound is primarily related to the lower VOC extraction rate of 50 pounds per year or 150 pounds over three years. This mass removal rate is based on an average groundwater extraction flow of 3.1 gpm and VOC concentration of 4,000 µg/L. In addition effluent treatment costs per pound of VOC are higher due to lower adsorption efficiency of activated carbon in groundwater as compared to soil vapor applications. Initial capital costs and yearly electrical power costs are significantly lower than 2PE.

It is important to note SVE would need to be combined with PT (DPE) to provide a technology that is capable of extracting both groundwater and soil vapor. In low permeable soils such as fine sand and silt, well and pump maintenance can add significant costs to operations. 2PE does not require well pumps and eliminates the need for any rotating equipment below ground surface and is often more practical under these conditions. The reverse may be true in permeable formations such as sand and gravel. Less cost is often required for DPE equipment and utilities under these conditions.

Following are detailed assumptions by cost category used as a basis of comparison:

Site Preparation

Site preparation costs for SVE and PT are assumed to be 75% and 50%, respectively, of 2PE costs. The primary difference is electrical power. A 50 kilovolt-amperes (kva) electrical service is required for 2PE whereas SVE and PT require much less electrical power. Well costs and other site preparation costs are assumed equal to 2PE. These costs are dependent on actual site conditions and can vary widely.

Permitting and Regulatory

State and federal treatment/discharge permit cost is estimated to be $10,000 for 2PE and SVE. Local and federal water treatment/ discharge cost is estimated to be $8,000 for 2PE and PT. Local permits for 2PE, SVE, and PT are assumed to cost $2,000 each.

Equipment

Costs cited in the ITER for 2PE include a prepackaged fully automated unit and piping connections to a single well. The total equipment cost is estimated to be $111,500. Annualized costs are $16,993. PT costs are assumed to be 10% or approximately $11,000 for procurement and installation of a pump rated at 8 gpm and nominal piping from the well head and to the carbon treatment system.

Annualized costs are estimated to be $1,700.

Equipment costs for a 100 scfm SVE unit are estimated to be $15,000 (Paragon Environmental Services, Inc., 1997) and annualized costs are estimated to be $2,287.

Startup and Fixed

Labor costs, per diem, transportation, insurance are estimated to be equal for SVE and 2PE and 10% of the cost for PT. Labor hours include assembly, shakedown and testing, training, and disassembly upon closure. PT is less complex and therefore requires less time and a lower labor spread cost per hour than 2PE and SVE.

Operating

Annual operating labor is assumed equal for 2PE, SVE and PT. Labor is assumed at 10 hours per week for one technician and includes travel to and from the site, field readings, troubleshooting, and reporting. All systems are assumed to be automated with alarms, telephone 'call up', and fail safe shutdown features.

Supplies

Cost for supplies is assumed equal for 2PE and SVE. Costs include lubricants, personal protective equipment PPE level D (hard hat, safety shoes, glasses), field sheets, recorder paper, and other items not included under maintenance. The PT system is less complex than 2PE and SVE and therefore requires less supplies and associated costs. An annual cost one half of 2PE and SVE is estimated.

Consumables

Electrical consumption for 2PE was approximately 500 kilowatt hours (kwh) per day during the demonstration. SVE is estimated to be 150 kwh based on using a 7.5 hp positive displacement blower rated at 150 scfm at 8 inches of mercury vacuum (Paragon Environmental Systems Inc., 1997) PT electrical power required for a multistaged centrifugal pump rated at 4 gpm at 140 feet is 1/3rd hp (Grundfos, 1991).

Effluent Treatment

Treatment cost for SVE and 2PE per pound of contaminant removed are assumed to be approximately equal. The carbon is assumed to be regenerated at an EPA-permitted facility and recycled to McClellan AFB for reuse. A replacement cost of approximately $2.15 per pound of carbon is estimated and an organic loading of 25% is assumed. A slight difference—$18.40 average 2PE versus $18.46 per pound VOCs SVE—is attributable to a small portion of 2PE VOCs being removed in the groundwater phase.

Aqueous treatment costs for PT and 2PE are based on 5% loading on activated carbon in series and off-site regeneration and recycling. Two 1,000-pound activated carbon vessels in series are used as a basis. Contaminant mass removal rate for 2PE groundwater is 34 pounds per year and PT is estimated at 50 pounds per year (URS, 1996b). Replacement carbon costs are based on $2.15 per pound.

Analytical

Analytical costs for 2PE are estimated to cost $20,000. Twenty soil and 20 groundwater analyses at $500 per sample are assumed. SVE costs are based on 20 soil samples or $10,000. PT costs are based on 20 groundwater samples at a cost of $10,000.

Residuals and Waste

2PE is estimated to generate 10 drums of waste consisting of 3 drums of vacuum oil and 7 drums of PPE. At $500 per drum, the total estimated cost is $5,000. SVE and PT are assumed to generate 7 drums of PPE at an estimated cost of approximately $4,000 each.

