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HYDRAULIC FRACTURING TECHNOLOGY

TECHNOLOGY EVALUATION REPORT

UNIVERSITY OF CINCINNATI/RISK REDUCTION ENGINEERING LABORATORY
CINCINNATI, OHIO

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FOREWORD

The SITE program was authorized by the Superfund Amendments and Reauthorization Act (SARA) of 1986. The program is administered by the EPA Office of Research and Development (ORD). The purpose of the SITE program is to accelerate the development and use of innovative cleanup technologies applicable to Superfund and other hazardous waste sites. This purpose is accomplished through technology demonstrations designed to provide performance and cost data on selected technologies.

This project consisted of two pilot-scale demonstrations conducted under the SITE program to evaluate the hydraulic fracturing technology developed by the University of Cincinnati (UC) and EPA's Risk Reduction Engineering Laboratory (RREL) A full-scale demonstration using an EPA approved Quality Assurance Project Plan (QAPP) has not been conducted for this technology. The technology demonstrations were conducted at a Xerox Corporation (Xerox) vapor extraction site in Oak Brook, Illinois (Xerox Oak Brook site); and at a bioremediation site near Dayton, Ohio (the Dayton site). The demonstrations provided information on the performance and cost of the technology. Tests to determine the performance of hydraulic fractures over a l-year period were conducted at an uncontaminated site at the UC Center Hill Solid and Hazardous Waste Research (Center Hill) Facility in Cincinnati, Ohio. This technology evaluation report (TER) describes the development, demonstration, and evaluation of the hydraulic fracturing technology.

Copies of the TER can be purchased from the National Technical Information Service (NTIS), Ravenswortb Building, Springfield, Virginia 22161, 703/487-4600. Reference copies will be available at EPA libraries in the Hazardous Waste Collection.

E. Timothy Oppelt, Director
Risk Reduction Engineering Laboratory

ABSTRACT

This report evaluates the effectiveness of the hydraulic fracturing technology developed jointly by the UC and EPA's RREL in enhancing the permeability of contaminated silty clays and presents technical data from tests conducted at the UC Center Hill Facility and from two pilot-scale SITE demonstrations,

The hydraulic fracturing technology creates sand-filled fractures up to 1 inch thick and 30 feet (ft) in radius. These fractures are placed at multiple depths ranging from 5 to 40 ft below ground surface (bgs) to enhance the efficiency of treatment technologies such as soil vapor extraction (SVE), in situ bioremediation, and pump-and-treat systems.

Tests were conducted at the Center Hill Facility by UC to determine the factors affecting soil vapor flow through sand-filled hydraulic fractures. A significant finding from these tests is that rainfall decreases vapor yield and increases the suction head of fractured wells. The zone of pneumatic control of a fractured well was 15 to 30 times farther from the well than that of an unfractured well at the Center Hill Facility, and vapor yield was about an order of magnitude higher than from an unfractured well.

The hydraulic fracturing technology was demonstrated in 1991 and 1992 at the Xerox Oak Brook site, where SVE was being conducted. On-site soil contamination included ethylbenzene; 1,1-dichloroethane (DCA); trichloroethene (TCE); tetrachloroethene (PCE); **1, 1,** 1-trichloroethane (TCA); toluene; and xylene. The vapor flow rates, soil vacuums, and contaminant yields of two hydraulically fractured and two unfractured wells were compared. The fractured wells were fractured at 6, 10, and 15 ft bgs. The vapor yield from fractured wells was one order of magnitude greater than from unfractured wells. This higher yield was obtained in an area 30 times greater than the area affected by the unfractured well. The contaminant mass recovery from fractured wells was 7 to 14 times greater than that from the unfractured well.

Another pilot-scale demonstration was conducted in 1991 and 1992 at the Dayton site, where bioremediation was being conducted. Site contamination included benzene, toluene, ethylbenzene, and xylene (BTEX); and total petroleum hydrocarbons (TPH). Fractures were created at 7, 8, 10,

and 12 ft bgs at one of two on-site wells. Water containing hydrogen peroxide and nutrients was pumped into the hydraulically fractured well and into one unfractured well 50 ft from the fractured well. The injection rates, soil moisture contents, microbial metabolic activity, numbers of colony forming units (CFU), and rates of bioremediation at the fractured and unfractured wells were compared. In the fractured well, the injection rate was 25 to 40 times greater, and moisture content increased 2 to 4 times near the fracture. Comparison of microbial metabolic activity, CFU, and rates of bioremediation were inconclusive.

Economic data indicate that the capital cost for hydraulic fracturing equipment is $92,900 and the cost of renting the equipment is $1,000 per day. Rental, operating, and monitoring costs for creating a fracture range from $950 to $1,425, depending on site-specific conditions. Typically, two to three fractures are created per well, and four to six fractures can be created in 1 day. The cost of creating a fracture is not materially affected by the depth of fracture for depths ranging from 5 to 40 ft bgs. The cost is also unaffected by the type of soil encountered.

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LIST OF ACRONYMS AND ABBREVIATIONS

ASTM	American Society for Testing and Materials
bgs	Below ground surface
BTEX	Benzene, toluene, ethylbenzene, and xylene
Center Hill Facility	Center Hill Solid and Hazardous Waste Research Facility
Cfm	Cubic foot per minute
CFU	Colony forming unit
cm/sec	Centimeter per second
DCA	l,l-Dichloroethane
EPA	U.S. Environmental Protection Agency
ft	foot
ft^3	Cubic foot
GC	Gas chromatography
GEMS	Ground Elevation Measurement System
gpd	Gallon per day
gpm	Gallon per minute
mm	Millimeter
NA	Not applicable
ND	Not detected
NI	No impact
ORD	Office of Research and Development
OSWER	Office of Solid Waste and Emergency Response
PCE	Tetrachloroethene
ppb	Part per billion
psi	Pound per square inch
PVC	Polyvinyl chloride
QAPP	Quality Assurance Project Plan
QA/QC	Quality assurance and quality control
RREL	Risk Reduction Engineering Laboratory
SARA	Superfund Amendments and Reauthorization Act of 1986
SITE	Super-fund Innovative Technology Evaluation

SVE	Soil vapor extraction
TCA	l,l,l-Trichloroethane
TCE	Trichloroethene
TER	Technology evaluation report
TPH	Total petroleum hydrocarbon
UC	University of Cincinnati
μg/kg	Microgram per kilogram
UST	Underground storage tank
V O C	Volatile organic compound
Xerox	Xerox Corporation

ACKNOWLEDGEMENTS

This report was prepared under the direction of Naomi Barkley, the EPA SITE project manager at EPA's RREL in Cincinnati, Ohio. Contributors and reviewers for this report were Messrs. Allen Wolf and Mark Kemper, Dr. Lawrence Murdoch, and Dr. Steven Vesper of UC in Cincinnati, Ohio; and Mr. Elliott Duffney of Xerox in Rochester, New York. Peer reviewers were Dr. Ronald Lewis and Robert Stenburg of RREL.

This report was prepared by Drs. V. Rajaram and Pinaki Banerjee of PRC Environmental Management, Inc. (PRC). The report was typed by Ms. Cheryl Vaccarello, edited by Ms. Shelley Fu, and reviewed by Dr. Kenneth Partymiller and Mr. Stanley Labunski, all of PRC.

EXECUTIVE SUMMARY

The cleanup of volatile organic chemical (VOC) and petroleum hydrocarbon spills in low permeability soils is a significant problem in many parts of the United States. In situ techniques for cleaning up these sites are preferable because they minimize the risk of spreading the contamination and are cost-effective. However, these techniques are hampered by the low permeability of the soils. A method of enhancing the permeability of the contaminated soil will enhance in situ remediation.

The University of Cincinnati (UC) and U.S. Environmental Protection Agency (EPA) Risk Reduction Engineering Laboratory (RREL) developed the hydraulic fracturing technology to enhance the permeability of silty clays. This technology was evaluated under the EPA Superfund Innovative Technology Evaluation (SITE) program. The hydraulic fracturing technology was developed at the Center Hill Solid and Hazardous Waste Research (Center Hill) Facility. Tests were conducted at the Center Hill Facility to determine factors affecting the performance of the hydraulic fractures. Demonstrations were conducted during 1991 and 1992 at two sites, a Xerox Corporation (Xerox) site in Oak Brook, Illinois (the Xerox Oak Brook site), where soil vapor extraction (SVE) was being conducted, and at a site in Dayton, Ohio (the Dayton site), where bioremediation was being conducted.

The technology demonstrations had the following objectives:

- To establish the viability of creating sand-filled hydraulic fractures in low permeability silty clays
- To study the factors that affect the performance of the fractures over time
- To compare the vapor flow rates in wells in fractured and unfracturecl soils
- To compare the water flow rates and moisture contents in fractured and unfractured soils
- To develop information required to estimate the operating costs of the technology

The results obtained at the Center Hill Facility and the two SITE demonstrations are discussed below.

Center Hill Facility Tests

Researchers from UC conducted field testing during the winter and summer of 1992 to determine the effect of sand-filled hydraulic fractures on SVE performance. The tests were conducted next to the Center Hill Facility. The soil at the testing location is underlain by silty clay with minor amounts of sand and gravel. Five wells were used during the tests. Wells No. CHFl, CHF2, and CHF3 intersected hydraulic fractures. Well No. CHFl was screened with a 2-inch-diameter screen centered on the fracture in ground fractured at 5 and 10 feet (ft) below ground surface (bgs); Well No. CHF2 was screened in ground fractured at 5 ft bgs and the fracture reached the ground surface (vented); and Well No. CHF3 was screened in ground fractured at 5 ft bgs. Two conventional wells, Wells No. CHC1 and CHC2, were screened in unfractured ground. Well No. CHC1 was screened from 51 to 69 and 111 to 129 inches bgs, and Well No. CHC2 was screened from 47 to 60 inches bgs.

Comparison of the performance of fractured wells individually and with the performance of conventional wells over two distinct periods (January 20 to March 2, 1992; and June 8 to July 7, 1992) yielded the following results:

- The air flow from a fractured well was about an order of magnitude higher than from an unfractured well.
- The zone of pneumatic control extended more than 10 times farther from the fractured well than from the unfractured well.
- Rainfall decreased the air flow and increased the suction head of fractured wells, and unfractured wells were not affected by rainfall.
- The effect of a vented fractured well was not significantly different than that of an unvented fractured well.

Xerox Oak Brook Site Demonstration

At the Xerox Oak Brook site, contaminants consisting of trichloroethene (TCE); **1,** 1, 1-trichloroethane (TCA); 1, l-dichloroethane (DCA), tetrachloroethene (PCE) and other solvents are present in silty clay till to depths of 20 ft bgs. Xerox installed a two-phase vapor extraction system to clean up the site. In an effort to enhance SVE, Xerox requested UC to create hydraulic fractures. Fractures were created at depths of 6, 10, and 15 ft bgs at two locations; these fractures measured about 20 ft in length. Multilevel recovery wells, Wells No. RW3 and RW4, were installed to access each fracture individually. The vapor recovery rates from these wells were compared to rates from unfractured Wells No. RWl and RW2. A multilevel monitoring system consisting of as many as six pneumatic piezometers per borehole was installed at radial distances of 5, 10, 15, and 20 ft from each recovery well.

The vapor flow rates and contaminant concentrations were measured on a continuous basis using vortex shedding flow meters and on-line gas chromatography, respectively. Other parameters measured included water quality in monitoring wells around the site, water discharge from the vapor extraction system, soil moisture content, and soil vacuum at the recovery wells and monitoring holes. Results obtained from December 1991 through December 1992 led to the following conclusions:

- Fractured wells yielded vapor flow rates 15 to 30 times greater than unfractured wells.
- Vapor flow rates were adversely affected by precipitation.
- Contaminant yields from the fractured wells were one order of magnitude greater than from comparable zones in the unfractured wells.
- The zone of pneumatic control extended more than 10 times farther from the fractured well than from the unfractured well.

Dayton Site Demonstration

At the Dayton site, six underground storage tanks (UST) were removed in December 1989. Laboratory analysis of the soil samples collected from the UST excavations indicated that benzene, toluene, ethylbenzene, xylene (BTEX); and total petroleum hydrocarbons (TPH) are present. The site consists of stiff sandy to silty clay with traces of gravel. A remedial action contractor initiated bioremediation activities at the site in 1991. UC created hydraulic fractures at the site in August 1991 at depths of 7, 8, 10, and 12 ft bgs. Water containing hydrogen peroxide and nutrients was introduced into a fractured well, Well No. SAD-2, and an unfractured well, Well No. SAD-4, from December 1991 to August 1992.

A set of samples was collected in September, 1991 to establish initial contaminant concentrations. Soil samples taken at 5, 10, and 15 ft north of the wells were analyzed for moisture, BTEX, and TPHs. In February 1992, after about 30 days of bioremediation, soil samples were obtained at the same locations and analyzed for moisture content, BTEX, TPHs, number of hydrocarbon degraders (colony forming units [CFU]), and microbial metabolic activity. A similar round of sampling and analysis was conducted in July 1992.

Comparison of the data obtained from the fractured and unfractured well yielded the following findings:

- Moisture content increased in the vicinity of the fractured well, especially in the fractured zones. No change in moisture content was detected in the unfractured well.

- The flow of water was about 25 to 40 times greater in the fractured well than in the unfractured well.

Conclusions

Pilot-scale demonstrations at the Xerox Oak Brook two-phase SVE site and at the Dayton bioremediation site indicate the significant benefits of hydraulic fracturing in remediating contaminated sites. The cost and time needed to create the sand-filled hydraulic fractures is small; therefore, the benefit-to-cost ratio is high.

The technology of creating and monitoring the location of sand-filled hydraulic fractures was established over the past 2 years. Future work in improving this technology should focus on creating vertical fractures to connect the in situ horizontal fractures and further increase the overall permeability of the soil mass.

1.0 INTRODUCTION

PRC Environmental Management, Inc. (PRC), was awarded a work assignment under the Superfund Innovative Technology Evaluation (SITE) program to monitor and prepare a technology evaluation report (TER) on hydraulic fracturing. This technology has the potential to significantly improve the performance of in situ vapor extraction systems and bioremediation processes in low-permeability silty clays. The technology was included in the U.S. Environmental Protection Agency's (EPA) SITE program in 1991. The technology was jointly developed by the Department of Civil and Environmental Engineering at the University of Cincinnati (UC) and EPA's Risk Reduction Engineering Laboratory (RREL).

Field studies at the Center Hill Solid and Hazardous Waste Research (Center Hill) Facility were conducted to determine the performance of hydraulic fracturing in silty clays. UC also created sand-filled hydraulic fractures at a contaminated site owned by the Xerox Corporation (Xerox) in Oak Brook, Illinois (the Xerox Oak Brook site). The performance of these fractures in remediating the site was studied in 1991 and 1992. Another contaminated site in Dayton, Ohio (the Dayton site), was studied from September 1991 to July 1992 to determine the effectiveness of this technology in enhancing bioremediation. The SITE program, demonstration program objectives, purpose of the TER, and TER report organization are discussed below.

1.1 SITE PROGRAM

In response to the Superfund Amendments and Reauthorization Act of 1986 (SARA), EPA's Office of Research and Development (ORD) and Office of Solid Waste and Emergency Response (OSWER) established the SITE program to (1) accelerate the development, demonstration, and use of new or innovative technologies to clean up Superfund sites; (2) foster further investigation and development of treatment technologies that are still at the laboratory scale; and (3) demonstrate and evaluate new or innovative measurement and monitoring technologies

The primary purpose of the SITE program is to enhance the development and demonstration, and thereby promote the commercial availability, of innovative technologies applicable to Superfund sites Major goals of the SITE program are the following:

- Identify and remove impediments to the development and commercial use of alternative technologies
- Demonstrate more promising innovative technologies in order to establish reliable performance and cost information for site cleanup decision making
- Develop procedures and policies that encourage selection of available alternative treatment remedies at Superfund sites
- Structure a development program that nurtures emerging technologies

EPA recognizes that a number of forces inhibit the expanded use of alternative technologies at Superfund sites. One of the objectives of the program is to identify these impediments and remove them or develop methods to promote the expanded use of alternative technologies.

Another objective of the SITE program is to demonstrate and evaluate selected technologies. This objective is a significant ongoing effort involving ORD, OSWER, EPA Regions, and the private sector. The demonstration program tests field-ready technologies and provides Superfund decision makers with information necessary to evaluate the use of these technologies for future cleanup actions.

Other aspects of the SITE program include developing procedures and policies that match available technologies with wastes, media, and sites requiring actual remediation; and providing assistance in nurturing the development of emerging innovative technologies from the laboratory- or bench-scale to the full-scale stage.

Technologies chosen for a SITE demonstration must be innovative, pilot- or full-scale applications, and offer some advantage over existing technologies. Mobile technologies are of particular interest.

1.2 DEMONSTRATION PROGRAM OBJECTIVES

The objectives of the SITE Demonstration Program for the hydraulic fracturing technology are as follows:

- To establish the viability of creating sand-filled hydraulic fractures in low permeability silty clays
- To study the factors that affect these fractures over time
- To compare vapor flow rates in fractured and unfractured wells
- To compare the water flow rates and moisture content in fractured and unfractured wells
- To develop information required to estimate operating costs for hydraulic fracturing

1.3 PURPOSE OF THE TER

This TER provides a comprehensive description of the demonstrations at the Xerox Oak Brook and Dayton sites and their results. This report is intended for individuals performing a detailed evaluation of the hydraulic fracturing technology for a specific site and waste situation. The purpose of these technical evaluations is to obtain a detailed understanding of the performance of the technology during the demonstrations, and to ascertain the advantages, risks, and costs of the technology for the given applications. This information is used to produce conceptual designs of sufficient detail to enable the preparation of preliminary cost estimates for the demonstrated technology.

1.4 REPORT ORGANIZATION

This report provides an independent assessment of the technology and data from the Center Hill Facility and the Xerox Oak Brook and Dayton sites. Section 2.0 describes the hydraulic fracturing technology. Sections 3.0, 4.0, and 5.0 provide details of the studies conducted at the Center Hill Facility, the Xerox Oak Brook site, and the Dayton site. Section 6.0 describes the quality assurance and quality control (QA/QC) analyses conducted on this project. Section 7.0 discusses the costs of hydraulic fracturing and details the benefits of the technology. Conclusions are provided in Section 8.0. References are provided in Section 9.0.

- To establish the viability of creating sand-filled hydraulic fractures in low permeability silty clays

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2.0 DESCRIPTION OF TREATMENT TECHNOLOGY

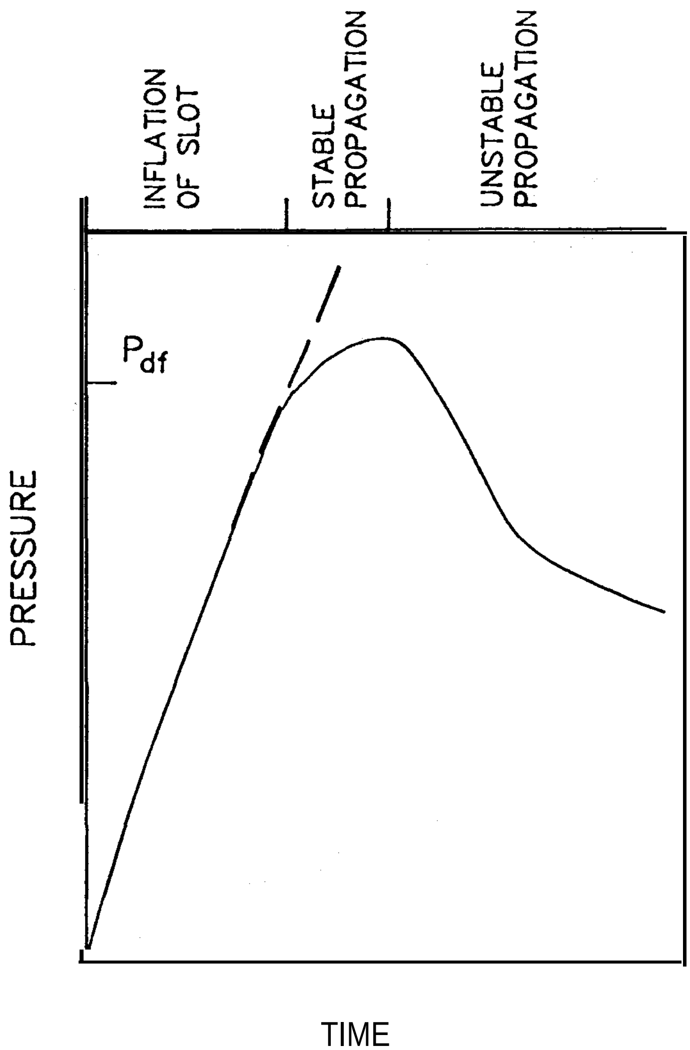
The removal of contaminants in shallow soil through vapor extraction or bioremediation is hampered by the low permeability of silty clays. In certain low permeability clays, in situ cleanup is impossible without enhancing soil permeability. Pneumatic fracturing has been attempted to increase the permeability of clay layers. The disadvantage of pneumatic fracturing is that pneumatic fractures may close as time passes. UC has been developing the hydraulic fracturing technique at the Center Hill Facility since 1990 with funding from EPA's RREL. Pilot-scale demonstrations to determine the technology's effectiveness in enhancing vapor extraction and bioremediation have been conducted in 1991 and 1992.

The hydraulic fracturing technique consists of creating fractures in low permeability clays by pumping a gel containing coarse sand into the zone to be fractured. Sand is deposited into the fractures and enhances the permeability of the contaminated soil. Hydraulic fracturing in shallow deposits and the hydraulic fracturing method are described in this section.

2.1 HYDRAULIC FRACTURING IN SHALLOW DEPOSITS

Hydraulic fracturing has been successfully used in the oil industry to enhance oil recovery from deep, tight (low permeability) oil reserves. The mechanics of hydraulic fracturing in rock formations is well understood (Hubbert and Willis, 1957). Application of hydraulic fracturing in cohesive soil formations has been attempted to increase soil permeability (Murdoch, 1990). When filled with permeable sand, the horizontal fractures created in an impermeable material improve the rate of flow through the material.

Laboratory experiments have been conducted at the Center Hill Facility to determine the effect of slot length (also known as "initial fracture") and soil moisture content on the propagation of fractures in silty clay (Murdoch, 1993). A typical record of injection pressure versus time obtained during laboratory tests is presented in Figure 2-l. This record indicates that fully developed (stable propagation) fracturing occurs at the break in slope, denoted by P_{df}. The injection pressure at this point is the critical pressure required to initiate fracturing. During the period of stable fracture propagation, the injection pressure increases. After reaching a peak pressure, the pressure decreases,



Source: Modified from Murdoch, 1993

Figure 2-1. Injection Pressure Versus Time.

and this period indicates unstable fracture propagation, when the fracture continues to propagate at decreasing pressure. The pressure at the onset of propagation depends on the length of the initial slot, the water content of the soil, and other factors. Injection pressure diminishes markedly as initial slot length and water content increase. A theoretical analysis of laboratory observations indicate that pore fluid infiltrating into the tip of a propagating fracture can control many details of hydraulic fracture development in soil (Murdoch, 1993).

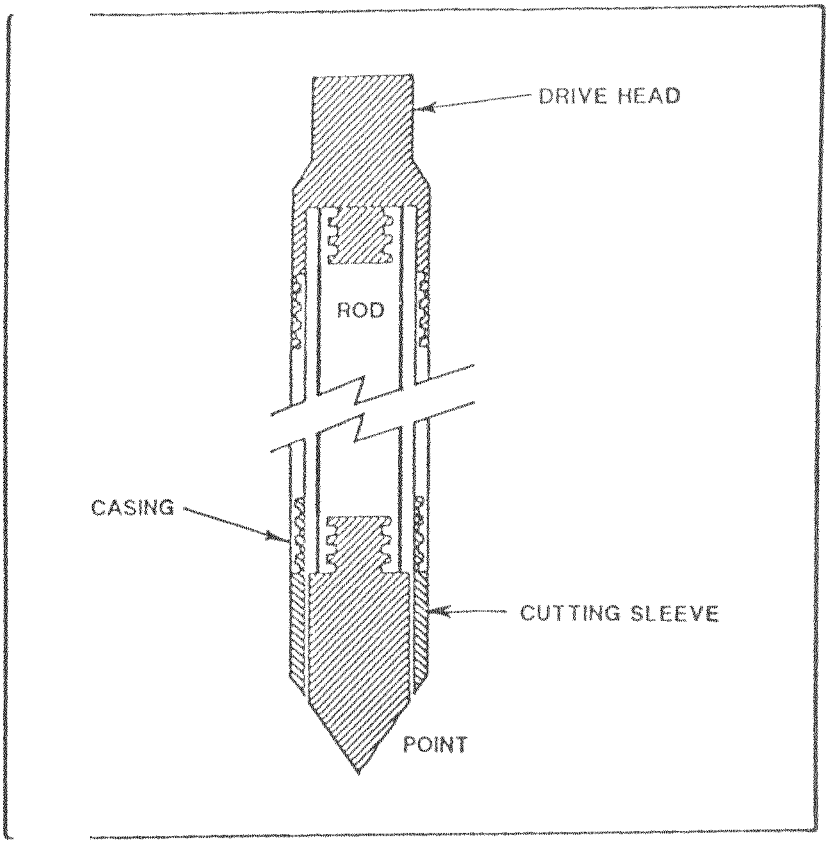
2.2 HYDRAULIC FRACTURING METHOD

The equipment and materials used for creating hydraulic fractures include the following:

- A piston pump or a progressive cavity pump to inject slurry, which consists of up to one part solid to two parts liquid
- A continuous mixer for creating the slurry
- A fracturing lance composed of an outer casing and an inner rod, both of which are tipped with hardened cutting surfaces that form a conical point to prepare boreholes used for hydraulic fracturing (see Figure 2-2)
- Steel tubing with a narrow orifice at one end
- Guar gum gel with a borate cross-linker and an enzyme breaker to carry the coarse sand proppant
- A rubber-tired trailer on which the slurry mixing equipment is mounted (see Figure 2-3)

The sequence of operations for creating hydraulic fractures follows Steps 1 through 5 in Figure 2-4. First, the lance is driven to the desired depth. Individual segments of the rod and casing are 5 feet (ft) long and are threaded together as required by borehole depth. Next, the lance is removed, leaving soil exposed at the bottom of the casing. Steel tubing with a narrow orifice at one end is then inserted in the casing.

Next, water is pumped through the steel tubing and into the narrow orifice, forming a jet that cuts laterally into the soil. The jetting device is rotated, producing a disc-shaped notch extending 4 to 6 inches away from the borehole. A simple measuring apparatus, built from a steel tape extending the length of the tube and making a right angle bend at the end of the tube, is inserted into the casing to measure the radius of the slot.



Source: Modified from UC, 1991a

Figure 2-2. Fracturing Lance Used to Prepare Boreholes for Hydraulic Fracturing.

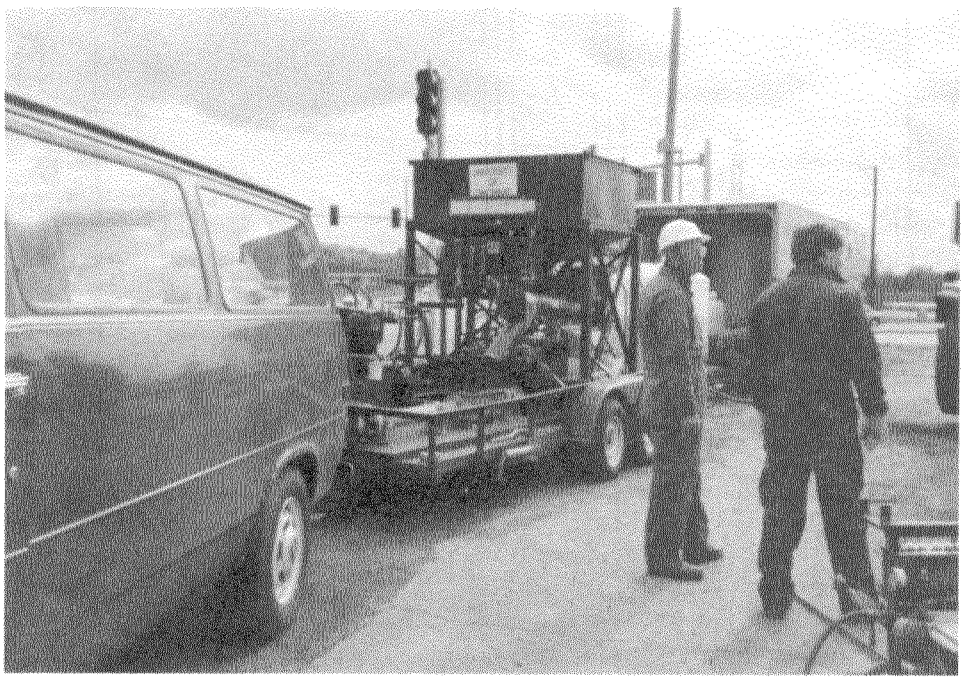
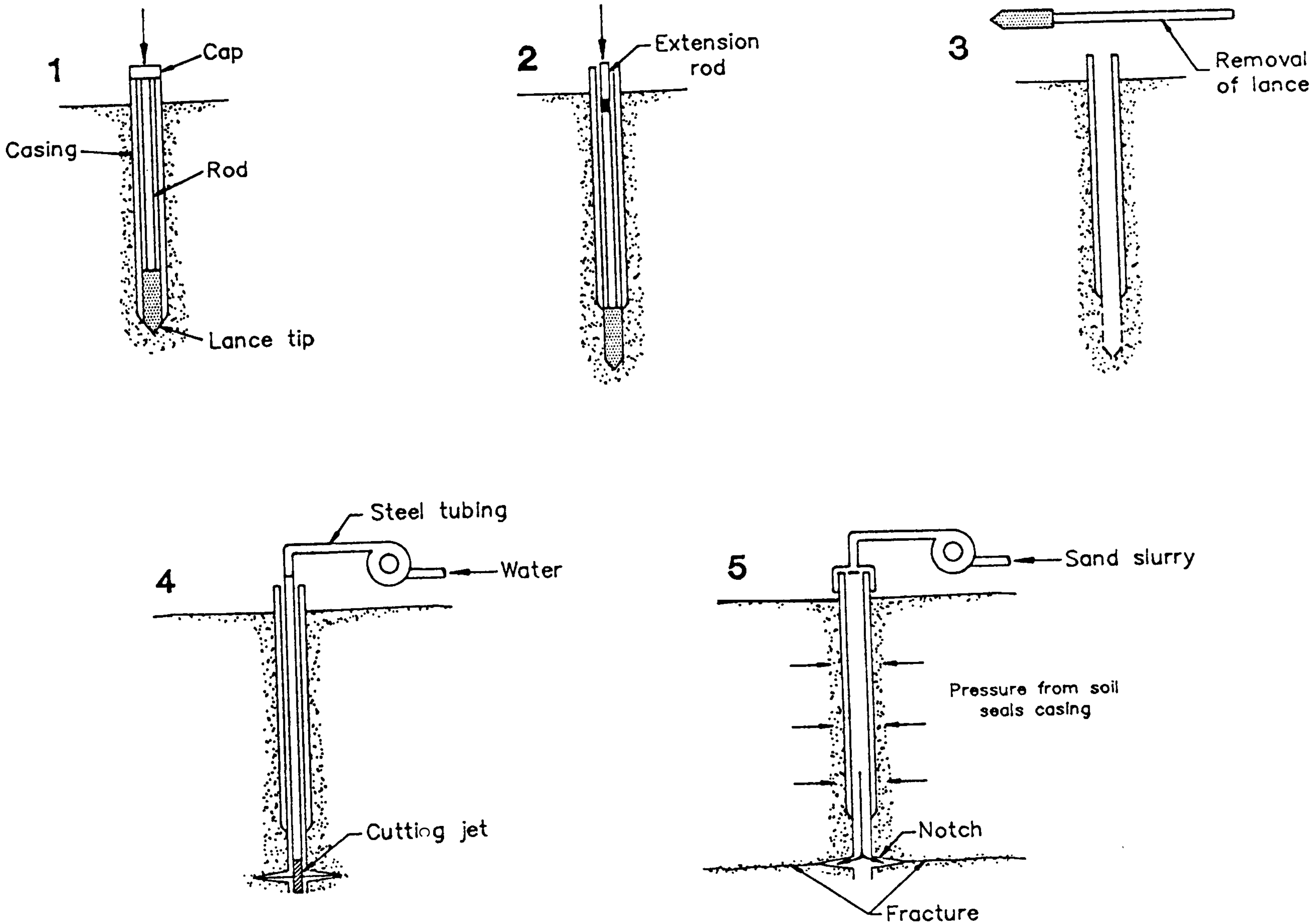


Figure 2-3. Surry Mixing Equipment Mounted on Trailers.



