INDUSTRY SURVEY FOR HORIZONTAL WELLS FINAL REPORT

by

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David D. Wilson and Dawn S. Kaback

JULY 1993

**Westinghouse Savannah River Company
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SIGNATURE PAGE

Industry Survey for Horizontal Wells

The attached document was completed under the direction of the Environmental Sciences Section, Geotechnical Group of the Savannah River Technology Center, Westinghouse Savannah River Company. I have reviewed the document, and to the best of my knowledge, it is true, accurate, and correct.

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LIST OF ACRONYMS AND ABBREVIATIONS

CDM Federal	CDM Federal Programs Corporation
DNAPL	dense non-aqueous phase liquid
DOE	Department of Energy
ft	feet
gpm	gallons per minute
GWE	groundwater extraction
HDPE	high density polyethylene
ID	internal diameter
in.	inch
lb	pound
LNAPL	light non-aqueous phase liquid
MD	measured depth
OD	outside diameter
PVC	polyvinyl chloride
RCRA	Resource Conservation and Recovery Act
SRS	Savannah River Site
SS	stainless steel
SVE	soil vapor extraction
TCE	Trichloroethylene
TPH	total petroleum hydrocarbons
VD	vertical depth
VOCs	volatile organic compounds

EXECUTIVE SUMMARY

An international survey of horizontal environmental wells was performed during May and June of 1993. The purpose of the survey was to provide the environmental industry with an inventory of horizontal environmental wells and information pertaining to the extent of the use of horizontal environmental wells, the variety of horizontal environmental well applications, the types of geologic and hydrogeologic conditions within which horizontal environmental wells have been installed, and the companies that perform horizontal environmental well installations. Other information, such as the cost of horizontal environmental well installations and the results of tests performed on the wells, is not complete but is provided as general information with the caveat that the information should not be used to compare drilling companies.

The inventory was compiled through a telephone/telefacsimile survey. The strategy used consisted of contacting drilling companies and drilling equipment suppliers and acquiring a list of locations that horizontal environmental wells have been installed. Once the locations had been determined, personnel familiar with the drilling projects were contacted and information was gathered concerning the objectives of the project, the directional drilling methods used, description of the drilling and well installation method, the current status of the wells, results of tests performed on the wells, and the approximate cost of the wells.

The result of the survey is a catalogue of horizontal environmental wells that are categorized by the objective or use of the wells, the vertical depth of the wells, and the drilling company contracted to install the wells. The salient information garnered from the catalogue follows.

- Over one hundred horizontal environmental wells have been installed in the United States.
- The international survey did not produce any completed questionnaires; however, verbal communication indicates that up to six shallow (<25-ft) horizontal wells have been installed in Germany and Czechoslovakia.
- One-fourth of the horizontal environmental wells installed in the United States have been used for groundwater extraction, one-fourth of the wells have been used for soil vapor extraction, and one-half of the wells have been used for alternate purposes including air injection, bioventing, and petroleum recovery (Table 4.1).
- Twenty-seven of the horizontal wells were installed as components of multi-media, integrated remediation systems. The systems integrated air injection, soil vapor extraction, free product recovery, or groundwater extraction. Some of the wells were multi-purpose and were designed to perform soil vapor extraction, air injection, and free product removal.
- More than 80% of the horizontal wells have been installed at vertical depths of less than or equal to 25 ft (Table 4.1). These installations may be performed (depending on site geology) by small to medium utility drilling rigs with less sophisticated guidance tools, and therefore, for less cost.
- The rate of horizontal well installations has increased significantly in the last year.

1.0 INTRODUCTION

The Department of Energy's (DOE's) Office of Technology Development initiated an integrated demonstration of innovative technologies and systems for cleanup of volatile organic compounds (VOCs) in soil and groundwater at the Savannah River Site (SRS). The overall goal of the program is the demonstration of multiple technologies and systems in the fields of drilling, characterization, monitoring, and remediation at a single test bed. Transfer of demonstration information to DOE environmental restoration management, to other federal agencies, and to the national environmental industry is a critical part of the program.

Horizontal environmental well installation technology was one of the drilling technologies that was demonstrated at SRS. Four distinctly different systems of directional drilling and horizontal well installations were successfully demonstrated and evaluated. The four systems were developed in the petroleum industry, the river crossing industry, and the utility industry (the systems are described in Section 2.0). The transfer of information concerning the horizontal environmental well installations will be accomplished by publishing evaluations of each individual demonstration and a comprehensive evaluation of all four systems.

The objective of this task was to conduct an international survey of the directional drilling/horizontal environmental well installation industry and to determine the extent to which horizontal environmental wells are being used as remediation alternatives. The study is, in essence, an inventory of the horizontal environmental wells that have been installed around the world. The purpose of the survey was to:

- Determine which drilling companies have performed horizontal environmental well installations.
- Create a catalogue of the drilling companies' experience that includes the following:
 - Locations of horizontal environmental well installations
 - Purpose of the wells
 - Approximate cost of the well installations
 - Techniques used to directionally drill and install horizontal environmental wells
- Provide information to environmental problem holders who may require horizontally installed remediation devices as a remediation alternative and to regulators who may be interested in sites that have set precedents for using horizontal environmental wells to satisfy restoration needs.

This document is organized into five sections: an introduction, a brief description of the environmental directional drilling and horizontal well installation industry, the catalogue of horizontal environmental well installations, a summary of the survey results, and recommendations for future studies.

The Westinghouse Savannah River Technology Center expresses their appreciation to the contributors to this inventory. The individuals, organizations, and companies listed in the inventory deserve commendations for taking time out of busy schedules to contribute to this project.

2.0 DESCRIPTION OF THE ENVIRONMENTAL DIRECTIONAL DRILLING AND HORIZONTAL WELL INSTALLATION INDUSTRY

Horizontal environmental well technology is currently being developed from three established technological fields: the horizontal oil well technology field, the trenchless technology field, and the water well installation technology field. Not one of these technologies by itself offers all the solutions to the challenges of constructing horizontal environmental wells, but from this triad a new technology is emerging. Directional drilling techniques are being borrowed from both the petroleum and the trenchless technology industries, whereas well construction materials developed in the water resources industry are being modified to withstand the rigors of a horizontal installation.

2.1 History of Directional Drilling and Horizontal Well Installation

Directional drilling has been used by several industries (petroleum, trenchless technology, and mining) for a number of years. The petroleum industry has used horizontal wells to improve petroleum recovery from low permeability or fractured reservoirs and to provide multiple access points to a reservoir from a single offshore drilling and production platform. The first horizontal petroleum well drilled in the United States from a vertical borehole was completed in 1942. Directional drilling technology has significantly improved since that first well. Down-hole mud motors and steering tools enable drillers to drill and install wells accurately in many different configurations. Directional drilling increased dramatically in the 1980s, and directionally wells are now routinely considered as exploration and production wells.

Directional drilling in the trenchless technology industry was initiated in the 1970s to accommodate installation of pipelines and utilities beneath bodies of water, roads, subdivisions, and buildings without disturbing surface features. The trenchless technology industry, which adapted directional drilling techniques from the petroleum industry, grew as the drilling technology was refined and new markets, such as installations of fiber optic telecommunication systems and cable television, were developed.

The trenchless technology industry generally distinguishes drilling projects as either river crossing projects or utility installation projects. The differentiation is based on drilling techniques and equipment. In general, river crossing drilling projects require large drilling rigs, drilling fluid systems, sophisticated guidance systems, and specialty drill tools or down-hole mud motors. River crossing drilling projects have included boreholes beneath most of the great rivers of North America, including the Mississippi River. River crossing boreholes have been as large as 60 inches in diameter, thousands of feet long, and have had pipes as large as 48 inches in diameter installed in the boreholes. Drilling companies that undertake river crossing drilling projects will often also perform smaller utility installation projects.

Utility installations are usually performed with small to medium-sized drilling rigs, simplified drilling fluid systems (most often water or a dilute bentonite-based fluid is used), simple electronic beacon guidance tools, and simple drilling tools. There are many companies that specialize in the smaller scale utility installation projects.

The mining industry has also used directional drilling for many years. The most recent innovative use of directional drilling in the mining industry is for coal degasification applications. The boreholes are usually drilled from a vertical face in a mine.

The environmental industry began modifying directional drilling technology in 1988 to install horizontal extraction and injection remediation systems where it was not practical to excavate trenches. The first directionally drilled horizontal environmental wells were installed at the Department of Energy's Savannah River Site in 1988. Since that time horizontal environmental wells have been installed at several Department of Defense sites and various private industry sites. Directional drilling and horizontal well installation techniques are continually being modified to meet the requirements of the environmental industry.

2.2 Directional Drilling and Horizontal Well Installation Techniques

The techniques used to directionally drill and install a horizontal environmental well depend on the location, type, and purpose of the well. For each specific site and well configuration, a drilling company will assemble a drilling system that is best suited to successfully install the horizontal well. The drilling system will be assembled from the drilling company's "tool bag". The tool bag for a drilling company contains different types of drilling tools, mud motors, guidance tools, drilling fluid systems, and sizes of drilling rigs. Each of these tools will be described below.

2.2.1 DRILLING METHOD

The drilling methods used to install the horizontal environmental well must be compatible with the function and design of the well. The drilling method used to construct a borehole for a horizontal well is dependent on the type and design of the borehole. There are two types of boreholes used to install horizontal wells: a continuous borehole and a blind borehole. Each type has its advantages and disadvantages.

Continuous Boreholes

Continuous boreholes possess two surface locations: the entrance hole location and the exit hole location. Directional drilling technologies that have developed this system of installation are the river crossing and utility industries. The continuous borehole generally has a 7° to 25° approach angle and a medium (150-ft to 800-ft) to long (>800-ft) radius of curvature (Figure 2.1). A pilot hole is first drilled from the surface, through the curved section to the target depth, through the horizontal section, through another curved section, and back to the ground surface. The pilot hole is then enlarged to the desired diameter by pulling or pushing a hole opener (reamer) through the pilot hole. The well materials are then pulled back through the borehole from the exit hole to the entrance hole.

Blind Boreholes

Blind horizontal boreholes have only an entrance hole and terminate at the vertical depth of the target zone (Figure 2.2). This type of horizontal borehole was first developed in the petroleum industry. The radius of curvature for a blind borehole can be short (<150 ft), medium, or long. Figure 2.3 provides a schematic containing all of the necessary formulas for calculating distances necessary for the placement of a blind borehole. These same formulas can be applied to calculating the trace of continuous boreholes.

DRILLING SUBCONTRACTOR _____
 DRILLER _____
 DATE OF WELL INSTALLATION _____
 TECH. O.S. / CO. NAME _____

WELL NUMBER _____
 COORDINATES N- _____ / E- _____
 SANITARY SEAL ELEVATION _____
 LIQUID LEVEL PIPE _____

NOTE: ALL MEASUREMENTS ARE FROM GROUND SURFACE AT START OF BORING - MEASUREMENTS TO NEAREST 0.1 FOOT.

1) Total Drilled Depth / Hole Diameter _____
 2) Casing / Screen Tally (Measured to the Nearest 0.01Foot)
 (a) Sump and Plug Length _____ N/A
 (b) Screen Length _____
 3) Depth to Centralizers _____
 4) Total Depth of Installed Well _____
 5) Casing Stick Up _____
 Miscellaneous Comments (Radius of Curvature, etc...) _____
 6) Depth to Top of Filter Pack _____
 7) Depth to Top of Fine Sand Seal _____
 8) Depth to Top of Bentonite Seal _____
 9) Thickness of Grout _____
 10) Initial Azimuth / Dip of Well _____
 11) Vertical Depth of Installed Well _____

(c) Casing Joint Lengths (Measured in Uphole Sequence From Top of Screen) _____

 (d) Depth to Top of Screen _____

Figure 2.1 - Typical Continuous Horizontal Environmental Well Construction Diagram

DRILLING SUBCONTRACTOR _____
 DRILLER _____
 DATE OF WELL INSTALLATION _____
 TECH. O.S. / CO. NAME _____

WELL NUMBER _____
 COORDINATES N- _____ / E- _____
 SANITARY SEAL ELEVATION _____
 LIQUID LEVEL PIPE _____

NOTE: ALL MEASUREMENTS ARE FROM GROUND SURFACE AT START OF BORING - MEASUREMENTS TO NEAREST 0.1 FOOT.

1) Total Drilled Depth / Hole Diameter _____
 2) Casing / Screen Tally (Measured to the Nearest 0.01Foot)
 (a) Sump and Plug Length _____
 (b) Screen Length _____
 (c) Casing Joint Lengths (Measured in Uphole Sequence From Top of Screen) _____
 (d) Depth to Top of Screen _____

3) Depth to Centralizers _____
 4) Total Depth of Installed Well _____
 5) Casing Stick Up _____
 Miscellaneous Comments (Radius of Curvature, etc...) _____

6) Depth to Top of Filter Pack _____
 7) Depth to Top of Fine Sand Seal _____
 8) Depth to Top of Bentonite Seal _____
 9) Thickness of Grout _____
 10) Initial Azimuth / Dip of Well _____
 11) Vertical Depth of Installed Well _____

Figure 2.2 - Typical Blind Horizontal Well Construction Diagram

Length of Well Screen - _____
 Elevation of Entry - _____
 Elevation of Target - _____
 Entry Angle - _____
 Depth to Target - _____
 Radius of Curvature - _____

Arc of 1 degree (Radius = 1) = .0174533

L = Length of Curve = $.0174533 \times \text{entry angle} \times \text{radius of curvature}$

EOC = End of Curve

K_1 = Constant for degrees / ft = $(1 / 0.0174533) \times 100 = 5730$

BUR = Build Up Rate = $2 \times \arcsin(50 / \text{radius of curvature})$

KOP = Kick Off Point

VD_{kop} = Vertical Depth to Kick Off Point = $\text{Depth to Target} - K_1 / \text{BUR} \times (\sin(90) - \sin(90 - \text{entry angle}))$

H_{kop} = Horizontal Distance to Kick Off Point = $T_{kop} / \tan(\text{entry angle})$

H_{eoc} = Horizontal Step Off Distance from End of Curve = $H_{kop} + K_1 / \text{BUR} \times (\cos(90 - \text{entry angle}) - \cos(90))$

VD_{eoc} = Vertical Depth to End of Curve or Depth to Target Horizon = $T_{kop} + K_1 / \text{BUR} \times (\sin(90) - \sin(90 - \text{entry angle}))$

MD_{kop} = Measured Depth to the Kick Off Point = $T_{kop} / \sin(\text{entry angle})$

MD_{eoc} = Measured Depth to the End of the Curve = $MD_{kop} + ((\pi \times K_1) / 180) \times (\text{entry angle} / \text{BUR})$ or $(MD_{kop} + L)$

MD_{total} = Measured Depth to the End of the Borehole = $MD_{eoc} + \text{horizontal distance required for well screen}$

H_{total} = $H_{eoc} + \text{horizontal distance required for well screen}$

Figure 2.3 - Typical Blind Horizontal Environmental Well Construction Schematic

Blind borehole wells can be installed using three techniques: installing a washover pipe, completing an open borehole, or pulling the casing through as the borehole is drilled. The washover pipe drilling technique was developed in the river crossing industry. A pilot hole is initially drilled and then the washover pipe is drilled over the pilot drill stem to enlarge the borehole and provide a conduit for well installation. The washover pipe installation is difficult because it requires drilling two pipes into the ground, and therefore the chances of experiencing drilling problems are doubled. However, well installation is much easier in a washover pipe than an open borehole.

Open borehole completions have the advantage of being the simplest and easiest to complete but are limited to sites where borehole stability is not a problem. In this method, the borehole is drilled and cased to the end of the curve, a pilot hole is drilled in the horizontal section, and the horizontal section is completed to the desired diameter with a hole opener. The well materials are pushed into the open borehole.