Maintenance

Maintenance costs for 2PE are assumed to be 3% of fixed capital investment and are estimated to be $6,000 per year or $18,000 over these years. Likewise, SVE and PT are also assumed to be 3% of fixed capital investment and are estimated at approximately $2,000 each.

Site Demobilization

Demobilization including rental of equipment and disassembly of 2PE at the completion of remediation is estimated at $4,000. Included is labor and rental equipment necessary for decontaminating and disconnecting piping and electrical, disposal of used oil, and securing the 2PE unit for transport. SVE is expected to have approximately the same costs. PT is estimated at half these costs because the system is smaller and less complex.

6.0 CONCLUSIONS

In conclusion, 2PE has been demonstrated to provide effective groundwater and soils vapor removal of VOCs contamination. 2PE can often increase groundwater flow rates and VOCs mass removal in existing PT extraction wells in low permeability formations. At McClellan AFB a two-fold increase in groundwater production and an order of magnitude increase in chemical contaminant removal was achieved within the same well. In comparing performance with SVE, it is important to note that 2PE well EW-233 was located outside the source area whereas SVE well VW-1 was located within the source area. Higher VOCs mass removal are expected if 2PE were located in the source area. 2PE generally requires more electrical energy than SVE or DPE per pound of contaminant removed. The additional energy is required to generate sufficient vacuum to provide an influence in low permeability formations and convey soil gas and water to the surface. Under these conditions, the majority of VOCs are transferred from groundwater to soil vapor reducing the costs and complexity for treatment. In addition, well pumps and associated maintenance are eliminated.

7.0 REFERENCES

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APPENDIX A

Volume Computation Sheets

VOLUME COMPUTATIONS

UPPER SURFACE

Grid File: H:/ALF/SURFER/AUG93.GRD
Rows: 0 to 32766
Cols: 0 to 32766
Grid size as read: 70 cols by 70 rows
Delta X: 5.65217
Delta Y: 5.26087
X-Range: 2.16936E+006 to 2.16975E+006
Y-Range: 357690 to 358053
Z-Range: -57.343 to -42.4243

LOWER SURFACE

Level Surface defined by Z = -44.03

VOLUMES

Approximated Volume by
Trapezoidal Rule: -163329
Simpson's Rule: -163377
Simpson's 3/8 Rule: -163378

CUT & FILL VOLUMES

Positive Volume [Cuts]: 48508.1
Negative Volume [Fills]: 211840
Cuts minus Fills: -163332

AREAS

Positive Planar Area
(Upper above Lower): 66530.4
Negative Planar Area
(Lower above Upper): 75039.6
Blanked Planar Area: 0
Total Planar Area: 141570

Positive Surface Area
(Upper above Lower): 66535.1
Negative Surface Area
(Lower above Upper): 75245

VOLUME COMPUTATIONS

UPPER SURFACE

Grid File: H:/ALF/SURFER/JAN94.GRD
Rows: 0 to 32766
Cols: 0 to 32766
Grid size as read: 70 cols by 70 rows
Delta X: 5.65217
Delta Y: 5.26087
X-Range: 2.16936E+006 to 2.16975E+006
Y-Range: 357690 to 358053
Z-Range: -52.1501 to -43.6542

LOWER SURFACE

Level Surface defined by Z = -44.63

VOLUMES

Approximated Volume by
Trapezoidal Rule: -139288
Simpson's Rule: -139307
Simpson's 3/8 Rule: -139308

CUT & FILL VOLUMES

Positive Volume [Cuts]: 13266.1
Negative Volume [Fills]: 152559
Cuts minus Fills: -139293

AREAS

Positive Planar Area
(Upper above Lower): 33225.8
Negative Planar Area
(Lower above Upper): 108344
Blanked Planar Area: 0
Total Planar Area: 141570

Positive Surface Area
(Upper above Lower): 33227.3
Negative Surface Area
(Lower above Upper): 108410

2PE August 1994 (limited dataset)

VOLUME COMPUTATIONS

UPPER SURFACE

Grid File: H:/ALF/SURFER/AUG94.GRD
Rows: 0 to 32766
Cols: 0 to 32766
Grid size as read: 70 cols by 70 rows
Delta X: 5.65217
Delta Y: 5.26087
X-Range: 2.16936E+006 to 2.16975E+006
Y-Range: 357690 to 358053
Z-Range: -61.0022 to -44.5899

LOWER SURFACE

Level Surface defined by Z = -46.28

VOLUMES

Approximated Volume by
Trapezoidal Rule: -176588
Simpson's Rule: -176640
Simpson's 3/8 Rule: -176642

CUT & FILL VOLUMES

Positive Volume [Cuts]: 51038.1
Negative Volume [Fills]: 227630
Cuts minus Fills: -176592

AREAS

Positive Planar Area
(Upper above Lower): 67220.8
Negative Planar Area
(Lower above Upper): 74349.2
Blanked Planar Area: 0
Total Planar Area: 141570

Positive Surface Area
(Upper above Lower): 67226.6
Negative Surface Area
(Lower above Upper): 74602