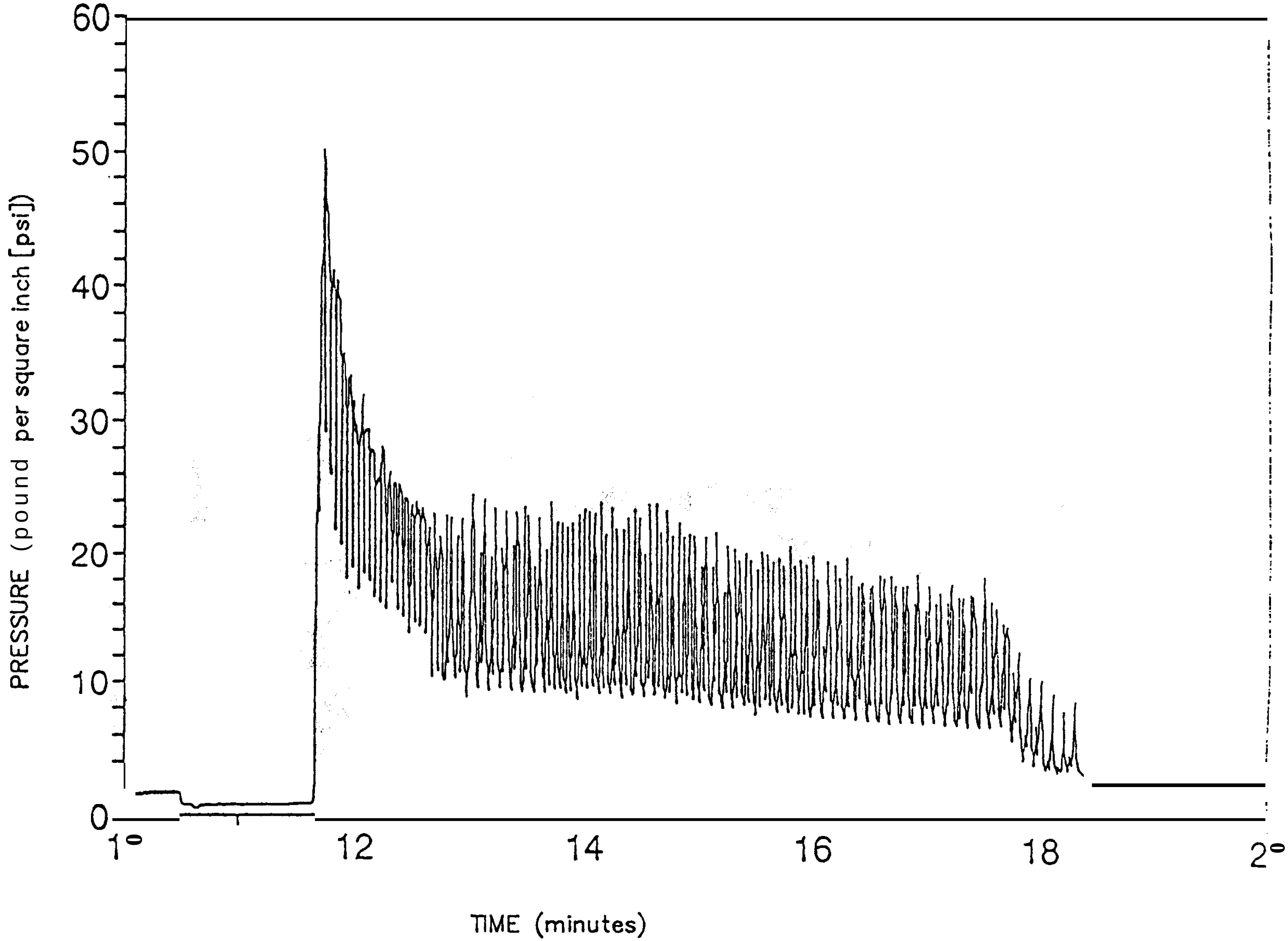
Source: Modified from UC, 1991a

Figure 2–4. Sequence of Operations for Creating

Hydraulic fractures are created by injecting the cross-linked guar gum gel and sand slurry into the casing. Injection rates of 16 to 24 gallons per minute (gpm) are used. Lateral pressure of the soil on the outer wall of the casing effectively seals the casing and prevents leakage of the slurry. The fractures nucleate at the notch and grow away from the borehole. The direction and distance of propagation of the fracture from the wall of the borehole is measured by monitoring the uplift of the ground surface. A leveling telescope is used to measure ground elevation at an array of points before and after each fracture is created to determine the location and net uplift resulting from the fracture. A laser system called the Ground Elevation Measurement System (GEMS) was developed by UC to measure uplift in real time during hydraulic fracturing. The system uses a laser and an array of sensors to track the displacement of each point in the array with time (see Figure 2-5).

A typical pressure versus time plot during hydraulic fracturing is presented in Figure 2-6. The peak pressure indicates the onset of fracturing, and the subsequent reduction of pressure with time denotes the period of fracture propagation.

Figure 2-5. Layout of GEMS.



Source: Modified from Wolf and Murdoch, 1992

Figure 2–6. Pressure Versus Time During the Creation of a Hydraulic Fracture.

3.0 CENTER HILL FACILITY TESTS

UC conducted field testing during the winter and summer of 1992 to determine the effect of sand-filled hydraulic fractures on SVE performance. The testing location is next to the Center Hill Facility in Cincinnati, Ohio. The testing location is underlain by glacial drift that is predominantly composed of silty clay with lesser amounts of sand and gravel. Five wells were used during the tests. Three wells, Wells No. CHF1, CHF2, and CHF3, intersected hydraulic fractures. These wells will be referred to in this report as “fractured wells.” Two conventional wells, Wells No. CHC1 and CHC2, were screened in unfractured ground. These two wells will be referred to as “unfractured wells.” The locations of the wells are shown in Figure 3-l.

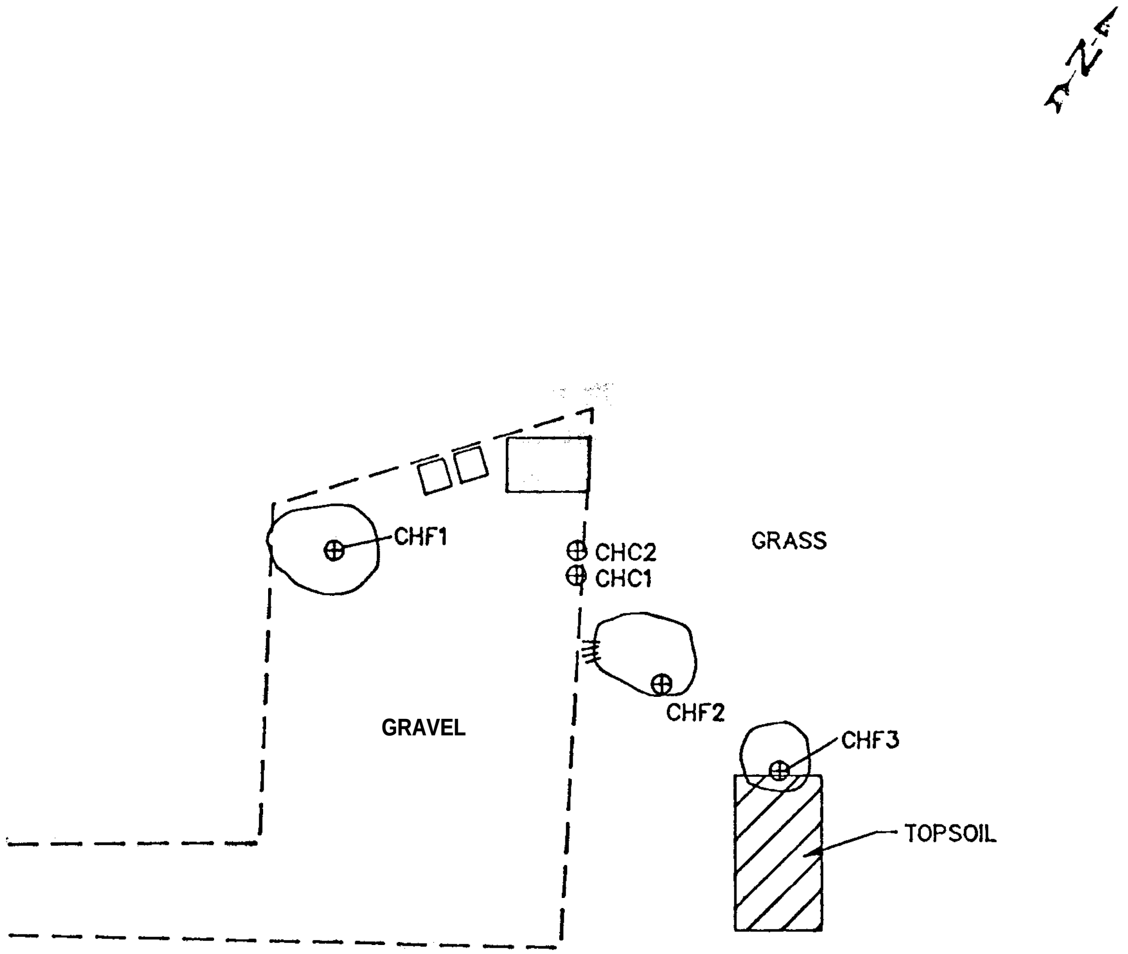
Well No. CHF1 intersects hydraulic fractures at 5 and 10 ft below ground surface (bgs). Wells No. CHF2 and CHF3 both intersect fractures at 5 ft bgs. The principle difference between the two wells is that the fracture at Well No. CHF2 reached the ground surface 23 ft from the well, whereas the fracture at Well No. CHF3 remained in the subsurface. All five fractured and conventional wells were monitored to accomplish the following objectives:

- Compare the performance of fractured and unfractured wells
- Determine the effect of venting on fracture performance
- Assess the difference in performance of fractured wells with one or two fractures per well

Hydraulic fracturing activities, data acquisition, fracturing results, and conclusions from Center Hill Facility tests are discussed below.

3.1 HYDRAULIC FRACTURING ACTIVITIES

Hydraulic fractures were created at the Center Hill Facility using the technique described in Section 2.0. The fractures are shallow dipping layers of sand several tenths of an inch thick that extend from the borehole for 10 to 30 ft. The maximum pressure, maximum uplift, size of the fractured zone, and volume of sand pumped into the fracture are detailed in Table 3-l.



LEGEND

⊕ **WELL LOCATION**

O **UPLIFT CONTOUR**

||||||| **VENTED FRACTURE**

NOTE: WELL NO. CHF2 IS VENTED TO THE SURFACE.

NOT TO SCALE

Source: Modified from Wolf ond Murdoch, 1992

flgure 3-l. Well Locations at the Center Hill Facility.

Table 3-l. Fracture Characteristics at the Center Hill Facility

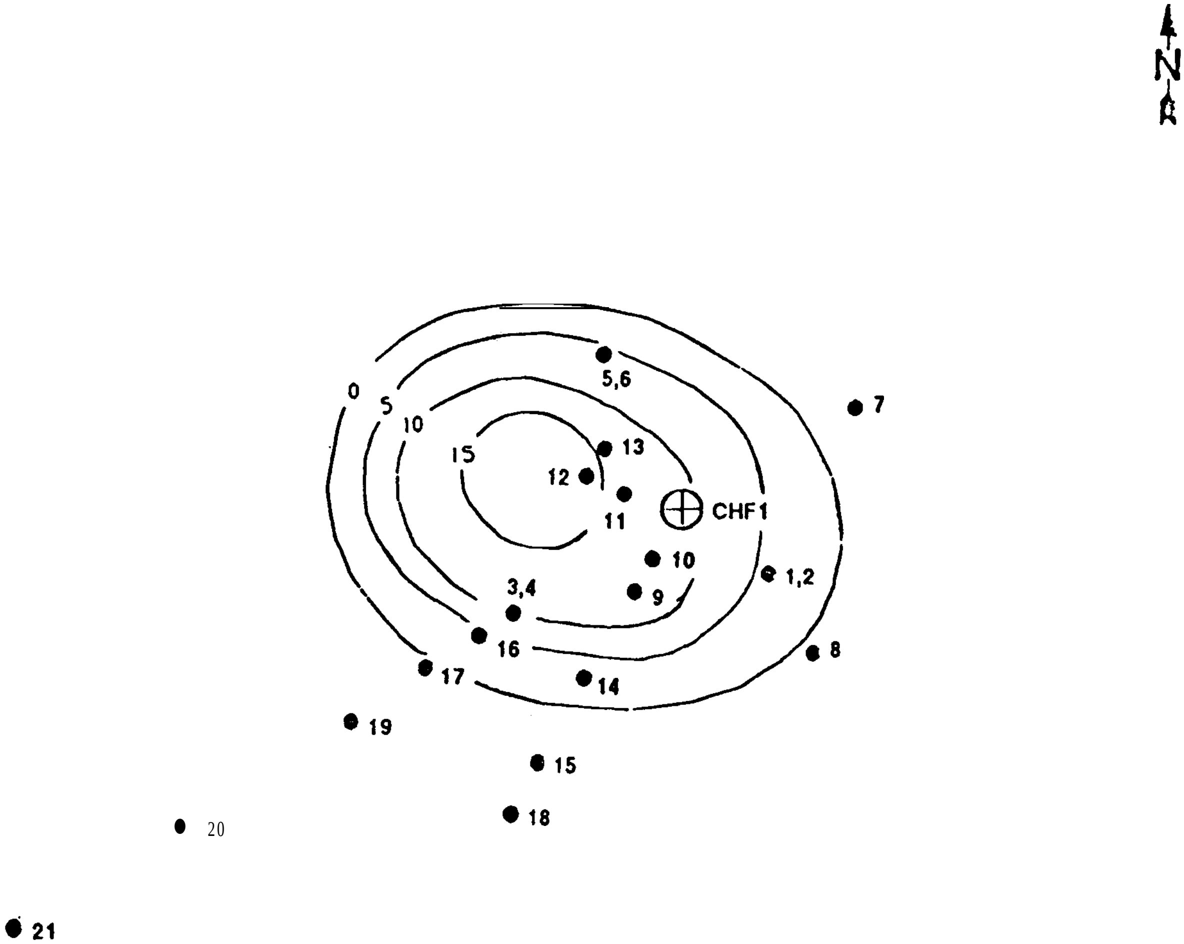
Fracture Designation No.	Maximum Pressure (psi)	Maximum Uplift (inches)	Size (ft)	Volume of Sand (cubic feet, ft^3)
CHFl - 5	50	1.02	22 by 27	7
CHFl - 10	Not available	0.87	20 by 27	11
CHF2 - 5	59	0.71	22 by 33	9
CHF3 - 5	68	0.63	Not available	5

The maximum uplift was measured at stations along four radial lines. Measurement of uplift of the ground surface can be correlated to thickness of sand in the fracture. The thickness of the sand was also verified by collecting split-spoon samples. The GEMS was used to obtain real-time uplift data during hydraulic fracturing. The data obtained from this system correlated well with measurements made with a leveling telescope.

3.2 DATA ACQUISITION

The wells were designed primarily for vapor extraction, but are also capable of removing liquid. These two-phase extraction wells are similar to the wells installed by Xerox at the Xerox Oak Brook site. The wells consist of a 2-inchdiameter polyvinyl chloride (PVC) casing and screen into which a 0.5-inch-diameter tube is placed to the bottom of the well. Vacuum is applied to the 0.5-inch tube. Water at the bottom of the well is removed along with the vapor when a valve connected to the annu1us between the 0.5-inch-diameter tube and the casing is opened. Pneumatic piezometers were used to determine the distribution of pressure as a function of radial distance from the well. The locations of pneumatic piezometers and uplift contours in the vicinity of Well No. CHFl are shown in Figure 3-2, and the locations of piezometers and uplift contours in the vicinity of Wells No. CHF2, CHF3, CHC1, and CHC2 are shown in Figure 3-3.

A blower capable of generating 120 inches of water suction head was used to apply vacuum pressure to the wells. A 20-gallon vapor-liquid separator was used to remove the contained water. Variable area flow meters were used to measure air flow upstream of the vapor-liquid separator.



LEGEND

● PNEUMATIC PIEZOMETER LOCATION AND NUMBER

⊕ WELL LOCATION AND NUMBER

UPLIFT CONTOUR

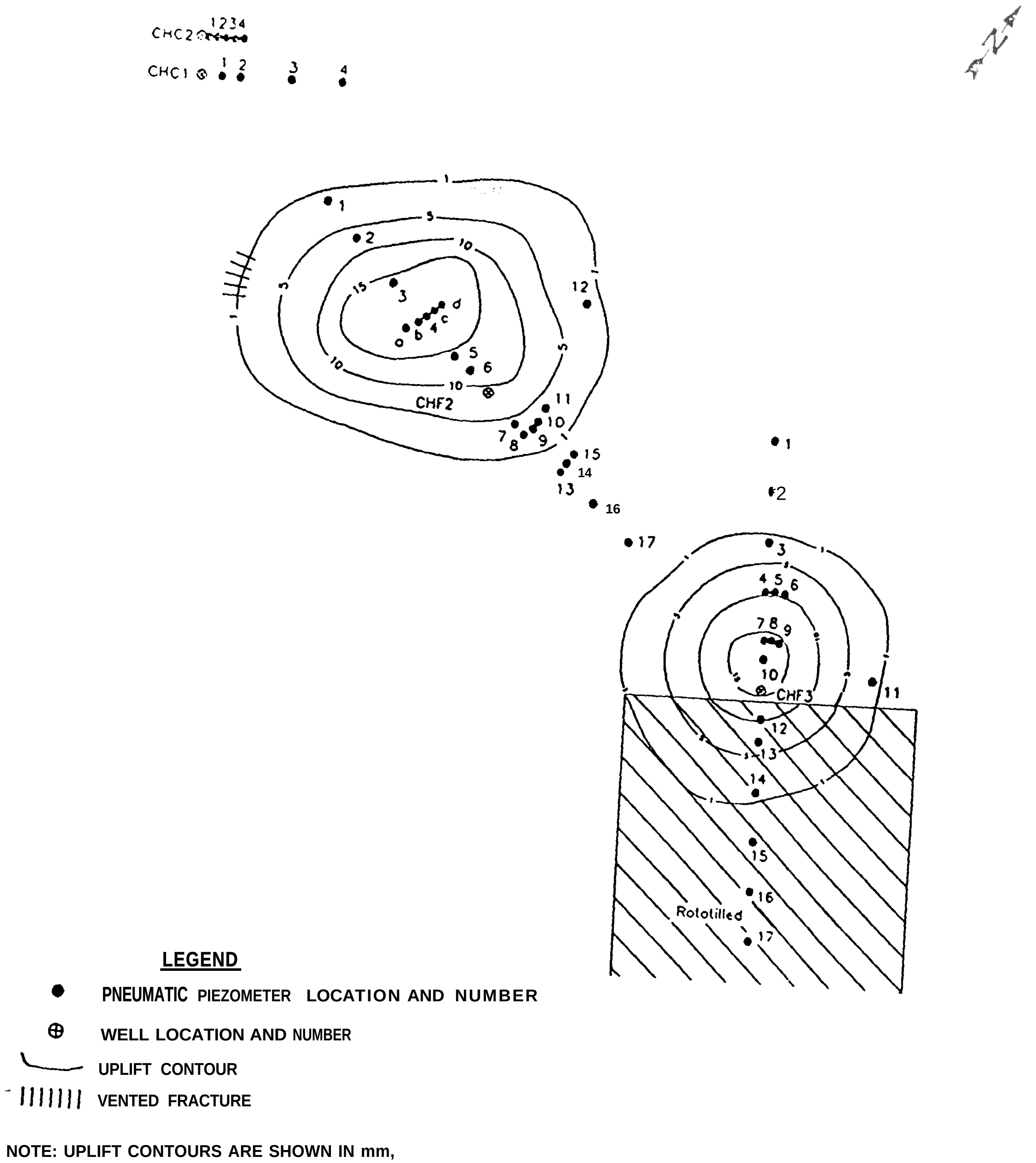
NOTES: UPLIFT CONTOURS ARE SHOWN IN MILLIMETERS (mm).

PIEZOMETERS WITH TWO NUMBERS ARE SCREENED AT TWO DEPTHS.

NOT TO SCALE

Source: Modified from Wolf ond Murdoch. 1992

Figure 3-2. Well No. CHF1 Uplift Contours and Pneumatic Piezometer Locations.



NOT TO SCALE

Source: Modified from Wolf ond Murdoch, 1992

Figure 3-3. Wells No. CHF2. CHF3, CHC1, and CHC2 Uplift Contours and Pneumatic Piezometer Locations.

3.3 FRACTURING RESULTS

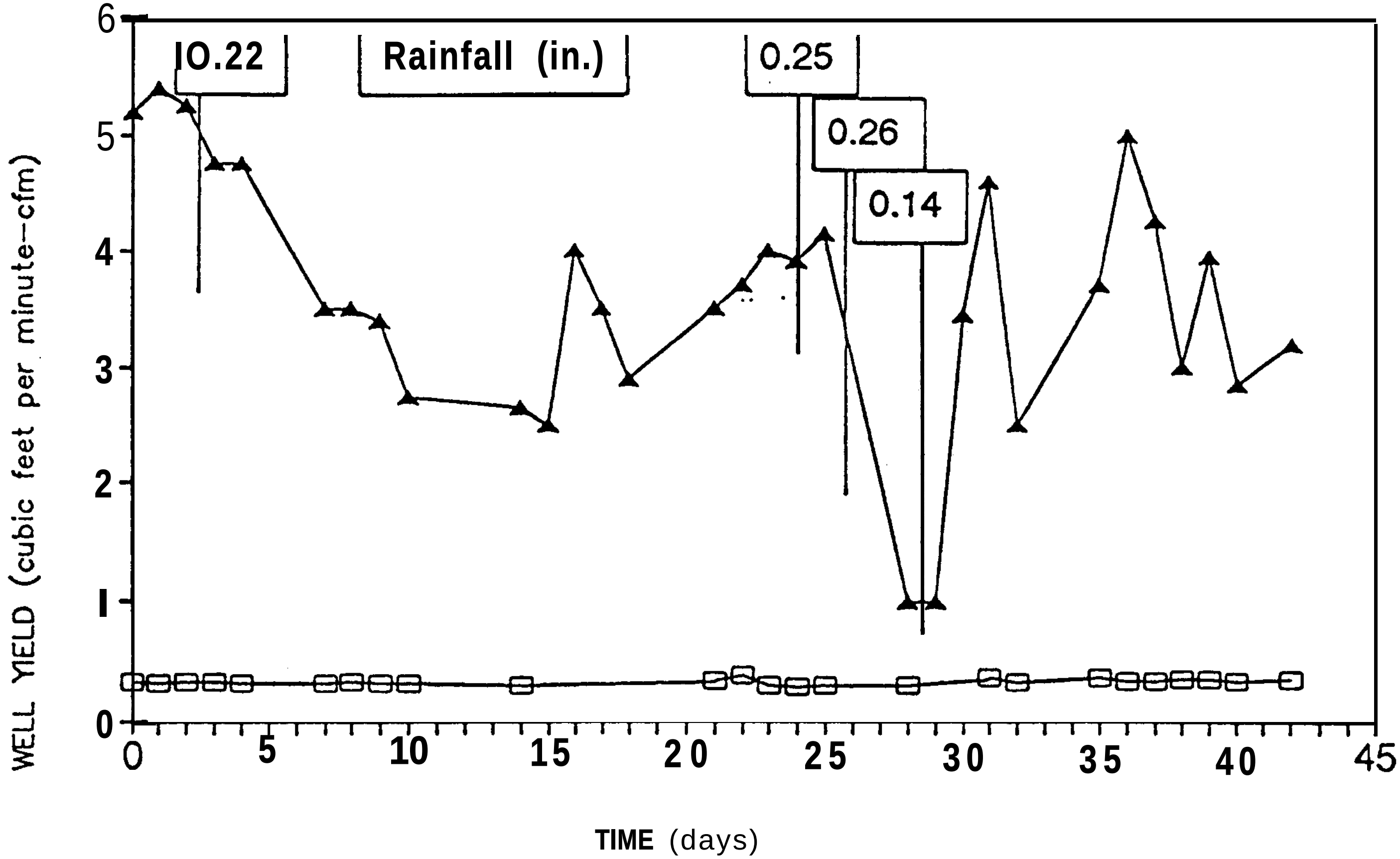
Two distinct periods of testing occurred at the Center Hill Facility, one during the winter from January 20 to March 2, 1992, and the other during the summer, from June 8 to July 7, 1992. Air yield and pressure distribution were measured for the five wells. These results are presented below.

Well yield as a function of time and rainfall for Wells No. CHF1 and CHC1 is presented in Figure 3-4, and well yield as a function of time for Wells No. CHF2, CHF3, and CHC2 is presented in Figure 3-5. Figure 3-4 demonstrates that yields from Well No. CHC1 are about an order of magnitude less than the yield from fractured Well No. CHF1. Sharp increases in yield follow the removal of water from Well No. CHFl. The unfractured well was unaffected by rainfall and did not produce water.

Figure 3-5 demonstrates that the fractured wells yielded air flows about an order of magnitude higher than unfractured Well No. CHC2 during the summer testing period. The air yields from fractured wells decreased after rainfall, and the vented fracture was more affected by rainfall than the unvented fracture. The vented fracture is connected to the ground surface and therefore produces higher yields of both air and water than the unvented fracture.

The suction head (soil vacuum) measured by each piezometer varied throughout the tests and typically increased after rainfall. Suction head near fractured wells was several times to roughly an order of magnitude greater than at similar locations around the unfractured wells. Figure 3-6 presents the pressure distribution near Well No. CHF1 and near conventional wells. The pressure drops off rapidly near the conventional wells and is about 1 inch of water within 3 ft of the wells. The pressure near the fractured well drops gradually and extends to a distance of 25 ft from the well. Figure 3-7 depicts pressure distribution as a function of time and rainfall measured by a pneumatic piezometer 10 ft from Well No. CHF2. Apparently, suction head decreases over time as soil dries, and increases significantly after heavy precipitation. As shown in Figure 3-8, pressure also increases with depth from the ground surface to the fracture and then decreases rapidly below the fracture.

The average yield, maximum yield, and the average radial distance of influence of each well is summarized in Table 3-2.



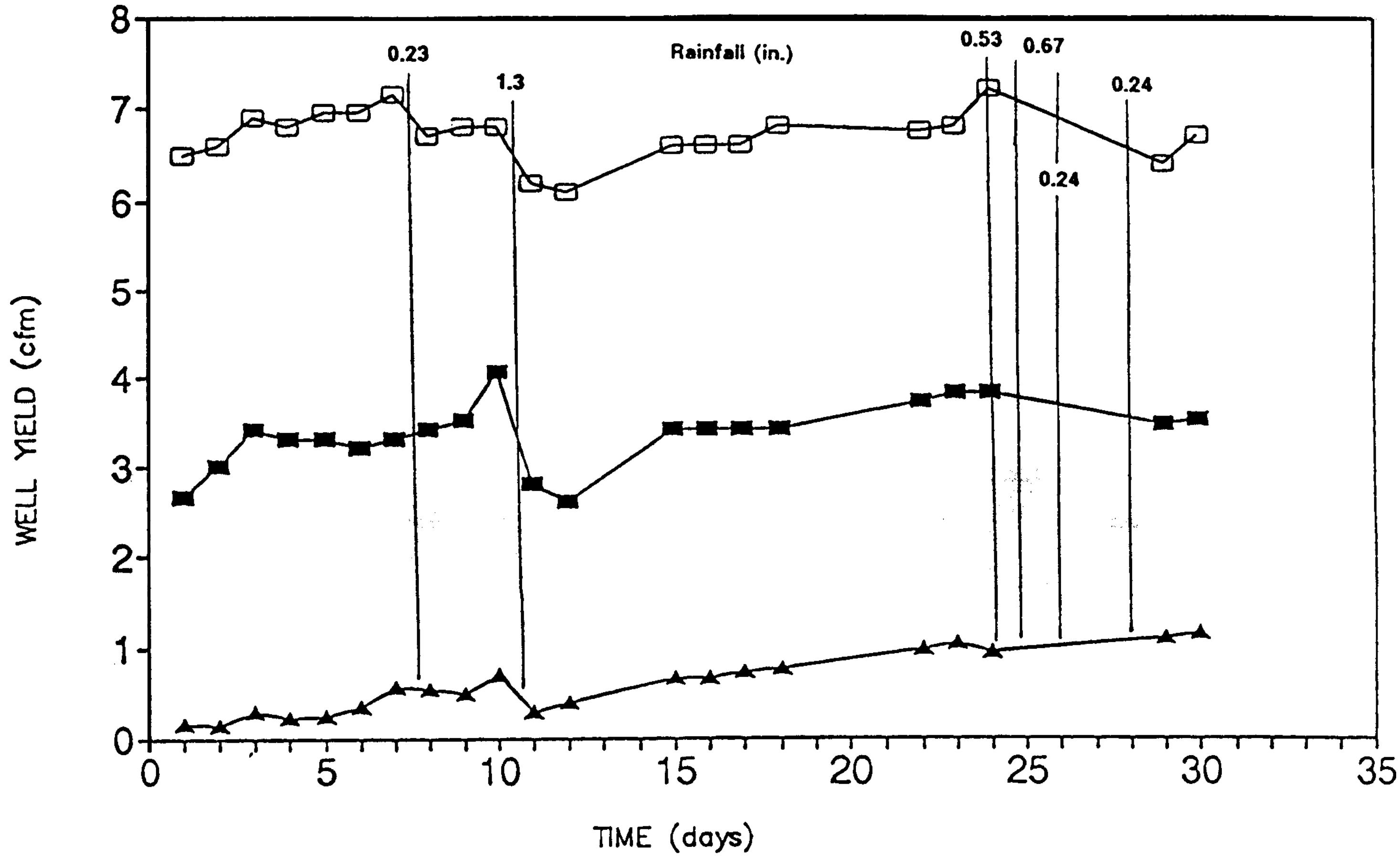
LEGEND

▲ WELL NO. CHF1

□ WELL NO. CHC1

Source: Modified from Wolf ond Murdoch. 1992

figure 3-4. Well Yield as a Function of Time and Rolnfall for Wells No. CHF1 and CHC1--January 20, to March 2. 1992,



LEGEND

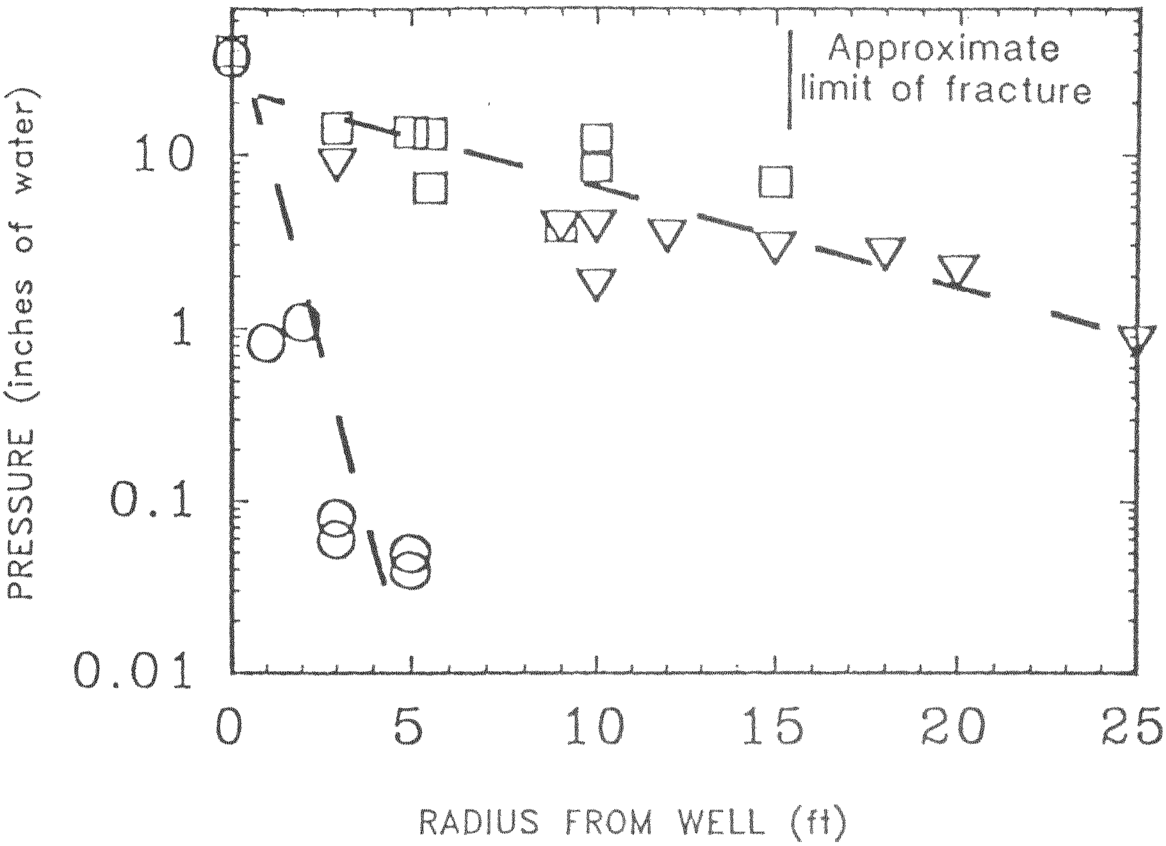
□ WELL NO. CHF2 (VENTED, FRACTURED)

■ WELL NO. CHF3 (FRACTURED)

▲ WELL NO. CHC2 (UNFRACTURED)

Source: Modified from Wolf and Murdoch, 1992

Figure 3–5. Well Yield as a Function of Time and Rainfall for Wells No. CHF2, CHF3, and CHC2—June 8 to July 7, 1992.