The most complicated technique of completing a blind borehole involves pulling a casing as drilling proceeds. Application of this technique has been limited by problems associated with sticking of the well casing materials due to the inability to properly clean out the hole as it is drilled. A modified method involves drilling a pilot hole and installing the casing as the pilot hole is reamed to a larger diameter.

2.2.2 BOTTOM-HOLE ASSEMBLIES

Drilling curved and horizontal boreholes requires specialized drilling equipment. The specialized drilling equipment is contained in a bottom-hole assembly that consists of a drilling tool, a bent sub-assembly, and a guidance tool. The drilling tool is preferentially oriented in the borehole by the bent subassembly in order to drill in the desired direction. The guidance tool supplies drilling tool orientation and the azimuth and inclination of the borehole to the driller. There are three types of drilling tools used in directional drilling: the down-hole mud motor, the jetting tool, and the compaction tool.

Drilling Tools

Down-hole mud motors have the advantage of eliminating drill string rotation, thus making it possible to drill short radius of curvature boreholes. Down-hole mud motors may be either positive displacement motors or turbodrills. Drilling fluid is pumped down the drill pipe into the cavities of the motor. The drilling fluid causes the motor, and therefore the drill bit, to turn. The speed of the mud motor is controlled with the drilling fluid pressure. Different types of drill bits can be attached to the motor to accommodate the drilling conditions.

Jetting tools use hydraulic pressure to cut the geologic formations and can be used in rotary drilling. The hydraulic jet is directed from a bent housing or from a drilling fluid port on a drill bit that is attached to a bent sub-assembly. The force of the hydraulic jet is controlled with the drilling fluid pump. To drill the curved section of borehole, the bent sub-assembly and the hydraulic jet is placed in the direction of the borehole deviation. The drill string is then advanced by the force of the weight on the bit and with the hydraulic force of the drill rig. The drill string will follow the direction of the hydraulic jet. To drill a straight segment of borehole, the drill string is rotated. The rotation prevents the hydraulic jet from having a preferred orientation. Another method for drilling a straight segment of borehole

calls for alternating the direction of the bent sub-assembly from one direction and its 180° opposite. The resulting borehole will have a saw tooth profile.

Compaction drilling tools work on the same principle as a wood chisel. Compaction tools are wedge-shaped and move in the direction of the slant on the face of the wedge when the drill string is pushed into the geologic formation. The drill string is pushed when the borehole direction needs to be changed, and rotated and pushed when the borehole direction is to remain unchanged. Compaction tools are generally used in geologic conditions that are unconsolidated and in small boreholes with limited vertical depth (< 50 ft). Water is used to help lubricate and cool the drilling tool, but drill cuttings or drilling fluid does not return to the surface.

Bent Sub-Assembly

The bent sub-assembly either can be a fixed-angle assembly or can be adjusted while drilling. The fixed-angle assemblies are used with down-hole mud motors, jetting, and compaction drilling tools. A fixed-angle bent sub-assembly can be part of the down-hole motor housing or jetting tool or can be a separate interchangeable part of the bottom-hole assembly. An adjustable-angle assembly is less common and is used with down-hole mud motors.

Guidance System

The guidance system is located in the bottom-hole assembly behind the drilling tool and the bent sub-assembly. Guidance systems are either a combination magnetometer-accelerometer system, an inertial (gyroscope) system, or a radio beacon-receiver system.

The magnetometer-accelerometer guidance system uses three magnetometers to measure the position (azimuth) of the tool in the earth's magnetic field and three accelerometers to measure the position (inclination) of the tool in the earth's gravitational field. The steering tool sends information to a computer at the surface where the tool azimuth, inclination, and drilling tool orientation are calculated. The azimuth and inclination, along with the distance that the steering tool has penetrated into the borehole, allow the driller to calculate the position of the steering tool in the subsurface.

Some magnetometer-accelerometer guidance systems use a secondary survey system, which induces a known magnetic field at the ground surface. A computer program connected to both the surface magnetic field and the steering tool compares the magnetic field measured by the steering tool and the theoretical magnetic field at the steering tool. If there is a discrepancy between the actual and theoretical values, then the secondary survey may be repeated or the steering tool is removed and recalibrated.

The inertial guidance system is based on the same navigation principles as used in navigation systems in guided missiles and airplanes. The system uses three gyroscopes to measure the azimuth of the steering tool and three accelerometers to measure the inclination of the steering tool. The gyroscopes are aligned to True North at the ground surface before the survey is made. Any deviation from True North during the survey is detected by the gyroscopes and relayed to the surface where the azimuth, inclination, and drilling tool orientation are calculated by a computer.

The radio beacon-receiver guidance system is a battery-operated system that sends a constant electro-magnetic signal from the bottom-hole assembly to a receiver in a surface

unit. The surface unit then locates the position of the beacon and calculates the depth to the beacon. This method is often called the "walk over" method because the surface unit is walked-over the beacon. The radio beacon-receiver guidance system is limited to applications with vertical depths less than 25 ft. At depths greater than 25 ft, sediment defuses the radio beacon and the beacon can no longer be accurately received by the surface unit.

2.2.3 DRILLING FLUIDS

Different drilling methods use varying amounts of drilling fluids and influence the target formation in different ways. For example, drilling fluids remaining in the formation after drilling will reduce the efficiency of a soil vapor extraction (SVE) well. The optimum for environmental directional drilling would be minimization or elimination of drilling fluids. As mentioned above, compaction drilling techniques require a minimum amount of drilling fluid. However, since this is not possible for all drilling targets, drilling fluids are utilized for installation of horizontal environmental wells. Drilling fluids are based on either bentonite clays or synthetic or natural polymers.

2.2.4 DRILLING RIGS

Drilling rigs are built in small, medium, and large sizes. Drilling companies that specialize in utility installation will own small and medium-sized drilling rigs. Drilling companies that provide a river crossing service will own large drilling rigs and may own medium and small rigs also. All directional drilling rigs have a few common characteristics: a capacity for using a fluid while drilling and a method for providing a thrust force to the drill string to compensate for lost weight on the bit when drilling the horizontal section of a borehole.

Small Drilling Rigs

Small drilling rigs are mounted on a trailer, truck, or a self-propelled, tracked vehicle. The drilling fluid system is limited and water or a dilute bentonite-based fluid are the common drilling fluids. The maximum thrust force provided to the drill string is less than 40,000 lb. These drilling rigs are used to install utilities beneath roads and subdivisions in continuous boreholes and offer a limited range of horizontal well installation capabilities. Horizontal well installations are generally limited to small diameter pipes (4-in. outside diameter [OD]) at vertical depths of less than 30 ft in semi-consolidated sediments. A pre-pack well screen may be installed.

Medium Drilling Rigs

Medium drilling rigs are mounted on a trailer or a self-propelled, tracked vehicle. The drilling fluid systems are more sophisticated than those on small drilling rigs and can accommodate all types of drilling fluids. The maximum thrust force provided to the drill string is generally less than 80,000 lb. These drilling rigs are used to install utilities beneath roads, subdivisions, and small rivers. Horizontal well installations can be in continuous or blind boreholes with pipes less than or equal to 8-in. OD. The pipe may have a pre-packed well screen, or a filter pack can be installed around the pipe. The wells can be installed in unconsolidated to consolidated sediments.

Large Drilling Rigs

Large drilling rigs are mounted on trailers. The drilling fluid systems are sophisticated and can accommodate all types of drilling fluids. The maximum thrust force provided to the drill string is generally less than 800,000 lb. Horizontal well installations can be in continuous or blind boreholes with large diameter pipes (<14-in. OD). The well pipe may have a pre-packed well screen, or a filter pack can be installed around the pipe. The wells can be installed in unconsolidated to consolidated sediments and rock.

2.3 Cost of Horizontal Environmental Well Installation

Several factors establish the cost of a horizontal environmental well project:

- Risk. Each drilling project entails an amount of risk of losing equipment and well materials down a hole and of damaging equipment. The risk can be shared by the environmental problem holder and the drilling contractor, or the onus can be entirely placed on the drilling contractor. The cost of the drilling project is proportional to the amount of risk that the drilling contractor bears.
- The size of the drilling rig. Large drilling rigs require greater mobilization costs than small drilling rigs due to permits, fuel, insurance, and track and/or trailer rental rates. The daily charge of the drilling rig is based on the original capital cost, daily maintenance, etc., of the equipment; therefore, larger drilling rigs will have a greater daily rental rate.
- The type of drilling tool or down-hole mud motor. The drilling tool or down-hole mud motor may be rented or owned by the driller. The daily rate for this equipment will increase with its complexity. The replacement cost of the drilling tools and down-hole mud motors will increase the risk factor in the project cost if there is a perceived danger that this equipment may become stuck in the borehole.
- The type of guidance system. Guidance systems vary from relatively simple radio beacon-receiver systems to very sophisticated guidance systems similar to those used in aeronautics. The guidance system may be rented or owned by the drilling company. The daily rate for this equipment will increase with its complexity. The replacement cost of the guidance system will increase the risk factor in the project cost. Radio beacon-receiver guidance systems can only be used at depths less than 25 ft; therefore, drilling projects at greater depths will necessarily have the additional cost of a more sophisticated guidance system.
- The use of a secondary, confirmatory survey for the guidance system. A secondary survey is needed to accurately locate the down-hole magnetic guidance tool in areas that have magnetic interferences. Such a survey will increase the daily rate of the drilling project.
- The use of a drilling fluid system. The complexity and cost of the drilling fluid system will depend on the geologic drilling conditions and the drilling method used. In general, drilling below the water table requires a drilling fluid system, especially if the sediment is unconsolidated. The drilling fluid system will increase the daily rate of the drilling project.

- Number of personnel. Personnel will add to the daily cost of the drilling project. Larger drilling rigs require larger crews, and sophisticated drilling programs require highly skilled and more expensive drillers. Drilling projects that involve shallow, low risk drilling can be performed by less experienced personnel.
- The type and amount of well materials. In general, horizontal well installations, particularly in continuous boreholes, will put a greater stress on well materials than the stress experienced in vertical well installations. Well materials that can withstand the additional stress will increase the project cost. Pre-pack well screens are commonly used in horizontal wells because of the difficulty of installing a filter pack in a horizontal well. The pre-pack well screens will increase the cost of the drilling project. Large horizontal wells require more material and are therefore more expensive.

The factors listed above do not include considerations for the cost of designing the horizontal well and the management of the field effort. Depending on the sophistication of the horizontal well system and the length of time it takes to install the horizontal well system, these costs may be substantial.

3.0 HORIZONTAL ENVIRONMENTAL WELL INVENTORY

An international survey of horizontal environmental wells was performed during May and June of 1993. The purpose of the survey was to provide the environmental industry with an inventory of horizontal environmental wells and information pertaining to the extent of the use of horizontal environmental wells, the variety of horizontal environmental well applications, the types of geologic and hydrogeologic conditions within which horizontal environmental wells have been installed, and the companies that have performed horizontal environmental well installations. Other information, such as the cost of horizontal environmental well installations and the results of tests performed on the wells, is not complete but is provided with the caveat that the information should not be used to compare drilling companies. Additionally, the costs of the drilling projects presented in the inventory may or may not include well materials, design, field management, and report writing. The drilling companies that have participated in this survey come from different industries and have varying capabilities and limitations. The reader is encouraged to contact these companies to determine the specific capabilities of each company.

3.1 Survey Methodology

The inventory was compiled through a telephone/telefacsimile survey. The strategy used consisted of contacting drilling companies and drilling equipment suppliers and acquiring a list of locations where horizontal environmental wells have been installed. Once the locations had been determined, personnel familiar with the drilling projects were contacted and information was gathered concerning the objectives of the project, the directional drilling methods used, the horizontal well installation method, description of the drilling and well installation method, the current status of the wells, results of tests performed on the wells, and the approximate cost of the wells.

3.2 Results of the Survey

The result of the survey is an inventory or catalogue of horizontal environmental wells that are categorized by the objective or use of the wells, the vertical depth of the wells, and the drilling company contracted to install the wells. The scheme for categorizing the wells was chosen to aid the reader in finding descriptions of applications of the technology that are similar to solutions for their environmental problems. This section is organized into three main subdivisions: horizontal wells installed as components of groundwater extraction systems; wells installed as components of SVE systems; and wells installed for various other purposes, such as for free product recovery, air sparging, *in situ* air stripping, and infiltration galleries. Furthermore, the horizontal well projects described in each section are organized by the vertical depth at which they were completed and the drilling contractor that drilled the borehole and installed the wells.

3.2.1 HORIZONTAL WELLS INSTALLED FOR THE PURPOSE OF EXTRACTING GROUNDWATER

3.2.1.1 Groundwater Extraction Well Installations at Less Than or Equal to 25-ft Vertical Depth

Horizontal Well Installation Site: One groundwater extraction well was installed under a gas station in Carson City, Nevada, during April 1992.

Contracting Agency or Company and Point of Contact:

Jay Lucas - (916) 444-0123

Brown & Caldwell Consulting Engineers

Drilling Contractor and Point of Contact:

Carlos Kenda - (713) 722-7777

Eastman Cherrington Environmental Corp.

1055 Conrad Sauer

Houston, TX 77043-5201

Remediation Objectives: The remediation objective was to remove the free product and dissolved VOC plume beneath the gas station. The well was designed for extracting groundwater.

Site Conditions: The site geology consisted of uniform, unconsolidated, saturated channel sands.

Well Geometry: The borehole was a blind hole with a 250-ft radius of curvature, 170-ft MD, 20-ft VD, and 100-ft horizontal length. The entry angle was 23° from the horizontal.

Directional Drilling Method: A pilot hole was drilled with a medium-sized utility drilling rig equipped with a hydraulic spud-jet drilling tool and a magnetometer-accelerometer guidance tool. The pilot hole was opened with a washover pipe.

Well Installation Method: The well was installed in the washover pipe, and the filter pack was installed around the well screen as the washover pipe was withdrawn from the borehole.

Well Materials: The well casing and 0.010-in. slotted screen were constructed of 3-in. ID schedule 40 polyvinyl chloride (PVC) pipe.

Field Effort/Performance: The gas station remained open during the drilling project. Minor amounts of drilling fluid followed fractures to the surface. A subsurface obstruction was encountered but the bit eventually drilled through it. The project lasted one week longer than planned.

Results of Tests Performed on Well: No tests were performed; however, the well will sustain a yield of 10 gpm with 1 ft of drawdown.

Current Status of Well: The well is being used in a groundwater pumping and treatment system.

Approximate Cost of Well: Information withheld.

3.2.1.1 Groundwater Extraction Well Installations at Less Than or Equal to 25-ft Vertical Depth (cont'd)

Horizontal Well Installation Site: One groundwater extraction well was installed in Union City, California, during July 1992.

Contracting Agency or Company and Point of Contact:

David Bose - (510) 210-2372

Brown & Caldwell Consulting Engineers

Drilling Contractor and Point of Contact:

Carlos Kenda - (713) 722-7777

Eastman Cherrington Environmental Corp.

1055 Conrad Sauer

Houston, TX 77043-5201

Remediation Objectives: The well was designed for extracting Trichloroethylene (TCE)-contaminated groundwater.

Site Conditions: The borehole was drilled through back-fill, silty sand, fine sand, and clay.

Well Geometry: The borehole was a blind hole with a medium radius of curvature, 15-ft VD, 100-ft MD, and 70-ft horizontal length.

Directional Drilling Method: A pilot hole was drilled with a medium-sized utility drilling rig equipped with a hydraulic spud-jet drilling tool and a magnetometer-accelerometer guidance tool. The pilot hole was opened with a washover pipe.

Well Installation Method: The well was installed in the washover pipe and then the washover pipe was withdrawn.

Well Materials: The well casing and 0.010-in. slotted screen were constructed of 3-in. ID schedule 40 PVC pipe. A "filter sock" was used around the screened portion of the well.

Field Effort/Performance: The driller experienced difficulty in drilling the curve. The borehole was completed on the third attempt.

Results of Tests Performed on Well: The radius of influence of the well exceeded expectations.

Current Status of Well: The well is being used in a groundwater pumping and treatment system. Two more wells are planned during the summer of 1993.

Approximate Cost of Well: The cost of the well was approximately \$21,000.

3.2.1.1 Groundwater Extraction Well Installations at Less Than or Equal to 25-ft Vertical Depth (cont'd)

Horizontal Well Installation Site: Three wells were installed in the south San Francisco Bay Area, California, during October 1992. Two of the wells were installed to remove groundwater and are described here; the third well was installed to remove soil vapor and is described in Section 3.2.2.1.

Contracting Agency or Company and Point of Contact:

Rudy Milan - (510) 372-5274
IT Corp.

Drilling Contractor and Point of Contact:

Carlos Kenda - (713) 722-7777
Eastman Cherrington Environmental Corp.
1055 Conrad Sauer
Houston, TX 77043-5201

Remediation Objectives: The wells were installed as components of a pumping and treatment groundwater extraction and soil vapor extraction system. One groundwater extraction well was installed at the top of the lower confining layer to aid in removing dense non-aqueous phase liquids (DNAPLs). The other groundwater extraction well was installed to control the water table during SVE operations.

Site Conditions: The upper 10 ft consisted of a persistent clay unit followed by 5 ft of well-sorted sand, about 1.5-ft of intermittent clay, 10 ft of poorly sorted sand with gravel, and a 5-ft to 12-ft persistent clay confining layer.

Well Geometry: The lower groundwater extraction well was installed at 25-ft VD, 200-ft MD, and had a 80-ft horizontal screen. The upper groundwater extraction well was installed at 20-ft VD, 210-ft MD, and had a 110-ft horizontal screen.

Directional Drilling Method: A pilot hole was drilled with a medium-sized utility-type drilling rig equipped with a hydraulic spud-jet drilling tool and a magnetometer-accelerometer guidance tool. The pilot hole was opened with a washover pipe.

Well Installation Method: The well materials were installed in the washover pipe and then the washover pipe was withdrawn. The two groundwater extraction wells had filter packs installed as the washover pipe was withdrawn.

Well Materials: The groundwater pump and treatment wells were constructed of 3-in. ID stainless steel casing and 3-in. ID 0.020-in. slotted stainless steel screen.

Field Effort/Performance: The drill pipe broke at an inherently weak place near the guidance tool in the bottom-hole assembly.

Results of Tests Performed on Wells: The upper well was tested and sustained a yield of 4.5 gpm. The lower well was not tested.

Current Status of Wells: The groundwater extraction wells are currently idle, awaiting construction of the remediation system.

Approximate Cost of Wells: The cost of all three wells was approximately \$90,000.

3.2.1.1 Groundwater Extraction Well Installations at Less Than or Equal to 25-ft Vertical Depth (cont'd)

Horizontal Well Installation Site: A groundwater extraction well was installed beneath a retail gasoline station in Houston, Texas, during September 1992.

Contracting Agency or Company and Point of Contact:

Bruce Morlock - (713) 775-2313
Mobil Oil Corp.

Drilling Contractor and Point of Contact:

Carlos Kenda - (713) 722-7777
Eastman Cherrington Environmental Corp.
1055 Conrad Sauer
Houston, TX 77043-5201

Remediation Objectives: The well was installed as a component of a pumping and treatment groundwater extraction system. The well is also capable of extracting free product when necessary.

Site Conditions: The well was installed beneath a retail gasoline station in clayey soils.

Well Geometry: The well was installed at 35-ft VD, with a medium radius of curvature and 320-ft MD.

Directional Drilling Method: A pilot hole was drilled with a medium-sized utility-type drilling rig equipped with a hydraulic spud-jet drilling tool and a magnetometer-accelerometer guidance tool. The pilot hole was opened with a washover pipe.

Well Installation Method: The well materials were installed in the washover pipe and then the washover pipe was withdrawn. A filter pack was installed as the washover pipe was withdrawn.

Well Materials: The well was constructed of 4-in. ID, 0.010-in. slotted schedule 40 PVC.

Field Effort/Performance: The only problem reported was that drilling fluid fractured out at the ground surface.

Results of Tests Performed on Well: No tests were reported.

Current Status of Well: The well is now producing; groundwater and fuel are being pumped with two pneumatic pumps.

Approximate Cost of Well: The cost of the well was approximately \$65,000.

3.2.1.1 Groundwater Extraction Well Installations at Less Than or Equal to 25-ft Vertical Depth (cont'd)

Horizontal Well Installation Site: Two groundwater extraction wells were installed at an abandoned landfill in Texas, during July 1992.

Contracting Agency or Company and Point of Contact:

Information withheld upon request.

Drilling Contractor and Point of Contact:

Carlos Kenda - (713) 722-7777
Eastman Cherrington Environmental Corp.
1055 Conrad Sauer
Houston, TX 77043-5201

Remediation Objectives: The wells were installed as components of a pumping and treatment groundwater extraction system to remediate groundwater contaminated with hydrocarbons.

Site Conditions: The wells were installed beneath an abandoned landfill. The sediment consisted of silty sand with clay stringers.

Well Geometry: The two wells were blind boreholes, drilled with a 110-ft radius of curvature, 25-ft VD, and 300-ft horizontal screen.

Directional Drilling Method: The boreholes were drilled with a large slant drilling rig equipped with a down-hole mud motor and a magnetometer-accelerometer guidance tool. The boreholes were cased through the curved section.

Well Installation Method: The well materials were installed in an open borehole.

Well Materials: The wells were constructed of 6-in. ID, 0.020-in. slotted high density polyethylene (HDPE). A filter pack of HDPE beads was installed.

Field Effort/Performance: The wells were installed in two attempts. Only one-half of the HDPE filter pack beads needed to fill the annulus around the well screen were installed in each well.

Results of Tests Performed on Wells: The wells are producing approximately 2 gpm each.

Current Status of Wells: The wells are pumping as part of a full-scale remediation system.

Approximate Cost of Wells: The wells cost approximately \$70,000 each.

3.2.1.1 Groundwater Extraction Well Installations at Less Than or Equal to 25-ft Vertical Depth (cont'd)

Horizontal Well Installation Site: Two groundwater extraction wells were installed in Geismar, Louisiana, during August 1992.

Contracting Agency or Company and Point of Contact:

Mark Conger - (504) 339-7941
BASF Corp.
Box 457
Geismar, LA

Drilling Contractor and Point of Contact:

Carlos Kenda - (713) 722-7777
Eastman Cherrington Environmental Corp.
1055 Conrad Sauer
Houston, TX 77043-5201

Remediation Objectives: The wells were installed as components of a pumping and treatment groundwater extraction system to remediate groundwater contaminated with halogenated hydrocarbons.

Site Conditions: The wells were installed beneath an abandoned building in sand and clay.

Well Geometry: The two wells were installed in blind boreholes, drilled with a 110-ft radius of curvature, 14-ft and 16-ft VD, 435-ft and 469-ft MD, and 363-ft and 400-ft VD.

Directional Drilling Method: The boreholes were drilled with a large slant drilling rig equipped with a down-hole mud motor and a magnetometer-accelerometer guidance tool. The boreholes were cased through the curved section.

Well Installation Method: The well materials were installed in an open borehole.

Well Materials: The wells were constructed of 6-in. ID, 0.020-in. slotted HDPE with a 4-in. ID stainless steel pre-pack inside.

Field Effort/Performance: The two wells were installed in a total of three attempts.

Results of Tests Performed on Wells: The wells are producing approximately 2 gpm and 7 gpm, respectively.

Current Status of Wells: The wells are pumping as part of a full-scale remediation system.

Approximate Cost of Wells: The wells cost approximately \$400,000 each.

3.2.1.1 Groundwater Extraction Well Installations at Less Than or Equal to 25-ft Vertical Depth (cont'd)

Horizontal Well Installation Site: One groundwater extraction well was installed in Geismar, Louisiana, during November 1992.

Contracting Agency or Company and Point of Contact:

Mary Logue - (504) 642-5454
Cosmar Co.
P.O. Box 11
Geismar, LA

Drilling Contractor and Point of Contact:

Carlos Kenda - (713) 722-7777
Eastman Cherrington Environmental Corp.
1055 Conrad Sauer
Houston, TX 77043-5201

Remediation Objectives: The well was installed as a component of a pumping and treatment groundwater extraction system to remediate groundwater contaminated with hydrocarbons.

Site Conditions: The well was installed beneath a railroad loading rack in clay and sand.

Well Geometry: The well was a blind borehole, drilled with a 150-ft radius of curvature, 18-ft VD, and 185-ft MD.

Directional Drilling Method: The boreholes were drilled with a large slant drilling rig equipped with a down-hole mud motor and a magnetometer-accelerometer guidance tool.

Well Installation Method: The well materials were installed in an open borehole.

Well Materials: The well was constructed of 6-in. ID, 0.020-in. slotted HDPE.

Field Effort/Performance: The well was installed in two attempts.

Results of Tests Performed on Well: The well is producing approximately 3 gpm.

Current Status of Well: The well is pumping as part of a remediation system.

Approximate Cost of Well: The well cost approximately \$85,000.

3.2.1.1 Groundwater Extraction Well Installations at Less Than or Equal to 25-ft Vertical Depth (cont'd)

Horizontal Well Installation Site: Two groundwater extraction wells were installed in Geismar, Louisiana, during February 1993. One well was installed at a vertical depth of 20 ft and is described here. See Section 3.2.1.2 for a description of the second well installed at 36-ft VD.

Contracting Agency or Company and Point of Contact:

Lisa Adams - (504) 473-5000
P.O. Box 227
Geismar, LA

Drilling Contractor and Point of Contact:

Carlos Kenda - (713) 722-7777
Eastman Cherrington Environmental Corp.
1055 Conrad Sauer
Houston, TX 77043-5201

Remediation Objectives: The wells were installed as components of a pumping and treatment groundwater extraction system to remediate groundwater contaminated with hydrocarbons.

Site Conditions: The wells were installed beneath a pipe rack in clay and sand.

Well Geometry: The wells were installed in a blind borehole, drilled with a 110-ft radius of curvature, 20-ft VD, and 320-ft MD.

Directional Drilling Method: The boreholes were drilled with a large slant drilling rig equipped with a down-hole mud motor and a magnetometer-accelerometer guidance tool. The curved section of the borehole was cased while drilled.

Well Installation Method: The well materials were installed in an open borehole.

Well Materials: The wells were constructed of 6-in. ID Enviroscreen.

Field Effort/Performance: The wells were installed in one attempt.

Results of Tests Performed on Wells: The wells are producing approximately 2 gpm each.

Current Status of Wells: The wells are pumping as part of a remediation system.

Approximate Cost of Wells: The wells cost approximately \$150,000 each.

3.2.1.1 Groundwater Extraction Well Installations at Less Than or Equal to 25-ft Vertical Depth (cont'd)

Horizontal Well Installation Site: Two horizontal wells were installed at a retail gasoline station in Portland, Oregon, during April 1993. One well was designed to extract groundwater and is described here. See Section 3.2.2.1 for the description of the second SVE well.

Contracting Agency or Company and Point of Contact:
Charles Esler/Senior Environmental Scientist - (503) 639-3400
RZA-AGRA

Drilling Contractor and Point of Contact:
Michael J. Kirby/Vice President of Environmental Services - (206) 395-4530
UTILX Corporation
22404 66th Avenue S.
Kent, WA 98032

Remediation Objectives: Two wells were installed as an integrated system for soil vapor extraction of hydrocarbon and for groundwater control.

Site Conditions: The wells were installed along a high traffic right of way in front of five adjacent properties including two street crossings. Soil was primarily silt.

Well Geometry: The groundwater control well was placed at 475-ft MD (300-ft screen) and was installed at 23-ft VD with a 1% slope. Wells were placed above one another and had to intersect two pre-existing manholes at the middle and end of the run.

Directional Drilling Method: The continuous boreholes were drilled using the FlowMole® patented GuideDril - guided horizontal drilling system. The system uses a low volume, high pressure hydraulic jet to cut through the sediments and a radio beacon-receiver guidance system. A guar gum-based fluid or water is used to deliver the hydraulic pressure to the sediment.

Well Installation Method: The well materials were pulled back from the exit hole to the entrance hole behind a hole opening device (reamer).

Well Materials: The well screen was 4-in. ID by 6-in. OD, sand pre-pack, 0.020-in. slotted PVC.

Field Effort/Performance: The groundwater extraction well took five days to install.

Results of Tests Performed on Wells: No tests were reported.

Current Status of Wells: The remediation system was under construction as of July 1993.

Approximate Cost of Wells: This well and the associated SVE well cost a total of \$100,000 including materials.

3.2.1.1 Groundwater Extraction Well Installations at Less Than or Equal to 25-ft Vertical Depth (cont'd)

Horizontal Well Installation Site: Two horizontal wells were installed at Tinker Air Force Base in Oklahoma City, Oklahoma, during November 1991. One of the wells was a groundwater extraction well installed at 25-ft VD and is described here. A description of the second, SVE well may be found in Section 3.2.2.1.

Contracting Agency or Company and Point of Contact:

David D. Wilson - (303) 232-0131
CDM Federal Programs Corp.
1626 Cole Blvd., Ste 100
Golden, CO 80401

Drilling Contractor and Point of Contact:

Tim C. McGuire - (303) 423-5761
Michels Environmental Services
8415 Parfet Ct.
Arvada, CO 80005

Remediation Objectives: The wells were installed as a pilot demonstration to get horizontal wells approved as remedial alternatives to the record of decision for the Building 3001 Superfund site. The contaminant of concern was halogenated hydrocarbons in the unconfined perched aquifer, the semi-confined aquifer, and the confined aquifer beneath Building 3001.

Site Conditions: The site geology consisted of Permian sand, sandstone, silt, clay, and shale. The target was in the unconfined perched aquifer and the unsaturated zone above it.

Well Geometry: The blind borehole had a 1000-ft radius of curvature, 25-ft VD, 275-ft MD, and a 70-ft well screen.

Directional Drilling Method: A pilot hole was drilled with a medium-size, utility-type drilling rig equipped with a down-hole mud motor and a magnetometer-accelerometer guidance tool. The pilot hole was opened with a reamer.

Well Installation Method: The well materials were installed in an open hole by pushing on the end cap of the screen.

Well Materials: The well materials were 6-in. ID, 0.012-in. slotted sand pre-packed stainless steel screen with a schedule 40 PVC riser.

Field Effort/Performance: The well borehole was drilled in two attempts. The well materials were installed in one attempt.

Results of Tests Performed on Wells: The well produces 1 gpm from low permeability silty sand, sandstone, and shale.

Current Status of Wells: The well is currently idle.

Approximate Cost of Wells: The well cost approximately \$248,800 including engineering services and field management provided by Harrison Western, Lakewood, Colorado.

3.2.1.1 Groundwater Extraction Well Installations at Less Than or Equal to 25-ft Vertical Depth (cont'd)

Horizontal Well Installation Site: Four groundwater extraction wells were installed in Ponca City, Oklahoma, during May 1987.

Contracting Agency or Company and Point of Contact:

C. E. Downs, PhD. - (405) 767-6344

Conoco Inc.