LEGEND

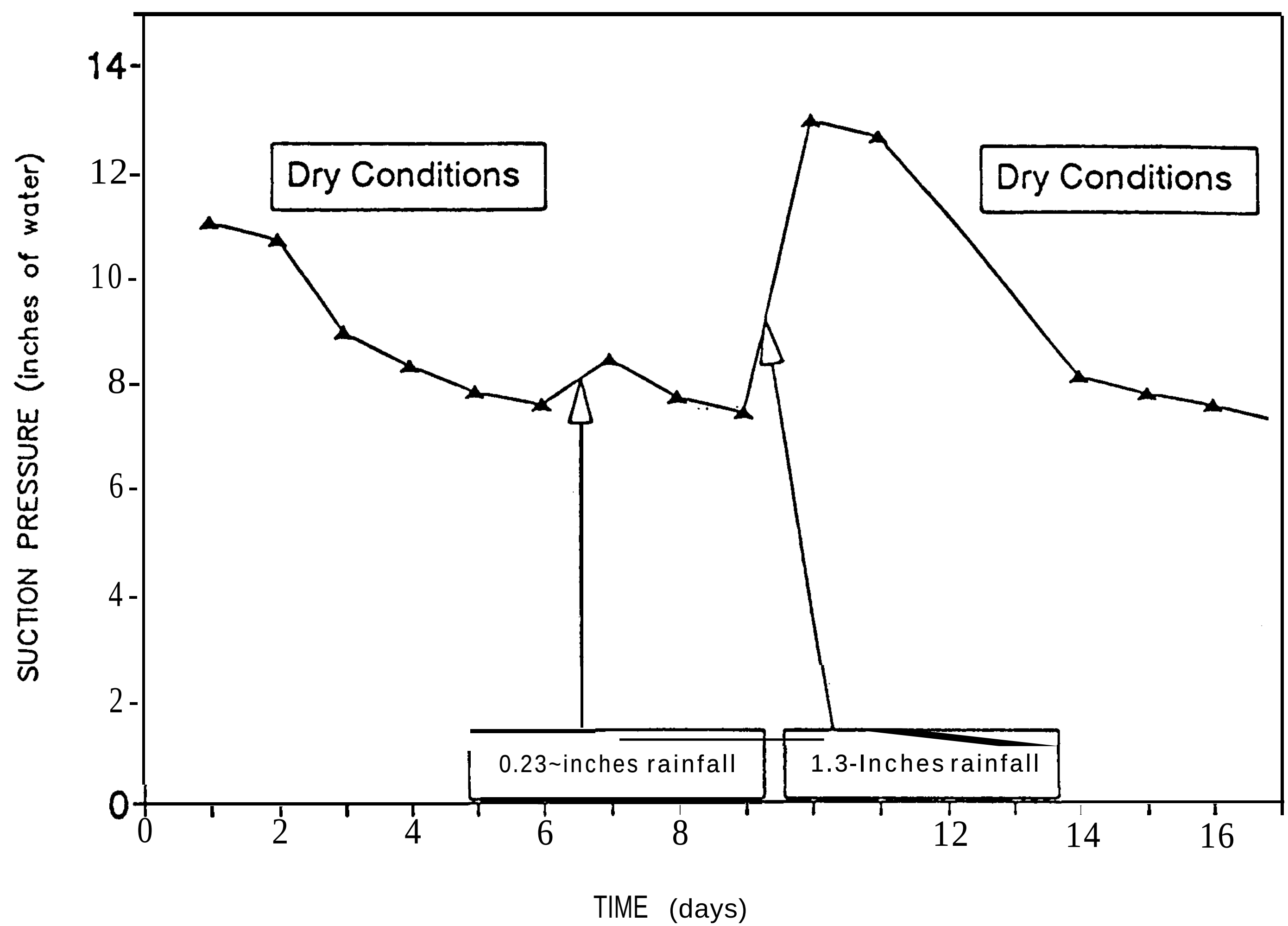
○ CONVENTIONAL WELL PIEZOMETER READING

▽ WELL NO. CHF1 PIEZOMETER READING ABOVE FRACTURE

□ WELL NO. CHF1 PIEZOMETER READING IN FRACTURE

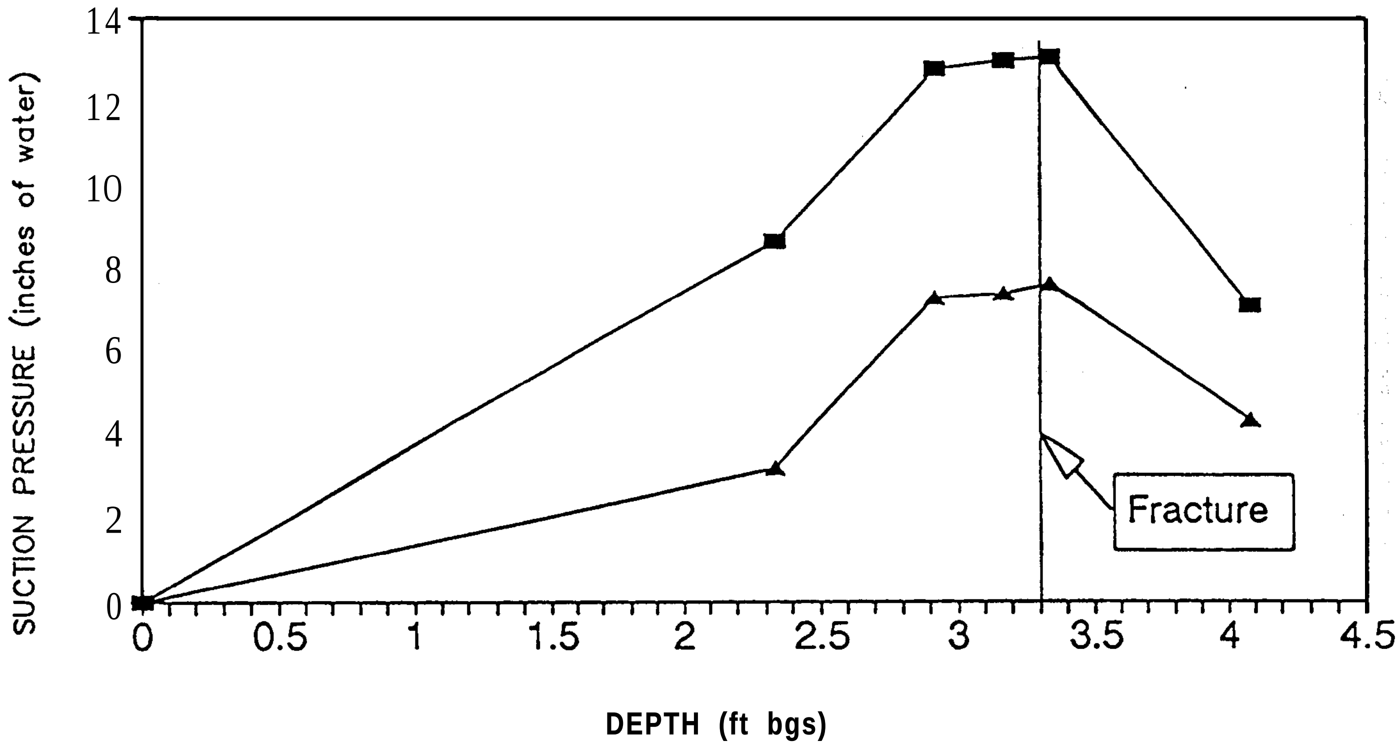
Source: Modified from Wolf and Murdoch, 1992

Figure 3-6. Pressure Distribution Near Well No. CHF1.



Source: Modlflbd from Wolf ond Murdoch, 1992

Figure 3-7. **Pressure Dlstrlbutlon Versus Tlme and Rainfall Near Well No. CHFP--June to 25. 1992.**



LEGEND

▲ PIEZOME'TER READING DURING DRY CONDITIONS

■ PIEZOMETER READING AFTER 1.3 INCHES OF RAINFALL

Source: Modified from Wolf ond Murdoch. 1992

Figure 3-8. Pressure Dlstributlon Versus Depth Near Well No. CHF2.

Table 3-2. Performance of Wells at the Center Hill Facility

Well No.	Average Yield (cfm)	Maximum Yield (cfm)	Average Zone of Pneumatic **Control*** **(ft)**
CHF1	3.7	6.1	25 to 30
CHF2	6.7	7.2	20 to 2s
CHF3	3.4	4.05	1s to 20
CHC1	0.33	0.38	0.5 to 1
CHC2	0.59	1.25	Less than 1

*Zone in which the pressure distribution can be controlled by varying the applied suction head.

3.4 CONCLUSIONS

The air yield and zone of pneumatic control of extraction wells increase significantly after the creation of sand-filled hydraulic fractures. The air yield at the Center Hill Facility tests increased by one order of magnitude, and the fracture remained effective for 1 year at Well No. CHFl. The zone of pneumatic control of the fractured wells was more than 10 times greater than that of the unfractured wells

Rainfall affected the performance of vapor extraction wells by decreasing the yield and increasing the suction head. The fractured wells yielded a larger amount of water than the unfractured wells, which never produced water. This difference indicates that continuous recovery of both liquid and vapor phases is essential to maximize yield from fractured vapor extraction wells. Also, infiltration of water into the area where vapor extraction is conducted should be minimized to increase the efficiency of vapor extraction.

Fractures that vent to the surface have gradients that drive flow through the soil toward the fracture. However, such vented fractures increase infiltration, which reduces air yield from the well. Because of site-specific conditions that increased water content in unvented fractured Well No. CHF3, vented fractured Well No. CHF2 appeared to yield significantly higher flows than the unvented fractured well. Therefore, the effect of a vented fracture is not significantly different from that of an unvented fracture.

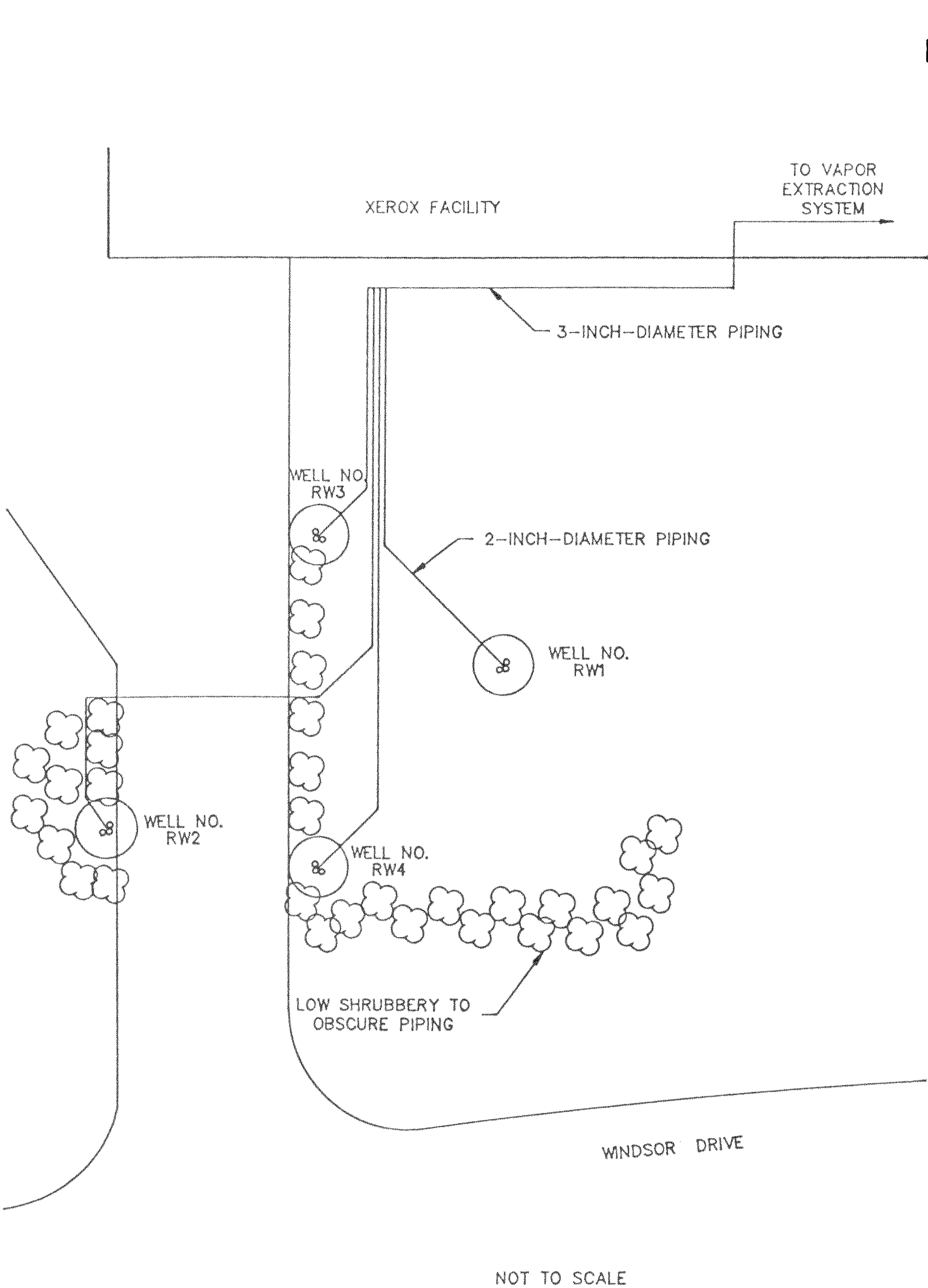
4.0 XEROX OAK BROOK SITE TESTS

At the Xerox Oak Brook site, contaminants consisting of trichloroethene (TCE); 1, 1 ,1-trichloroethane (TCA); 1,l-dichloroethane (DCA), tetrachloroethene (PCE), and other solvents are present in silty clay till to depths of 20 ft bgs. Xerox investigated the site in 1987. In 1991, a two-phase soil vapor extraction (SVE) system was installed. The layout of the two-phase vapor extraction system is shown in Figures 4-l and 4-2. Vacuum is applied to the wells by a pump, and the water and vapor in the soils around the vapor extraction wells is withdrawn. An inlet separator removes the water and a discharge separator removes the water vapor. The remaining vapor is treated in a vapor-phase carbon adsorption unit and clean air is vented out of the treatment building. The water is passed through a liquid-phase carbon adsorption unit and discharged to the sewer system. The discharge water is sampled to ensure that it meets sanitary sewer permit requirements.

The hydraulic conductivity at the site varies from 10^{-7} to 10^{-8} centimeters per second (cm/sec). This low conductivity hampered the rate of vapor extraction. In an effort to enhance vapor extraction, fractures were created at the site during the week of July 15, 1991. A work plan prepared by UC’s Center Hill Facility describes the pilot-scale study (UC, 1991a). The pilot-scale demonstration consisted of creating six hydraulic fractures at two locations. Figure 4-3 presents extraction well and piezometer locations. Wells No. RW1 and RW2 are recovery wells in unfractured ground, and Wells No. RW3 and RW4 are recovery wells in fractured ground. Before fracturing, soil samples were obtained in the vicinity of the four wells to a depth of 15 ft bgs. Soil moisture content was measured every foot bgs, and two samples from each borehole were analyzed for volatile organic compounds (VOC). This work was performed in accordance with the Quality Assurance Plan prepared by Xerox’s subcontractor, Woodward-Clyde Consultants (Woodward-Clyde Consultants, 1991). Hydraulic fracturing activities, data acquisition, fracturing results, and conclusions for the Xerox Oak Brook site tests are discussed below.

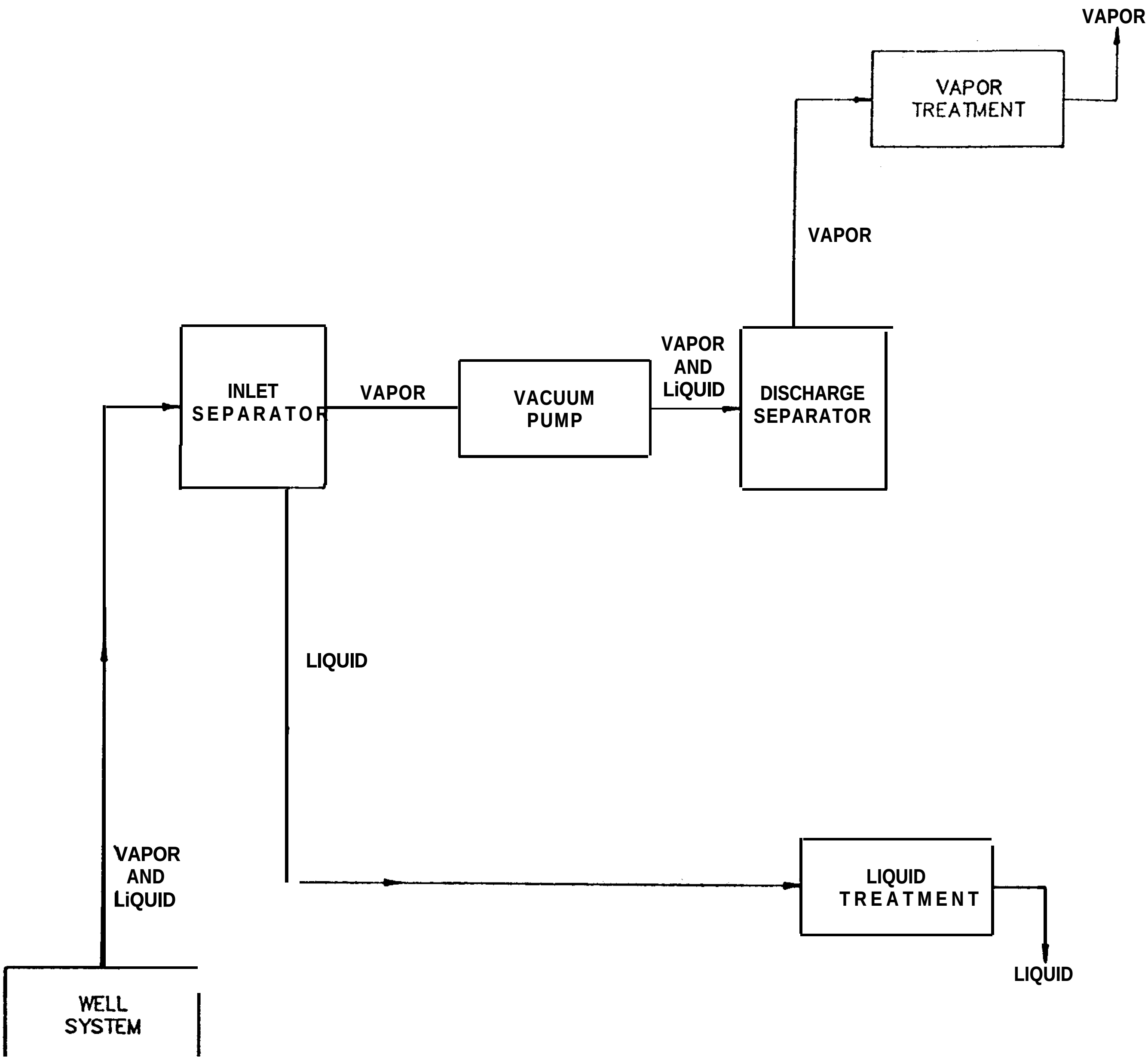
4.1 HYDRAULIC FRACTURING ACTIVITIES

Hydraulic fractures were created at Wells No. RW3 and RW4 at depths of 6, 10, and 15 ft bgs. Most of the fractures were gently dipping and 10 to 15-ft in radius, except the fracture at Well No. RW4 at 6 ft bgs vented to the surface. Ground surface uplift measurements of up to 1.04 inches were measured at radii of 11.5 and 16.4 ft from the fracturing hole.



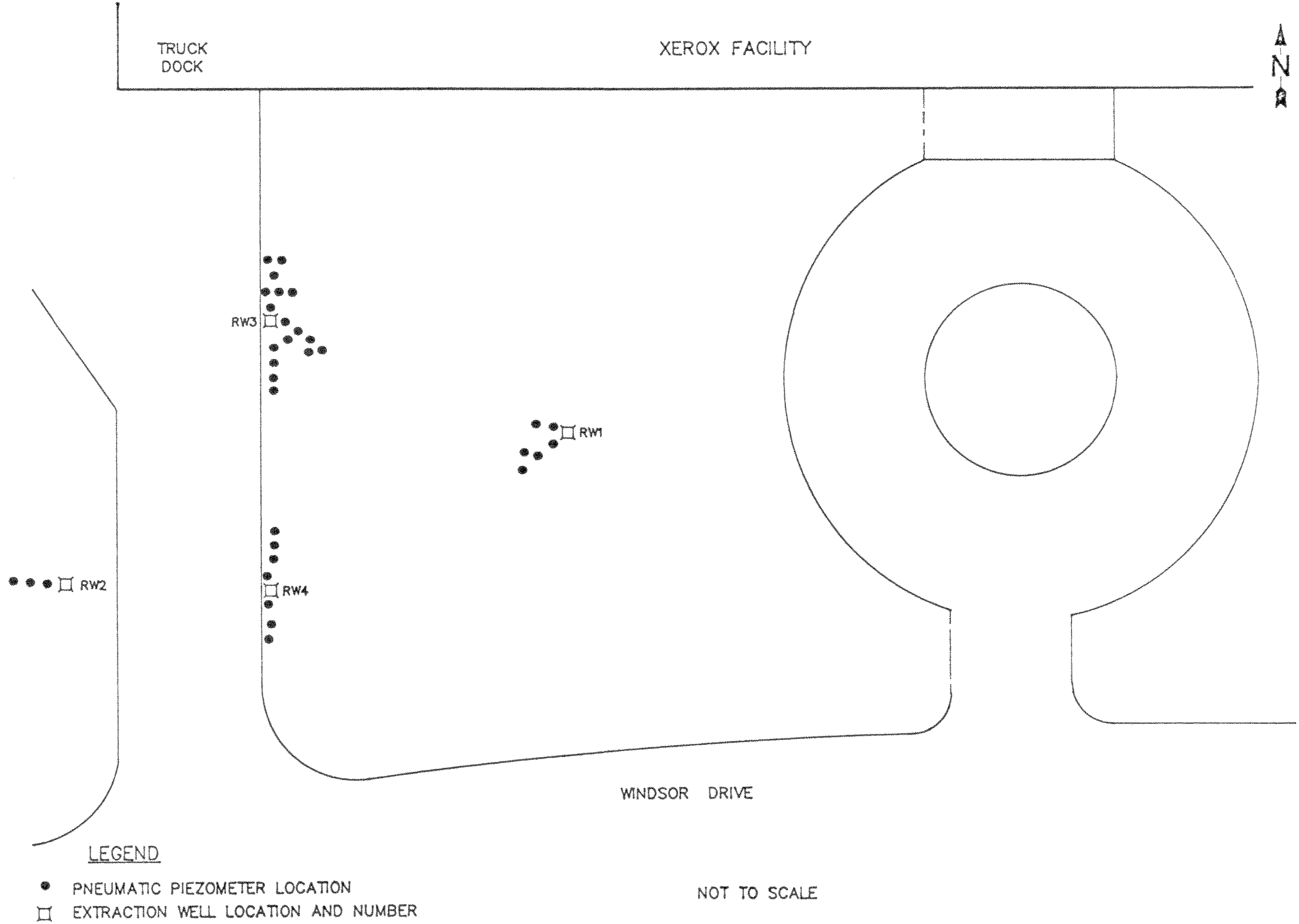
Source: Modified from Xerox, 1992

Figure 4-1. Xerox Oak Brook Site Piping Plan for Vapor Extraction System.



Source: Modified from Xerox. 1992

Figure 4-2. Schemotlc Diagram of Xerox Oak Brook Site Vapor Extraction System.



Source: odified from Xerox, 1992

Figure 4–3. Extraction Well and Piezometer Locations.

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A week after the fractures were created, recovery wells and monitoring boreholes were drilled. Multilevel recovery wells consisting of separate screens and risers for each fracture were installed to allow individual access to each fracture. Multilevel monitoring boreholes containing as many as six pneumatic piezometers were installed at radial distances of 5, 10, 15, and 20 ft from each recovery well (see Figure 4-3).

The six fractures were created on the same day, and each fracture required 1.5 to 2 hours to complete. Essential details of the fractures are summarized in the table below. The details include the depth bgs at the point where the fracture was created, the bulk volume of sand pumped into the fracture, the volume of gel in the fracture, the maximum pressure at the point of injection, the pressure at the end of pumping, the maximum uplift (typically not at the point of injection), and the approximate radius of the uplifted area over the fracture. The radius of each fracture depends on the amount of slurry pumped into the fracture.

Table 4-l. Fracture Characteristics at the Xerox Oak Brook Site

Fracture Designation No.	Depth (ft bgs)	Sand (ft^3)	Gel (gallons)	Maximum Pressure (psi)	End Pressure (psi)	Maximum Uplift (inches)	Radius (ft)	Comment
OXP1F1	6.0	NA*	20	22	20	0.12	NA*	Vented to surface
OXP1F2	10.0	12	130	38	8	0.8	13.1	Recovery Well No. RW4
OXP1F3	15.0	13	150	55	34	0.96	16.4	Recovery Well No. RW4
OXP2F1	6.0	6	100	25	8	1.04	11.5	Recovery Well No. RW3
OXP2F2	10.0	12	140	45	10	0.75	13.1	Recovery Well No. RW3
OXP2F3	15.0	14	150	72	35	1.2	14.8	Recovery Well

*Not Applicable

Xerox monitored the following parameters for the two fractured recovery wells (Wells No. RW3 and RW4) and the two unfractured recovery wells (Wells No. RW 1 and RW2) from December 199 1 to November 1992:

- Water discharge from the system
- Soil moisture content at depths of 4, 8, and 12 ft bgs, and at lateral distances of 5, 10, 15, and 20 ft north of the wells
- Soil vacuum (suction head) at recovery wells and monitoring points
- Vapor flow rates from recovery wells
- On-line gas chromatography (GC) analyses of DCA, TCA, TCE, toluene, PCE, ethylbenzene, and xylenes

The UC Center Hill Facility coordinated data acquisition with Woodward-Clyde Consultants for vapor discharge and suction head from June to November 1992.

4.2 DATA ACQUISITION

Xerox's data acquisition system records the actual vapor flow rates from individual recovery wells. Valving arrangements were available to measure flows from individual fractures in Wells No. RW3 and RW4. The wells were screened, as follows.

- Well No. RW1 screened from 5 to 15 ft bgs
- Well No. RW2 screened at three l-foot intervals at 6, 10, and 15 ft bgs
- Well No. RW3 screened at three l-foot intervals at 6, 10, and 15 ft bgs
- Well No. RW4 screened at three l-foot intervals at 6, 10, and 15 ft bgs

UC Center Hill Facility researchers coordinated data acquisition with Woodward-Clyde Consultants for vapor discharge from and suction head in Wells No. RW2, RW3, and RW4. The pneumatic piezometers shown in Figure 4-3 were used to measure the suction head (soil vacuum), and variable area flow meters were used to measure vapor discharge. Pressure readings in the piezometers were obtained with a hand-held digital manometer with an accuracy of $\pm$ 0.2 inches of water. The variable area flow meters measured vapor discharge from 6, 10, and 15 feet bgs in all four wells.

Data were not obtained from Well No. RWl since a leak existed in the annulus between the riser and the borehole wall, allowing air from the surface to flow into the well.

Vapor discharge data from variable area flow meters was generally higher than data from vortex shedding flow meters. After consultation with the meter manufacturer, it was concluded that vortex shedding flow meters cannot accurately measure two-phase flow. Installation of liquid-vapor separators upstream of the flowmeter to remove the liquid phase improved the performance of these meters. However, because an inadequate number of vortex shedding flow meters were available to automatically record the flow from each zone in each well, only variable area flow meter data were used in data analysis. In order to improve the accuracy of variable area flow meter readings, a demister pot was used to remove liquid from the airstream before it entered the meter.

4.3 FRACTURING RESULTS

The vapor discharge, contaminant recovery, and suction head results presented below were collected from June to November 1992 and analyzed by UC Center Hill Facility researchers. The contaminant concentrations obtained by Xerox were reviewed by the UC Center Hill Facility, and are summarized below.

4.3.1 Vapor Discharge

The vapor discharge data for Wells No. RW2, RW3, and RW4 are presented in Table 4-2. The data indicate that discharge from fractured Wells No. RW3 and RW4 is 15 to 20 times greater than from unfractured Well No. RW2. The discharge rate versus time is plotted in Figure 4-4. The discharge from fractured wells tends to fluctuate, and the discharge from unfractured Well No. RW2 is more consistent. These fluctuations may be due to changes in the subsurface caused by precipitation events.

The relationship between vapor discharge and precipitation was studied by plotting the water recovery rate for the system over the same period (see Figure 4-5). The water recovery rate was obtained by dividing the total water discharge from the system during a specific period by the number of days in that period (typically 3 to 4 days). The water recovery rate fluctuated widely, ranging from 20 to as many as 500 gallons per day (gpd). Higher water recovery rates generally produced low vapor discharge rates. The inverse relationship between water recovery rate and vapor discharge rate

Table 4-2. Well Discharge Readings at the Xerox Oak Brook Site

Well No.	Discharge Rate (aver age cfm)	Discharge Rate (average cfm)	Discharge Percentage (at 6 ft bgs)	Discharge Percentage (at 10 ft bgs)	Discharge Percentage (at 15 ft bgs)
RW2	0.1 to 4.6	1.1	46.3	27.3	23.2
RW3	2.2 to 22.0	14.3	61.2	8.4	30.4
RW4*	27.9 to 42.7	34.2	36.0	41.0	23.0
RW4**	17.1 to 29.7	22.6	Not Applicable	Not Available	Not Available

* The 6-foot-deep fracture at Well No. RW4 vented to the surface. The data for this well includes discharge when suction is applied to all three of the fractures.

** Well discharge average when suction was applied to the l0- and 15-foot-deep fractures only; hence, well discharge smaller than when suction applied to all three of the fractures

is demonstrated on days 116, 120, and 136 in Figure 4-5. The increased water recovery rate, in general, related to significant rainfall events (see Figure 4-6). Therefore, Xerox decided to cover the site with an impermeable membrane to minimize infiltration of water into the subsurface.