Ponca City, OK 74602

Drilling Contractor and Point of Contact:

Michael J. Kirby/Vice President of Environmental Services - (206) 395-4530

UTILX Corporation

22404 66th Avenue S.

Kent, WA 98032

Remediation Objectives: The four wells were installed as an integrated system for groundwater elevation control, contaminant removal, and enhanced contaminant recovery by water injection. The wells were installed in the vicinity of a residential neighborhood adjacent to an old refinery.

Site Conditions: The wells were installed beneath school grounds. The soils were silty-clayey sand with gravel at depth.

Well Geometry: The geometry of the wells was as follows:

1. 100-ft radius of curvature, 20-ft VD, 580-ft MD, and 500-ft horizontal length.
2. 200-ft radius of curvature, 20-ft VD, 475-ft MD, and 350-ft horizontal length.
3. 200-ft radius of curvature, 20-ft VD, 360-ft MD, and 300-ft horizontal length.
4. 1000-ft radius of curvature, 18-ft VD, 560-ft MD, and 500-ft horizontal length.

Directional Drilling Method: The continuous boreholes were drilled with the FlowMole® patented GuideDril - guided horizontal drilling system. The system uses a low volume, high pressure hydraulic jet to cut through the sediments and a radio beacon-receiver guidance system. A guar gum-based fluid or water is used to deliver the hydraulic pressure to the sediment.

Well Installation Method: The well materials were pulled back from the exit hole to the entrance hole behind a hole opening device (reamer).

Well Materials: The well screen was 2-in. ID, 0.020-in. slotted PVC.

Field Effort/Performance: The installations encountered underground obstacles that caused delays.

Results of Tests Performed on Wells: The wells produce under gravity drainage; the total yield is 100-150 gpm.

Current Status of Wells: The system is operational.

Approximate Cost of Wells: These wells had a combined total cost of greater than \$100,000.

3.2.1.1 Groundwater Extraction Well Installations at Less Than or Equal to 25-ft Vertical Depth (cont'd)

Horizontal Well Installation Site: Two wells were installed in Cincinnati, Ohio, during December 1992. One well was for groundwater extraction (described here) and the second well was for petroleum product recovery. See Section 3.2.3.1 for a description of the product recovery well.

Contracting Agency or Company and Point of Contact:

Larry Murdock - (513) 569-7885
Univ. of Cincinnati - Center of GeoEnvironmental Science and Technology
5995 Center Hill Rd.
Cincinnati, OH 45224

Drilling Contractor and Point of Contact:

Frank Kinnon - (503) 445-2425
Underground Research Inc.
4091 Camas Rd.
Camas Valley, OR 97416

Remediation Objectives: The two wells were designed to work in concert to remove diesel fuel from the subsurface. A lower well was installed in the saturated zone and was used to control the elevation of the water table. The other well was installed above the water table and was designed to remove diesel fuel floating on the water table.

Site Conditions: The wells were installed in an open railroad yard. The site geology consisted of fluvial deposits. The water table was located 19 ft below ground surface.

Well Geometry: The groundwater well had a 50-ft radius of curvature, 325-ft MD, and 19-ft to 21-ft VD.

Directional Drilling Method: The well was installed in a continuous borehole with a medium-sized utility drilling rig equipped with a hydrojet drilling tool and a radio beacon-receiver walk-over guidance system. Water was used as a drilling fluid.

Well Installation Method: The well was installed by pulling the materials from the exit hole to the entrance hole behind a borehole reamer.

Well Materials: The groundwater well was constructed of 4-in. ID schedule 40 PVC casing and 0.020-in. slotted well screen.

Field Effort/Performance: The groundwater well was drilled and completed in three days. The initial casing broke in the second well and it took one day to replace the casing.

Results of Tests Performed on Wells: The well was developed with sodium tripolyphosphate followed by sodium hypochlorate. The well development resulted in enhanced recovery of sediment from the wells. An experimental sonic well development tool will also be used during the summer of 1993.

Current Status of Wells: Well development will continue during the summer of 1993.

Approximate Cost of Wells: The approximate cost of both the groundwater and product recovery well was \$35,000.

3.2.1.2 Groundwater Extraction Installations at Greater Than 25-ft and Less Than 100-ft Vertical Depth (cont'd)

Horizontal Well Installation Site: One groundwater extraction well was installed at Barberton, Ohio, during February 1993.

Contracting Agency or Company and Point of Contact:

Gary Gaillot - (412) 372-7701
IT Corp
William Penn Plaza
2790 Mosside Blvd.
Monroeville, PA 15146-2792

Drilling Contractor and Point of Contact:

Carlos Kenda - (713) 722-7777
Eastman Cherrington Environmental Corp
1055 Conrad Sauer
Houston, TX 77043-5201

Remediation Objectives: The well was installed to de-water a lime lake.

Site Conditions: The well was installed beneath a lime lake in clay- to sand-sized chemical process tailings.

Well Geometry: The well was a blind borehole, drilled with a 550-ft radius of curvature, 757-ft MD, 500-ft horizontal length, and 35-ft VD.

Directional Drilling Method: A pilot hole was drilled with a medium-sized utility-type drilling rig equipped with a hydraulic spud-jet drilling tool, a mud motor, and a magnetometer-accelerometer guidance tool. The pilot hole was opened with a washover pipe.

Well Installation Method: The well was installed in the washover pipe, and the filter pack was installed around the well screen as the washover pipe was withdrawn from the borehole.

Well Materials: The well was constructed of 4-in. ID, 0.020-in. slotted HDPE casing and a 20/40 sand filter pack.

Field Effort/Performance: The well was installed in two attempts.

Results of Tests Performed on Well: The well is producing approximately 2 gpm.

Current Status of Well: The well is pumping as part of a dewatering system.

Approximate Cost of Well: The well cost approximately \$120,000.

3.2.1.2 Groundwater Extraction Well Installations at Greater Than 25-ft and Less Than 100-ft Vertical Depth (cont'd)

Horizontal Well Installation Site: Two wells were installed in Geismar, Louisiana, during February 1993. One well was installed at a vertical depth of 20 ft, and one well was installed at a depth of 36 ft. See Section 3.2.1.1 for a description of the well installed at 20-ft VD.

Contracting Agency or Company and Point of Contact:

Lisa Adams - (504) 473-5000
P.O. Box 227
Geismar, LA

Drilling Contractor and Point of Contact:

Carlos Kenda - (713) 722-7777
Eastman Cherrington Environmental Corp.
1055 Conrad Sauer
Houston, TX 77043-5201

Remediation Objectives: The wells were installed as components of a pumping and treatment groundwater extraction system to remediate groundwater contaminated with hydrocarbons.

Site Conditions: The wells were installed beneath a pipe rack in clay and sand.

Well Geometry: The deeper well was a blind borehole, drilled with a 110-ft radius of curvature, 36-ft VD, and 295-ft MD.

Directional Drilling Method: The borehole was drilled with a large slant drilling rig equipped with a down-hole mud motor and a magnetometer accelerometer guidance tool. The curved section of the borehole was cased while drilled.

Well Installation Method: The well materials were installed in an open borehole.

Well Materials: The wells were constructed of 6-in. ID Enviroscreen.

Field Effort/Performance: The well was installed in one attempt.

Results of Tests Performed on Wells: The wells are producing approximately 4 gpm each.

Current Status of Wells: The wells are pumping as part of a remediation system.

Approximate Cost of Wells: The wells cost approximately \$150,000 each.

3.2.1.2 Groundwater Extraction Well Installations at Greater Than 25-ft and Less Than 100-ft Vertical Depth (cont'd)

Horizontal Well Installation Site: Five groundwater extraction wells were installed at Tinker Air Force Base, Oklahoma City, Oklahoma, between November 1992 and February 1993. Three of the wells were installed at a vertical depth of 35 ft and are described here. See Section 3.2.1.3 for a description of the other two wells that were installed at depths greater than 100 ft.

Contracting Agency or Company and Point of Contact:

David Rendini - (619) 225-9641
CH&A

Drilling Contractor and Point of Contact:

Carlos Kenda - (713) 722-7777
Eastman Cherrington Environmental Corp.
1055 Conrad Sauer
Houston, TX 77043-5201

Remediation Objectives: The wells were installed as approved remedial alternatives to the ROD for the Building. 3001 Superfund site. The contaminant of concern was halogenated hydrocarbons in the unconfined perched aquifer beneath Building. 3001.

Site Conditions: The wells were installed beneath Building. 3001 in Permian sand, sandstone, silt, clay, and shale.

Well Geometry: The blind boreholes had 600 ft to 700-ft radii of curvature, with 35-ft VD, 920-ft MD, and 200-ft well screen.

Directional Drilling Method: A pilot hole was drilled with a medium-sized utility-type drilling rig equipped with a hydraulic-jet drilling tool and a magnetometer/accelerometer guidance tool. The pilot hole was opened with a washover pipe.

Well Installation Method: The well materials were installed in the washover pipe and then the washover pipe was withdrawn.

Well Materials: The well materials consisted of a slotted 6-in. ID HDPE outer casing with a 4-in. ID stainless steel pre-pack inner screen.

Field Effort/Performance: The drillers encountered difficult drilling that was mitigated by changing the drill bit. One borehole required two attempts; the drill bit was lost during the first attempt.

Results of Tests performed on Wells: No tests were reported.

Current Status of the Wells: The wells have not been put on line with the remediation system but have performed above expectations.

Approximate Cost of Wells: This information is not available at this time.

3.2.1.2 Groundwater Extraction Well Installations at Greater Than 25-ft and Less Than 100-ft Vertical Depth (cont'd)

Horizontal Well Installation Site: A groundwater extraction well was installed in Sacramento, California, during December 1991.

Contracting Agency or Company and Point of Contact:

Robert Moore - (713) 293-3642
Conoco Corp.

Drilling Contractor and Point of Contact:

Carlos Kenda - (713) 722-7777
Eastman Cherrington Environmental Corp.
1055 Conrad Sauer
Houston, TX 77043-5201

Remediation Objectives: The well was installed beneath a retail gasoline station as a component of a groundwater pump and treat system.

Site Conditions: The well was installed in sandy clay.

Well Geometry: The blind borehole had a medium radius of curvature, with 50-ft VD, 362-ft MD, and 100-ft well screen.

Directional Drilling Method: A pilot hole was drilled with a medium-sized utility-type drilling rig equipped with a hydraulic-jet drilling tool and a magnetometer/accelerometer guidance tool. The pilot hole was opened with a washover pipe.

Well Installation Method: The well materials were installed in the washover pipe and then the washover pipe was withdrawn. A filter pack was installed as the washover pipe was withdrawn.

Well Materials: The well consisted of a 3-in. ID, 0.020-in. slotted schedule 40 PVC.

Field Effort/Performance: No problems were reported; the project was performed as a demonstration.

Results of Tests Performed on Well: No tests were reported.

Current Status of Well: The well is currently being used.

Approximate Cost of Well: The approximate cost of the well was \$30,000. However, it must be noted that the well was installed as a demonstration and not as a commercial venture.

3.2.1.3 Groundwater Extraction Well Installations at Greater Than 100-ft Vertical Depth

Horizontal Well Installation Site: Five horizontal wells were installed at Tinker Air Force Base, Oklahoma City, Oklahoma, during the fall and winter of 1992-1993. Two of those wells were installed at 110 ft and 150 ft VD and are described here. See Section 3.2.1.2 for a description of the other three wells installed at 35-ft VD.

Contracting Agency or Company and Point of Contact:

David Rendini - (619) 225-9641
CH&A

Drilling Contractor and Point of Contact:

Carlos Kenda - (713) 722-7777
Eastman Cherrington Environmental Corp.
1055 Conrad Sauer
Houston, TX 77043-5201

Remediation Objectives: The wells were installed as an approved remedial alternative to the ROD for the Building. 3001 Superfund site. The contaminant of concern was halogenated hydrocarbons in the unconfined perched aquifer, the semi-confined aquifer, and confined aquifer beneath Building. 3001.

Site Conditions: The site geology consisted of Permian sand, sandstone, silt, clay, and shale. The target zones beneath Building. 3001 were the semi-confined aquifer (110 ft), and the regional confined aquifer (150 ft).

Well Geometry: The blind boreholes had 600-ft to 700-ft radii of curvature, with 110-ft and 150-ft VD, 920-ft MD, and 200-ft well screen.

Directional Drilling Method: A pilot hole was drilled with a medium-sized utility-type drilling rig equipped with a hydraulic-jet drilling tool and a magnetometer-accelerometer guidance tool. The pilot hole was opened with a washover pipe.

Well Installation Method: The well materials were installed in the washover pipe and then the washover pipe was withdrawn.

Well Materials: The well materials consisted of a slotted 6-in. ID HDPE outer casing with a 4-in. ID stainless steel pre-pack inner screen.

Field Effort/Performance: Several delays were incurred during the drilling of the 150-ft VD borehole due to failure of the washover pipe. The first borehole was abandoned; a second attempt was required to complete the borehole. The 110-ft VD well screen was located 120 ft short of the required design.

Results of Tests Performed on Wells: No tests were reported.

Current Status of Wells: The wells have not been put on-line with the remediation system but have performed above expectations.

Approximate Cost of Wells: This information is not available at this time.

3.2.1.3 Groundwater Extraction Well Installations at Greater Than 100-ft Vertical Depth
(cont'd)

Horizontal Well Installation Site: One groundwater extraction well was installed at an industrial park in Fullerton, California, during April 1992.

Contracting Agency or Company and Point of Contact:

Ken Puentes - (619) 454-0165

Hargis & Assoc.

7223 Avenion De La Playa

La Jolla, CA

Drilling Contractor and Point of Contact:

Carlos Kenda - (713) 722-7777

Eastman Cherrington Environmental Corp.

1055 Conrad Sauer

Houston, TX 77043-5201

Remediation Objectives: The well was installed as a component of a pumping and treatment groundwater extraction system.

Site Conditions: The well was installed beneath an industrial park. The site geology consisted of silt and clay with intermittent fine grained sand from the surface to 100-ft VD. The well screen was installed in a continuous fine grained sand.

Well Geometry: A blind borehole was drilled with a 100-ft radius of curvature, 110-ft VD, 460-ft MD, 325-ft horizontal borehole, and 230-ft well screen.

Directional Drilling Method: The borehole was drilled with a large slant drilling rig equipped with a down-hole mud motor and a magnetometer-accelerometer guidance tool. The borehole was cased through the curved section.

Well Installation Method: The well materials were installed in an open borehole.

Well Materials: The well was constructed of 6-in. ID, 0.020-in. slotted HDPE. The filter pack consisted of HDPE beads.

Field Effort/Performance: The well was installed in one attempt. Approximately 40% of the required volume of HDPE beads were installed in the annulus around the screen.

Results of Tests Performed on Well: The well has a continuous yield of 10 gpm.

The well was constructed as a pilot demonstration; eight additional wells are planned.

Current Status of Well: The well is pumping.

Approximate Cost of Well: The well cost approximately \$110,000.

3.2.1.3 Groundwater Extraction Well Installations at Greater Than 100-ft Vertical Depth
(cont'd)

Horizontal Well Installation Site: One groundwater extraction well was installed at Williams Air Force Base, Chandler, Arizona, during July 1992.

Contracting Agency or Company and Point of Contact:

David D. Wilson - (303) 232-0131
CDM Federal Programs Corp.
1626 Cole Blvd., Ste 100
Golden, CO 80401

Drilling Contractor and Point of Contact:

Tim C. McGuire - (303) 423-5761
Michels Environmental Services
8415 Parfet Ct.
Arvada, CO 80005

Remediation Objectives: The well was installed as a pilot demonstration to get horizontal wells approved as remedial alternatives to the ROD. The contaminant of concern was JP-4 in the unconfined aquifer.

Site Conditions: The site geology consisted of fluvial and alluvial sediments consisting of cobbles, gravels, sand, silt, and clay.

Well Geometry: The continuous borehole had a 1000-ft radius of curvature, 235-ft VD, a 500-ft horizontal screen, and 2200-ft MD.

Directional Drilling Method: A pilot hole was drilled with a large size river crossing type drilling rig equipped with a tricone hydraulic drilling tool and a magnetometer-accelerometer guidance tool. The pilot hole was opened with a reamer.

Well Installation Method: The well materials were installed by pulling back in an open hole.

Well Materials: The well materials were 6-in. ID (10.75-in. OD), 10 slot pre-packed stainless steel screen with a 10-in. OD carbon steel riser.

Field Effort/Performance: During the first attempt the borehole was completed but the well materials separated during installation. During the second attempt, the drill string became stuck in the borehole while conducting a downhole survey, and the borehole and drill string were lost. The borehole was drilled and the well successfully installed during the third attempt.

Results of Tests Performed on Well: The well produces greater than 30 gpm from a low permeability formation.

Current Status of Well: The well was being tested during the summer of 1993.

Approximate Cost of Well: The well cost approximately \$960,000 including engineering services and field management provided by Harrison Western, Lakewood, Colorado.

3.2.2 HORIZONTAL WELLS INSTALLED AS COMPONENTS OF SOIL VAPOR EXTRACTION SYSTEMS

3.2.2.1 SVE Well Installations at Less Than or Equal to 25-ft Vertical Depth

Horizontal Well Installation Site: Three wells were installed in the south San Francisco Bay area, California, during October 1992. One well was an SVE well and is described here. See Section 3.2.1.1 for a description of the wells installed for groundwater extraction.

Contracting Agency or Company and Point of Contact:

Rudy Milan - (510) 372-5274
IT Corp.

Drilling Contractor and Point of Contact:

Carlos Kenda - (713) 722-7777
Eastman Cherrington Environmental Corp.
1055 Conrad Sauer
Houston, TX 77043-5201

Remediation Objectives: The well was installed as a component of a pumping and treatment groundwater extraction and soil vapor extraction system.

Site Conditions: The upper 10 ft consisted of a persistent clay unit followed by 5 ft of well-sorted sand, about 1.5 ft of intermittent clay, 10 ft of poorly sorted sand with gravel, and a 5-ft to 12-ft persistent clay confining layer.

Well Geometry: The SVE well was installed at 210-ft MD, 18-ft VD, and had a 110-ft horizontal screen.

Directional Drilling Method: A pilot hole was drilled with a medium-sized utility-type drilling rig equipped with a hydraulic spud-jet drilling tool and a magnetometer-accelerometer guidance tool. The pilot hole was opened with a washover pipe.

Well Installation Method: The well materials were installed in the washover pipe and then the washover pipe was withdrawn. The two groundwater pump and treat wells had filter packs installed as the washover pipe was withdrawn.

Well Materials: The SVE well was constructed of 3-in. ID schedule 40 HDPE casing and 0.020-in. slotted screen.

Field Effort/Performance: The drill pipe broke at an inherently weak spot on the bottom hole assembly.

Results of Tests Performed on Wells: No tests were performed.

Current Status of Wells: The SVE system is currently operating and is exceeding all expectations with respect to contaminant removal.

Approximate Cost of Wells: The cost of all three wells was approximately \$90,000.

3.2.2.1 SVE Well Installations at Less Than or Equal to 25-ft Vertical Depth (cont'd)

Horizontal Well Installation Site: Two SVE wells were installed at the Defense Depot, Norwalk, California, during September 1992.

Contracting Agency or Company and Point of Contact:

Neil Irish - (310) 371-1394, ext. 306
Groundwater Technology Government Services
20000 Mariner Ave., Suite 200
Torence, CA 90503

Drilling Contractor and Point of Contact:

Carlos Kenda - (713) 722-7777
Eastman Cherrington Environmental Corp.
1055 Conrad Sauer
Houston, TX 77043-5201

Remediation Objectives: The wells were designed as components of an SVE system to extract petroleum hydrocarbons from the vadose zone soil and to recover free product. The wells were installed as part of a pilot SVE test.

Site Conditions: There was a 3-acre free product plume beneath a residential neighborhood. The borehole was drilled through silty sand and sandy silt. Depth to the water table was 30 ft.

Well Geometry: Both wells were blind boreholes drilled at 25-ft VD, 359-ft and 315-ft MD, 84-ft and 80-ft horizontal length, and medium radii of curvature.

Directional Drilling Method: A pilot hole was drilled with a medium-sized utility-type drilling rig equipped with a hydraulic spud-jet drilling tool and a magnetometer-accelerometer guidance tool. The pilot hole was opened with a washover pipe.

Well Installation Method: The well was installed in the washover pipe and the filter pack was installed around the well screen as the washover pipe was withdrawn from the borehole.

Well Materials: The casing and 0.020-in. slotted screen were constructed from 4-in. ID schedule 40 HDPE pipe. The filter pack was 2/12 sized sand.

Field Effort/Performance: It took 14 days to install both wells.

Results of Tests Performed on Wells: Tests results indicated that 1100 lb of total petroleum hydrocarbons (TPH) were removed per well per day.

Current Status of Wells: As of the end of June 1993 the wells were undergoing a 90-day long-term evaluation.

Approximate Cost of Wells: The total cost of both wells including disposal of cuttings and project management was \$200,000.

3.2.2.1 SVE Well Installations at Less Than or Equal to 25-ft Vertical Depth (cont'd)

Horizontal Well Installation Site: Two horizontal wells were installed at a retail gasoline station in Portland, Oregon, during April 1993. One well was an SVE well (described here), and the other well was a groundwater extraction well (see Section 3.2.1.1 for the description).

Contracting Agency or Company and Point of Contact:

Charles Esler/Senior Environmental Scientist - (503) 639-3400
RZA-AGRA
7477 SW. Tech Center Dr.
Portland, OR 97223-8024

Drilling Contractor and Point of Contact:

Michael J. Kirby/Vice President of Environmental Services - (206) 395-4530
UTILX Corporation
22404 66th Avenue S.
Kent, WA 98032

Remediation Objectives: The wells were designed for soil vapor extraction of hydrocarbons and groundwater control.

Site Conditions: The wells were drilled and installed along a high traffic right of way in front of five adjacent properties including two street crossings. The wells had to intersect two manholes at depths of up to 20 ft. The soil was a loess composed primarily of silt.

Well Geometry: The continuous borehole was 475-ft MD (300-ft screen) at 6.5-ft VD with a 100-ft radius of curvature. The SVE well was placed above the groundwater control well. The well had to intersect two pre-existing manholes at the middle and end of the run.

Directional Drilling Method: The continuous boreholes were drilled using the FlowMole® patented GuideDril - guided horizontal drilling system. The system uses a low volume, high pressure hydraulic jet to cut through the sediments and a radio beacon-receiver guidance system. A guar gum-based fluid or water is used to deliver the hydraulic pressure to the sediment.

Well Installation Method: An HDPE casing was pulled back through the borehole from the exit to the entrance hole while the borehole was reamed to the desired diameter. The well materials were installed in the HDPE casing and then the HDPE casing was removed.

Well Materials: The well casing and 0.020-in. slotted screen were constructed of 4-in. ID schedule 40 PVC.

Field Effort/Performance: Installation of the SVE well took 12 days due to problems with manholes, subzero weather, and HDPE.

Results of Tests Performed on Wells: No tests were performed.

Current Status of Wells: The remediation system was under construction as of July 1993.

Approximate Cost of Wells: This well and the groundwater control well cost a total of \$100,000 including materials.

3.2.2.1 SVE Well Installations at Less Than or Equal to 25-ft Vertical Depth (cont'd)

Horizontal Well Installation Site: Four SVE wells were installed at a service station in Orcutt, California, during May 1992.

Contracting Agency or Company and Point of Contact:

The information was withheld by request.

Drilling Contractor and Point of Contact:

Michael J. Kirby/Vice President of Environmental Services - (206) 395-4530

UTILX Corporation

22404 66th Avenue S.

Kent, WA 98032

Remediation Objectives: The wells were designed for soil vapor extraction of petroleum hydrocarbons in the vadose zone.

Site Conditions: Four wells were installed under the service station building and the service islands in silty sand. The station remained open with full service operations during well drilling and installation. All wells were drilled from one entrance pit to two exit pits.

Well Geometry: The continuous boreholes had medium radii of curvature with 120-ft MD and 5-ft VD, 70-ft MD and 5-ft VD, and 70-ft MD and 4-ft VD, 70-ft MD and 5-ft VD.

Directional Drilling Method: The boreholes were drilled using the FlowMole® patented GuideDril - guided horizontal drilling system. The system uses a low volume, high pressure hydraulic jet to cut through the sediments and a radio beacon-receiver guidance system. A guar gum-based fluid or water is used to deliver the hydraulic pressure to the sediment.

Well Installation Method: An HDPE casing was pulled back through the borehole from the exit to the entrance hole while the borehole was reamed to the desired diameter. The well materials were installed in the HDPE casing and then the HDPE casing was removed.

Well Materials: The well casing and 0.010-in. slotted screen were 2-in. ID schedule 40 PVC with hydrocarbon resistant open cell foam covering.

Field Effort/Performance: The four wells were installed in two days.

Results of Tests Performed on Wells: No tests were reported.

Current Status of Wells: The wells are currently idle, awaiting installation of a remediation system.

Approximate Cost of Wells: The four wells were installed for a total cost of \$15,100, including materials.

3.2.2.1 SVE Well Installations at Less Than or Equal to 25-ft Vertical Depth (cont'd)

Horizontal Well Installation Site: An eight-well air injection and recovery system was installed at a utility fleet service facility in Fallon, Nevada, during December 1992. The four SVE wells are described here. The four air injection wells are described in Section 3.2.3.1.

Contracting Agency or Company and Point of Contact:

Ms. Jacquelin Buratovich-Collins, P.E./Senior Engineer - (702) 829-1200
Simon Hydro-Search

Drilling Contractor & Point of Contact:

Michael J. Kirby/Vice President of Environmental Services - (206) 395-4530
UTILX Corporation
22404 66th Avenue S.
Kent, WA 98032

Remediation Objectives: The wells were installed as part of a program for the removal of contaminants from groundwater below a building through air injection and complimentary vapor extraction.

Site Conditions: Four SVE wells were installed in a radial pattern for alternating pressure and vacuum. The wells were installed under asphalt and one under a building. The soil was primarily silty sand.

Well Geometry: One well was 170-ft MD and 4-ft VD; two wells were 170-ft MD and 5-ft VD; and the fourth well was 280-ft MD and 4-ft VD.

Directional Drilling Method: The continuous boreholes were drilled using the FlowMole® patented GuideDril - guided horizontal drilling system. The system uses a low volume, high pressure hydraulic jet to cut through the sediments and a radio beacon-receiver guidance system. A guar gum-based fluid or water is used to deliver the hydraulic pressure to the sediment.

Well Installation Method: A 4-in. ID HDPE casing was pulled back through the borehole from the exit to the entrance hole while the borehole was reamed to the desired diameter. The well materials were installed in the HDPE casing and then the HDPE casing was removed.

Well Materials: The SVE wells were constructed of 2-in. ID PVC wrapped with hydrocarbon resistant green cell foam.

Field Effort/Performance: All eight wells were installed in 18 days. Snow and subzero weather caused numerous problems and delays.

Results of Tests Performed on Wells: No tests were reported.

Current Status of Wells: The remediation system has exceeded expectations. Contaminant is being recovered at a higher rate and higher concentrations than expected.

Approximate Cost of Wells: The eight wells (four described here and those in Section 3.2.3.1) cost a total of \$82,000 including materials.

3.2.2.1 SVE Well Installations at Less Than or Equal to 25-ft Vertical Depth (cont'd)

Horizontal Well Installation Site: Two SVE wells installed at a convenience store in Charlotte, North Carolina, during June 1993.

Contracting Agency or Company and Point of Contact:

Stewart M. Hines/Hydrogeologist - (704) 523-4726
S&ME, Inc.

Drilling Contractor and Point of Contact:

Michael J. Kirby/Vice President of Environmental Services - (206) 395-4530
UTILX Corporation
22404 66th Avenue S.
Kent, WA 98032

Remediation Objectives: Soil vapor extraction and air sparging soil remediation system.

Site Conditions: The borehole was drilled through sandy clay and sandy silt.

Well Geometry: One well was 150-ft MD (100-ft screen) and 8-ft VD; the other well was 120-ft MD (110-ft screen) and 7-ft VD.

Directional Drilling Method: The continuous boreholes were drilled using the FlowMole® patented GuideDril - guided horizontal drilling system. The system uses a low volume, high pressure hydraulic jet to cut through the sediments and a radio beacon-receiver guidance system. A guar gum-based fluid or water is used to deliver the hydraulic pressure to the sediment.

Well Installation Method: A 4-in. ID HDPE casing was pulled back through the borehole from the exit to the entrance hole while the borehole was reamed to the desired diameter. The well materials were installed in the HDPE casing and then the HDPE casing was removed.

Well Materials: The well casing and 0.010-in. slotted screen were constructed from 2-in. ID schedule 40 PVC.

Field Effort/Performance: Both wells were drilled and installed in two days.

Results of Tests Performed on Wells: No tests were reported.

Current Status of Wells: The remediation system is currently in operation.

Approximate Cost of Wells: Both wells were installed at a cost of \$19,000 including materials.

3.2.2.1 SVE Well Installations at Less Than or Equal to 25-ft Vertical Depth (cont'd)

Horizontal Well Installation Site: Two horizontal wells were installed at Tinker Air Force Base in Oklahoma City, Oklahoma, during November 1991. One of the wells was a SVE well installed at depth of 15-ft VD and is described here. A description of the second, groundwater extraction well may be found in Section 3.2.1.1.

Contracting Agency or Company and Point of Contact:

David D. Wilson - (303) 232-0131
CDM Federal Programs Corp.
1626 Cole Blvd., Ste 100
Golden, CO 80401

Drilling Contractor and Point of Contact:

Tim C. McGuire - (303) 423-5761
Michels Environmental Services
8415 Parfet Ct.
Arvada, CO 80005

Remediation Objectives: The wells were installed as a pilot demonstration to get horizontal wells approved as remedial alternatives to the record of decision for the Building 3001 Superfund site. The contaminant of concern was halogenated hydrocarbons in the unconfined perched aquifer, the semi-confined aquifer, and confined aquifer beneath Building 3001.

Site Conditions: The site geology consisted of Permian sand, sandstone, silt, clay, and shale. The target was in the unconfined perched aquifer and the unsaturated zone above it.

Well Geometry: The blind borehole had a 1000-ft radius of curvature, 15-ft VD, 270-ft MD and a 70-ft well screen.

Directional Drilling Method: A pilot hole was drilled with a medium-size, utility-type drilling rig equipped with a down-hole mud motor and a magnetometer-accelerometer guidance tool. The pilot hole was opened with a reamer.

Well Installation Method: The well materials were installed in an open hole by pushing on the end cap of the screen.

Well Materials: The well materials were 6-in. ID, 0.012-in. slotted sand pre-packed stainless steel screen with a schedule 40 PVC riser.

Field Effort/Performance: The well borehole was drilled in one attempt. The well was installed in one attempt.

Results of Tests Performed on Wells: The soil permeability was approximately 3.9 darcys. Based on the soil pressure distribution established for a well vacuum of 180-in. of water, it was established that 2,000 cubic yards of soil were affected by the horizontal well.