4.3.2 **Contaminant Recovery**

The mass recovery rate of a particular contaminant was determined as follows:

Mass Recovery Rate = Concentration x Flow x Molecular Weight of Contaminant x (1.53×10^{10}) (4-l)

where

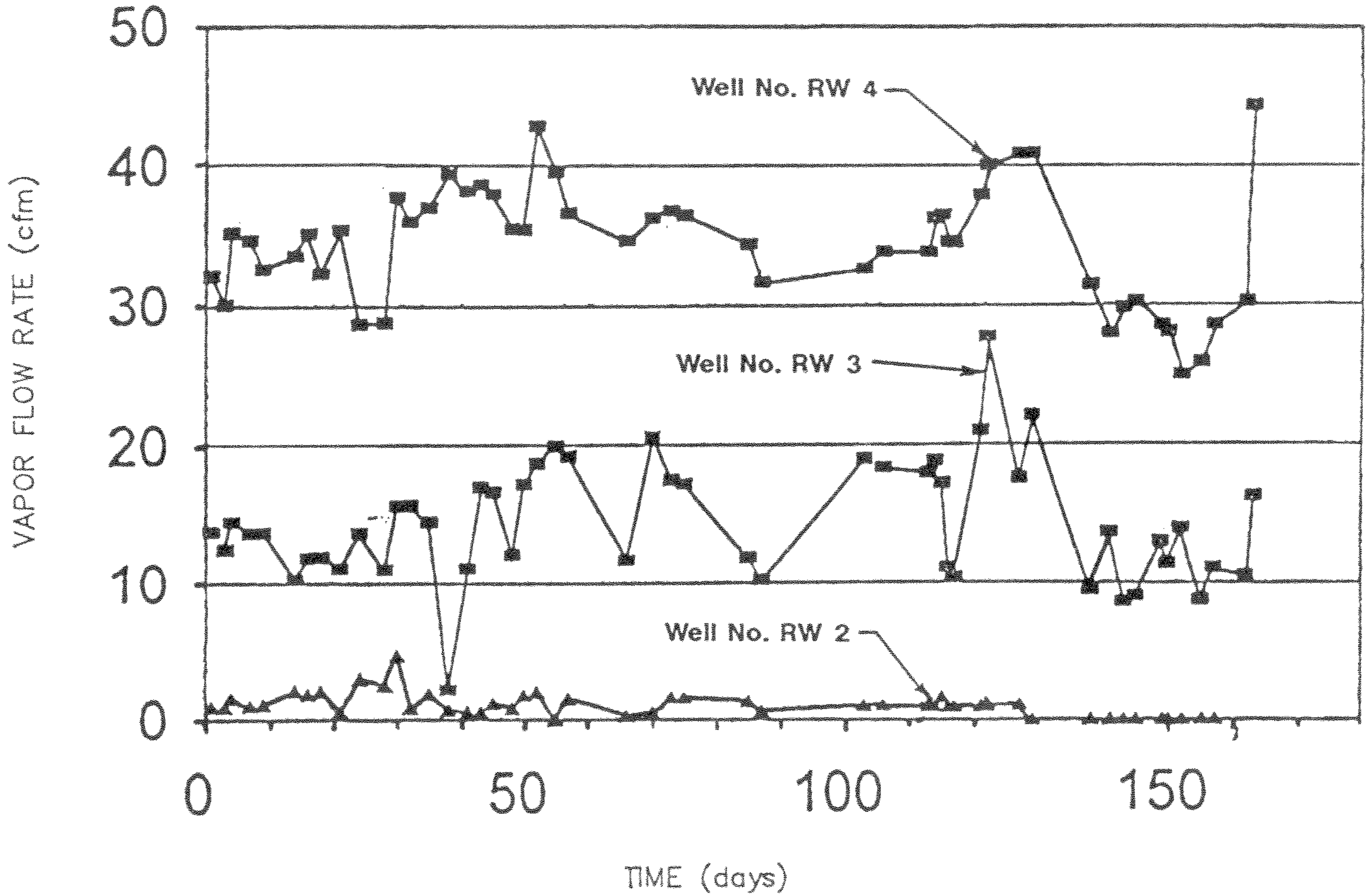
Mass Recovery Rate is in pounds per hour

Concentration is in parts per billion (ppb) measured by the GC

Flow is in cfm

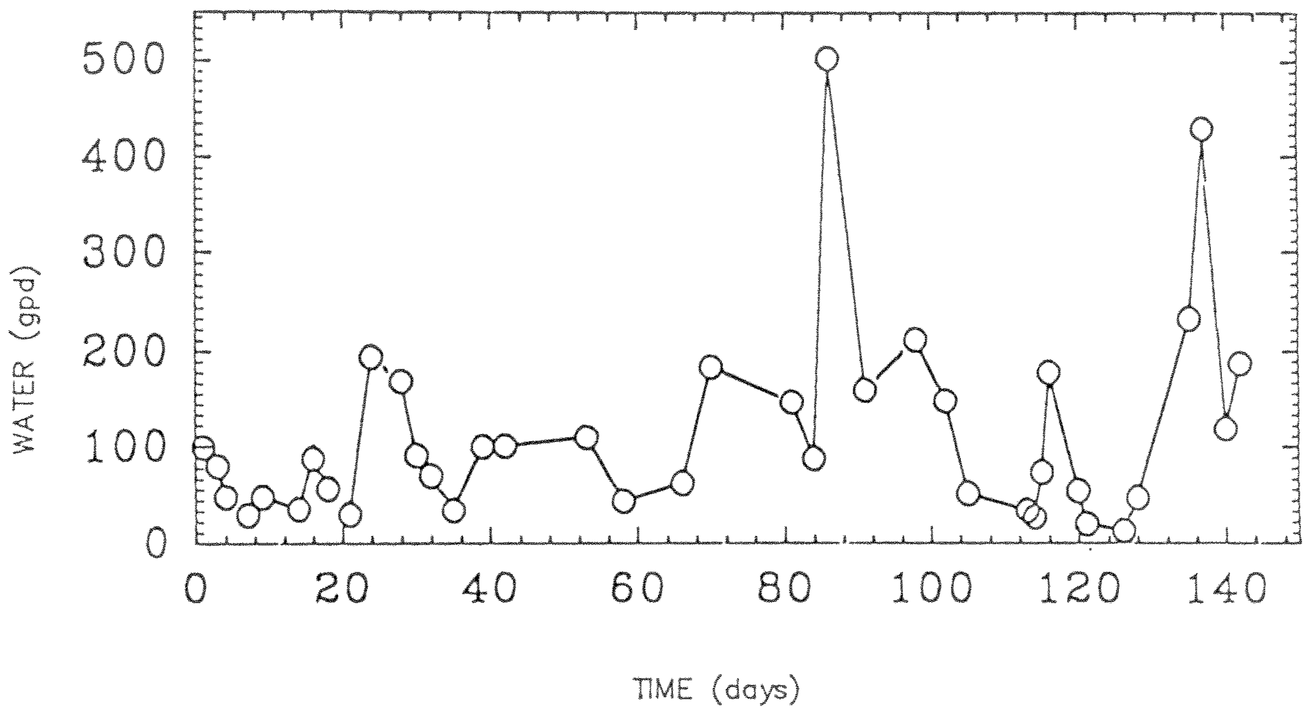
Molecular weight of contaminant is in grams per mole

1.53×10^{10} is a constant



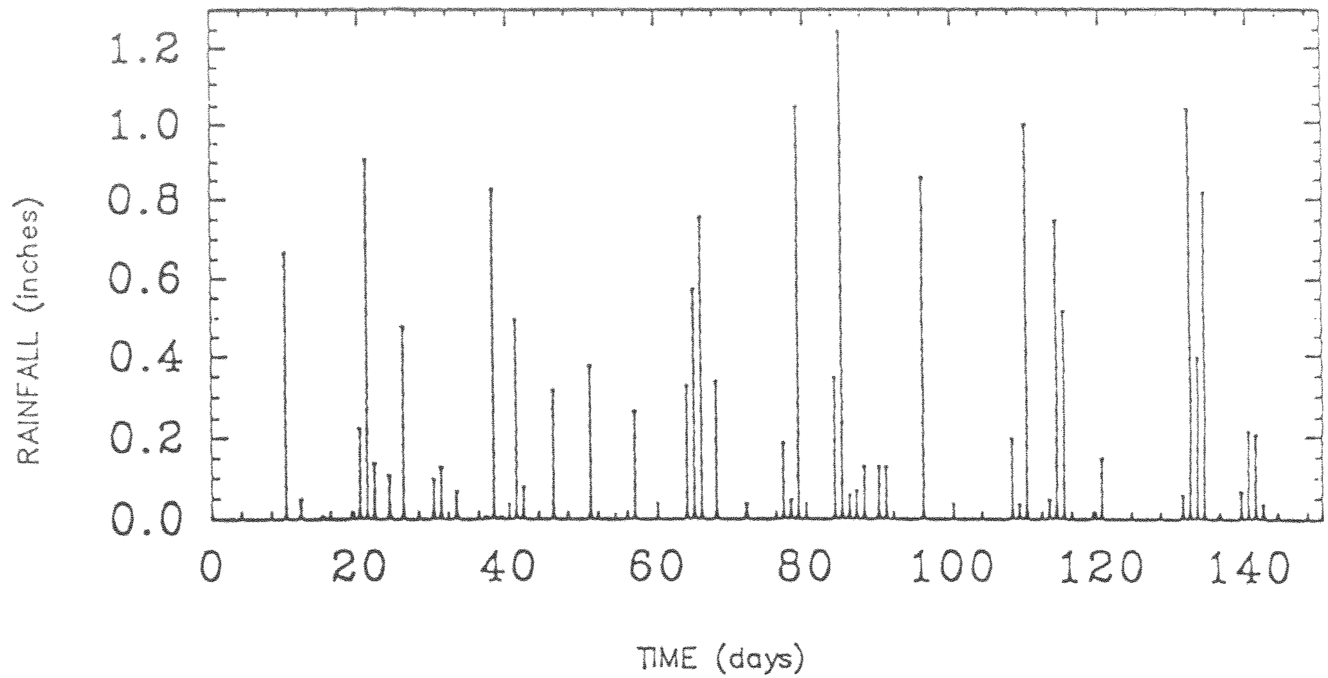
Source: Modified from UC, 1993

Figure 4-4. Vapor Flow Rate Versus Time in Wells No. RW2, RW3, and RW4
--June 23 to November 30, 1992.



Source: from UC, 1993

Figure Water Recovery Rate Versus Time—June 23 to November 30, 1992.



Source: Modified from UC, 1993

Figure 4-6. Rainfall Versus Time at the Xerox Oak Brook Site--June 23 to November 30, 1992.

The mass recovery rates for the seven target compounds were then added to give the total mass recovery rate. Total rates were added for each fracture to give the total mass recovery rate for each well. The total mass recovery rate was multiplied by the number of hours the well was operated per day to obtain the cumulative contaminant mass recovered per well. The cumulative mass of contaminants removed from Wells No. RW2, RW3, and RW4 versus time is presented in Figure 4-7.

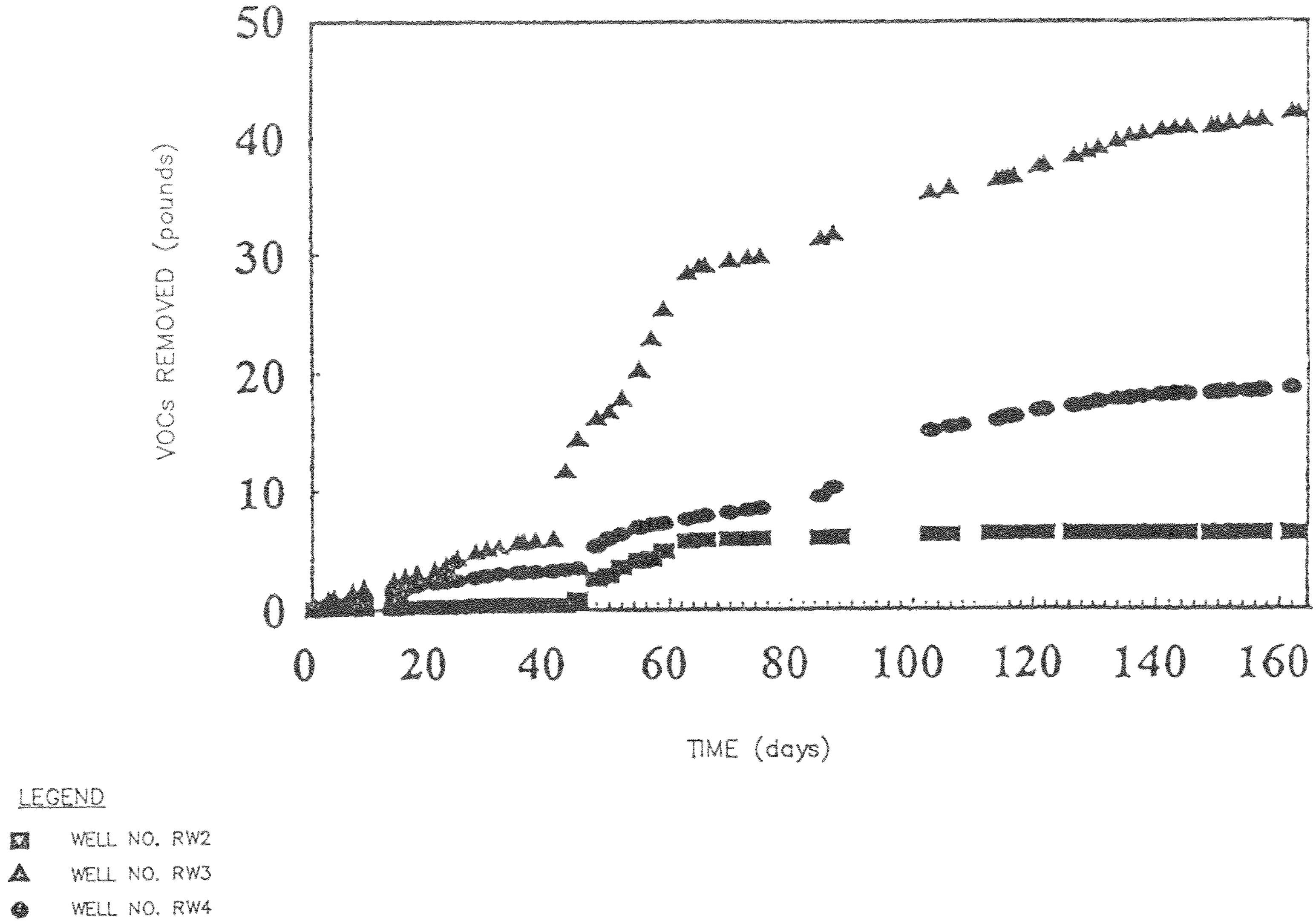
The mass recovery rates from hydraulically fractured Wells No. RW3 and RW4 are approximately one order of magnitude greater than that from unfractured Well No. RW2. The mass recovery rate from all wells decreased with time. The mass recovery rates from the two fractured wells suggest a difference between fractures that remain in the subsurface and those that vent to the surface. Recovery rates from Well No. RW3, where all three fractures remained in the subsurface, was approximately twice the recovery rates from Well No. RW4, where the 6-foot-deep fracture vented to the ground surface. The high volumetric recovery rate in Well No. RW4 is apparently from flow through the 6-foot-deep fracture which is not in contact with contaminated ground. Nevertheless, the recovery from Well No. RW4 is markedly greater than from Well No. RW2.

Xerox monitored the recovery of contaminants from the site from December 1991 through November 1992. The recovery rate of contaminants decreased exponentially throughout the study period in a manner consistent with SVE results at other sites. Maximum recovery occurred before June 1992, and cumulative mass recovery from December 1991 through November 1992 was an order of magnitude higher than the recovery rates presented in Figure 4-7.

4.3.3 Suction Head

Suction at the well heads and bgs near unfractured Wells No. RWl and RW2 varied little over the 6-month period from June to November 1992. Suction head decreased abruptly with distance from the well, from 245 to 285 inches of water to a few tenths of an inch of water at piezometers 5 feet from Wells No. RWl and RW2.

In fractured Well No. RW3, however, the suction head decreased gradually from 16 to 13 inches between radial distances of 5 and 10 ft from the well at about 5 ft bgs, and decreased from 13 to 3 inches between radial distances of 10 to 15 ft from the well. The suction head was 1.2 inches, 25 ft from the well. Therefore, creation of a hydraulic fracture apparently increased the distance where suction head is affected by a well from a few feet to about 25 ft at the Xerox site.



Source: Modified from UC, 1993

Figure 4–7. Contaminants Removed from Wells No. RW2, RW3, and RW4
––June 23 to November 30, 1992.

Suction head in the subsurface changed during the study period near fractured Wells No. RW3 and, RW4. UC Center Hill Facility researchers concluded that the changes could be related to infiltration of rainwater. Similar distributions of suction head were observed around fractured wells in silty clays during the Center Hill Facility tests, and these distributions are consistent with theoretical analysis of air flow near sand-filled hydraulic fractures (UC, 1993).

4.4 CONCLUSIONS

The measurement of vapor discharge, contaminant recovery, and suction head at the Xerox Oak Brook site led to the following conclusions:

1. Vapor discharge from unfractured Well No. RW2 averaged 1.1 cfm, whereas it averaged 14.3 cfm from fractured Well No. RW3 and 34.2 cfm from fractured Well No. RW4. The difference in vapor discharge in Wells No. RW3 and RW4 appears to result from air drawn from the ground surface through the 6-ft-deep fracture in Well No. RW4, which vented to the surface. Fractured wells increased vapor discharge by 15 to 30 times higher than from unfractured wells.

2. The contaminant mass recovery rate from fractured wells was 7 to 14 times greater than from the unfractured well.

3. Suction head was essentially nonexistent within a few feet of the unfractured well but was detected at 25 ft from fractured Well No. RW3, demonstrating that the zone of remediation may extend for distances of up to 25 ft from a fractured well; therefore, fewer wells will be required to remediate a site.

4. Vapor discharge is inversely related to the amount of water recovered from the subsurface.

5.0 DAYTON SITE TESTS

At the Dayton site, six underground storage tanks (UST) were removed in December 1989. Three tanks contained gasoline, one tank contained No. 2 fuel oil, and two tanks contained kerosene. Laboratory analyses of soil samples collected from the UST excavations indicate that benzene concentrations ranged from not detected (ND) to 622 microgram per kilogram (μg/kg). Ethylbenzene concentrations ranged from ND to 3,800 μg/kg; toluene concentrations from ND to 10,400 μg/kg; and xylene concentrations from ND to 41,900 μg/kg. Total petroleum hydrocarbon (TPH) compounds ranged in concentration from 32 to 8,550 μg/kg; and total lead concentrations from 21 to 150 μg/kg.

A remedial action contractor investigated the extent of contamination at the site in 1990. The investigation revealed the following site characteristics:

- The site is underlain by stiff, sandy to silty clay with traces of gravel.
- The bedrock is shallow, at depths ranging from 15.5 to 17.0 ft bgs, and consists of claystone and limestone.
- The horizontal extent of hydrocarbons is limited to the tank excavation area and the area east of the former tanks.
- The vertical extent of hydrocarbons appears limited to the upper 6.5 to 16.0 ft bgs in soils.

Fracturing activities, data acquisition, fracturing results, and conclusions for the Dayton site demonstration are discussed below.

5.1 FRACTURING ACTIVITIES

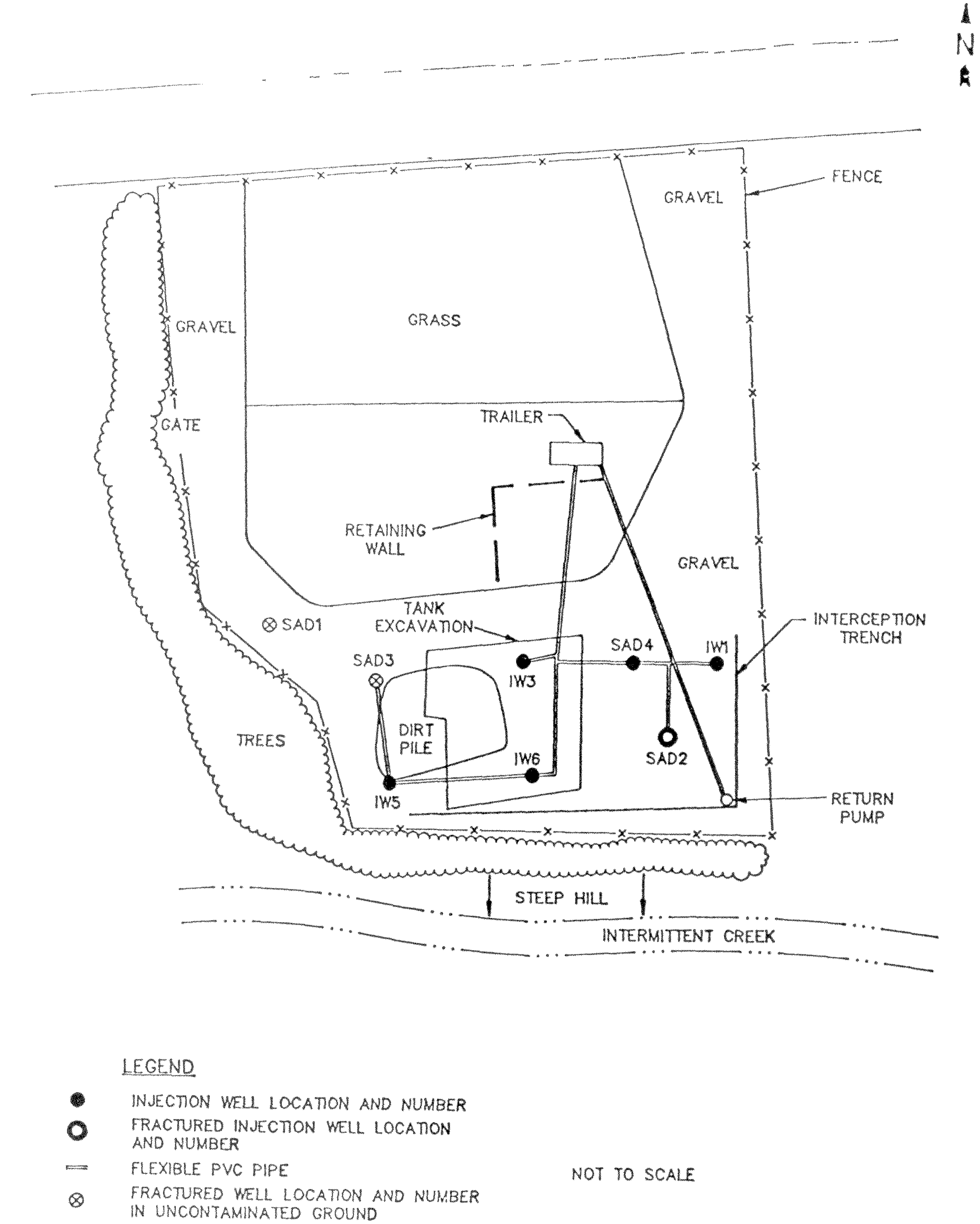
The remedial action contractor initiated bioremediation activities at the site in 199 1. In July 199 1, UC's Center Hill Facility proposed an investigation to determine the extent to which creating sand-filled hydraulic fractures would enhance bioremediation of the site. A Quality Assurance Project Plan (QAPP) was prepared by UC (UC, 1991b). The delivery of water containing hydrogen peroxide and nutrients to sustain microorganisms through fractured wells was compared to the delivery of similar water through conventional unfractured wells.

Field tests were conducted from August 16 through 21, 1991. The tests consisted of a feasibility study, where two hydraulic fractures were created at a location in uncontaminated ground near Well No. SAD1 to verify that fractures could be successfully created in the contaminated areas. The feasibility study was followed by the creation of seven fractures at two locations in contaminated ground near Wells No. SAD2 and SAD3. After fracturing was completed, it was discovered that no contamination existed near Well No. SAD-3. Figure 5-l shows a site layout and these fracturing locations. Essential details of these fractures are summarized below in Table 5-l and include the depth in ft bgs at the point where the fracture was created, the bulk volume of sand pumped into the fracture, the volume of gel in the fracture, the maximum pressure at the point of injection, the pressure after pumping, the maximum uplift (typically not at the point of injection), and the approximate radius of the uplifted area over the fracture.

Table 5-1. Fracture Characteristics at the Dayton Site

Fracture Designation No.	Depth (ft bgs)	Sand Volume (ft^3)	Gel Volume (gallons)	Maximum Pressure (psi)	End Pressure (psi)	Maximum Uplift (inches)	Radius (ft)	Comment
SAD1-6	6	5	90	27	7 to 12	0.92	14.8	Test fracture in uncontaminated soil
SAD1-12	12	10	125	60	15 to 22	0.56	21.0	
SAD2-7	7	6	110	42	7 to 11	0.88	15.1	Contaminated soil fractures
SAD2-8	8	6	100	17	7 to 15	0.8	14.8	
SAD2-10	10	9	110	37	10 to 20	0.68	16.4	
SAD2-12	12	9	125	42	18 to 26	0.48	23.0	
SAD3-5	5	5	85	19	3 to 7	0.72	14.8	No contamination detected
SAD3-7	7	8	100	43	7 to 10	0.68	15.4	No contamination detected
SAD3-9	9	9	115	39	12 to 17	0.52	23.0	No contamination detected

During the first week of September 1991, injection Wells No. SAD2 and SAD3 were installed. Soil samples were obtained using a 2-inch-diameter split-spoon sampler at depths of 6 and 8 ft bgs and were analyzed for moisture content, BTEX, and TPH. Results of samples collected during the first round of sampling and also during second and third rounds of sampling are presented in Table 5-2.



Source: Modified from UC, 1991b

Figure 5–1. Fractured and Injection Well Locations at the Dayton Site.

Samples were collected 5, 10, and 15 ft north of fractured Well No. SAD2 and unfractured Well No. SAD4, and 10 ft south of Well No. SAD2.

Water containing hydrogen peroxide and nutrients was introduced into Well Nos. SAD2 and SAD4 in December 1991. The unfractured well, Well No. SAD4, was filled with sand, and the water was gravity fed by a l-inch-diameter pipe grouted into place for delivery at 5 ft bgs. The water was gravity fed into the fractured well which was screened from 6 to 12 ft and accessed fractures at depths of 7, 8, 10, and 12 ft bgs. The same head was applied during injection into fractured and unfractured wells. A system of interception trenches and a return pump were installed to recover water injected into the wells (see Figure 5-l).

5.2 DATA ACQUISITION

In February 1992, a second round of soil core samples were collected with a 2-inch-diameter by 2-ft-long split-spoon sampler near the fractured and unfractured wells. The bottom 0.6 inch of soil from each core was placed in a jar containing 0.08 gallon of methanol and was later analyzed for BTEX using the methods described in EPA Test Methods for Evaluating Solid Waste, SW-846 (EPA, 1986). The remainder of the core was wrapped tightly in sterile plastic and returned to a laboratory for analysis within 72 hours. In the laboratory, the cores were aseptically cut into l-inch-long sections. Alternating sections were analyzed to quantify the number of microbes that have the capacity to degrade hydrocarbons (expressed in CFUs), moisture content, and microbial activity. Moisture content was determined in accordance with American Society for Testing and Materials (ASTM) Standard D2216 (ASTM, 1991).

A third round of sampling and analysis was conducted in July 1992 to measure the same parameters measured in the second round and to determine the progress of bioremediation. Water flow rates into Wells No. SAD2 and SAD4 were also measured throughout the demonstration.

The contaminant removal percentages for the fractured and unfractured wells are presented in Table 5-3. Measurements of BTEX, TPH, CFU, and microbial activity produced erratic results for the second and third rounds of sampling because water was not fed continuously during the period of the demonstration (December 1991 through July 1992). The remediation contractor encountered mechanical problems during the demonstration, and UC was not provided data on when the water was shut off and when it was

Table 5-2. Analytical Results of Dayton Site Samples

Well No.	Sampling Location	Sampling Round	Average Concentration (mg/Kg)			
			Benzene	Ethyl- benzene	Toluene	TPH
Fractured Well No. SAD2	5 ft north of well	First Second Third	4.0 4.4 0.8	15.0 0.4 6.0	0.2 TL[b] 1.0	490 112 143
Unfractured Well No. SAD4	5 ft north of well	First Second Third	3.7 4.9 5.0	8.9 8.1 6.6	0.8 1.6 0.5	230 235 104
Fractured Well No. SAD2	10 ft north of well	First Second Third	6.0 3.2 5.3	20.0 4.3 20.0	0.5 TL 2.8	235 98 108
Unfractured Well No. SAD4	10 ft north of well	First Second Third	0.8 0.7 0.6	2.1 0.6 0.2	0.1 TL 0.2	75 55 25
Fractured Well No. SAD2	15 ft north of well	First Second Third	9.8 3.5 6.1	26.0 7.1 11.4	1.2 0.7 2.7	385 188 123
Unfractured Well No. SAD4	15 ft north of well	First Second Third	0.3 0.3 0.7	0.2 TL 0.7	TL TL TL	8 11 6
Fractured Well No. SAD2	10 ft north of well	First Second Third	1.0 1.0 0.9	0.9 TL 2.3	TL TL 1.1	290 131 57

Notes:

[a] mg/Kg = milligrams per Kilogram
[b] TL = Too low to measure

Samples were collected 5, 10, and 15 ft north of fractured Well No. SAD2 and unfractured Well No. SAD4, and 10 ft south of Well No. SAD2.

Water containing hydrogen peroxide and nutrients was introduced into Well Nos. SAD2 and SAD4 in December 1991. The unfractured well, Well No. SAD4, was filled with sand, and the water was gravity fed by a 1-inchdiameter pipe grouted into place for delivery at 5 ft bgs. The water was gravity fed into the fractured well which was screened from 6 to 12 ft and accessed fractures at depths of 7, 8, 10, and 12 ft bgs. The same head was applied during injection into fractured and unfractured wells. A system of interception trenches and a return pump were installed to recover water injected into the wells (see Figure 5-l).

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In February 1992, a second round of soil core samples were collected with a 2-inch-diameter by 2-ft-long split-spoon sampler near the fractured and unfractured wells. The bottom 0.6 inch of soil from each core was placed in a jar containing 0.08 gallon of methanol and was later analyzed for BTEX using the methods described in EPA Test Methods for Evaluating Solid Waste, SW-846 (EPA, 1986). The remainder of the core was wrapped tightly in sterile plastic and returned to a laboratory for analysis within 72 hours. In the laboratory, the cores were aseptically cut into l-inch-long sections. Alternating sections were analyzed to quantify the number of microbes that have the capacity to degrade hydrocarbons (expressed in CFUs), moisture content, and microbial activity. Moisture content was determined in accordance with American Society for Testing and Materials (ASTM) Standard D2216 (ASTM, 1991).

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The contaminant removal percentages for the fractured and unfractured wells are presented in Table 5-3. Measurements of BTEX, TPH, CFU, and microbial activity produced erratic results for the second and third rounds of sampling because water was not fed continuously during the period of the demonstration (December 1991 through July 1992). The remediation contractor encountered mechanical problems during the demonstration, and UC was not provided data on when the water was shut off and when it was

Table 5-3. Contaminants Removed at the Dayton Site

Treatment	Location From Well	Sampling Round	Benzene, Ethylbenzene, and Toluene Removal (Percent compared to first round)			TPH Removed (Percent compared to first round)
			Benzene	Ethyl-benzene	Toluene	
Fractured Well No. SAD2	5ftnorth	Second Third	NI* 80	97 60	NI NI	77% 71%
Unfractured Well No. SAD4	5 ft north	Second Third	NI NI	7.9 37.0	NI NI	0% 55%
Fractured Well No. SAD2	10 ft north	Second Third	46.7 11.7	78.5 NI	NI NI	58% 54%
Unfractured Well No. SAD4	10 ft north	Second Third	NI NI	71.4 90.5	NI NI	27% 67%
Fractured Well No. SAD2	15 ft north	Second Third	64.3 37.8	72.7 56.2	NI NI	51% 68%
Unfractured Well No. SAD4	15 ft north	Second Third	NI NI	NI NI	NI NI	0% 25%
Fractured Well No. SAD2	10 ft south	Second Third	NI NI	NI NI	NI NI	55% 80%

* No impact

restarted. In addition, UC was unable to sample the water recovered from the trench. Hence, it is not possible to determine the relative role of soil flushing and bioremediation in the removal of contaminants at the site.

5.3 FRACTURING RESULTS

Flow rates in the unfractured and fractured wells are presented in Figure 5-2. Water flow was about 25 to 40 times greater in the fractured well. This increased flow resulted in higher moisture content near the fractured well.

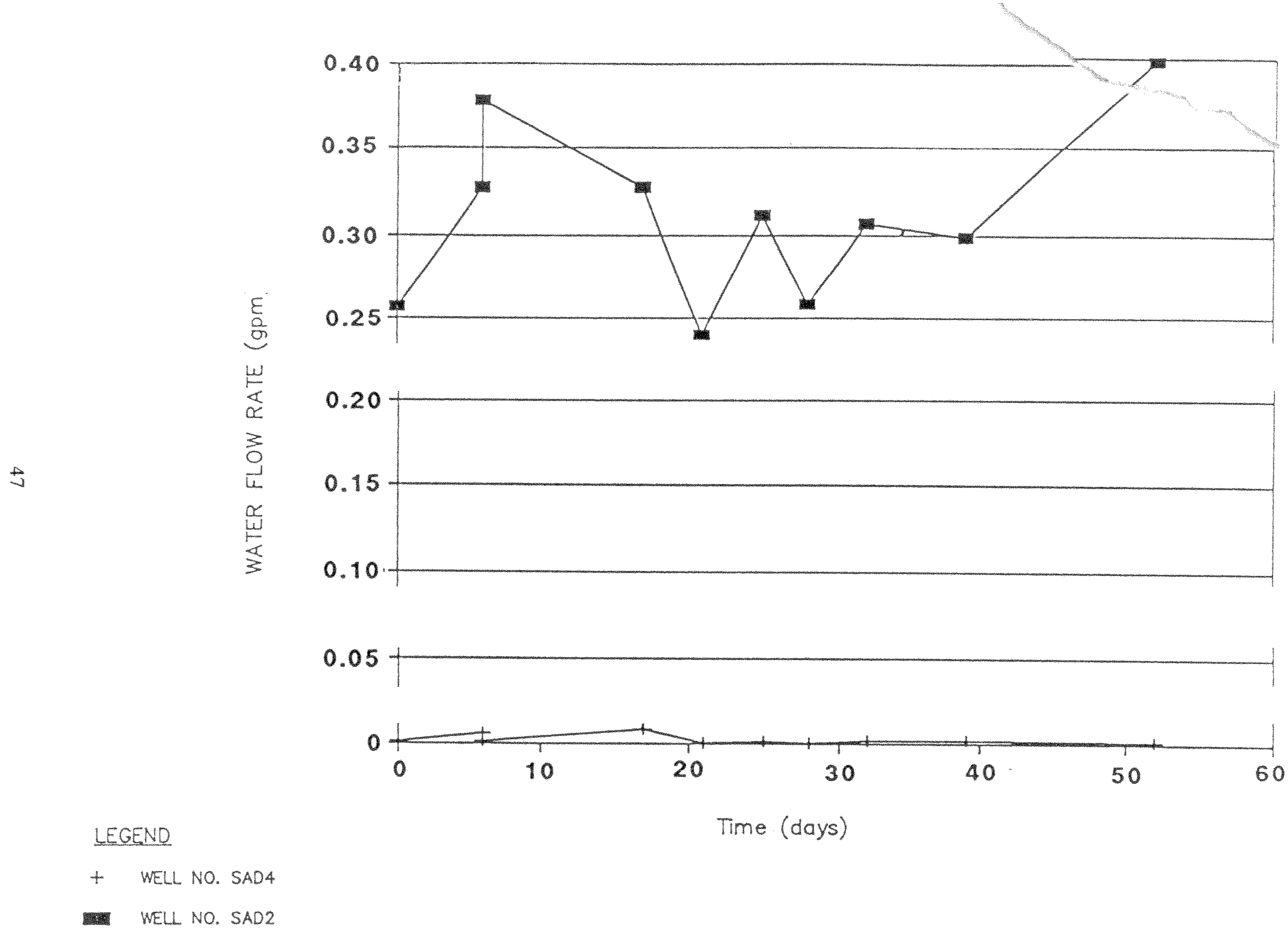
Results from the sampling location 5 ft north of the wells indicate that fractured Well No. SAD2 had moisture contents of 1.4 to 4 times greater than the unfractured well. Moisture contents were generally higher near the fracture, with the highest increase near the top fracture. This trend of increasing moisture contents was also present at sampling locations 10 and 15 ft north of fractured Well No. SAD2.

The contaminant removal percentages near the fractured and unfractured wells shown in Table 5-3 indicate that benzene, ethylbenzene, and TPHs were significantly remediated near the fractured well. The variability in removal percentages observed in the second and third rounds of sampling resulted from the system not being optimized.

CONCLUSIONS

Fluid flow rates in the fractured well was 25 to 40 times higher than in the unfractured well. On certain days, water flow rate near the unfractured well was minimal, but significant flow passed through the soil around the fractured well. Fluid flow increased moisture content around the fractured well, with a fourfold increase near the fractures. Hydrocarbon concentrations decreased in the soils around the hydraulically fractured well, whereas they remained nearly the same near the unfractured well.

The bioremediation activities were conducted by an independent contractor, and UC had no control over the operating parameters. Hence, reliable results on contaminant removal could not be obtained from the pilot-scale demonstration. However, increased permeability near the fractured well was demonstrated by higher flow rates and increased moisture contents.



Source: Modified from Vesper, 1992

Figure 5–2. Flow Volumes of Water Injected in Wells No. SAD2 and SAD4.

6.0 QA/QC ANALYSIS

The objective of this study was to evaluate the effectiveness of sand-filled hydraulic fractures in enhancing the remediation of contaminated clay soils. The study was conducted by UC Center Hill Facility researchers in Cincinnati, at the Xerox Oak Brook site, and at the Dayton bioremediation site. The UC Center Hill Facility prepared a QAPP (Project Category IV) that was approved by RREL for use at the Center Hill Facility and the Dayton site (UC, 1990 and 1991b). At the Xerox Oak Brook site, Woodward-Clyde Consultants was responsible for data collection and prepared a quality assurance and quality control (QA/QC) plan to be used in conjunction with the UC Center Hill Facility work plan for the site (UC, 1991a and Woodward-Clyde Consultants, 1991).