Current Status of Wells: The well is currently idle.

Approximate Cost of Wells: The wells cost approximately \$148,700 including engineering services and field management provided by Harrison Western, Lakewood, Colorado.

3.2.2.2 SVE Well Installations at Greater Than 25-ft and Less Than 100-ft Vertical Depth

Horizontal Well Installation Site: Two SVE wells were installed at a bulk terminal in Los Angeles, California, during February 1992.

Contracting Agency or Company and Point of Contact:

Steve Hoffman - (303) 694-7300
Chevron, USA

Drilling Contractor and Point of Contact:

Carlos Kenda - (713) 722-7777
Eastman Cherrington Environmental Corp
1055 Conrad Sauer
Houston, TX 77043-5201

Remediation Objectives: The wells were designed as components of a soil vapor extraction system used to remove petroleum hydrocarbons from the vadose zone.

Site Conditions: The site geology consisted of unconsolidated, unsaturated silty sand.

Well Geometry: The wells were installed in blind boreholes with 250-ft radii of curvature, 600-ft MD, 45-ft and 75-ft VD, and 400-ft horizontal length. The entry angle was 23° from horizontal.

Directional Drilling Method: A pilot hole was drilled with a hydraulic spud-jet drilling tool and a magnetometer-accelerometer guidance tool. The pilot hole was opened with a washover pipe.

Well Installation Method: The well was installed in the washover pipe and the filter pack was installed around the screen as the washover pipe was withdrawn from the borehole.

Well Materials: The well casing and 0.010-in. slotted screen were constructed of schedule 40 PVC pipe.

Field Effort/Performance: The installation was successful, although the PVC pipe appeared to crack in a couple of places.

Results of Tests Performed on Wells: Test results showed that the radius of influence of the well was 65 ft to 80 ft. A vertical SVE well had a radius of influence of 40 ft. There was no apparent short-circuiting along the horizontal well.

Current Status of Wells: A long-term field test was being performed on the horizontal wells during the summer of 1993.

Approximate Cost of Wells: The approximate cost of both wells was \$130,000.

3.2.2.2 SVE Well Installations at Greater Than 25-ft and Less Than 100-ft Vertical Depth
(cont'd)

Horizontal Well Installation Site: One SVE well was installed at the Savannah River Site, Aiken, South Carolina, during September 1992.

Contracting Agency or Company and Point of Contact:

Robert P. Wemple - (505) 844-2230
Sandia National Laboratory - Environmental Projects
P.O. Box 5800, Dept. 611
Albuquerque, NM 87185

Drilling Contractor and Point of Contact:

Roger Layne - (405) 336-3591
Sandia National Laboratory Industrial Partner
Charles Machine Works Inc., Perry, OK

Remediation Objectives: The well was designed to contain a radio frequency heating source and to act as a conduit for an SVE system. The target was a TCE-contaminated clay horizon.

Site Conditions: The well was installed along an abandoned pipe line. The site geology consisted of saturated fine silty sand, silt and clay.

Well Geometry: The borehole was continuous. The two curves had approximately 250-ft radii, 570-ft MD, 40-ft VD, and 230-ft horizontal screen length.

Directional Drilling Method: The drilling rig was a prototype medium-sized utility rig. The drilling tool was a 6-in. OD dry bore/compaction tool (water was used to cool and lubricate tool). A magnetometer-accelerometer wireline guidance tool was used.

Well Installation Method: The well materials were pulled from the exit hole to the entrance hole behind a hole opener (reamer).

Well Materials: The casing and 0.010-in. slotted screen were 3-in. OD schedule 40 spun fiberglass pipe. The well screen was 210 ft long.

Field Effort/Performance: The borehole was drilled in the first attempt. The original PVC casing failed during the first attempt at well installation. The second attempt at well installation was successful.

Results of Tests Performed on Well: The radio frequency heating and SVE test were successful. Contact Savannah River Technology Center for results (Tim Jarosch 803-725-5189).

Current Status of Well: The well has been tested and will be used in the SVE system.

Approximate Cost of Well: The well was installed as part of a partnership between DOE and Charles Machine Works Inc. No cost analysis was performed.

3.2.2.2 SVE Well Installations at Greater Than 25-ft and Less Than 100-ft Vertical Depth
(cont'd)

Horizontal Well Installation Site: An *in situ* air stripping system with two wells was installed at the DOE's Savannah River Site, Aiken, South Carolina, during September and October 1988. The SVE well is described here; the air injection well is described in Section 3.2.3.3.

Contracting Agency or Company and Point of Contact:

Miles Denham - (803) 725-6317
Westinghouse Savannah River Technology Center
Savannah River Site
Aiken, SC 29808

Drilling Contractor and Point of Contact:

Carlos Kenda - (713) 722-7777
Eastman Cherrington Environmental Corp
1055 Conrad Sauer
Houston, TX 77043-5201

Remediation Objectives: The two wells were designed as components of an *in situ* air stripping system beneath an abandoned waste line. The vadose zone soils are contaminated with halogenated hydrocarbons and the groundwater is contaminated with dissolved halogenated hydrocarbons.

Site Conditions: The site geology consisted of unsaturated fine grained sand, silty sand, silt, and clay. The target zone for the SVE well was approximately 65 ft to 75 ft below ground surface.

Well Geometry: The well was installed in a blind borehole that had a radius of curvature less than 50 ft, an entry angle 90° from horizontal, 200-ft horizontal length, 290-ft MD, and 75-ft VD.

Directional Drilling Method: The curve was drilled using a whipstock and a drill guide. The horizontal section was drilled by rotating a rigid drill mandrel.

Well Installation Method: The well was installed in an open borehole.

Well Materials: The well materials consisted of 4-in. ID, 0.010-in. slotted wire wrapped stainless steel screen, and 4-in. ID stainless steel riser casing.

Field Effort/Performance: The bore hole was drilled in five attempts. The well was installed in one attempt; however, the screen was not able to reach the total measured depth due to the borehole sloughing in.

Results of Tests Performed on Wells: No evaluations of the well have been performed; however, the well is performing up to expectations. Approximately 20,000 lb of solvent was extracted in a 19 month period.

Current Status of Wells: The well is currently being used to remove soil vapor.

Approximate Cost of Wells: The two-well system cost approximately \$464,000.

3.2.2.3 SVE Well Installations at Greater Than 100-ft Vertical Depth

Horizontal Well Installation Site: Two SVE wells were installed at the DOE's Savannah River Site, Aiken, South Carolina, during November 1992.

Contracting Agency or Company and Point of Contact:

Miles Denham - (803) 725-6317
Westinghouse Savannah River Technology Center
Savannah River Site
Aiken, SC 29808

Drilling Contractor and Point of Contact:

Carlos Kenda - (713) 722-7777
Eastman Cherrington Environmental Corp
1055 Conrad Sauer
Houston, TX 77043-5201

Remediation Objectives: The two wells were designed as components of an SVE system beneath a closed RCRA facility. The vadose zone soils are contaminated with halogenated hydrocarbons.

Site Conditions: The site geology consisted of unsaturated fine grained sand, silty sand, silt, and clay. The target zone was approximately 110 ft below ground surface.

Well Geometry: The two wells were designed to have 110-ft VD, 400-ft radius of curvature, 720-ft MD, and a 420-ft horizontal section.

Directional Drilling Method: A pilot hole was drilled with a medium-sized utility drilling rig equipped with a hydraulic spud-jet drilling tool and a magnetometer-accelerometer guidance tool. The pilot hole was opened with a washover pipe.

Well Installation Method: The well was installed in the washover pipe and then the washover pipe was withdrawn.

Well Materials: The casing and 0.010-in. slotted screen was constructed of 3-in. diameter, schedule 40 PVC pipe. No filter packs were installed around the wells.

Field Effort/Performance: One horizontal well was installed without incident. During the drilling of the borehole of the second horizontal well, the washover pipe broke and was not retrieved from the subsurface. The result was that the second well has only approximately 200 ft of well screen open to the formation.

Results of Tests Performed on Wells: Air permeability tests will be performed on the wells during the summer of 1993.

Current Status of Wells: The wells are being prepared for evaluation.

Approximate Cost of Wells: The cost of both wells was approximately \$330,000.

3.2.2.3 SVE Well Installations at Greater Than 100-ft Vertical Depth (cont'd)

Horizontal Well Installation Site: An *in situ* air stripping system with two wells were installed at the DOE's Savannah River Site, Aiken, South Carolina, during May and June 1991. The air injection well is described in Section 3.2.3.3; the other is described below.

Contracting Agency or Company and Point of Contact:

Miles Denham - (803) 725-6317
Westinghouse Savannah River Technology Center
Savannah River Site
Aiken, SC 29808

Drilling Contractor and Point of Contact:

Carlos Kenda - (713) 722-7777
Eastman Cherrington Environmental Corp
1055 Conrad Sauer
Houston, TX 77043-5201

Remediation Objectives: The two wells were designed as components of an *in situ* air stripping system beneath an abandoned waste line. The vadose zone soils are contaminated with halogenated hydrocarbons and the groundwater is contaminated with dissolved halogenated hydrocarbons.

Site Conditions: The site geology consisted of unsaturated fine grained sand, silty sand, silt, and clay. The target zone for the SVE well was approximately 100 ft below ground surface.

Well Geometry: The well was installed in a blind borehole that had a radius of curvature less than 100 ft, an entry angle 85° from horizontal, 152-ft horizontal length, 300-ft MD, and 101-ft VD.

Directional Drilling Method: The borehole was drilled with a down-hole mud motor. The screen and casing were advanced while drilling.

Well Installation Method: The well materials were advanced while drilling.

Well Materials: The well materials consisted of 6-in. ID, 0.010-in. slotted HDPE screen.

Field Effort/Performance: The borehole was drilled in six attempts.

Results of Tests Performed on Wells: No evaluations of the well have been performed.

Current Status of Wells: The well is currently idle.

Approximate Cost of Wells: The cost of the two well system was approximately \$228,000.

3.2.3 HORIZONTAL WELLS INSTALLED FOR ALTERNATE PURPOSES

3.2.3.1 Alternate Purpose Well Installations at Less Than or Equal to 25-ft Vertical Depth

Horizontal Well Installation Site: An air injection and recovery system was installed at a utility fleet service facility in Fallon, Nevada, during December 1992. The air injection wells are described here, the SVE wells are described in Section 3.2.2.1.

Contracting Agency or Company and Point of Contact:

Ms. Jacquelin Buratovich-Collins, P.E./Senior Engineer - (702) 829-1200
Simon Hydro-Search

Drilling Contractor and Point of Contact:

Michael J. Kirby/Vice President of Environmental Services - (206) 395-4530
UTILX Corporation
22404 66th Avenue S.
Kent, WA 98032

Remediation Objectives: The wells were installed as part of a program for the removal of contaminants from groundwater below a building through air injection and complimentary vapor extraction.

Site Conditions: Four air injection wells were installed in a radial pattern. Wells were installed under asphalt and one under a building. The soil was primarily silt. The air injection wells are described below.

Well Geometry: One well was 150-ft MD and 14-ft VD; the second well was 240-ft MD and 14-ft VD; the third well was 280-ft MD and 14-ft VD; and the fourth well was 180-ft MD and 14-ft VD.

Directional Drilling Method: The continuous boreholes were drilled using the FlowMole® patented GuideDril - guided horizontal drilling system. The system uses a low volume, high pressure hydraulic jet to cut through the sediments and a radio beacon-receiver guidance system. A guar gum-based fluid or water is used to deliver the hydraulic pressure to the sediment.

Well Installation Method: A 4-in. ID HDPE casing was pulled back through the borehole from the exit to the entrance hole while the borehole was reamed to the desired diameter. The well materials were installed in the HDPE casing and then the HDPE casing was removed.

Well Materials: The wells had 2-in. schedule 40 PVC with varying slot size, smaller slots near the pump.

Field Effort/Performance: All eight SVE and air injection wells were installed in 18 days. Snow and subzero weather caused numerous problems and delays.

Results of Tests Performed on Wells: No tests were reported.

Current Status of Wells: The remediation system has exceeded expectations. Contaminant is being recovered at a higher rate and higher concentrations than expected.

Approximate Cost of Wells: The eight wells (four described here and those in Section 3.2.2.1) cost a total of \$82,000 including materials.

3.2.3.1 Alternate Purpose Well Installations at Less Than or Equal to 25-ft Vertical Depth
(cont'd)

Horizontal Well Installation Site: One oil recovery well was installed in a machining and fabrication facility in Seattle, Washington, during June 1993.

Contracting Agency or Company and Point of Contact:

Gary E. Nagal/Associate Engineer - (206) 646-0280
SEACOR

Drilling Contractor and Point of Contact:

Michael J. Kirby/Vice President of Environmental Services - (206) 395-4530
UTILX Corporation
22404 66th Avenue S.
Kent, WA 98032

Remediation Objectives: The objective was to recover machine cutting oil, which is a light non-aqueous phase liquid (LNAPL).

Site Conditions: The well was installed under buried oil storage tanks beneath the water table. Soil was medium to coarse sand.

Well Geometry: The borehole was continuous at 13-ft VD, 320-ft MD, with 180-ft of screen.

Directional Drilling Method: The boreholes were drilled using the FlowMole® patented GuideDril - guided horizontal drilling system. The system uses a low volume, high pressure hydraulic jet to cut through the sediments and a radio beacon-receiver guidance system. A guar gum-based fluid or water is used to deliver the hydraulic pressure to the sediment.

Well Installation Method: The pilot hole was drilled as a continuous hole and then back-reamed to the desired diameter. Then pre-packed well screen was pulled back from the exit hole to the entrance hole.

Well Materials: The well materials were constructed of PVC. The well screen was a sand pre-pack with 4-in. ID and 6-in. OD.

Field Effort/Performance: The well was drilled and installed in five days.

Results of Tests Performed on Well: Well evaluation was being performed during July 1993.

Current Status of Well: The well is currently producing 3 gpm of cutting oil with a pneumatic pump.

Approximate Cost of Well: The cost of the well was \$31,000 not including materials.

3.2.3.1 Alternate Purpose Well Installations at Less Than or Equal to 25-ft Vertical Depth
(cont'd)

Horizontal Well Installation Site: A twenty-eight well *in situ* soil washing remediation system was installed at a former bulk storage facility in Minden, Nevada, during October 1992.

Contracting Agency or Company and Point of Contact:

The information was withheld by request.

Drilling Contractor and Point of Contact:

Michael J. Kirby/Vice President of Environmental Services (206) 395-4530
UTILX Corporation
22404 66th Avenue S.
Kent, WA 98032

Remediation Objectives: The system was designed as an infiltration gallery for *in situ* soil washing to remediate soil contaminated with petroleum hydrocarbons. Twenty-six 2-in. diameter infiltration gallery wells and two 4-in. diameter product recovery wells were installed.

Site Conditions: The soil consisted of sandy clay with up to 40% medium gravel.

Well Geometry:

Twenty-two wells - 2-in. ID, 20-ft MD, 3-ft VD
One well - 4-in. ID, 35-ft MD, 3-ft VD
One well - 4-in. ID, 65-ft MD, 3-ft VD
Four wells - 2-in. ID, 135-ft MD, 3-ft VD

Directional Drilling Method: The blind boreholes were drilled using the FlowMole® patented GuideDril - guided horizontal drilling system. The system uses a low volume, high pressure hydraulic jet to cut through the sediments and a radio beacon-receiver guidance system. A guar gum-based fluid or water is used to deliver the hydraulic pressure to the sediment.

Well Installation Method: The 2-in. pilot hole was drilled then reamed to 4-in. diameter. The drill rods were tripped out and the well materials were installed in the open borehole.

Well Materials: The wells consisted of 2-in. ID and 4-in. ID slotted PVC.

Field Effort/Performance: Twenty-eight wells were drilled and installed in seven days. Productivity suffered from subzero weather, wind, and snow.

Results of Tests Performed on Wells: No tests were reported.

Current Status of Wells: The wells are currently idle.

Approximate Cost of Wells: Twenty-eight wells totaling 1080 ft were installed at a cost of \$35,000. Materials were not included.

3.2.3.1 Alternate Purpose Well Installations at Less Than or Equal to 25-ft Vertical Depth
(cont'd)

Horizontal Well Installation Site: Numerous test wells were drilled and installed on a test range at Sandia National Laboratory, Albuquerque, New Mexico, between 1991 and 1993.

Contracting Agency or Company and Point of Contact:

Robert P. Wemple - (505) 844-2230
Sandia National Laboratory - Environmental Projects
P.O. Box 5800, Dept 611
Albuquerque, NM 87185

Drilling Contractor and Point of Contact:

Roger Layne - (405) 336-3591
Sandia National Laboratory Industrial Partner
Charles Machine Works Inc., Perry, OK

Remediation Objectives: The wells were designed to test and evaluate dry bore thrusting, cutting, and compaction drilling equipment and methods.

Site Conditions: The site geology consisted of unsaturated alluvial sand, gravel, and cobbles.

Well Geometry: Test wells had varying geometries, all had continuous boreholes, radii of curvature were 150 ft to 250 ft, vertical depths were from 5 ft to 25 ft, measured depths were from 100 ft to 250 ft.

Directional Drilling Method: The drilling rig was a prototype medium-sized utility rig. The drilling tool was a 6-in. OD dry bore/compaction tool (water was used to cool and lubricate tool). A magnetometer-accelerometer wireline guidance tool was used.

Well Installation Method: The well materials were pulled from the exit hole to the entrance hole behind a hole opener (reamer).

Well Materials: The well casing and screen were constructed of PVC and HDPE pipe.

Field Effort/Performance: The wells were installed as part of a research and development program; therefore, many drilling attempts were performed that would not normally be necessary.

Results of Tests Performed on Wells: No tests were performed on the wells.

Current Status of Wells: Installed wells were used for SEAMIST® tests and cross-borehole geophysical surveys.

Approximate Cost of Wells: The wells were installed under an industrial partnership; no costs are available.

3.2.3.1 Alternate Purpose Well Installations at Less Than or Equal to 25-ft Vertical Depth
(cont'd)

Horizontal Well Installation Site: Three wells were installed as an integrated multi-media remediation system in a residential area in Del City, Oklahoma, during October 1992.

Contracting Agency or Company and Point of Contact:

C. E. Downs, PhD. - (405) 767-6344

Conoco Inc.

Ponca City, OK 74602

Drilling Contractor and Point of Contact:

Sam Harris - (918) 225-5695

S&S Harris and Associates

Box 2550, Route 2

Cushing, OK 74023

Remediation Objectives: The wells were designed to remediate soils and groundwater contaminated with gasoline. The wells will alternately be used for air injection, SVE, and petroleum recovery.

Site Conditions: The wells were installed beneath residential housing and a swimming pool. The near surface soils are fine sand, silt, and clay.

Well Geometry: The wells were 300-ft MD, 12-ft VD, and had 300-ft radii of curvature.

Directional Drilling Method: The continuous boreholes were drilled with a small utility drilling rig equipped with a hydraulic jet drill tool and a radio beacon-receiver guidance system.

Well Installation Method: The well materials were pulled from the exit hole to the entrance hole.

Well Materials: The casing and 0.020-in. slotted screen were constructed from 2-in. ID schedule 40 HDPE pipe.

Field Effort/Performance: The three wells were installed without incident.

Results of Tests Performed on Wells: The wells produced approximately 5-10 gpm.

Current Status of Wells: The wells are currently in use.

Approximate Cost of Wells: The wells cost approximately \$9000 each.

3.2.3.1 Alternate Purpose Well Installations at Less Than or Equal to 25-ft Vertical Depth
(cont'd)

Horizontal Well Installation Site: Three wells were installed as an integrated remediation system beneath a pipeline in Moore, Oklahoma, during March 1993.

Contracting Agency or Company and Point of Contact:

C. E. Downs PhD - (405) 767-6344
Conoco Inc.
Ponca City, OK 74602

Drilling Contractor and Point of Contact:

Sam Harris - (918) 225-5695
S&S Harris and Associates
Box 2550, Route 2
Cushing, OK 74023

Remediation Objectives: The wells were designed to remediate soils and groundwater contaminated with gasoline. The wells will alternately be used for air injection, SVE, and petroleum recovery.

Site Conditions: The wells were installed beneath a pipeline. The near surface soils were fine sand, silt, and clay.

Well Geometry: The wells were 500-ft MD, 12-ft VD, and had 100-ft radii of curvature.

Directional Drilling Method: The boreholes were continuous and were drilled with a small utility drilling rig equipped with a hydraulic jet drill tool and a radio beacon-receiver guidance system.

Well Installation Method: The well materials were pulled from the exit hole to the entrance hole.

Well Materials: The casing and 0.020-in. slotted screen were constructed from 4-in. ID schedule 40 PVC pipe.

Field Effort/Performance: The three wells were installed without incident.

Results of Tests Performed on Wells: The wells produced approximately 3-7 gpm.

Current Status of Wells: The wells are currently in use.

Approximate Cost of Wells: The wells cost approximately \$27,000 each.

3.2.3.1 Alternate Purpose Well Installations at Less Than or Equal to 25-ft Vertical Depth
(cont'd)

Horizontal Well Installation Site: Three wells were installed beneath a land farm as a barrier to potential petroleum hydrocarbon migration in Ponca City Oklahoma during 1989.

Contracting Agency or Company and Point of Contact:

Charles Downs PhD - (405) 767-6344
Conoco Inc.
Ponca City, OK 74602

Drilling Contractor and Point of Contact:

Sam Harris - (918) 225-5695
S&S Harris and Associates
Box 2550, Route 2
Cushing, OK 74023

Remediation Objectives: The wells were designed to prevent migration of petroleum hydrocarbons to the water table through the creation of a bioactive barrier accentuated by SVE and sparging.

Site Conditions: The wells were installed beneath a land farm. The near surface soils are fine sand, silt, and clay.

Well Geometry: The wells were 410-ft, 450-ft, and 450-ft MD with 370-ft, 400-ft, and 400-ft horizontal length, all wells were 20-ft VD, and had 100-ft radii of curvature.

Directional Drilling Method: The boreholes were pit launched and were drilled with a Ditch Witch P-80 equipped with a hydraulic jet drill tool and a radio beacon "walk over" guidance tool.

Well Installation Method: The well materials were pulled from the exit hole to the entrance pit.

Well Materials: The casing and 0.020-in. slotted screen were constructed from both 2-in. (for two wells) and 4-in. ID schedule 40 PVC pipe.

Field Effort/Performance: The three wells were installed with six attempts.

Results of Tests Performed on Wells: No tests were reported at this time.

Current Status of Wells: The wells are currently operating.

Approximate Cost of Wells: Cost information was not reported.

3.2.3.1 Alternate Purpose Well Installations at Less Than or Equal to 25-ft Vertical Depth
(cont'd)

Horizontal Well Installation Site: Two wells were installed in Cincinnati, Ohio during December 1992. One well was for petroleum product recovery (described here) and the second well was groundwater recovery (described in Section 3.2.1.1).

Contracting Agency or Company and Point of Contact:

Larry Murdock - (513) 569-7885
Univ. of Cincinnati - Center of GeoEnvironmental Science and Technology
5995 Center Hill Rd.
Cincinnati, OH 45224

Drilling Contractor and Point of Contact:

Frank Kinnon - (503) 445-2425
Underground Research Inc.
4091 Camas Rd.
Camas Valley, OR 97416

Remediation Objectives: The two wells were designed to work in concert to remove diesel fuel from the subsurface. A lower well was installed in the saturated zone and was used to control the elevation of the water table. The other well was installed above the water table and was designed to remove diesel fuel floating on the water table.

Site Conditions: The wells were installed in an open railroad yard. The site geology consisted of fluvial deposits. The water table was located 19 ft below ground surface.

Well Geometry: The petroleum recovery well had a 50-ft radius of curvature, 297-ft MD, and 18-ft to 19-ft VD.

Directional Drilling Method: The wells were installed in continuous boreholes with a medium-sized utility-type drilling rig equipped with a hydrojet drilling tool and a radio beacon-receiver guidance system. Water was used as a drilling fluid.

Well Installation Method: The wells were installed by pulling the materials from the exit hole to the entrance hole behind a borehole reamer.

Well Materials: The wells were constructed of 4-in. ID schedule 40 PVC casing and 0.020-in. slotted well screen.

Field Effort/Performance: The wells were drilled and completed in two days.

Results of Tests Performed on Wells: The wells were developed with sodium tripolyphosphate followed by sodium hypochlorate. The well development resulted in enhanced recovery of sediment from the wells. An experimental sonic well development tool will also be used during the summer of 1993.

Current Status of Wells: Well development will continue during the summer of 1993.

Approximate Cost of Wells: The approximate cost of the both wells was \$35,000.

3.2.3.1 Alternate Purpose Well Installations at Less Than or Equal to 25-ft Vertical Depth
(cont'd)

Horizontal Well Installation Site: Two bioventing wells were installed in Cincinnati, Ohio, during June 1993.

Contracting Agency or Company and Point of Contact:

Larry Murdock - (513) 569-7885
Univ. of Cincinnati - Center of GeoEnvironmental Science and Technology
5995 Center Hill Rd.
Cincinnati, OH 45224

Drilling Contractor and Point of Contact:

Larry Murdock - (513) 569-7885
Univ. of Cincinnati - Center of GeoEnvironmental Science and Technology
5995 Center Hill Rd.
Cincinnati OH 45224

Remediation Objectives: The two wells were designed to enhance microbiological activity in the vadose zone to remediate diesel fuel in the subsurface.

Site Conditions: The wells were installed in an open railroad yard. The site geology consisted of fluvial deposits. The water table was located 19 ft below ground surface.

Well Geometry: The wells had a 150-ft radius of curvature, 190-ft MD, 140-ft horizontal length, and 10-ft VD.

Directional Drilling Method: The wells were installed in continuous boreholes with a medium-sized utility drilling rig equipped with a hydrojet drilling tool and a radio beacon-receiver guidance system. Water was used as a drilling fluid.

Well Installation Method: The wells were installed by pulling the materials from the exit hole to the entrance hole behind a borehole reamer.

Well Materials: The wells were constructed of 2-in. ID schedule 40 PVC casing and 0.020-in. slotted well screen.

Field Effort/Performance: The wells were drilled and completed in 3.5 days.

Results of Tests Performed on Wells: No tests were performed in the wells.

Current Status of Wells: The wells were idle in July 1993.

Approximate Cost of Wells: The wells were installed as an academic research project and not a commercial venture. The cost to the researchers for installing the wells was \$20-\$25 per foot.

3.2.3.2 Alternate Purpose Well Installations at Greater Than 25-ft and Less Than 100-ft Vertical Depth

Horizontal Well Installation Site: A test well was attempted at Kirtland Air Force Base, Albuquerque, New Mexico, during December 1992.

Contracting Agency or Company and Point of Contact:

Robert P. Wemple - (505) 844-2230
Sandia National Laboratory - Environmental Projects
P.O. Box 5800, Dept 611
Albuquerque, NM 87185

Drilling Contractor and Point of Contact:

Roger Layne - (405) 336-3591
Sandia National Laboratory Industrial Partner
Charles Machine Works Inc., Perry, OK

Remediation Objectives: The well was designed to test and evaluate of dry bore thrusting, cutting, and compaction drilling equipment and methods.

Site Conditions: The site geology consisted of unsaturated alluvial sand, gravel, and cobbles near the contaminated drilling site.

Well Geometry: The borehole was continuous; the two curves had approximately 250-ft radii, 300-ft MD, and 30-ft VD.

Directional Drilling Method: The drilling rig was a prototype medium-sized utility rig. The drilling tool was a 6-in. OD dry bore/compaction tool (water was used to cool and lubricate tool). A magnetometer-accelerometer wireline guidance tool was used.

Well Installation Method: No materials were installed; the hole was abandoned.

Field Effort/Performance: The borehole was drilled in the first attempt. The PVC casing failed during the first attempt at well installation. A second well installation was not attempted.

Results of Tests Performed on Wells: No tests were performed.

Current Status of Wells: The borehole was abandoned.

Approximate Cost of Wells: The borehole was drilled as part of a partnership between DOE and Charles Machine Works Inc. No cost analysis was performed.

3.2.3.2 Alternate Purpose Well Installations at Greater Than 25-ft and Less Than 100-ft Vertical Depth (cont'd)

Horizontal Well Installation Site: A characterization borehole/monitor well was drilled at Kirtland Air Force Base, Albuquerque, New Mexico, during May 1993.

Contracting Agency or Company and Point of Contact:

Robert P. Wemple - (505) 844-2230
Sandia National Laboratory - Environmental Projects
P.O. Box 5800, Dept 611
Albuquerque, NM 87185

Drilling Contractor and Point of Contact:

Roger Layne - (405) 336-3591
Sandia National Laboratory Industrial Partner
Charles Machine Works Inc., Perry, OK

Remediation Objectives: The well was used to help in the characterization of a radioactive waste burial ground and provide a conduit for other experiments.

Site Conditions: The site geology consisted of unsaturated alluvial sand, gravel, and cobbles.

Well Geometry: The borehole was continuous; the two curves had approximately 250-ft radii, 400-ft MD, and 30-ft VD.

Directional Drilling Method: The drilling rig was a prototype medium-sized utility rig. The drilling tool was a 6-in. OD dry bore/compaction tool (water was used to cool and lubricate the tool). A magnetometer-accelerometer wireline guidance tool was used.

Well Installation Method: The well materials were to be pulled from the exit hole to the entrance hole behind a hole opener (reamer).

Well Materials: The casing and 0.010-in. slotted screen were 4-in. ID schedule 40 fiberglass pipe.

Field Effort/Performance: The borehole was drilled in the first attempt. The fiberglass casing failed during the first attempt at well installation. A second well installation will be attempted with fiberglass casing that has a tensile strength of approximately 80,000 lb.

Results of Tests Performed on Well: No tests were performed.

Current Status of Well: The well installation will be attempted again.

Approximate Cost of Well: The well was installed as part of a partnership between DOE and Charles Machine Works Inc. No cost analysis was performed.

3.2.3.3 Alternate Purpose Well Installations at Greater Than 100-ft Vertical Depth

Horizontal Well Installation Site: An *in situ* air stripping system with two wells were installed at the DOE's Savannah River Site, Aiken, South Carolina, during September and October 1988. The air injection well is described here; the SVE well is described in Section 3.2.2.2.

Contracting Agency or Company and Point of Contact:

Miles Denham - (803) 725-6317
Westinghouse Savannah River Technology Center
Savannah River Site
Aiken, SC 29808

Drilling Contractor and Point of Contact:

Carlos Kenda - (713) 722-7777
Eastman Cherrington Environmental Corp
1055 Conrad Sauer
Houston, TX 77043-5201

Remediation Objectives: The two wells were designed as components of an *in situ* air stripping system beneath an abandoned waste line. The vadose zone soils are contaminated with halogenated hydrocarbons and the groundwater is contaminated with dissolved halogenated hydrocarbons.

Site Conditions: The site geology consisted of unsaturated fine grained sand, silty sand, silt, and clay. The target zone for the air injection well was approximately 151 ft to 157 ft below ground surface.