Sampling and analysis at the Center Hill Facility was conducted solely by UC without independent verification. Sampling and analysis at the Xerox Oak Brook site was conducted by Woodward Clyde Consultants. The data obtained from variable area flow meters and pressure gauges at the Xerox Oak Brook site by Woodward-Clyde Consultants were independently verified by UC researchers. These data were the only critical parameters at the Xerox Oak Brook site. All data obtained at the Dayton site were collected by UC without independent verification.

Hydraulic fracturing is a technology that enhances the effectiveness of other remediation technologies in low permeability soils. The evaluation of this technology required measurement of vapor and water flow rates, soil moisture contents, and soil vacuum pressures. Chemical analysis of soil and vapor samples were primarily conducted to measure the progress of remediation. Hence, the QA/QC analyses were not as rigorous as for technology evaluations that require extensive chemical analyses.

The QAPP developed by UC and the QA/QC plan prepared by Woodward-Clyde Consultants did not specify the number of QA/QC samples to be collected for critical parameters during the pilot-scale demonstrations. Also, the number of QA/QC measurements to be conducted for flow rate and suction head were not provided for the Center Hill Facility tests and the two pilot-scale demonstrations. QA/QC sample analyses for the Center Hill Facility and the Xerox Oak Brook and Dayton sites are discussed below.

6.1 CENTER HILL FACILITY

The work at the Center Hill Facility included the design, fabrication, and demonstration of hydraulic fracturing field equipment. This work was conducted using a Project Category IV QAPP prepared by the UC Center Hill Facility (UC, 1990). The objectives of the QA/QC analysis were to ensure that the fracturing fluid was appropriate for use in fracturing and that the injection pressure and ground surface uplift were accurately measured. QA objectives for critical measurements of the fracturing fluid are provided in Table 6-l. The suction head was measured with a Meri Cal® Model DP 2001 gauge having an accuracy of ± 0.1 percent. Air flow through the wells was measured with variable area flow meters having an accuracy of ± 2 percent.

Sampling and analytical procedures, measurement of injection pressure and ground surface uplift, calibration frequency, and data validation used for Center Hill Facility results are discussed below.

6.1.1 Sampling and Analytical Procedures

No laboratory measurements are associated with the Center Hill Facility tests. All measurements are field measurements and are performed as the fractures are being created (except the suction head and air flow). Measurements to determine the optimum fracturing fluid were made using nonstandard methods since no standard methods exist for these measurements.

Grab samples of fracturing fluid were obtained at various points in the mixing procedures. The samples were obtained by filling a bucket with fluid from the desired locations. Turbulence and in-line mixers were used to ensure the fluid additives were well mixed so that representative samples could be collected. Duplicate samples were collected at critical points in the fracturing procedure. If both samples were not within the range specified or within specified precision objectives, a second duplicate was tested. If results were still unacceptable, adjustments to the mix were made and additional duplicate samples were tested until the mix met the stated specifications.

Samples were tested immediately after collection and results were recorded on a field data sheet. The significant measurement in the mixing operation was the guar gum gel concentration (see Table 6-l). A standard Marsh funnel was used to determine the time required for a 0.3-gallon sample to pass through

Table 6-l. QA Objectives for Critical Measurements of Fracturing Fluid

Measurement	Method	Precision Range”	Accuracy Percentage
Degree of Mixing	Qualitative Visual Inspection	NA[b]	NA
Hydration Time	Minimum Hydration Time: 25 minutes	NA	NA
Guar Gum Gel Concentration	Marsh Funnel Test: 44 to 46 seconds	2 seconds	90
Guar Gum Post-Cross-link Viscosity	Nationwise Funnel Test: 37 to 68 seconds	31 seconds	90
Sand Concentration	Weight of 0.053 gallon sample: 0.573 to 0.705 pounds	0.132 pounds	90

Notes:

a Maximum absolute range, duplicates must both be within designated range

b NA = Not applicable

Source: Modified from UC, 1990

the funnel. A Marsh funnel time of 44 to 46 seconds indicated optimum guar gum concentration. Other parameters monitored during the preparation of the fracturing fluid include hydration time, guar gum gel viscosity after the addition of cross-linker (an aqueous solution of borax), and sand concentration to produce the desired guar gum gel-and-sand slurry.

The most important measurable property of the gel (guar gum) is its viscosity . The gel must be viscous enough to keep the proppant (sand) in suspension, but not so viscous that it cannot be pumped effectively. A field test was devised using a modified Marsh funnel (called a Nationwise funnel) to determine the viscosity of the cross-linked gel. The Nationwide funnel is a long, steep-sided funnel having an orifice with an inside diameter of 0.8 7 inch. Three-tenths gallon of the gel sample was poured into the funnel, and the time taken for 0.24 gallon of the gel to flow through the funnel was measured. An acceptable range of 37 to 68 seconds was established from these tests (see Table 6-l).

The final step in the production of the fracturing fluid is the addition of the sand proppant to produce the gel-and-sand slurry. A high quality, well rounded, well sorted, 12/2 0 silica fracturing sand was used. A sand concentration of 8 to 12 pounds per gallon provides a pumpable slurry with enough sand to prevent fracture closure. Quality control of the slurry involves visual inspection of the sand as well as checks to ensure that the sand is in the acceptable concentration range. Crosslinked gel and sand have specific gravities of 0.98 and 2.65, respectively. The range of acceptable sand concentration is a weight of 0.573 to 0.705 pounds for a 0.053 gallon sample. Field measurements of the specified volume of fracturing fluid ensured that the acceptable sand concentration was achieved.

6.1.2 Measurement of Injection Pressure and Ground Surface Uplift

Injection pressure and ground surface uplift are noncritical parameters measured during hydraulic fracturing . Injection pressures were measured at the ground surface using Druck® transducers interfaced with a data acquisition system and laptop computer. The transducer calibration charts were obtained from the manufacturer. A manual mechanical pressure gauge was available as a backup for the transducers.

The surface uplift was measured using standard surveying techniques. Elevations of points on a square grid around the fracturing hole were measured using a leveling rod and a Deitzen® dumpy level . Uplift measurements were also made using a borehole extensiometer and GEMS. The readings obtained by these systems were comparable.

6.1.3 Calibration Frequency

The flowmeter calibration was done prior to the field tests, and was checked whenever the gels and slurries were found to be outside the acceptable range. The laboratory scale used for weighing guar gum samples and slurries is calibrated and cleaned by a professional calibration service on a yearly basis, and routine calibration checks with standard weights are made throughout the year. Manufacturer recommended calibration procedures are used during the calibration.

6.1.4 Data Validation

Data quality was assessed continuously during the field fracturing process to ensure reliability of the data collected. Fracturing fluid test data was monitored continuously to ensure that proper concentrations and viscosities were obtained. Injection pressure plots were monitored in the field to determine anomalous conditions. Surface elevation data were verified by using base station reference points. Three base station points were situated as far as possible from the fracturing borehole to ensure that their ground elevations were not affected by ground tilt resulting from the hydraulic fracturing operation. All data was reviewed by the project principal investigator before acceptance.

After the initial runs, all fracturing fluid samples met the QA objectives. The injection pressures and surface elevation data provided details on the orientation, thickness, and length of the fractures. There were no deviations from the QAPP.

6.2 XEROX OAK BROOK SITE

The primary objective of Woodward-Clyde Consultants' field QA/QC program was to generate scientifically representative, legally defensible data (Woodward-Clyde Consultants, 1991). Before the startup of the demonstration, split-spoon soil samples and groundwater samples were collected from fractured and unfractured wells. During well installation, continuous 2-ft-long split-spoon samples were collected by Woodward-Clyde Consultants. These samples were divided into two equal portions. The first sample was prepared for VOC analysis by EPA Methods 8010 and 8020, and the second sample was prepared for headspace screening and visual classification.

During the pilot-scale demonstration, continuous vapor samples were collected for VOC analysis by GC. Tedlar bag vapor samples were also obtained for VOC analysis. Flow rates were measured using vortex shedding flow meters and variable area flow meters. The soil vacuum pressure was measured using pneumatic piezometers. Sampling and analytical procedures used by Woodward-Clyde Consultants are described below. Calibration frequency and data validation procedures used by UC during hydraulic fracturing are described in Sections 6.1.3 and 6.1.4.

Split-spoon soil samples were collected using a drill rig. Samples collected in jars were immediately covered with aluminum foil, dull side down, and the tops of the jars were screwed on. After the samples reached room temperature, the jar was unscrewed, and an analytical probe was punched through the aluminum foil for headspace reading. Samples sent to the laboratory were tagged and labeled and analyzed for VOCs.

Soil samples established the background levels of contamination at the site. The important parameters measured to evaluate the effectiveness of hydraulic fracturing were flow rates from the fractured and unfractured wells, and soil vacuum near the wells. Significant difficulty arose in measuring two-phase flow from the wells using vortex shedding flow meters. As discussed in Section 4.2, a liquid separator placed in line with these flow meters improved their performance but did not yield reliable, consistent data. Hence, variable area flow meters with an accuracy of $\pm$ 2 percent were used to measure vapor flow from screened intervals in the wells. A demister pot used in conjunction with variable area flow meters improved flow measurement accuracy. The soil vacuum readings were obtained with a pressure gauge having $\pm$ 0.1 percent accuracy.

Vapor samples collected continuously for GC analysis and with Tedlar bags for analysis by EPA Methods 8010 and 8020 established the concentration of contaminants recovered from the site. However, the concentration of contaminants recovered also depended on factors unrelated to the hydraulic fracturing technology.

There were no deviations from the Quality Assurance Plan developed by Woodward-Clyde Consultants

6.3 DAYTON SITE

Soil samples were collected by UC at 5, 10, and 15 ft north of fractured Well No. SAD2 and unfractured Well No. SAD4. UC also collected soil samples 10 ft south of Well No. SAD2. These samples were obtained in September 1991 (before the demonstration) and February and July 1992. Samples were analyzed for moisture content, CFUs, microbial metabolic activity, and chemical composition. The chemical composition analyses included benzene, toluene, ethylbenzene, and TPHs.
The hydraulic fracturing technology was evaluated by measuring the flow of water containing hydrogen peroxide and nutrients through fractured and unfractured wells. The only critical parameter was the flow rate. Parameters related to bioremediation activity were measured, and chemical analyses were conducted to determine the extent of bioremediation near the fractured and unfractured wells. The parameters related to bioremediation and chemical analyses did not yield statistically significant data because UC did not have control on the introduction of water into the subsurface, and the general heterogeneity of the soil.

The flow rate in the fractured and unfractured wells was measured with a flowmeter having an accuracy of $\pm$ 2 percent. The flowmeter was calibrated prior to the pilot-scale demonstration, and at least once a week during the duration of the demonstration. The QA/QC plan was followed for all non-critical parameters. There were no deviations from the QA/QC plan.

7.0 COST AND BENEFIT COMPARISON

The application of hydraulic fracturing to enhance vapor extraction at the Xerox Oak Brook site and bioremediation at the Dayton site yielded the following benefits:

Vapor Extraction

- Increased air flow from a radius of up to 25 ft from recovery wells, which is 15 to 30 times greater than flow observed in conventional wells
- Increased mass removal rates of contaminants in vapor extraction system recovery wells by about 7 to 14 times higher compared to conventional unfractured wells

Bioremediation

- Increased flow in fractured wells of 25 to 40 times higher compared to conventional unfractured wells; flow is directed mainly into the fractures, which extend up to 25 feet from the injection well
- Moisture content increased by 1.4 to 4 times near the fractures compared to no impact near the conventional well

These improvements in remedial activities have been accomplished at a low cost increase associated with the creation of sand-filled hydraulic fractures. The costs associated with the hydraulic fracturing operation are detailed in Table 7-1. These costs are based on a SVE site because cost information is available from the pilot-scale demonstration conducted at the Xerox Oak Brook site. The cost of drilling the conventional well is not included. The number of wells required to remediate a site can be significantly reduced by using hydraulic fracturing.

The site preparation cost includes the mobilization of equipment and rental of a bobcat to move material. Permitting and regulatory costs are based on costs incurred at the Xerox Oak Brook site. There are no startup costs because the trailer-mounted hydraulic fracturing equipment can be brought to a site and immediately begin operation. There are no utility costs since hydraulic fracturing uses diesel- or gasoline-powered pumps and the cost of fuel is included in the supply and consumable costs, The technology does not treat wastes; therefore, there are no costs associated with effluent treatment and

Table 7-1. Estimated Costs Associated With Hydraulic Fracturing

Cost Category		Estimated Daily Cost (1993 Dollars)
1.	Site Preparation	$ 1,000
2.	Permitting and Regulatory*	5,000
3.	Capital Equipment Rental[b]	l,000
4.	startup	0
5.	Labor	2,000
6.	Supply and Consumables	l,000
7.	Utilities	0
8.	Effluent Treatment and Disposal	0
9.	Residual and Waste Shipping and Handling	0
10.	Analytical and Monitoring	**700**
11.	Maintenance and Modifications	**0**
12.	Demobilization*	**400**
	Total One-Time Costs	**$ 5,400**
	Total Daily Costs	**$ 5,700**
	Estimated Cost per Fracture"	$950 to $1,425

Notes:

a One time costs

b Capital equipment includes the following:

- Equipment trailer
- Slurry mixer and pump
- Mixing pumps, tanks, and hose
- Fracturing lance and wellhead assembly
- Notching pump and accessories
- Pressure transducer and display
- Uplift survey equipment
- Scale
- Miscellaneous tools and hardware

Rental cost is based on 30 rentals per year and a depreciation of the $92,900 capital cost over 3 years.

c Total daily costs (excluding one-time costs) divided by 4 or 6 fractures per day disposal and residual and waste shipping and handling. Labor costs include the cost of four to five persons and their per diem expenses. Supplies and consumables include sand proppant, guar gum gel, enzyme, and diesel or gasoline (for running the pumps). Analytical and monitoring costs include the cost of pneumatic piezometer installation near the fractured wells. Equipment maintenance and modification costs would be incurred by the technology vendor and would be included in the rental fee. The demobilization costs are estimated to be about $400 to move the equipment from Chicago, Illinois, to Cincinnati, Ohio.

The cost per fracture is estimated to be $950 to $1,425, based on creating 4 to 6 fractures per day. This cost is small compared to the benefits of enhanced remediation and the reduced number of wells needed to complete the remediation.

8.0 CONCLUSIONS

Conclusions from the tests conducted at the Center Hill Facility and the pilot-scale demonstrations completed at the Xerox Oak Brook and the Dayton sites are discussed below.

8.1 CENTER HILL FACILITY TESTS

- The vapor yield from a fractured well was about an order of magnitude higher than from an unfractured well.
- The zone of pneumatic control extended more than 10 times farther from the fractured well than from the unfractured well.
- Rainfall decreased vapor yield and increased suction head of fractured wells. Unfractured wells were not affected by rainfall.
- The effect of a vented fractured well was not significantly different from that of an unvented fractured well.

8.2 XEROX OAK BROOK SITE TESTS

- Fractured wells yielded vapor flow rates 15 to 30 times greater than unfractured wells.
- The vapor flow rate from fractured wells was adversely affected by precipitation.
- The contaminant yields from the fractured well zones were 7 to 14 times greater than from comparable zones in the unfractured wells.

8.3 DAYTON SITE TESTS

- The flow of water was about 25 to 40 times greater in the fractured well than in the unfractured well.
- Moisture content increased in the vicinity of the fractured well, especially in the fractured zones. Only a minor change in moisture content was detected in the unfractured well.

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HYDRAULIC FRACTURING TECHNOLOGY

APPLICATIONS ANALYSIS REPORT

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NOTICE

The information in this document has been prepared for the U.S. Environmental Protection Agency's (EPA) Superfund Innovative Technology Evaluate (SITE) program under Contract No. 68-C0-0047. This document has been subjected to the Agency's peer and administrative reviews and it has been approved for publication as an EPA document. Mention of trade names or commercial products does not constitute an endorsement or recommendation for use.

FOREWORD

The SITE program was authorized by the Superfund Amendments and Reauthorization Act (SARA) of 1986. The program is administered by the EPA Office of Research and Development (ORD). The purpose of the SITE program is to accelerate the development and use of innovative cleanup technologies applicable to Superfund and other hazardous waste sites. This purpose is accomplished through technology demonstrations designed to provide performance and cost data on selected technologies.

This project consists of two pilot-scale demonstrations conducted under the SITE program to evaluate the hydraulic fracturing technology developed by the University of Cincinnati (UC) and EPA's Risk Reduction Engineering Laboratory (RREL). A full-scale demonstration using an EPA approved Quality Assurance Project Plan (QAPP) has not been conducted for this technology. The technology demonstrations were conducted at a Xerox Corporation vapor extraction site in Oak Brook, Illinois (Xerox Oak Brook site); and at a bioremediation site near Dayton, Ohio (the Dayton site). The demonstrations provided information on the performance and cost of the hydraulic fracturing technology. Tests to determine the performance of fractures over a l-year period were conducted at an uncontaminated site at the Center Hill Research Facility (Center Hill) Cincinnati, Ohio. This Applications Analysis Report provides an interpretation of the data and discusses the potential applicability of the technology.

Copies of this report can be purchased from the National Technical Information Service (NTIS), Ravensworth Building, Springfield, Virginia 22161, 703/487-4600. Requests should include the EPA document number found on the report's cover. Reference copies of this report will be available at EPA libraries as part of the Hazardous Waste Collection.

E. Timothy Oppelt, Director
Risk Reduction Engineering Laboratory

ABSTRACT

This report evaluates the effectiveness of the hydraulic fracturing technology, developed by the UC and EPA's RREL, in enhancing the permeability of contaminated silty clays and presents economic data from two pilot-scale SITE demonstrations.

The hydraulic fracturing technology creates sand-filled fractures up to 1 inch thick and 20 feet (ft) in radius. These fractures are placed at multiple depths ranging from 5 to 40 ft below ground surface (bgs) to enhance the efficiency of treatment technologies such as soil vapor extraction (SVE), in situ bioremediation, and pump-and-treat systems.

The hydraulic fracturing technology was demonstrated in 1991 and 1992 at the Xerox Oak Brook site, where SVE was in progress. On-site soil contamination included ethylbenzene; 1, ldichloroethane (DCA); trichloroethene (TCE); perchloroethane (PCA); l,l,l-trichloroethane (TCA); toluene; and xylene. The vapor flow rates, soil vacuums, and contaminant yields of two hydraulically fractured and two unfractured wells were compared. The fractured wells were fractured at 6, 10, and 15 ft bgs. The vapor‘yield from fractured wells was one order of magnitude greater than from unfractured wells. This yield was obtained from an area 30 times greater than the area affected by the unfractured well.

Another pilot-scale demonstration was conducted in 1991 and 1992 at the Dayton site where bioremediation was being conducted. Site contamination included benzene, toluene, ethylbenzene, and xylene (BTEX), and petroleum hydrocarbons. Fractures were created at 7, 8, 10, and 12 ft bgs at one of two on-site wells. Water containing hydrogen peroxide and nutrients was pumped into the hydraulically fractured well and into one unfractured well 50 ft from the fractured well. The injection flow rates, soil moisture contents, microbial metabolic activity, numbers of colony forming units (CFU), and rates of bioremediation at the fractured and unfractured wells were compared. In the fractured well, the injection flow rate was 25 to 40 times greater and the rate of bioremediation was higher for benzene, ethylbenzene, and petroleum hydrocarbons.

Possible sites where this technology is applicable include Superfund and other hazardous waste sites that have soil and ground water contaminated with organic compounds. The technology is to be used

in conjunction with remediation techniques such as SVE, in situ bioremediation, and pump-and-treat systems to enhance their effectiveness. Economic data indicate that the capital cost for hydraulic fracturing equipment is $92,900 and the cost of renting the equipment is $1,000 per day. Rental, operating, and monitoring costs for creating a fracture range from $950 to $1,425, depending on site-specific conditions. Typically, two to three fractures are created per well, and four to six fractures can be created in 1 day. The cost of creating a fracture is not materially affected by the depth of fracture for depths ranging from 5 to 40 ft bgs. The cost is also unaffected by the type of soil encountered,

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LIST OF ACRONYMS AND ABBREVIATIONS

AAR	Applications Analysis Report
ARAR	Applicable or relevant and appropriate requirements
bgs	Below ground surface
BTEX	Benzene, toluene, ethylbenzene, and xylene
Center Hill	Center Hill Research Facility
Cfm	Cubic feet per minute
CFU	Colony forming units
cm/sec	Centimeter per second
DCA	1, I-Dichloroethane
EPA	U.S. Environmental Protection Agency
FDA	Fluorescein Diacetate Analysis
ft	feet
GEMS	Ground Elevation Measurement Systems
gpm	gallons per minute
min	Minute
NA	Not applicable
ND	Not detected
NI	No impact
OD	outside diameter
ORD	Office of Research and Development
OSHA	Occupational Safety and Health Administration
OSWER	Office of Solid Waste and Emergency Response
PCA	Perchloroethane
PPb	Parts per billion
psi	Pounds per square inch
RCRA	Resource Conservation and Recovery Act
RREL	Risk Reduction Engineering Laboratory
SARA	Superfund Amendments and Reauthorization Act
SITE	Superfund Innovative Technology Evaluation
SVE	Soil vapor extraction

TCA	1, 1 , 1-Trichloroethane
TCE	Trichloroethene
TER	Technology Evaluation Report
TPH	Total petroleum hydrocarbon
UC	University of Cincinnati
μg/kg	Microgram per kilogram
UST	underground storage tank
VOC	Volatile organic compounds
Xerox	Xerox Corporation

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This report was prepared by Drs. V. Rajaram and Pinaki Banerjee, of PRC Environmental Management, Inc. (PRC). The report was typed by Ms. Cheryl Vaccarello, edited by Ms. Shelley Fu, and reviewed by Dr. Kenneth Partymiller and Mr. Stanley Labunski, all of PRC.

EXECUTIVE SUMMARY

Hydraulic fracturing has been used by the petroleum industry to create fractures in deep rock formations to enhance the flow of oil and gas to recovery wells. The University of Cincinnati (UC) and the U.S. Environmental Protection Agency (EPA) Risk Reduction Engineering Laboratory (RREL) developed the hydraulic fracturing technology in 1990 for creating fractures in low permeability soils to enhance the efficiency of treatment technologies such as soil vapor extraction (SVE), bioremediation, and pump-and-treat systems. The hydraulic fracturing technology creates sand-filled fractures up to l-inch thick and 20 feet (ft) in radius at multiple depths ranging from 5 to 40 ft below ground surface (bgs).

The hydraulic fracturing technology was evaluated under EPA Superfund Innovative Technology Evaluation (SITE) program. Pilot-scale demonstrations were conducted in 1991 and 1992, at a Xerox Corporation (Xerox) site in Oak Brook, Illinois (the Xerox Oak Brook site), where vapor extraction was being conducted, and at a site near Dayton, Ohio (the Dayton site), where bioremediation was used. Testing was also conducted by UC researchers at the Center Hill Research facility in 1992 to study the factors affecting the performance of hydraulic fractures in enhancing air flow through silty clays.

Hydraulic fracturing involves mixing a granular solid (termed a proppant), which is usually sand, with a viscous fluid (guar gum and water mixture), and pumping the mixture into a fracture as it grows away from the well. An enzyme added to the viscous fluid breaks down the gel, leaving the sand to hold open the fracture. Hydraulic fracturing equipment can be mounted on a trailer and includes a mixer, a slurry pump, and storage tanks. The fracturing process begins by the use of a high-pressure water jet to cut a disk-shaped notch extending 0.5 ft from the borehole wall of a well at which fractures are to be made. The slurry pump injects a mixture of sand and guar gum, water, and enzyme into the notch at a rate of 10 to 25 gallons per minute (gpm) until a critical pressure is reached and a fracture is propagated. The process is repeated at greater depths to produce a stack of multiple sand-filled hydraulic fractures.

The purpose of this Applications Analysis Report (AAR) is to present information from the two SITE pilot-scale demonstrations that can be used to implement the hydraulic fracturing technology at Superfund and Resource Conservation and Recovery Act (RCRA) hazardous waste sites.

Section 1.0, the introduction, discusses the purpose, history, and goals of the SITE program; discusses documentation of SITE demonstration results; presents the purpose of this AAR; provides a technology description; describes the fracturing procedure; and presents a list of key contacts. Section 2.0 presents a technology applications analysis that discusses other demonstration results, factors influencing the technology's effectiveness, SITE demonstration objectives and conclusions, personnel requirements, potential regulatory requirements, and appropriate waste and site conditions. Section 3.0, the economic analysis, summarizes site-specific factors affecting costs, the basis of the economic analysis, the cost categories used to determine hydraulic fracturing costs, and costs per fracture. References are presented in Section 4.0. Appendix A provides the vendor's claims regarding the hydraulic fracturing technology, Appendix B summarizes the SITE demonstration results, and Appendix C describes fracturing tests conducted at two sites.

The rest of this Executive Summary presents an overview of the SITE demonstrations, results from the demonstrations, waste applicability, an economic analysis, and conclusions for the hydraulic fracturing technology.

OVERVIEW OF THE SITE DEMONSTRATIONS

The SITE demonstrations at the Xerox Oak Brook site and the Dayton site, and the tests conducted at Center Hill had the following objectives:

- To assess the technology's ability to create sand-filled hydraulic fractures in silty clays and study the factors that affect these fractures over a period of 1 year
- To evaluate the technology's ability to significantly enhance SVE and contaminant removal at the Xerox Oak Brook site
- To determine the efficiency of hydraulic fracturing in delivering water containing hydrogen peroxide and nutrients to the Dayton site, which is contaminated with petroleum products

- To develop information required to estimate the costs for the technology

The Center Hill tests were conducted for over 1 year in uncontaminated silty clays to determine the effects of single and multiple depth hydraulic fractures on the enhancement of air flow through the soil. In addition, the effect of rainfall on fracture performance was studied.

The Xerox Oak Brook site contained silty clays contaminated with ethylbenzene, 1,1-dichloroethane (DCA), trichloroethene (TCE), perchloroethane (PCA), 1, 1, 1-trichloroethane (TCA), toluene, and xylene. Two out of four wells being used for two-phase soil vapor extraction (SVE) were fractured at depths of 6, 10, and 15 ft bgs. Over a period of one year, the soil vapor flow rates, suction head, and contaminant removal rates were measured and compared for the fractured and unfractured wells.

The Dayton site contamination included benzene, toluene, ethylbenzene, and xylene (BTEX), and petroleum hydrocarbons. One out of two wells was fractured at depths of 7, 8, 10, and 12 ft bgs. Water containing hydrogen peroxide and nutrients was gravity fed into these wells intermittently for about 6 months. The site operator was responsible for this activity, and UC Center Hill was responsible for monitoring the progress of bioremediation in the vicinity of the fractured and unfractured wells. Two rounds of sampling were conducted at locations 5, 10, and 15 ft north of the fractured and unfractured wells after bioremediation was in progress for 1 and 6 months. Soil samples only were obtained and analyzed for moisture content, microbial metabolic activity, number of colony forming units (CFU), BTEX, and petroleum hydrocarbons.

RESULTS FROM THE SITE DEMONSTRATIONS

The Center Hill tests show that the pneumatic control zone, which is the zone in which the pressure distribution can be controlled by varying the applied suction head, extended more than 10 times farther from the fractured well than from the unfractured well. The air yield from the fractured well was one order of magnitude higher than that from the unfractured well. Rainfall affected the performance of vapor extraction wells by decreasing the air yield and increasing the suction head.

The vapor extraction demonstration at the Xerox Oak Brook site involved two-phase vapor extraction that separated water from vapor. The vapor yield from hydraulically fractured wells was approximately one order of magnitude greater than from unfractured wells. The hydraulically fractured wells enhanced remediation over an area more than 10 times than that remediated by unfractured wells. The contaminant yields from the fractured well zones were approximately an order of magnitude greater than from comparable zones in the unfractured wells. Results from the Xerox Oak Brook site agreed with findings from Center Hill tests on the adverse impacts of rainfall.

The Dayton site results show that the water flow rate into the fractured well is 25 to 40 times greater than into the unfractured well. Because UC Center Hill did not control the bioremediation activities at the site, the amount of water fed into the fractured and unfractured wells was erratic during the 6-month testing period, resulting in anomalous findings from the second and third rounds of sampling. However, in the fractured well, the rate of bioremediation was higher for benzene, ethylbenzene, and petroleum hydrocarbons.

WASTE APPLICABILITY

The hydraulic fracturing technology can be applied to low permeability (less than 10^{-7} cm/s) silty clays or rock, and used to improve remedial methods that target organic compounds. The technology is effective up to depths of 40 ft bgs, and minimizes the number of wells needed for in situ remediation of the site. Potential sites for applying this technology to contaminated soils include Superfund and RCRA corrective action sites where solvents and/or petroleum hydrocarbons have spilled. Horizontal compressive stress that is greater than vertical stress in overconsolidated clays favors the propagation of horizontal fractures. Horizontal fractures are effective in increasing the permeability of the soil over larger radial distances than steeply dipping fractures; hence, overconsolidated clays are preferred sites for application of the hydraulic fracturing technology.

ECONOMIC ANALYSIS

The economic analysis was performed to determine the costs of creating a fracture using the pilot-scale, trailer-mounted equipment assembled by UC. The cost of creating a fracture varies from $950 to $1,425, depending on site-specific conditions. Four to six fractures can be created per day at one location, and typically; two to three fractures are created in one well.

CONCLUSIONS

Creating sand-filled hydraulic fractures in the vicinity of a vapor extraction well significantly affected both the vapor yield and the area influenced by the well. The vapor yield increased one order of magnitude for a fractured well, and the distance influenced by the well was more than 10 times greater than for a well without hydraulic fractures. Rainfall adversely affected the performance of vapor extraction wells by decreasing yield and increasing the suction head.

The amount of water introduced in the vicinity of a fractured well was 25 to 40 times greater than that in the vicinity of an unfractured well, significantly enhancing in situ bioremediation of soils in the vicinity of the fractured well.

1.0 INTRODUCTION

This section provides the purpose, history, and goals of the SITE program; documentation of the SITE demonstration results; the purpose of this AAR; the hydraulic fracturing technology; a description of the fracturing procedures; and a list of contacts.

1.1 PURPOSE, HISTORY, AND GOALS OF THE SITE PROGRAM

In response to the Superfund Amendments and Reauthorization Act of 1986 (SARA), EPA's Office of Research and Development (ORD) and Office of Solid Waste and Emergency Response (OSWER) established the SITE program to (1) accelerate the development, demonstration, and use of new or innovative technologies to clean up Superfund sites; (2) foster further investigation and development of treatment technologies that are still at the laboratory scale; and (3) demonstrate and evaluate new or innovative measurement and monitoring technologies.

The primary purpose of the SITE program is to enhance the development and demonstration of innovative technologies applicable to Super-fund sites to promote their commercial availability. Major goals of the SITE program are as follows:

- Identify and remove impediments to the development and commercial use of alternative technologies
- Demonstrate the more promising innovative technologies to establish reliable performance and cost information for site cleanup decision making
- Develop procedures and policies that encourage selection of available alternative treatment remedies at Superfund sites
- Structure a development program that nurtures emerging technologies

EPA recognizes that a number of forces inhibit the expanded use of alternative technologies at Superfund sites. One of the objectives of the program is to identify these impediments and remove them or to develop methods to promote the expanded use of alternative technologies.

Another objective of the SITE program is to demonstrate and evaluate selected technologies. This significant ongoing effort involves ORD, OSWER, EPA regions, and the private sector. The demonstration program tests field-ready technologies and provides Superfund decision makers with the information necessary to evaluate the use of these technologies for future cleanup actions.

Other aspects of the SITE program include developing procedures and policies that match available technologies with wastes, media, and sites for actual remediation, and assisting in the development of emerging innovative technologies from the laboratory- or bench-scale to the full-scale stage.

Technologies chosen for a SITE demonstration must be innovative, pilot- or full-scale applications, and offer some advantage over existing technologies. Mobile technologies are of particular interest.

1.2 DOCUMENTATION OF THE SITE DEMONSTRATION RESULTS

The results of each SITE demonstration are incorporated in two documents: the technology evaluation report (TER) and the AAR. The TER provides a comprehensive description of the demonstration and its results. A likely audience for the TER are engineers responsible for performing an in-depth evaluation of the technology for a specific site and waste situation. These technical evaluators seek to understand the performance of the technology in detail during the demonstration and the advantages, risks, and costs of the technology for the given application. This information is used to produce conceptual designs of sufficient detail for evaluators to estimate preliminary costs for the demonstrated technology.

The AAR is intended for technical decision makers responsible for screening available remedial alternatives. The AAR discusses factors such as site and waste characteristics that have a major impact on cost and performance. If the candidate technology appears to meet the needs of the site engineers, a more thorough analysis will be conducted based on the TER, AAR, and information from remedial investigations for the specific site.

1.3 PURPOSE OF THE AAR

To encourage the general use of demonstrated technologies, EPA provides information in the AAR on each technology's applicability to certain sites and wastes and presents the costs of these applications based on data from pilot- and full-scale demonstrations. These AARs synthesize available information on the technology and draw reasonable conclusions about the technology's broad range of applicability. The AAR is useful to those considering the technology for Superfund and other hazardous waste site cleanups and represents a critical step in the development and commercialization of the treatment technology.

Each SITE demonstration evaluates a technology's performance in remediating a site contaminated with a particular waste. Thus, the successful demonstration of a technology at one site does not ensure that it will work equally well at other sites. Data obtained from the demonstration should be used along with other information and case studies to estimate the total operating range over which the technology performs satisfactorily.

1.4 TECHNOLOGY DESCRIPTION

Hydraulic fracturing has been successfully used by the oil industry to enhance oil recovery from deep, low permeability rock formations. The mechanics of hydraulic fracturing in rock formations is well understood (Hubbert and Willis, 1957). In 1990, a team led by Dr. Murdoch of UC completed theoretical and laboratory investigations of hydraulic fracturing in low permeability soils. With funding from EPA's RREL, the team from UC conducted field experiments, and in 1991, submitted a proposal for demonstrating this technology under the SITE program. EPA selected the hydraulic fracturing technology for demonstration under the SITE program in July 1991.

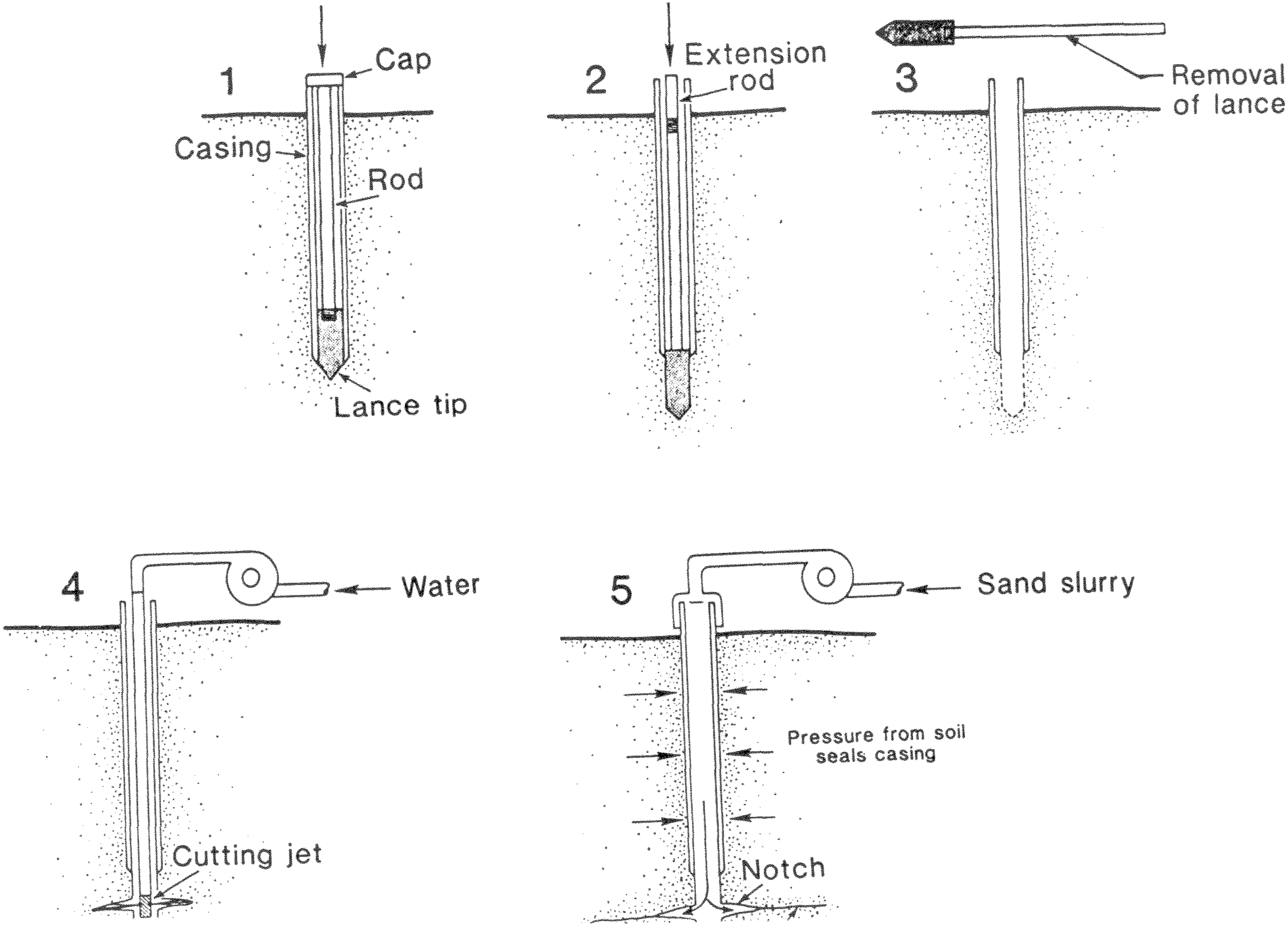
The hydraulic fracturing technology is designed to create sand-filled fractures up to l-inch thick and 30 ft in radius. These fractures, when created at several depths from 5 to 40 ft bgs, increase the in situ permeability of contaminated soil. This increased permeability promotes the flow of vapors and liquids through the soil and enhances the effectiveness of SVE, bioremediation, and pump-and-treat remediation techniques.

The hydraulic fracturing equipment consists of a continuous slurry-mixer and positive displacement pump mounted on a trailer. A typical sequence of operations for creating hydraulic fractures is shown in Figure l-l. Equipment and material required is as follows:

- A piston pump or a progressive cavity pump to inject slurry
- A continuous mixer for creating the slurry, which consists of up to one part of granular solid and two parts of viscous fluid
- A fracturing lance composed of an outer casing and an inner rod, both of which are tipped with hardened cutting surfaces that form a conical point, to prepare boreholes used for hydraulic fracturing (see Figure l-2)
- Steel tubing with a narrow orifice at one end
- Granular solid, termed proppant, which is usually a coarse sand
- A viscous fluid to carry the proppant into the fracture. This fluid is a mixture of guar gum gel, water, and an enzyme that breaks down the gel after the proppant has been deposited into the fracture.
- A trailer on which the slurry mixer and pump are mounted (see Figure l-3)

1.5 FRACTURING PROCEDURE

A borehole is drilled using 6 or 8-inch outside diameter (OD) hollow-stem augers. Individual segments of the rod and casing are 5 ft long and are threaded together as required by fracture depth. The tip of the fracturing lance is driven to a depth where a fracture is to be created. The lance is removed, leaving soil exposed at the bottom of the casing (see Figure l-l). Steel tubing with a narrow orifice at one end is inserted into the casing, and water is pumped through the tubing to create a high-pressure water jet. The water jet, which has a pressure of about 3,500 pounds per square inch (psi), is rotated within the borehole and produces a disc-shaped notch extending 4 to 6 inches from the borehole (see Figure l-l). A simple measuring apparatus comprised of a steel tape extending the length of the tube and making a right angle bend at the end of the tube can be inserted into the casing to measure the radius of the notch.



Source: Modified from University of Cincinnati, 1991

Figure 1–1. Sequence of Operations for Creating Hydraulic Fractures

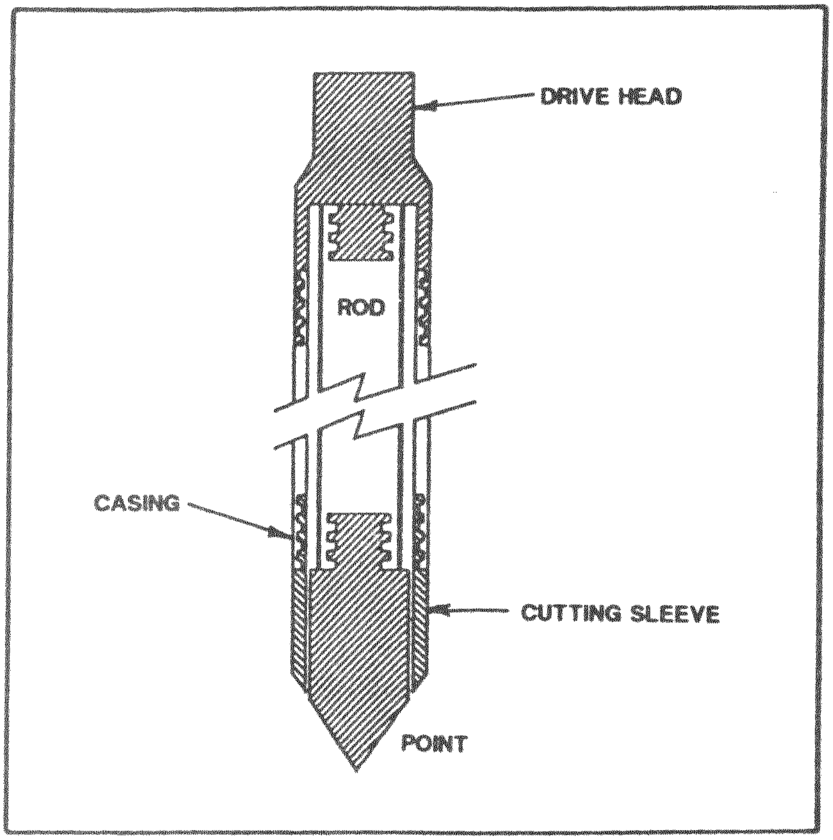


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Figure 1-2. Fracturing Lance Used to Prepare Boreholes for Hydraulic Fracturing

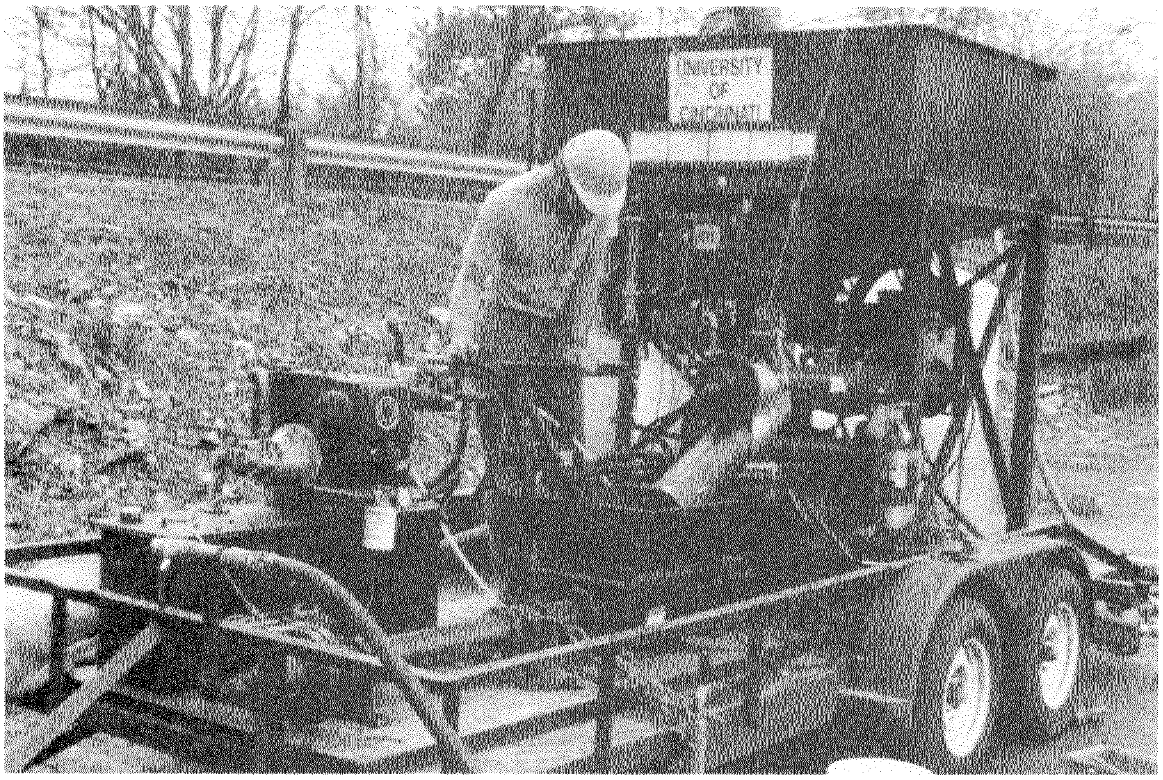


Figure 1-3. Slurry Mixing and Pumping Equlpment Mounted on Trailers

Sand slurry is produced by mixing one part of granular solid with two parts of viscous fluid in the continuous mixer. A hydraulic fracture is created by pumping a predetermined volume of slurry at rates of 10 to 25 gallons per minute (gpm). Lateral pressures from the soil on the outer wall of the casing effectively seals the casing and prevents leakage of the slurry. The fracture nucleates at the notch and grows up to 30 ft from the borehole wall.

The direction and distance of propagation of the fracture is measured by monitoring the uplift of the ground surface. Several stakes are placed along different radial directions around the borehole prior to fracturing. After fracturing, a leveling telescope can be used to measure the change in elevation of preexisting marks on the stakes to determine the location and net uplift of the ground surface resulting from the fracture. A laser system called the Ground Elevation Measurement System (GEMS) was developed by UC to measure uplift in real time during hydraulic fracturing. The system uses a laser and an array of sensors to track the displacement of each point in the array with time.

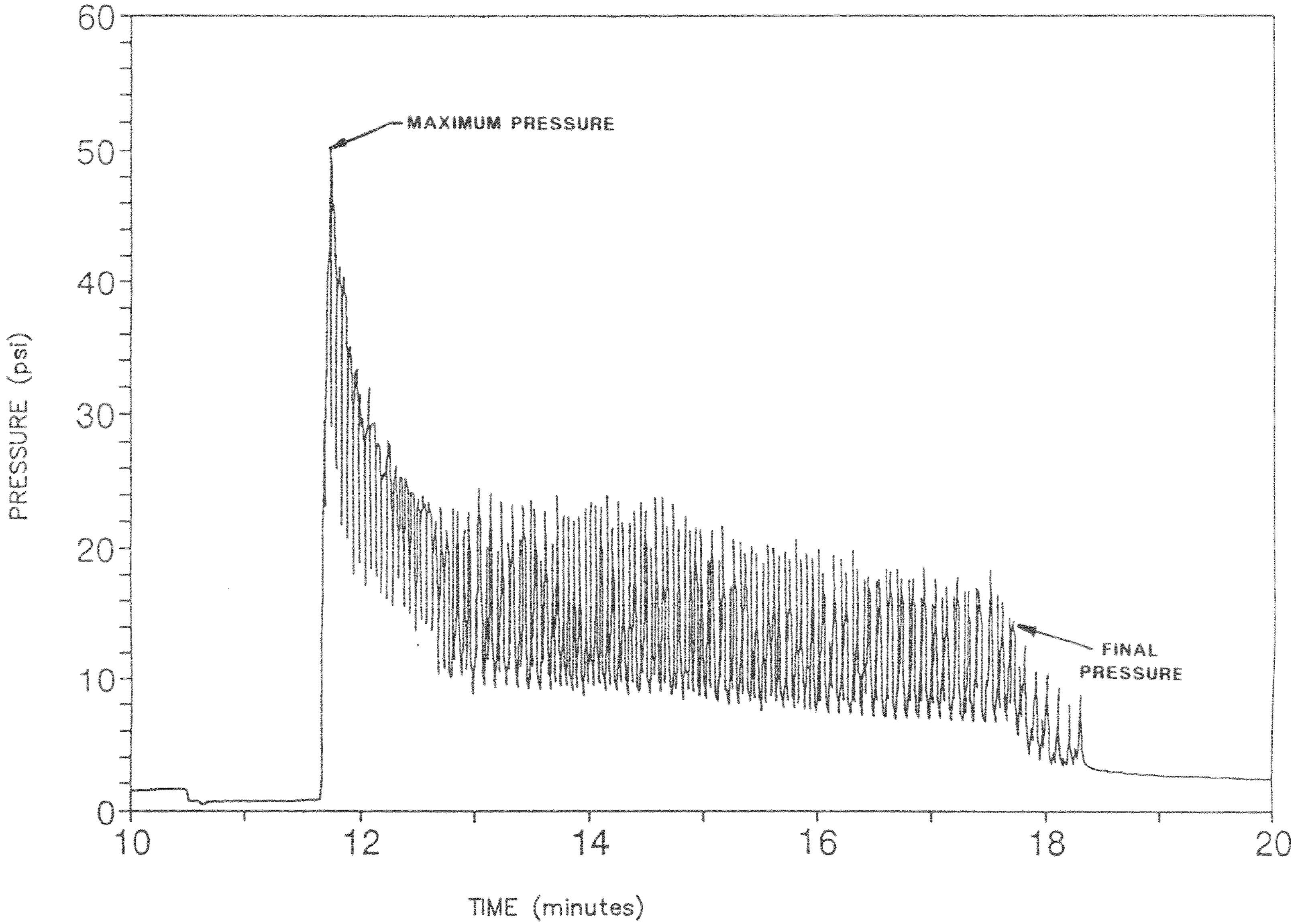
A typical pressure versus time plot obtained during hydraulic fracturing is presented in Figure l-4. The maximum pressure indicates the onset of fracturing, and the subsequent reduction of pressure with time denotes the period of fracture propagation. The rapid pressure oscillations shown in Figure l-4 result from the cycling of the piston pump, and are absent when a progressive cavity pump is used to inject the slurry.

1.6 KEY **CONTACTS**

Additional information on the hydraulic fracturing technology and the SITE program can be obtained from the following sources:

Hydraulic Fracturing Technology

Dr. Lawrence C. Murdoch
Director of Research
Department of Civil and Environmental Engineering
University of Cincinnati
5995 Center Hill Road
Cincinnati, OH 45224
Telephone No. (513) 569-7897



Source: Modified from Wolf and Murdock, 1992

Figure 1—4. Pressure Versus Time During the Creation of a Hydraulic Fracture

The SITE Program

Ms. Naomi Barkley
of Research and Development
Risk Reduction Engineering Laboratory
U.S. Environmental Protection Agency
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2.0 TECHNOLOGY APPLICATIONS ANALYSIS

This section describes SITE demonstration objectives and conclusions including UC Center Hill tests, other demonstration results, factors influencing the effectiveness of the hydraulic fracturing technology, personnel requirements, potential regulatory requirements, and appropriate waste and site conditions. The vendor's claims regarding the applicability and performance of the hydraulic fracturing technology are included in Appendix A. The technology's applicability is based on the results of two pilot-scale demonstrations conducted under the SITE program. The SITE demonstration results are presented in Appendix B and other applications of the technology are presented in Appendix C.

2.1 SITE DEMONSTRATION OBJECTIVES AND CONCLUSIONS

The SITE demonstrations were conducted at the Xerox Oak Brook site where SVE was being used, and the Dayton site where bioremediation was in progress. The technology developer also conducted tests at an uncontaminated site at Center Hill to determine factors affecting air flow through hydraulic fractures. The objectives of the two demonstrations and the Center Hill tests were as follows:

- To assess the technology's ability to create sand-filled hydraulic fractures in silty clays and study the factors that affect these fractures over a period of 1 year
- To evaluate the technology's ability to significantly enhance SVE and contaminant removal at the Xerox Oak Brook site
- To determine the efficiency of hydraulic fracturing in delivering water containing hydrogen peroxide and nutrients to the Dayton site, which is contaminated with petroleum products
- To develop information required to estimate the costs for the technology

2.1.1 Center Hill Tests

Fractures were created in three wells at the Center Hill facility site, and air flow through the three fractured wells over a l-year period was compared to the air flow through two unfractured conventional wells. In one well, a fracture was created at 5 ft bgs. In the second well, fractures were created at 5 and 10 ft bgs, and in the third well, a fracture was created at 5 ft bgs and vented to the surface.

A suction head of 120 inches of water was applied to the five wells, and the suction head was measured at several dozen pneumatic piezometers near each of the wells. The air yield from each of the wells was also measured. The impacts of rainfall on the suction head and air yield from the five wells was monitored during the winter and summer of 1992.

Conclusions from the Center Hill tests are as follows:

- The vapor yield from a fractured well was about an order of magnitude higher than from an unfractured well.
- The zone of pneumatic control of the fractured well was more than 10 times greater than that of the unfractured well.
- Rainfall decreased vapor yield and increased suction head of fractured wells. Unfractured wells were not affected by rainfall.
- The effect of a vented fractured well was not significantly different from that of an unvented fractured well.

2.1.2 Xerox Oak Brook Site Tests

The Xerox Oak Brook site contains silty clays contaminated with ethylbenzene, DCA, TCE, PCA, TCA, toluene, and xylene. Two out of four wells used for two-phase SVE were fractured at depths of 6, 10, and 15 ft bgs. A suction head was applied to the four wells, an in-line separator removed the water before the vapor flow rate was measured, and gas chromatograph analysis of the vapor was conducted. Over a period of 1 year, the vapor flow rates, suction head, and contaminant removal rates were measured for the fractured and unfractured wells.

Conclusions from the Xerox Oak Brook site tests are as follows:

- Fractured wells yielded vapor flow rates 15 to 30 times greater than unfractured wells.

- The vapor flow rate from fractured wells was adversely affected by precipitation.
- The contaminant yields from the fractured well zones were 7 to 14 times greater than from comparable zones in the unfractured wells.

2.1.3 Dayton Bioremediation Site Tests

Dayton site contamination included BTEX and petroleum hydrocarbons. One of two wells was fractured at depths of 6, 8, 10, and 12 ft bgs. Water containing hydrogen peroxide and nutrients was gravity fed into these wells intermittently for 6 months. Two rounds of soil sampling were conducted at locations 5, 10, and 15 ft north of the fractured and unfractured wells after bioremediation was in progress for 1 and 6 months.

Conclusions from the Dayton site tests are as follows:

- Moisture content increased in the vicinity of the fractured well, especially in the fractured zones. Only a minor change in moisture content was detected in the unfractured well.
- The flow of water was about 25 to 40 times greater in the fractured well than in the unfractured well.
- Benzene, ethylbenzene, and petroleum hydrocarbon removal was higher in the fractured well than in the unfractured well.

2.2 OTHER DEMONSTRATION RESULTS

The research team from UC used hydraulic fracturing to enhance remediation activities at two other sites. Results from the two sites are summarized in Appendix C A brief summary of the effectiveness of the hydraulic fracturing technology at these two sites is presented below.

The first site is an inactive gasoline retail facility located in Addison, Illinois. The site is contaminated with petroleum hydrocarbons to a depth of 10 ft bgs. The site is underlain by silty clay till. Groundwater is present at depths ranging from 5 to 8 ft bgs.

Three sand-filled hydraulic fractures were created at depths of 6.5, 9, and 11.75 ft bgs at two locations, and SVE wells were installed with screens intersecting these fractured depths. The performance of these wells was compared to the performance of two vapor extraction wells installed in unfractured ground. A suction head of up to 10 inches of mercury was applied to the wells.

The soil around the fractured well had greater permeability throughout the formation than the soil around the unfractured well; however, saturated soils prevented the flow of vapor in both fractured and unfractured wells. Hence, hydraulic fracturing does not enhance vapor extraction in saturated soils

The second site, which is located in Grand Ledge, Michigan, is contaminated with petroleum hydrocarbons resulting from the leakage of gasoline and waste oil from underground storage tanks (UST). The site is underlain by silty clay with occasional sand and silt seams. The boring logs indicate that the soils are underconsolidated and softer than at sites where hydraulic fracturing has been successfully completed.

Fracturing was attempted at uncontaminated areas of the site at depths varying from 18 to 30 ft bgs. At one location, the fractures vented to the surface. At another location, the stress gradients in the soil resulted in discontinuous, steeply dipping fractures. Hence, the fractures created in underconsolidated clays where vertical stress is more than horizontal stress, are steeply dipping and may be discontinuous. These fractures do not enhance SVE because the permeability increase from such fractures is significantly less than from gently dipping or horizontal fractures.

2.3 EFFECTIVENESS OF THE HYDRAULIC FRACTURING TECHNOLOGY

Hydraulic fracturing is an innovative technology that increases the permeability of silty clay and rock formations. The technology creates sand-filled fractures in the formation that are up to 1 inch thick and 30 ft long. Thus, the technology permanently enhances the flow of vapor or liquid through the formation.

Analytical results indicate that the hydraulic fracturing technology increases vapor flow by one order of magnitude, from distances of up to 30 ft from the recovery well. The water flow rate in a fractured well was 25 to 40 times that in a conventional unfractured well. This increased flow rate enhanced bioremediation of contaminated soil

2.4 FACTORS INFLUENCING EFFECTIVENESS

Several factors influence the effectiveness of the hydraulic fracturing technology. These factors include (1) site characteristics, (2) rainfall infiltrating into the site, and (3) operating parameters, Each of these factors is discussed below.

2.4.1 Site Characteristics

Hydraulic fractures can be created in both rock and relatively uniform silty clays that are overconsolidated and have low permeability (less than 10^{-7} cm/sec). Saturated sandy lenses in a clay layer may increase the water content of the soil and inhibit the flow of vapor during SVE. Care should be taken when creating fractures in the vicinity of sensitive structures such as precision manufacturing plants that may be damaged by deformations of the ground surface. Because the ground uplift is generally less than 1.5 inches, fractures can be created in the vicinity of roads, most buildings, and USTs.

Hydraulic fracturing is a permeability enhancement technique used in conjunction with other soil remediation methods. Sandy soils are permeable to liquid and vapor flow. Therefore, silty clays that have low in situ permeabilities are best suited for the use of hydraulic fracturing. The horizontal stress should be greater than the vertical stress at areas where hydraulic fracturing is to be implemented because this stress condition permits fractures to propagate in a horizontal orientation. Fractures that remain horizontal can grow to significant lengths, thereby enhancing flow in the subsurface.

Hydraulic fracturing is ineffective in normally consolidated clays. Demonstrations of hydraulic fracturing in such clays created fractures that were steeply dipping and vented to the surface. The presence of water decreases the efficiency of SVE; hence, the use of hydraulic fracturing to enhance SVE should be limited to unsaturated clays with moisture contents ranging from 20 to 30 percent.

2.4.2 Rainfall Infiltrating Into the Site

The amount of rainfall infiltrating into the site has a direct bearing on the effectiveness of SVE systems. The permeability enhancement produced by hydraulic fracturing improves liquid withdrawal from the subsurface, and until most of the pore water is recovered, relative vapor permeability will be negligible. Hence, any additional water introduced into the subsurface by rainfall will adversely affect vapor extraction from the site. Tests conducted for over 1 year at Center Hill and the Xerox Oak Brook site demonstrate the inverse relationship between rainfall and the SVE rates.

The use of a membrane that will prevent infiltration of rainfall into the subsurface, but that will allow inflow of air is recommended. SVE tests conducted at a site in Addison, Illinois, demonstrate that saturated soils must be dewatered before significant vapor flow rates can be achieved. Preventing rainfall from infiltrating into the site minimizes dewatering efforts and maximizes vapor recovery.

2.4.3 Operating Parameters

Several operating parameters affect hydraulic fracturing. The important parameters that are controlled during hydraulic fracturing are injection rate and gel-to-sand ratio. A brief summary of the manner in which these parameters affect hydraulic fracturing is presented below.

The injection rate affects the maximum and final pump pressures (see Figure l-4). The maximum pressure depends on initial slot length, in situ stress at the fracture location, and the water content of the soil. For a fracture created at a depth of 15 ft bgs, the maximum pressure can vary from 55 to 70 psi, and the final pressure is about 35 psi.

The gel-to-sand ratio in the slurry is adjusted to propagate the fracture and to move the sand into the fracture. The amount of the gel is reduced when a possibility exists of the fracture venting to the surface. In cases where the fracture propagates horizontally, the sand content is increased during pumping to increase the thickness and length of the fracture. The gel-to-sand ratio in the slurry is adjusted from fracture to fracture, depending on depth and site-specific soil conditions. For a fracture created at 15 ft bgs, about 150 gallons of gel and 14 cubic ft of sand are used.

2.5 PERSONNEL REQUIREMENTS

Equipment requirements for hydraulic fracturing include a slurry mixing tank, a slurry pump, a high-pressure water pump for creating the notch, a fracturing lance and well-head assembly, a pressure transducer and display terminal, and miscellaneous tools. A surveyor's level or the GEMS equipment is necessary for monitoring ground uplift. The major pieces of equipment, including the slurry mixing tank and pumps, are usually mounted on a trailer for ease of transport.

Assuming that a borehole has been drilled and is available for fracturing, only a qualified technician and two assistants are required to complete a set of hydraulic fractures from the borehole. The technician should be able to (1) keep the pumps and other equipment operational, (2) monitor and interpret the pressure versus time plot, (3) understand engineering properties of soil and well design, and (4) troubleshoot operational problems related to pump pressure and slurry volume. The assistants will monitor instrumentation and install pneumatic piezometers to measure the performance of fractures. If ground deformation measurements are to be taken, an individual familiar with the use of a surveyor's level and/or laser surveying equipment should be added to the crew.

Personnel working at a hazardous waste site should have an Occupational Safety and Health Administration (OSHA) 40-hour health and safety training, and take an annual 8-hour refresher course. Specific health and safety requirements will vary depending on the type of site contamination. Therefore, a site-specific health and safety plan should be prepared.

2.6 POTENTIAL REGULATORY REQUIREMENTS

Hydraulic fracturing can be used to enhance remediation at hazardous waste sites using SVE, in situ bioremediation, and pump-and-treat systems. The regulations that apply to a particular remediation activity will depend on the type of remediation site (Superfund or RCRA) and the type of waste being treated. Because hydraulic fracturing technology is an enhancement technique for other remediation activities used at the site, regulatory requirements for hydraulic fracturing are not distinct from those that apply to remediation being conducted at the site.

Hydraulic fracturing entails the injection of material into the subsurface. The permit requirements for using hydraulic fracturing at a site will depend on state and local regulations and may involve describing the process of creating fractures and assuring regulators that the gel is biodegradable and will break down after the sand is placed in the fracture. Local regulations relating to noise and hours of operation may also have to be complied with.

2.7 APPROPRIATE WASTE AND SITE CONDITIONS

Hydraulic fracturing can be used to enhance the permeability of any site contaminated with organic compounds. It has been demonstrated for sites contaminated up to 40 ft bgs. The suitability of the hydraulic fracturing technology for a hazardous waste site depends on certain site-specific characteristics. Any in situ treatment technology that can be applied to such a contaminated site can be enhanced by a thorough assessment of the following site conditions:

- Evaluating if the vertical stress is less than the horizontal stress, that is, if the soil is overconsolidated
- Evaluating if vapor extraction is the treatment technology applicable to the site and if the contaminated soil is unsaturated to permit the flow of vapor through the fractured soil
- Determining if any sand or soft clay lenses in the contaminated horizon tend to produce steeply dipping fractures that vent to the ground surface

3.0 ECONOMIC ANALYSIS

The primary purpose of this economic analysis is to estimate costs of utilizing hydraulic fracturing to enhance remediation in low permeability soils and rock. Site-specific factors affecting cost, the basis of the economic analysis, cost categories, and costs per fracture are described below. Costs have been divided into seven categories that are applicable to this technology. These categories include the following:

- Site preparation
- Permitting and regulatory
- Capital equipment
- Labor
- Supplies and consumables
- Analytical and monitoring costs
- Demobilization

Table 3-l presents the estimated costs for creating four to six fractures in two boreholes located about 100 ft apart. The costs presented in this analysis are order of magnitude estimates, with costs ranging from -30 to +50 percent.

The five cost categories out of the 12 typically associated with cleanup activities at Superfund and RCRA-corrective action sites that are not applicable to the hydraulic fracturing technology include the following:

- startup costs
- Utility costs
- Effluent treatment and disposal
- Residuals and waste shipping and handling
- Equipment maintenance and modifications

Table 3-l

ESTIMATED COSTS ASSOCIATED WITH HYDRAULIC FRACTURING

Cost Category		Estimated Daily Cost (1993 Dollars)
1.	Site Preparation	l,000
2.	Permitting and Regulatory [a]	5,000
3.	Capital Equipment Rental [b]	1 ,000
4.	startup	0
5.	Labor	2,000
6.	Supply and Consumables	1,000
7.	Utilities	0
8.	Effluent Treatment and Disposal	0
9.	Residual and Waste Shipping and Handling	0
10.	Analytical and Monitoring	700
11.	Maintenance and Modifications	0
12.	Demobilization”	400
	Total One-Time Costs	5,400
	Total Daily Costs	5,700
	Estimated Cost per Fracture [c]	$950 to $1,425

Notes:

[a] One time costs

[b] Capital equipment includes:

- Equipment trailer
- Slurry mixer and pump
- Mixing pumps, tanks, hose
- Fracturing lance, wellhead assembly
- Notching pump and accessories
- Pressure transducer and display
- Uplift survey equipment
- Scale
- Miscellaneous tools and hardware

Rental cost is based on 30 rentals per year, and depreciation of the $92,900 capital cost over 3 years.

[c] Total daily costs (excluding one-time costs) divided by 4 or 6 fractures per day

Hydraulic fracturing is an enhancement technology, not a treatment technology that reduces waste toxicity. The equipment used for creating hydraulic fracturing at contaminated sites is mounted on a mobile trailer and can be started up at minimal cost. Six to ten fractures can be created at a site in 2 to 3 days. Therefore, a site owner or operator will most probably rent the equipment and crew to create the fractures and will incur minimal startup costs. Equipment maintenance and modification costs would be incurred by the technology vendor and would be included in the rental fee.

Hydraulic fracturing uses diesel or gasoline engine powered pumps, and the cost of diesel fuel is included in the supply and consumable costs. Hence, no utility cost is incurred. The technology does not treat wastes; therefore, no cost is associated with effluent treatment and disposal and residuals and waste shipping and handling.

3.1 SITESPECIFIC FACTORS AFFECTING COST

A number of factors affect the estimated costs of creating hydraulic fractures at a site. These factors include (1) physical site conditions such as site accessibility and degree of soil consolidation; (2) degree of soil saturation; and (3) geographical location, which affects availability of services and supplies. The first two factors also affect the effectiveness of hydraulic fracturing.

The costs presented in this analysis are based on conditions found at the Xerox Oak Brook site. A full-scale demonstration was not conducted for this technology. Because operating costs were not independently monitored during the pilot-scale demonstrations at the Xerox Oak Brook and Dayton sites, all costs presented in this section were provided by Xerox and UC Center Hill.