Well Geometry: The well was installed in a blind borehole that had a radius of curvature less than 50 ft, a 90° entry angle from horizontal, 485-ft MD, 300-ft horizontal length, and 150-ft to 175-ft VD.

Directional Drilling Method: The curve was drilled using a whipstock and a drill guide. The horizontal section was drilled by rotating a rigid drill mandrel.

Well Installation Method: The well was installed in an open borehole.

Well Materials: The well materials consisted of 2-in. ID, perforated steel pipe in the horizontal and solid 2-in. ID pipe as a riser.

Field Effort/Performance: The borehole was drilled and the well installed in one attempt.

Results of Tests Performed on Wells: No evaluations of the well have been performed; however, the well is performing up to expectations, air can be injected at rates up to 270 standard cubic feet per second.

Current Status of Wells: The well is currently being used to inject air.

Approximate Cost of Wells: The two-well system cost approximately \$464,000.

3.2.3.3 Alternate Purpose Well Installations at Greater Than 100-ft Vertical Depth (cont'd)

Horizontal Well Installation Site: An *in situ* air stripping system with two wells was installed at the DOE's Savannah River Site, Aiken, South Carolina, during May and June 1991. The SVE well is described in Section 3.2.2.3; the air injection well is described below.

Contracting Agency or Company and Point of Contact:

Miles Denham - (803) 725-6317
Westinghouse Savannah River Technology Center
Savannah River Site
Aiken, SC 29808

Drilling Contractor and Point of Contact:

Carlos Kenda - (713) 722-7777
Eastman Cherrington Environmental Corp
1055 Conrad Sauer
Houston, TX 77043-5201

Remediation Objectives: The two wells were designed as components of an *in situ* air stripping system beneath an abandoned waste line. The vadose zone soils are contaminated with halogenated hydrocarbons and the groundwater is contaminated with dissolved halogenated hydrocarbons.

Site Conditions: The site geology consisted of unsaturated fine grained sand, silty sand, silt, and clay. The target zone for the air injection well was approximately 150 ft below ground surface.

Well Geometry: The well was installed in a blind borehole that had a radius of curvature less than 100 ft, an entry angle 90° from horizontal, a 488-ft MD, a 258-ft horizontal length, and 151-ft VD.

Directional Drilling Method: The borehole was drilled with a large slant drilling rig equipped with a down-hole mud motor. The screen and casing were advanced while drilling.

Well Installation Method: The well materials were advanced while drilling.

Well Materials: The well materials consisted of 6-in. ID, 0.010-in. slotted HDPE screen.

Field Effort/Performance: The borehole was drilled and the well installed in one attempt.

Results of Tests Performed on Wells: No evaluations of the wells have been performed.

Current Status of Wells: The well is currently idle.

Approximate Cost of Wells: The two-well system cost approximately \$228,000.

4.0 DISCUSSION AND SUMMARY

The horizontal environmental well catalogue presented in Section 3.0 contains much information about the individual well installation projects. This section provides a discussion and summary of the catalogue.

Information garnered from the catalogue includes the following:

- Over one hundred horizontal environmental wells have been installed in the United States.
- The international survey did not produce any completed questionnaires; however, verbal communication indicates that up to six shallow (<25-ft) horizontal wells have been installed in Germany and Czechoslovakia.
- One-fourth of the horizontal environmental wells installed in the United States have been used for groundwater extraction, one-fourth of the wells have been used for SVE, and one-half of the wells have been used for other purposes including air injection, bioventing, and petroleum recovery (Table 4.1).
- Twenty-seven of the horizontal wells were installed as components of multi-media, integrated remediation systems. The systems integrated air injection, SVE, free product recovery, or groundwater extraction. Some of the wells were multi-purpose and were designed to perform SVE, air injection, and free product removal.
- More than 80% of the horizontal wells have been installed at vertical depths of less than or equal to 25 ft (Table 4.1). These installations may be performed (depending on site geology) by small to medium utility drilling rigs with less sophisticated guidance tools, and therefore, for less cost.
- The rate of horizontal well installations has increased significantly in the last year.

Table 4.1 Summary of Catalogue

Depths	Groundwater Extraction Wells	Soil Vapor Extraction Wells	Other Wells	Totals
≤ 25 ft	13	18	52	83
>25 ft and <100 ft	9	4	1	14
≥ 100 ft	4	3	2	9
Totals	26	25	55	106

An alternative, useful method of organizing the catalogue is to group the survey results by the drilling contractors (Table 4.2). The utility of this method is that the experience of the drilling contractors is summarized in one location. This information is presented with the caveat that other drilling contractors have the ability to install horizontal environmental

wells and have not had the opportunity to perform that task. An ancillary consideration is that the drilling companies presented in Table 4.2 may or may not be able to perform different types of installations than those listed in the table and the catalogue presented in Section 3.0.

Table 4.2 Summary of Horizontal Well Installation

Drilling Contractor	Well Site	Date	Number of Wells	Purpose of Well	Site Geology	Type of Borehole	Measured Depth /Horizontal Length in feet	Vertical Depth	Well Materials	Cost
Charles Machine Works - Ditch Witch	Savannah River Site, Aiken, SC	September 1992	1	SVE	Fine silty sand, silt, clay	Continuous	570/230	40-ft	3" ID, 10 slot fiberglass	Industrial partnership
	Kirtland AFB, NM	May 1993	1	Characterization, Monitoring	Sand, gravel, cobbles	Continuous	400/ -	30-ft	None as of July 1993	Industrial partnership
	Ponca City, OK	1988	2	Air Injection	Not Provided	Blind hole	500/400	15-ft	2" ID, material unspecified	Not Provided
Drilex	Taylor, MI	March 1990	2	GWE	Unconsolidated glacial sediments	Blind hole	575/412 475/157	30-ft 35-ft	6"ID SS	Approx. cost for both wells \$218,000
Eastman Cherrington	Savannah River Site, Aiken, SC	September, October 1988	1	In Situ Stripping	Fine silty sand, silt, and clay	Blind hole	485/300	175-ft	2"ID, perforated steel pipe	Approx. cost for both wells \$464,000
			1	SVE		Blind hole	290/200	75-ft	4"ID, 10 slot SS screen	
	Savannah River Site, Aiken, SC	May, June 1991	1	SVE	Fine silty sand, silt, and clay	Blind hole	300/152	101-ft	6"ID, 10 slot, HDPE	Approx. cost for both wells \$228,000
			1	In Situ Air Stripping		Blind hole	488/258	151-ft	6"ID, 10 slot, HDPE	
	Sacramento, CA	December 1991	1	GWE	Sandy clay	Blind hole	362/100	50-ft	3"ID, 20 slot,PVC	Demonstration Project Approx. \$30,000

Drilling Contractor	Well Site	Date	Number of Wells	Purpose of Well	Site Geology	Type of Borehole	Measured Depth /Horizontal Length in feet	Vertical Depth in feet	Well Materials	Cost
Eastman Cherrington (cont.)	Los Angeles, CA	February, March 1992	2	SVE	Unconsolidated silty sand	Blind hole	600/400	45-ft, 75-ft	3"ID,10 slot,PVC	Approx. cost for both wells \$130,000
	Fullerton, CA	April 1992	1	GWE	Silt, clay, intermittent fine sand	Blind hole	460/325	110-ft	6"ID,20 slot,HDPE, HDPE bead filter pack	Approx. \$110,000
	Texas	July 1992	2	GWE	Silty sand with clay stringers	Blind hole	- /300	25-ft	6"ID,20 slot HDPE, HDPE bead filter pack	Approx. cost for both wells \$140,000
	Geismar, LA	August 1992	2	GWE	Sand and clay	Blind hole	435/363 469/400	14-ft and 16-ft	6"ID,20 slot HDPE 4"ID,12 slot SS Pre-pack	Approx. cost for both wells \$800,000
	Union City, CA	July 1992	1	GWE	Fine silty sand and clay	Blind hole	100/70	15-ft	3"ID,10 slot,PVC	Approx. \$21,000
	Carson City, NV	April 1992	1	GWE	Unconsolidated channel sands	Blind hole	170/100	20-ft	3"ID,10 slot,PVC	Information Withheld
	Norwalk, CA	September 1992	2	SVE	Silty sand, sandy silt	Blind hole	359/84 315/80	25-ft	4"ID,20 slot HDPE	Approx. cost for both wells \$200,000
	Houston, TX	September 1992	1	GWE	Clayey soils	Blind hole	320/ -	35-ft	4"ID, 10 slot PVC	Approx. \$65,000
	Geismar, CA	November 1992	1	GWE	Sand and clay	Blind hole	185/ -	18-ft	6"ID,20 slot HDPE	Approx. \$85,000
	South San Francisco Bay area, CA	October 1992	1	SVE	Sand, sand with gravel, intermittent clay	Blind hole	210/110	18-ft	3"ID,20 slot HDPE	Approx. cost for three wells \$90,000
			2	GWE		Blind hole	200/80 210/110	25-ft and 20-ft	3"ID,20 slot SS	

Table 4.2 Summary of Horizontal Well Installation (cont'd)

Drilling Contractor	Well Site	Date	Number of Wells	Purpose of Well	Site Geology	Type of Borehole	Measured Depth /Horizontal Length in feet	Vertical Depth in feet	Well Materials	Cost
Eastman Cherrington (cont.)	SRS, Aiken, SC	November 1992	2	SVE	Fine sand, silt, clay	Blind hole	720/420 720/420	110-ft	3"ID,10 slot,PVC	Approx. cost of both wells \$330,000
	Tinker AFB, OK	November 1992	1	GWE	Fine sand, silt, clay with shale and sandstone units	Blind hole	920/200	110-ft	6"ID,20 slot HDPE 4"ID,12 slot SS filter pack	Information concerning cost not available
	Tinker AFB, OK	December 1992	1	GWE	Fine sand, silt, clay with shale and sandstone units	Blind hole	920/200	150-ft	6"ID,20 slot HDPE 4"ID,12 slot SS filter pack	Information concerning cost not available
	Tinker AFB, OK	November, December 1992, February 1993	3	GWE	Fine sand, silt, clay with shale and sandstone units	Blind hole	920/200	35-ft	6"ID,20 slot HDPE 4"ID,12 slot SS filter pack	Information concerning cost not available
	Geismar, LA	February 1993	2	GWE	Clay and sand	Blind hole	295/- 320/-	36-ft and 20-ft	6" ID Enviro-screen	Approx. cost or both wells \$300,000
	Barberton, OH	February 1993	1	GWE	Clay and sand size tailings	Blind hole	757/500	35-ft	4" ID,20 slot HDPE	Approx. \$120,000
Michels Environmental	Tinker AFB, OK	November 1991	1	GWE	Fine silty sand, silt, and clay	Blind hole	275/70	25-ft	6"ID, 12-slot, pre-pack SS	Approx. \$248,800
			1	SVE		Blind hole	270/70	15-ft	6"ID, 12-slot, pre-pack SS	Approx. \$148,700
	Williams AFB, AZ	July 1992	1	GWE	Fine sand, silt clay with gravels and cobbles	Continuous	2200/500	235-ft	6"ID, 10 slot pre-pack SS	Appro: \$960,000

Table 4.2 Summary of Horizontal Well Installation (cont'd)

Drilling Contractor	Well Site	Date	Number of Wells	Purpose of Well	Site Geology	Type of Borehole	Measured Depth /Horizontal Length in feet	Vertical Depth in feet	Well Materials	Cost
S&S Harris	Del City, OK	October 1992	3	Integrated multimedia	Fine sand, silt, and clay	Continuous	300/-	12-ft	2"ID, 20 slot HDPE	Approx. \$9000/well
	Moore, OK	March 1993	3	Remed. system	Fine sand, silt, and clay	Continuous	500/-	12-ft	4"ID, 20 slot PVC	Approx. \$27,000/well
	Ponca City, OK	1989	3	Air injection, SVE, bio-active barrier	Unsaturated fine sand, silt, clay	Continuous	410/370 450/400 450/400	20-ft	4"ID, 20 slot PVC, 2"ID, 20 slot PVC, 2"ID, 20 slot PVC	The information was withheld
Underground Research Inc.	Cincinnati, OH	December 1992	1	Product Recovery	Fluvial Sediments	Continuous	297/-	19-ft	4"ID, 20 slot, PVC	Approx. cost of both wells \$35,000
			1	Ground-water Control		Continuous	325/-	21-ft	4"ID, 20 slot, PVC	
University of Cincinnati	Cincinnati, OH	June 1993	2	Bioventing	Fluvial sediments	Continuous	190/140	10-ft	2" ID, 20 slot PVC	Research project
UTILX	Orcutt, CA	May 1992	4	SVE	Silty sand	Continuous	1@120/- 3@70/-	1@4-ft 3@5-ft	2"ID, 10 slot PVC	\$15,100 for all 4 wells (including materials)
	Fallon, NV	December 1992	4	Air injection	Silty sand	Continuous	150/- 180/- 240/- 280/-	14-ft	2"ID, 10 slot PVC	\$82,000 for all 8 wells, (including materials)
			4	SVE		Continuous	170/- 170/- 170/- 280/-	4-ft 4-ft 5-ft 4-ft	2"ID PVC	

Table 4.2 Summary of Horizontal Well Installation (cont'd)

Drilling Contractor	Well Site	Date	Number of Wells	Purpose of Well	Site Geology	Type of Borehole	Measured Depth /Horizontal Length in feet	Vertical Depth	Well Materials	Cost
UTILX (cont.)	Minden, NV	October 1992	22	Infiltration Galleries	Sandy clay with gravel	Blind	22@20/-	3-ft	2"ID PVC	The 28 wells were installed for \$35,000 (materials not included)
			2	Product Recovery Wells		Blind	35/- 65/-	3-ft	4"ID PVC	
			4	Infiltration Galleries		Blind	4@135/-	3-ft	2"ID PVC	
	Ponca City, OK	May 1987	4	Product Recovery	Silty-clayey sand with gravel	Continuous	580/500 475/350 360/300 560/500	20-ft 20-ft 20-ft 18-ft	4"ID, 20 slot PVC	Approx. cost >\$100,000
	Portland, OR	April 1993	1	GWE	Silt	Continuous	475/300	23-ft	2"ID, 20 slot Pre-pack PVC	Total cost for both wells and materials \$100,000
			1	SVE		Continuous	475/300	6.5-ft	4"ID, 20 slot PVC	
	Seattle, WA	June 1993	1	GW and Petroleum Recovery	Medium to coarse sand	Continuous	320/180	13-ft	4"ID, Pre-pack PVC	\$31,000, materials not included
	Charlotte, NC	June 1993	2	SVE	Sandy silt and sandy clay	Continuous	150/100 120/110	8-ft 7-ft	2"ID, 10 slot PVC	\$19,000 including materials
	Las Vegas, NV	Not Provided	1	SVE	Not Provided	Continuous	426-ft	<5-ft	4"ID HDPE	Not Provided
	Las Vegas, NV	Not Provided	1	SVE	Not Provided	Continuous	840-ft	<5-ft	4"ID HDPE	Not Provided
	Cherry Hill, NJ	Not Provided	2	SVE	Not Provided	Continuous	140-ft	<5-ft	2"ID	Not Provided

Table 4.2 Summary of Horizontal Well Installation (cont'd)

5.0 RECOMMENDATIONS

The survey was terminated during July 1993, and therefore drilling events occurring during the last half of the 1993 field season will not be included in the results. The survey should be updated annually to provide current, state-of-the-art information on the horizontal environmental well installation industry. An important aspect of horizontal environmental drilling is the effect of drilling fluid on the host formation. Future surveys should include a more detailed look into the various drilling fluids used in the drilling projects and the effects, if any, the fluids have on the performance of the well.

6.0 REFERENCES

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