3.2 BASIS OF ECONOMIC ANALYSIS

The hydraulic fracturing technique can be used to enhance the treatment effectiveness of SVE, bioremediation, and pump-and-treat systems. For the purpose of this economic analysis, a SVE site is considered because this type of treatment system is commonly used for soil remediation and because cost information for this method is available from the pilot demonstration conducted at the Xerox Oak Brook site.

The following assumptions were made for this economic analysis:

- The site is located in the midwest.
- Suitable access roads are available.
- Boreholes have already been drilled.
- The GEMS is available to monitor real time ground uplift.
- Four to six fractures are created per day.

3.3 COST CATEGORIES

A discussion of the seven cost categories applicable to the hydraulic fracturing technology and the elements associated with each category is provided below.

3.3.1 Site Preparation Costs

The costs associated with site preparation include system design (including design of fracture depths and installation of ground uplift monitoring points), and mobilization of the hydraulic fracturing equipment.

Sites that require clearing of vegetation and access roads will have significantly increased site preparation costs. For this analysis, site preparation costs for a 7,500-square-foot site are estimated to be approximately $1,000. Costs included are for mobilization of the equipment from Cincinnati, Ohio, to Chicago, Illinois (350 miles) and for rental of a bobcat to move material.

3.3.2 Permitting and Regulatory Costs

These costs are dependent on the type of wastes being treated and the remediation method being used at Superfund or RCRA corrective action sites. Superfund regulations require that the remedial action be consistent with applicable or relevant and appropriate requirements (ARAR), including environmental laws, regulations, and ordinances of federal, state, and local jurisdictions. In general, ARARs must be determined on a site-specific basis.

Because hydraulic fracturing is an enhancement technique that results in the injection of guar gum gel and sand into the subsurface, the permits required are those needed for the remediation method used at the site and state or local injection permit to demonstrate that the material introduced during fracturing will not adversely impact soil or ground water.

Permitting and regulatory costs are estimated to be approximately $5,000 based on costs incurred at the Xerox Oak Brook site.

3.3.3 **Capital Equipment Costs**

Capital equipment costs include the cost of the hydraulic fracturing equipment and the ground uplift monitoring system. Based on a trailer mounted fracturing setup assembled by the UC, the capital cost of the system is $80,100. If real-time uplift monitoring is desired, the GEMS laser surveying system developed by UC could be acquired for an additional capital cost of $12,800. Because hydraulic fracturing at a site can be completed in only a few days, it would not be cost-effective to purchase the equipment and GEMS. Accordingly, this economic analysis assumes that the equipment would be rented on a daily basis. It is further assumed that the equipment would be in use about 30 times per year, and that the total capital cost would be recovered in about 3 years. Based on these assumptions, the rental cost is about $1,000 per day.

3.3.4 **Labor Costs**

Labor costs include the cost of personnel to operate the hydraulic fracturing equipment and the ground uplift monitoring system, and per diem expenses for the crew. Per diem expenses are included because the fracturing crew travels to a site for a few days to finish fracturing and then leaves. Four to five persons can operate the fracturing and monitoring equipment. One person will operate the slurry mixer and pumps, and three to four persons will handle the fracturing lance and the uplift monitoring system. Labor costs are estimated to be $2,000 per day, and include the costs associated with the annual health and safety training.

3.3.5 Supply and Consumables Costs

Supplies and consumables costs include the cost of materials and fuel. Materials include sand, guar gel, and enzyme. Diesel and gasoline for running the pumps is included in the supply cost. The cost of supplies and consumables is estimated to be $1,000 per day for creating 4 to 6 fractures.

3.3.6 Analytical and Monitoring Costs

If subsurface suction heads are monitored during SVE, pneumatic piezometers can be installed near the wells. A two-person crew can install about 10 to 15 piezometers per day at a cost of $700.

3.3.7 Demobilization and Decontamination Costs

Demobilization costs are estimated to be about $400 to move the equipment from Chicago, Illinois, to Cincinnati, Ohio. Decontamination water will be collected with other SVE-related wastes and treated later. Therefore, decontamination costs are assumed to be negligible.

3.4 COSTS PER FRACTURE

Based on the daily cost of $5,700 and the estimate of 4 to 6 fractures created per day in two boreholes, the cost per fracture is estimated to vary from $950 to $1,425. The total one-time cost for obtaining the permits and demobilization is estimated to be $5,400.

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APPENDIX A

VENDOR'S CLAIMS REGARDING HYDRAULIC FRACTURING

(Three Sheets)

APPENDIX **A**

VENDOR' S CLAIMS REGARDING HYDRAULIC FRACTURING

Applicability

Hydraulic fracturing is a method of creating layers of granular material in soil or rock. When filled with sand, these layers increase fluid flow through soils of low permeability and enhance the performance of in situ remedial technologies, such as soil vapor extraction, soil washing, bioventing, bioremediation, and pump and treat. Sand-filled fractures can also act as pathways for the delivery of steam to the subsurface to mobilize contaminants for recovery. Other granular materials may be placed in the fractures to serve as reservoirs of remediating compounds. These include granular nutrients and time-release oxygen compounds to enhance biodegradation of organic compounds. Fractures can also be filled with conductive materials to induce electroosmosis, electromigration, and electrophoresis. Fractures filled with electrically resistive materials can be used to generate heat in the subsurface to increase microorganism populations and metabolic activity, or to facilitate volatilization of organic compounds.

Waste Types

Hydraulic fracturing unto itself is not a method of remediation, but instead is a means of enhancing the performance of existing in situ remedial technologies. Thus, it is applicable to contaminated soils that are treatable by in situ methods. Wastes commonly treated in situ include petroleum hydrocarbons, volatile organic compounds, and other organic contaminants.

Favorable Conditions for Hydraulic Fracturing

Hydraulic fracturing is particularly suited to sites underlain by soils where the lateral component of stress exceeds the vertical stress applied by the weight of the overburden (these soils are termed overconsolidated). Fractures created in overconsolidated soils tend to propagate in a horizontal to subhorizontal plane, allowing the fractures to reach maximum dimension without intersecting the ground surface. This geometry, in most cases, will be the most favorable for in situ technologies that utilize vertical wells. Glacial drift of the Midwest and Northeast, swelling clays of the Gulf coast, and similar soils are frequently overconsolidated and suitable for hydraulic fracturing.

Fractures created in normally consolidated soils tend to propagate in a vertical direction. This fracture geometry may beneficial when utilizing directional recovery wells.

Advantages of Hydraulic Fracturing

Hydraulic fracturing will increase fluid flow through the subsurface and will facilitate in situ remediation of fine-grained soils. Advantages include:

- Hydraulic fracturing facilitates use of in situ remediation in soils of low permeability, typically less than 10^{-7} centimeters per second. Without fractures, many of these soils would not be considered candidates for in situ remediation.

- Wells containing sand-filled fractures have been demonstrated to have a greater area of influence than conventional wells. This reduces drilling and well completion costs by increasing the spacing of the wells.

- The increase in subsurface fluid flow associated with sand-filled hydraulic fractures may decrease the time required for remediation.

- Sand can be placed in hydraulic fractures to create highly permeable pathways for delivery or recovery of remedial fluids. Filling the fractures with a sand proppant allows fractures to remain open at depths and in formations where unpropped fractures may close.

- Hydraulic fractures can be filled with a variety of compounds to enhance remediation. Hydraulic fractures filled with granular nutrients and time-release oxygen compounds can act as subsurface reservoirs of materials needed for bioremediation. Electrically conductive materials placed in the fractures offer the potential to induce electroosmosis, electrophoresis, or electromigration of contaminants. Moreover, hydraulic fractures may be used as resistive heaters to increase temperature and volatilize contaminants or to increase bioactivity.

Hydraulic Fracturing Project Schedule

The following schedule is based on a hydraulic fracturing project located less than 500 miles away, a field crew of five, and installation of 4 recovery wells containing 3 hydraulic fractures each. It assumes fractures will be created between depths of 5 and 15 feet, will be 20 to 30 feet in diameter, 0.5 to 1 inch in thickness, and contain 600 to 1,400 pounds of sand.

Description	Days
1. Site assessment/fracture design	1
2. Mobilization	1
3. Hydraulic fracturing	3
4. Well completion/monitor installation/decontamination	2
5. Demobilization	
Total	8

Cost Information

Hydraulic fracturing capital equipment, including the cost of the Ground Elevation Measurement System (GEMS), is estimated to be $92,900. Based on renting this equipment about 30 times per year, and a depreciation period of 3 years, the rental cost per day is about $1,000. Costs for site preparation, labor, supplies and consumables (sand, guar gum gel, enzyme, and diesel fuel), and pneumatic piezometer installation for monitoring the fracture performance are estimated to be $4,700 per day. Assuming that 4 to 6 fractures are created per day, the cost per fracture is estimated to be $950 to $1,425.

APPENDIX B

SITE DEMONSTRATION RESULTS

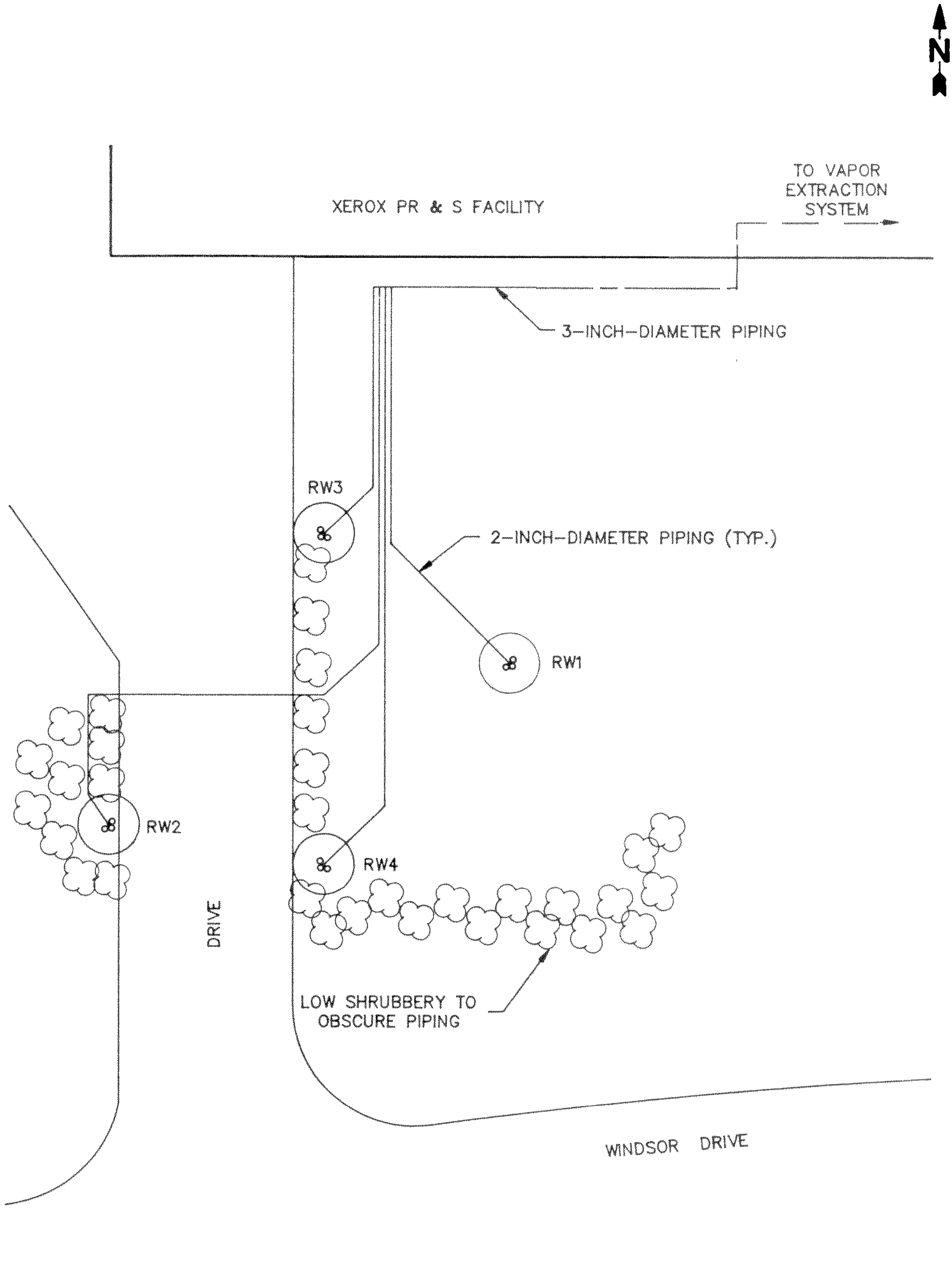
APPENDIX B
SITE DEMONSTRATION RESULTS

The hydraulic fracturing technology was demonstrated at a Xerox Corporation (Xerox) SVE site in Oak Brook, Illinois (the Xerox Oak Brook site), and at a bioremediation site near Dayton, Ohio (the Dayton site). The Superfund Innovative Technology Evaluation (SITE) demonstration activities and results are summarized in this appendix. More detailed information about the site demonstration results is presented in the technology evaluation report (TER).

XEROX OAK BROOK SITE

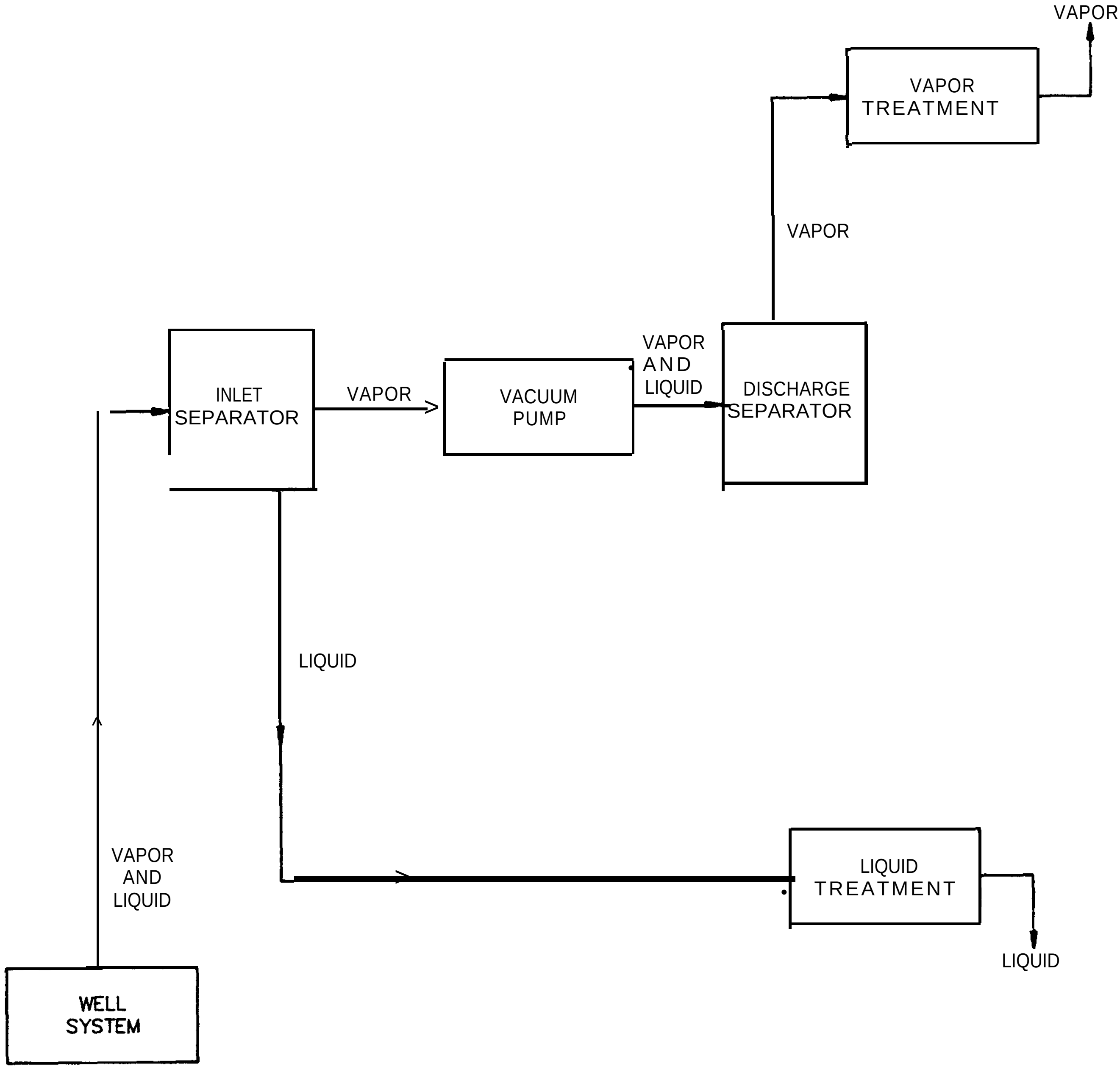
At the Xerox Oak Brook site, contaminants consisting of trichloroethene (TCE); 1, 1 , 1-trichloroethane (TCA); 1,1-dichloroethane (DCA); perchloroethane (PCA); ethylbenzene; toluene; and xylene are present in silty clay till to depths of 20 feet (ft) below ground surface (bgs) Xerox investigated the site in 1987. In 1991, a two-phase soil vapor extraction (SVE) system was installed. The layout of the vapor extraction system is shown in Figures B-l and B-2. Vacuum is applied to the wells by a pump, and the water and vapor in the soils surrounding the SVE wells is withdrawn. An inlet separator removes the water and a discharge separator removes the moisture in the vapor. The vapor is treated in a carbon adsorption unit, and clean air is vented out of the treatment building. The water is passed through a carbon adsorption unit and discharged to the sewer system. The discharge water is sampled to ensure that it meets the sewer permit requirements.

Hydraulic conductivity at the site varies from 10^{-7} to 10^{-8} centimeters per second (cm/sec) This low permeability hampers the rate of vapor extraction. To enhance vapor extraction, fractures were created at the site during the week of July 15, 1991. A work plan prepared by the University of Cincinnati (UC) Center Hill Research Facility (Center Hill) describes the pilot-scale study (UC, 1991a). The pilot-scale demonstration consisted of creating six hydraulic fractures at two locations. Figure B-3 presents piezometers and extraction well locations. RW1 and RW2 are recovery wells in unfractured ground, and RW3 and RW4 are recovery wells in fractured ground. Before fracturing, soil samples were obtained in the vicinity of the four wells to a depth of 15 ft bgs. Soil moisture content was measured every foot bgs, and two samples from each borehole were analyzed for volatile organic compounds (VOC). The work was performed in accordance with the Quality Assurance Plan prepared by Xerox's subcontractor, Woodward-Clyde Consultants (Woodward-Clyde Consultants, 1991).



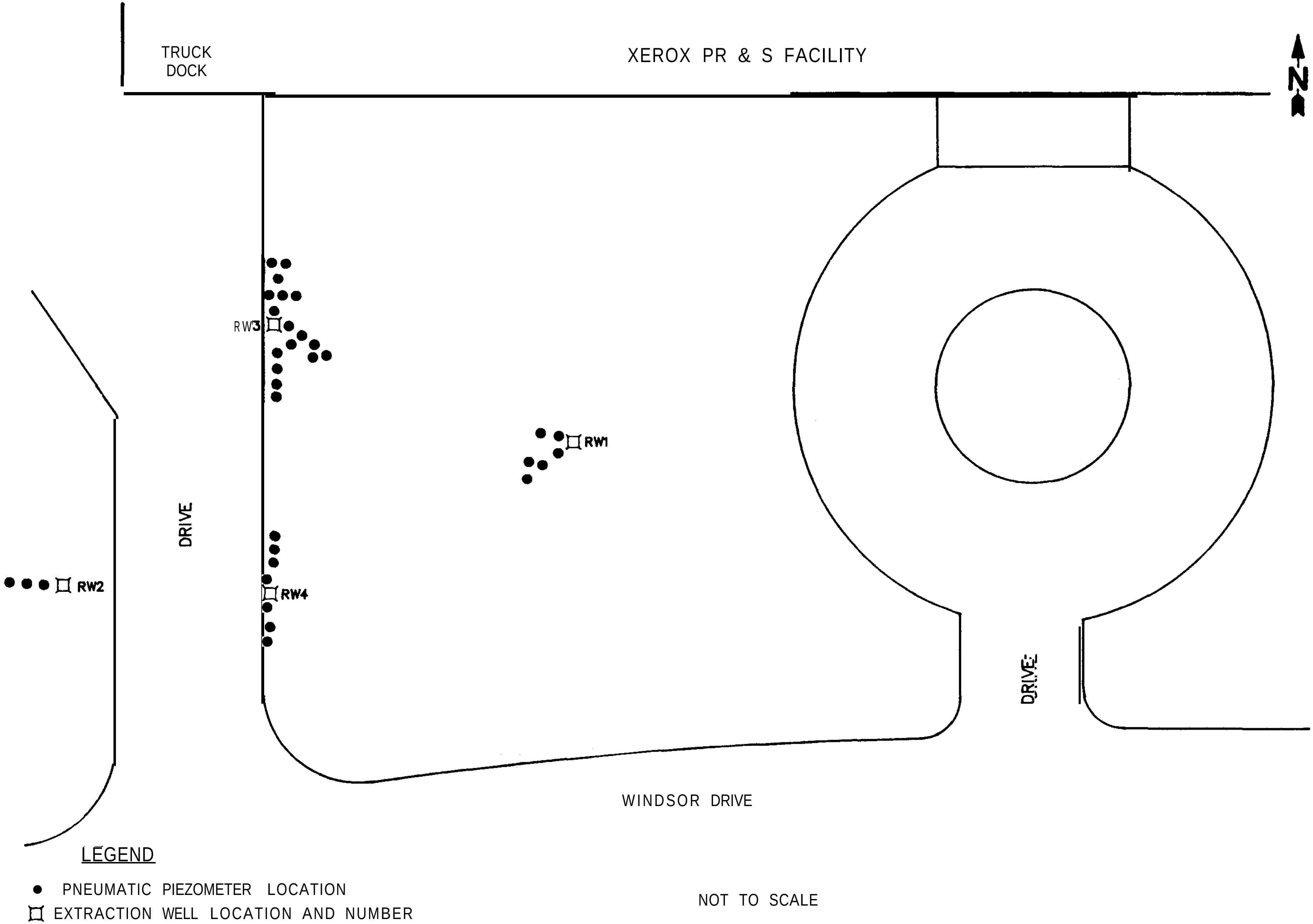
Source: Modified from Xerox, 1992

Figure B-1. Xerox Oak Brook Site Piping System Plan for Vapor Extraction



Source: Modified from Xerox. 1992

Figure B-2. Schematic Diagram of Xerox Oak Brook Site Vapor Extraction System



Source: Modified from Xerox. 1992

Figure B-3. Extraction well and Piezometer Locations

B-4

Fracturing Activities

Fractures were created at Wells No. RW3 and RW4 at depths of 6, 10, and 15 ft bgs. However, the fracture at Well No. RW4 at 6 ft bgs vented to the surface. Ground surface uplift measurements of up to 1.04 inches were measured at 11.5 and 16.4 ft from the fracturing hole. A week after the fractures were created, recovery wells and monitoring boreholes were drilled. Multilevel recovery wells consisting of separate screens and risers for each fracture were installed to make individual access to each fracture possible. Multilevel monitoring boreholes containing as many as six pneumatic piezometers were installed at 5, 10, 15, and 20 ft from each recovery well. Cased boreholes designed to serve as neutron probe access holes were installed near each monitoring borehole to measure soil moisture content.

The six fractures in contaminated ground were created on the same day, and each fracture required 1.5 to 2 hours to complete. Essential characteristics of the fractures are summarized in Table B-l. The details include the depth bgs at the point where the fracture was created, the bulk volume of sand pumped into the fracture, the volume of gel in the fracture, the maximum pressure at the point of injection, the pressure at the end of pumping, the maximum uplift (typically not at the point of injection), and the approximate radius of the uplifted area over the fracture. The radius of each fracture is dependent on the amount of slurry pumped into the fracture.

Xerox monitored the following parameters for the two fractured wells (Wells No. RW3 and RW4) and the two unfractured wells (Wells No. RWl and RW2):

- Water discharge from the system
- Soil moisture content at depths of 4, 8, and 12 ft bgs and at lateral distances of 10, 15, and 20 ft north of the wells
- Soil vacuum at recovery wells and monitoring points
- Vapor flow rates from recovery wells
- On-line gas chromatography (GC) analysis of 1,l-dichloroethane (DCA); l,l,l-TCA; TCE; toluene; ethylbenzene; perchloroethane (PCA); and xylenes

Table B-l. Fracture Characteristics at Xerox Oak Brook Site

Fracture Designation	Depth (ft bgs)	Sand (ft^3)	Gel (gallons)	Maximum Pressure (psi)	End Pressure (psi)	Maximum Uplift (inches)	Radius (ft)	Comment
OXPlFl	6.0	NA*	20	22	20	0.12	NA*	Vented to surface
OXPlF2	10.0	12	130	38	8	0.8	13.1	Recovery Well No. RW4
OXPlF3	15.0	13	150	55	34	0.96	16.4	Recovery Well No. RW4
OXP2Fl	6.0	6	100	25	8	1.04	11.5	Recovery Well No. RW3
OXP2F2	10.0	12	140	45	10	0.75	13.1	Recovery Well No. RW3
OXP2F3	15.0	14	150	72	35	1.2	14.8	Recovery Well No. RW3

*Not Applicable

Fracturing Results

Well discharge was measured using vortex shedding electronic flow meters from December 1991 until December 1992. These flow meters are very sensitive to the presence of water in the vapor and hence, did not provide reliable data for the flow from each well. Also, the range setting in these meters did not allow small readings (less than 10 cfm) to be accurately measured. Therefore, from June 1992 until December 1992, variable area flow meters (rotometers) were used to measure the flow from each riser connected to a fractured zone (or screened zone in RW2) in a well. A demister pot was utilized to remove any liquid from the vapor stream before it entered the rotometer, minimizing the effect of two-phase flow on the accuracy of the readings. A table summarizing the rotameter discharge is given below.

Table B-2. Summary of Well Discharge Readings

Well ID	Discharge range (acfm)	Discharge avg (acfm)	Discharge % 6 ft zone	Discharge % 10 ft zone	Discharge % 15 ft zone
RW2	0.1-4.6	1.1	46.3	27.3	23.2
RW3	2.2-22.0	14.3	61.2	8.4	30.4
RW4*	27.9-42.7	34.2	36.0	41.0	23.0
RW4	17.1-29.7	22.6	not applicable	not available	not available

* The six-foot-deep fracture at RW4 vented to the surface. This data includes discharge when suction is applied to all three of the fractures. The row below is well discharge when suction is applied to the l0- and 15-foot-deep fractures only.

The amount of contaminant removed from each well was calculated by using the following equation:

$$\text{Pounds/hour} = \text{Concentration} \times \text{Flow} \times \text{Molecular weight} \times 1.53 \times 10^{10} \qquad \text{(B-l)}$$

where

Concentration is in parts per billion measured by the GC

Flow is in cfm

Molecular weight of compound is in grams per mole

Vapor flow rates and contaminants removed from each well are presented in Figures B-4 and B-S, respectively. Data from Well No. RWl is not presented because it had a leak in its annulus between the riser and the borehole wall, which allows air from the surface to flow into the well. The discharge from the fractured Well Nos. RW3 and RW4 is 15 to 20 times greater than the discharge from the unfractured Well No. RW2. The amount of contaminants removed from fractured Well Nos. RW3 and RW4 is 7 to 14 times greater than from the unfractured Well No. RW2.

The vapor flow rates decreased during periods of precipitation in spring and early summer 1992, primarily because of water occupying the pore spaces in the soil. Xerox will cover the surface area in which the wells are screened with an impermeable membrane to prevent direct infiltration of rainfall into the contaminated soils.

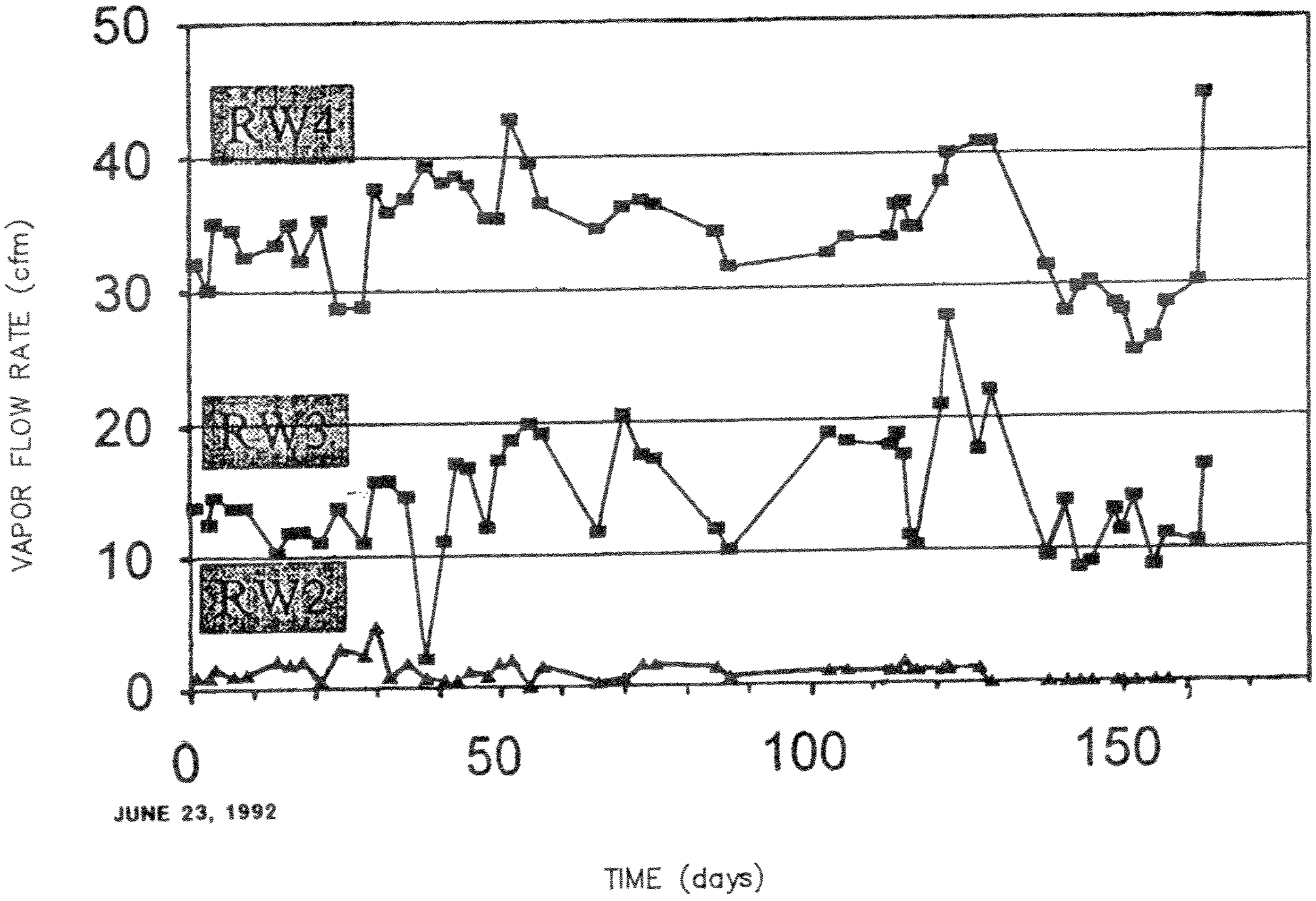
The soil vacuum readings obtained from pneumatic piezometers in the vicinity of the recovery wells showed that the zone of pneumatic control around fractured Well Nos. RW3 and RW4 is about 25 ft from the well compared to less than 1 ft from the unfractured Well No. RW2, demonstrating that significantly fewer fractured wells are required to remediate a contaminated site using SVE.

Conclusions

Hydraulic fracturing is an effective method to enhance the permeability of silty clays and thereby increase vapor flow rate by about one order of magnitude. The number of wells required to remediate the site is reduced significantly, and the rate of contaminant removal is increased by 7 to 14 times.

DAYTON SITE

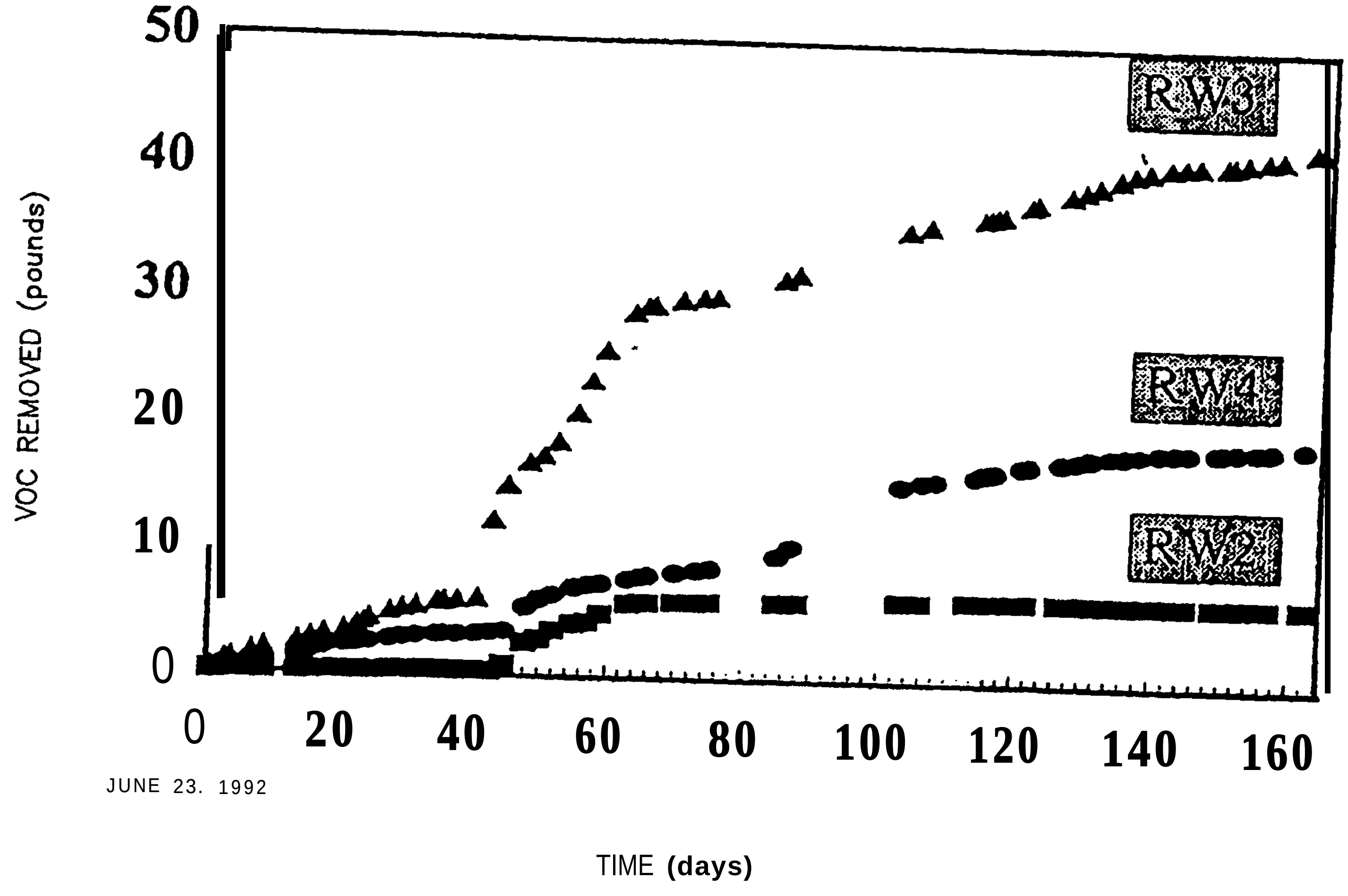
At the Dayton site, six underground storage tanks (UST) were removed in December 1989. Three tanks contained gasoline, one tank contained No. 2 fuel oil, and two tanks contained kerosene. Laboratory analyses of soil samples collected from the UST excavations indicate that benzene



Source: Modified from University of Cincinnati, 1993

Figure B-4. Vapor Flow Rates in Wells RW2, RW3, and RW4

B-9



Source: Modified from Unlverslty of Clnclnnatl, 1993

Figure B-5. Contaminants Removed from Wells RW2. RW3, and RW4

concentrations ranged from not detected (ND) to 622 microgram per kilogram **(μg/kg)**. Ethylbenzene concentrations ranged from ND to 3,800 **μg/kg;** toluene concentrations from ND to 10,400 **μg/kg;** and xylene concentrations from ND to 41,900 **μg/kg.** Total petroleum hydrocarbon (TPH) compounds ranged in concentrations from 32 to 8,550 **μg/kg;** and total lead concentrations from 21 to 150 **μg/kg.**

A remedial action contractor investigated the extent of contamination at the site in 1990. The investigation revealed the following site characteristics:

- The site is underlain by stiff, sandy to silty clay with traces of gravel.
- The bedrock is shallow, at depths ranging from 15.5 to 17.0 ft bgs, and consists of claystone and limestone.
- The horizontal extent of hydrocarbons is limited to the tank excavation area and the area east of the former tanks.
- The vertical extent of hydrocarbons appears limited to the upper 6.5 to 16.0 ft bgs in soils.

Fracturing Activities

The remedial action contractor initiated bioremediation activities at the site in 1991. In July 1991, the UC Center Hill proposed an investigation to determine the extent to which creating sand-filled hydraulic fractures would enhance bioremediation of the site. A Quality Assurance Project Plan was prepared by the UC (UC, 1991b). The delivery of water containing hydrogen peroxide and nutrients to sustain microorganisms through fractured wells was compared to the delivery of similar water through conventional unfractured wells.

Field tests were conducted from August 16 through 21, 1991. The tests consisted of creating seven fractures at two locations in contaminated ground near Wells No. SAD2 and SAD3. SAD4 is a conventional injection well in contaminated ground. Figure B-6 shows these well locations. Essential characteristics of these fractures are summarized in Table B-3 and include the depth bgs at the point where the fracture was created, the bulk volume of the sand, the volume of gel, the maximum pressure at the point of injection, the pressure at the end of pumping, the maximum uplift (typically

Table B-3. Fracture Characteristics at Dayton Site

Fracture Designation	Depth (ft bgs)	Sand Volume (ft³)	Gel Volume (gallons)	Maximum Pressure (psi)	End Pressure (psi)	Maximum Uplift (in)	Radius (ft)	Comment
SAD2-7	7	6	110	42	7 to 11	0.88	15.1	Contaminated soil fractures
SAD2-8	8	6	100	17	7 to 15	0.8	14.8	
SAD2-10	10	9	110	37	10 to 20	0.68	16.4	
SAD2-12	12	9	125	42	18 to 26	0.48	23.0	
SAD3-5	5	5	85	19	3 to 7	0.72	14.8	No contamination detected
SAD3-7	7	8	100	43	7to 10	0.68	15.4	No contamination detected
SAD3-9	9	9	115	39	12 to 17	0.52	23.0	No contamination detected

not at the point of injection), and the approximate radius of the uplifted area over the fracture.

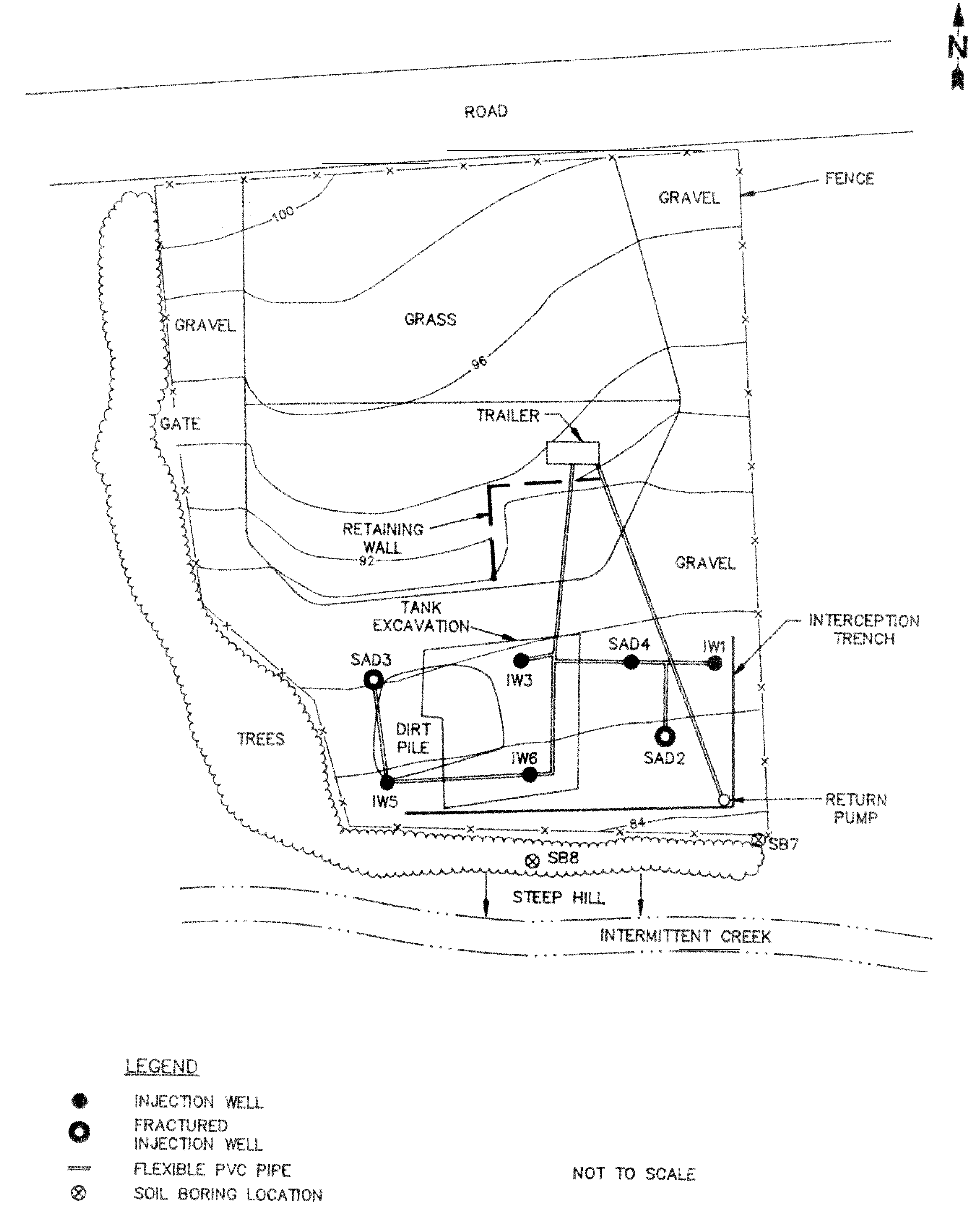
During the first week of September 1991, injection Wells No. SAD2 and SAD3 were installed. Soil samples were obtained using a 2-inch split-spoon sampler and were analyzed for moisture content, BTEX, and TPH. Samples were collected 5, 10, and 15 ft north of Wells No. SAD2 and SAD4 (the unfractured well) and 10 ft south of Well No. SAD2. Well No. SAD3 was found to contain no contamination. Clusters of piezometers were installed at 5, 10, and 15 ft north of Well No. SAD2 and 10 ft south of Well No. SAD2 at depths corresponding to the depths of individual fractures. Piezometers were installed 5, 10, and 15 ft north of Well No. SAD4.

Water containing hydrogen peroxide and nutrients was introduced into Wells No. SAD2 and SAD4 in December 1991. The unfractured well, Well No. SAD4, was filled with sand and the water was gravity fed by a 0.5-inch-diameter pipe grouted into place for delivery at 5 ft. The water was gravity fed into the fractured well at depths of 7, 8, 10, and 12 ft bgs. A system of capture trenches and a return pump were installed (see Figure B-6).

Fracturing Results

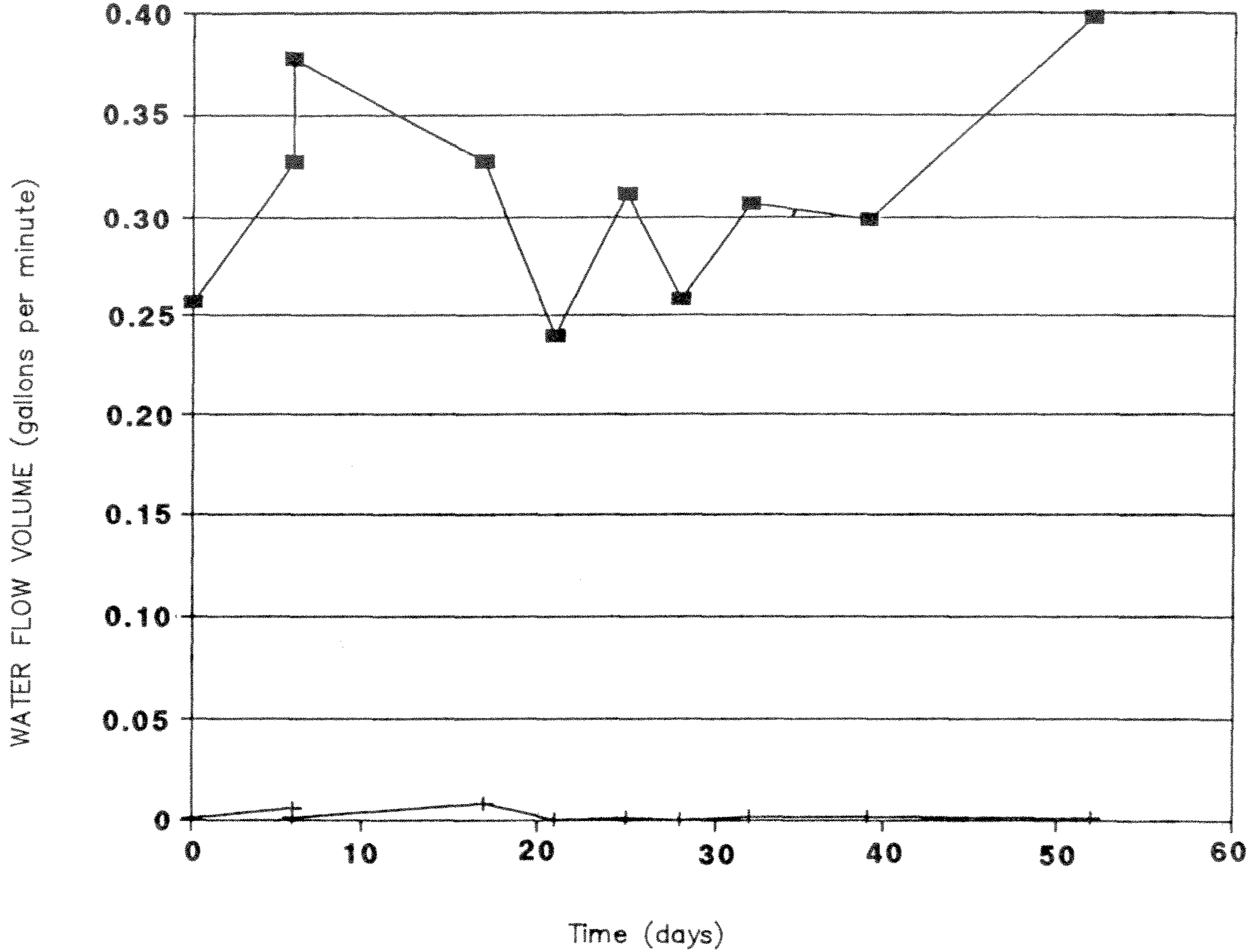
The impact of hydraulic fracturing at the Dayton site was measured by monitoring the rate of flow of water in the vicinity of the fractured well No. SAD2 and the unfractured well No. SAD4. Also, soil samples were obtained at 6 and 8 ft bgs from the vicinity of the wells after 1 and 6 months of bioremediation. These soil samples were analyzed for moisture content, number of colony forming units (CFU), microbial metabolic activity, pH, TPHs, and benzene, toluene, ethylbenzene, and xylene.

The flow rates in the fractured and unfractured wells are presented in Figure B-7. The flow rate in the fractured well was 25 to 40 times higher than in the unfractured well. Contaminant removal percentages in the vicinity of the fractured and unfractured wells are presented in Table B-4. This table shows that benzene, ethylbenzene, and TPHs were significantly remediated in the vicinity of the fractured well. The variability in removal percentages observed in the second and third rounds of sampling (after 1 and 6 months of bioremediation) resulted from the system not being run continuously or at optimal conditions.



Source: Modified from University of Cincinnati, 1991b

Figure B-6. General Dayton Site Plan



LEGEND

+ WELL NO. SAD4

■ WELL NO. SAD2

Source: Modified from Vesper, 1992

Figure B–7. Flow Volumes of Injected Water in Wells No. SAD2 and SAD4

Table B-4. Contaminants Removed at the Dayton Site

Treatment	Location From Well	Sampling Round	Benzene, Ethylbenzene, and Toluene Removal (Percent compared to first round)			TPH Removed (Percent compared to first round)
			Benzene	Ethyl-benzene	Toluene	
Fractured Well No. SAD2	5 ft north	Second Third	NI* 80	97 60	NI NI	77% 71%
Unfractured Well No. SAD4	5 ft north	Second Third	NI NI	7.9 37.0	NI NI	0% 55%
Fractured Well No. SAD2	10 ft north	Second Third	46.7 11.7	78.5 NI	NI NI	58% 54%
Unfractured Well No. SAD4	10 ft north	Second Third	NI NI	71.4 90.5	NI NI	27% 67%
Fractured Well No. SAD2	15 ft north	Second Third	64.3 37.8	72.7 56.2	NI NI	51% 68%
Unfractured Well No. SAD4	15 ft north	Second Third	NI NI	NI NI	NI NI	0% 25%
Fractured Well No. SAD2	10 ft south	Second Third	NI NI	NI NI	NI NI	55% 80%

* No impact

Conclusion

The bioremediation activities were conducted by an independent contractor, and UC had no control over the operating parameters. The erratic nature of the results obtained during the second and third round of sampling indicate that the system was not run continuously or at optimal conditions. However, the sampling results obtained during a l-year period indicate that fractured wells result in a significant increase in contaminant removal over unfractured wells.

Rates of fluid flow in the fractured well was 25 to 40 times higher than in the unfractured well. On certain days, water flow rate in the unfractured well was minimal, but significant flow passed through the soil around the fractured well (see Figure B-7). Fluid flow increased the moisture content around the fractured well twofold and near the fracture almost fourfold.

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APPENDIX C

DESCRIPTION OF FRACTURING TESTS

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DESCRIPTION OF FRACTURING TESTS

Hydraulic fracturing was conducted at sites in Addison, Illinois, and Grand Ledge, Michigan, in 1991 and 1992, respectively. Important data on the applicability and effectiveness of hydraulic fracturing was obtained during these tests, which are described below along with references used to prepare this appendix.

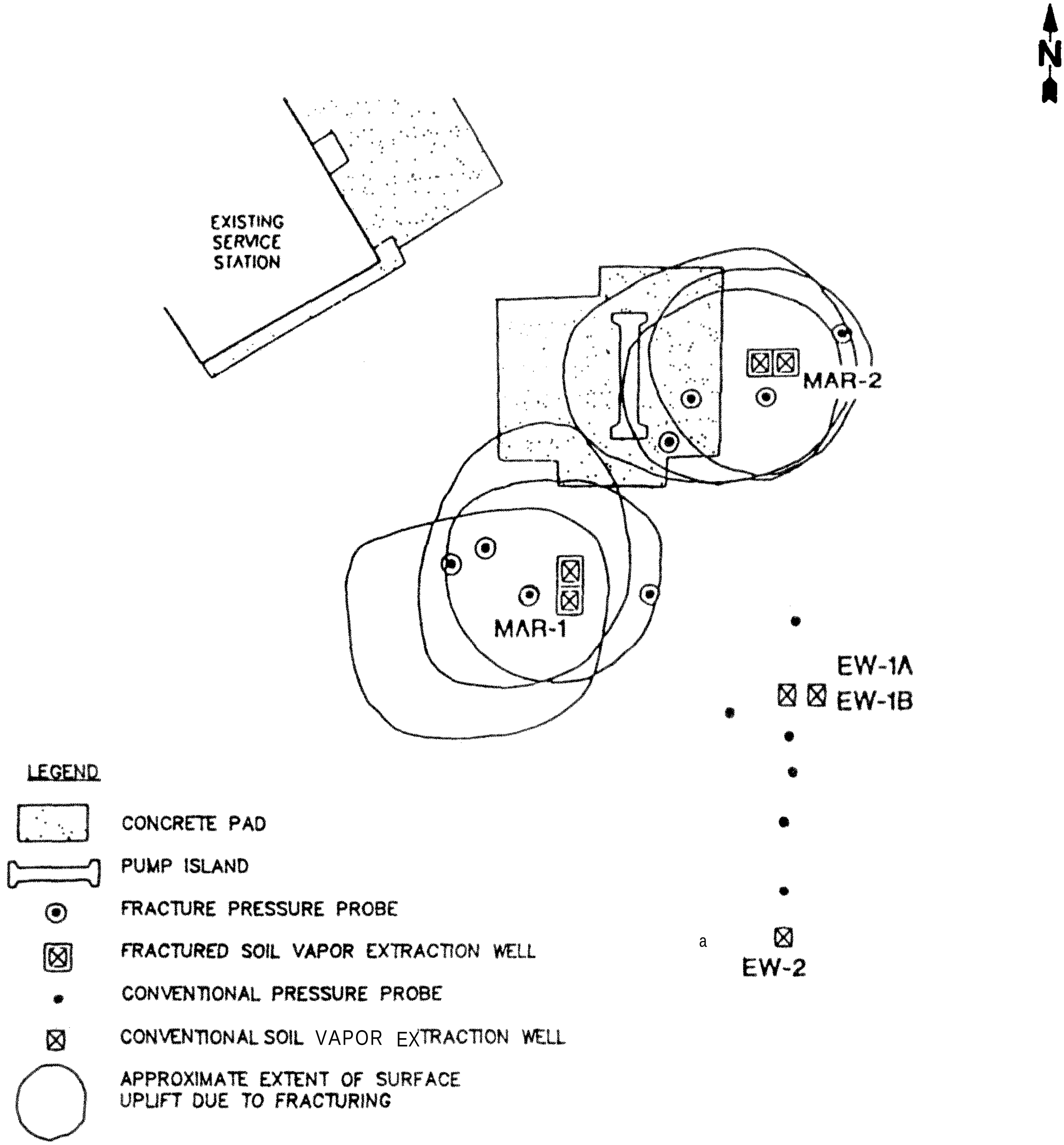
ADDISON, ILLINOIS

The test site is an inactive gasoline retail facility located in Addison, Illinois. The gasoline underground storage tanks (UST) and pump dispensers have been removed. About 3,900 cubic yards of soil are contaminated with benzene, toluene, ethylbenzene, and xylene (BTEX). The subsurface soil consists of silty clay till. Groundwater is present at depths ranging from 5 to 8 feet (ft) below ground surface (bgs).

Fracturing Activities

Three sand-filled hydraulic fractures were created at depths of 6.5, 9, and 11.75 ft bgs at each of two locations on site (see Figure C-l). After fracturing, soil vapor extraction (SVE) wells were installed so that each well screen intersected one of the fractures. Four nested pressure monitoring probes were installed within the fractured till so that soil pore pressure could be measured at various depths near of the fractures. Two SVE wells were installed in unfractured till to provide data to compare with data from the fractured wells. Seven nested pressure monitoring probes were located at lateral distances of 5, 7.5, 9, 15, 20, 25, and 30 ft from the SVE wells.

Each extraction well was connected to a vacuum blower with a 2-inch-diameter hose. A suction head of up to 10 inches mercury was applied to the wells. Vacuum gauges measured applied suction at the wells, and air flow rotometers were used to measure SVE rates. A manifold at the top of each SVE well allowed both soil vapors and accumulated ground water to be removed from the well. Water collection rates were measured periodically using a 40-gallon air-water separator.



NOTES:

1. ALL TEST WELL AND HYDRAULIC FRACTURE LOCATIONS ARE APPROXIMATE
2. FRACTURE PROPAGATION DEFINED BY SURFACE UPLIFT OF APPROXIMATELY 3 TO 5 MILLIMETERS.

10' 0 10' 20'
SCALE: 1" = 20'

Source: Modified from Kemper and Others, 1992

Figure C–1. Hydraulic Fracture and Test Well Locations, Addison, Illinois

Pilot-scale tests were conducted for 4 to 14 days. The applied suction head and soil vapor flow rate was monitored at 4- to 12-hour intervals at the extraction wells and blower unit. Suction heads were also measured at each of the pressure probes.

Fracturing Results

The performance of the fractured and unfractured wells is closely related to the presence of ground water and water used to create fractures and complete monitoring probes. In unfractured wells, the well was pumped dry and suction was applied. The yield was 1 cfm, and the suction head was 8 inches of mercury. Over several hours, the yield decreased to negligible values and suction head increased as water filled up the well. Vapor extraction from the fracture at the 9 ft bgs interval was highest after dewatering the well and decreased to 0 to 0.3 cfm at the end of 10 hours.

Suction at the fractured well was greater in magnitude and extended to greater depths than at the unfractured well. The radius of influence of the fracture created at a depth of 9 ft bgs was approximately 20 feet. The fluctuations in suction head were erratic and may be related to the movement of water, which was recovered throughout the test.

Conclusions

The SVE technique is not effective in moist to saturated silty clay because the pore water reduces air permeability to negligible values. Fracturing the clay increases the water and air permeability; however, vapor recovery is not significant until the moisture content of the soil has diminished to the point that vapor flow can be predominant.

GRAND **LEDGE, MICHIGAN**

Waldo's Auto Sales, a business located in the vicinity of Lansing, Michigan, is attempting to clean up on-site hydrocarbon contamination. Removal of gasoline and waste oil from the site revealed elevated concentrations of BTEX. The site is underlain by sandy clay with occasional sand and silt seams. The boring logs indicate that soils at the site are underconsolidated and softer than at sites where hydraulic fracturing has been successfully completed.

Fracturing Activities

A total of five fractures were created at two separate boreholes in the uncontaminated section of the site (see Figure C-2). The soft nature of the subsurface soil required the use of a 2.25inch outside diameter (OD) lance instead of the 1.82-inch OD lance for greater durability and seal surface area. Guar gum gel was also used instead of water to cut the notch because of the soft nature of the soil. Fractures were created at depths of 22 and 27 ft bgs in the first borehole and at depths of 18, 21, and 30 ft bgs in the second borehole.

Fracturing Results

The pressure log (see Figure C-3) reveals that the fractures were discontinuous because of stress gradients in the soil that pinched off propagating fractures. After the fracture pinches off and the effective length of the fracture decreases, an increase in the injection pressure is required to propagate the fracture. This increase results in the pressure versus time plot having several peaks and valleys.

Conclusions

Conducting hydraulic fracturing in clays that are underconsolidated (that is, where vertical stress is greater than horizontal stress) results in steeply dipping fractures that are not as effective in improving vapor phase permeability as gently dipping or horizontal fractures.

The hydraulic fracturing method is not effective in appreciably enhancing the permeability of underconsolidated soft clays. The in situ stresses in the clay result in steeply-dipping fractures that may be discontinuous and that will be less effective than fractures that are gently dipping and continuous.

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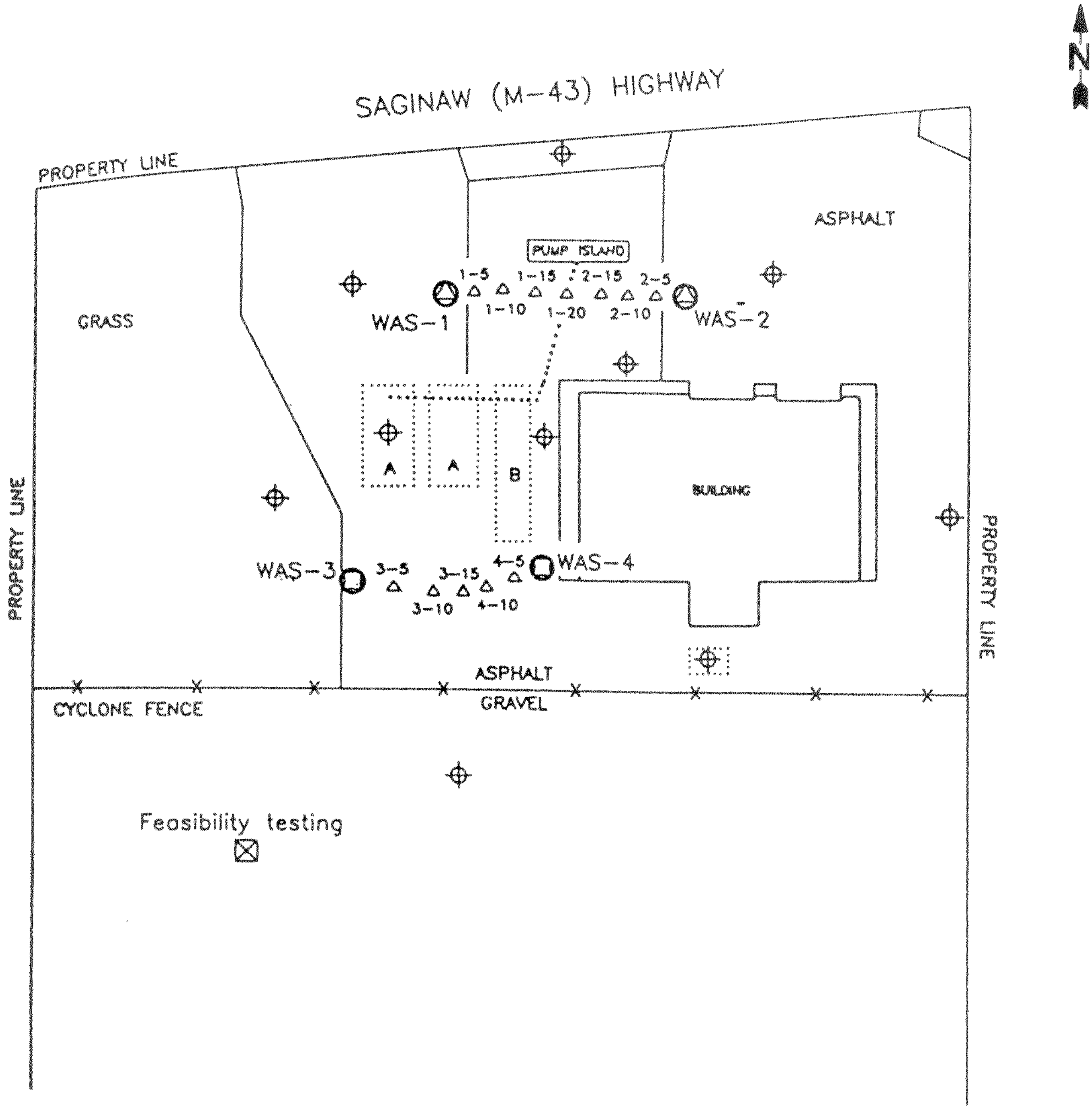


LEGEND

Hydraulically fractured recovery well

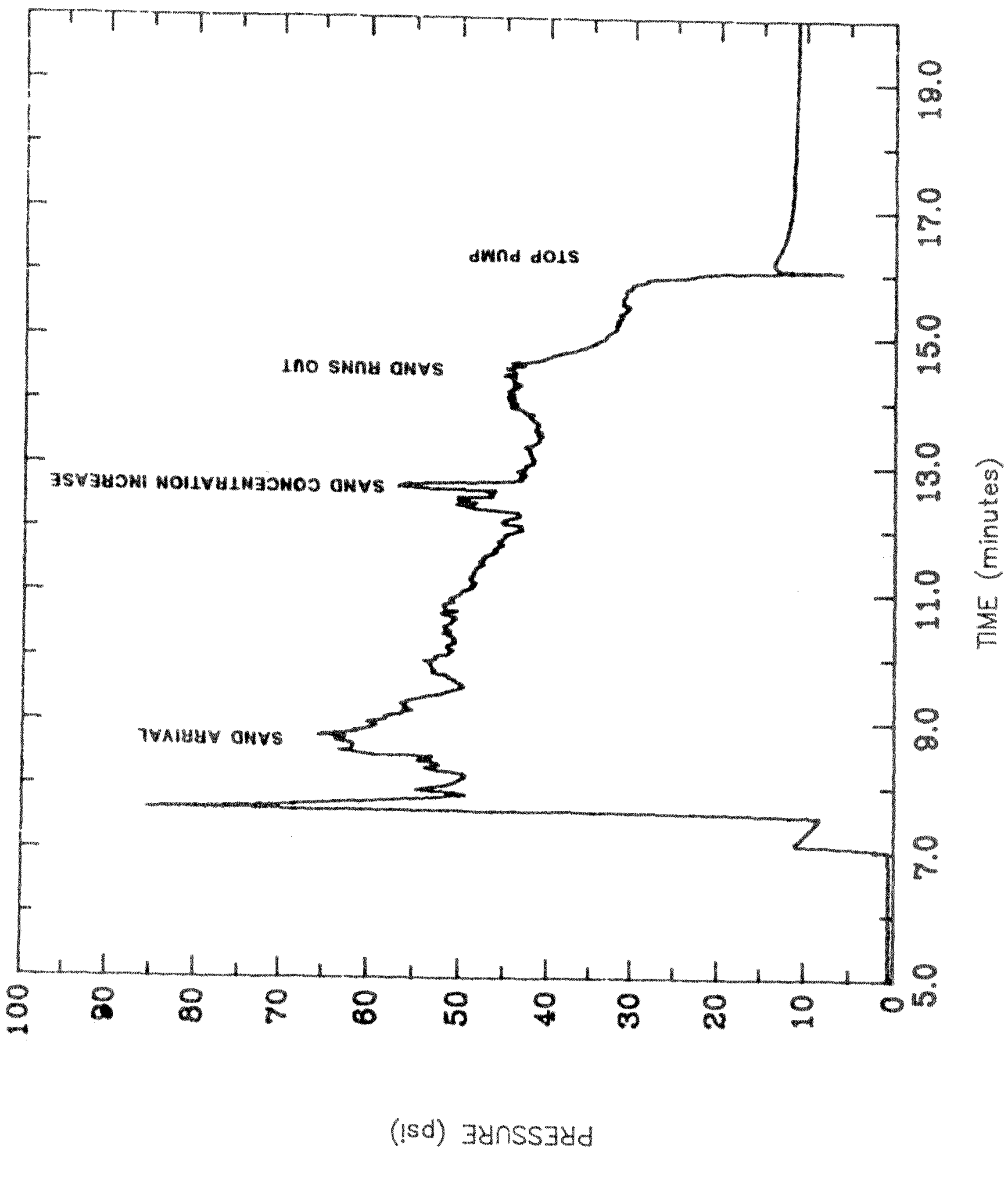
Conventional recovery well

A Monitoring borehole

NOT TO SCALE

Source: Modified from Kemper and Others, 1992

C-2. Location of Proposed Wells and Monitoring Probes, Grand Ledge. Michigan



Source: Modified from Kemper and Others, 1992

Figure C–3. Pressure Versus Time During the Creation of a Hydraulic Fracture, Grand Ledge, Michigan

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