COMPARATIVE ANALYSIS OF AIR SPARGING TECHNOLOGY FOR REMEDIATING CONTAMINATED GROUNDWATER UTILIZING HORIZONTAL SOIL VAPOR EXTRACTION SYSTEMS

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PREFACE

This thesis was written in conjunction with research being performed by Oklahoma State University for an EPA Demonstration Project on Leaking Underground Storage Tanks (LUST's). OSU was selected to oversee the *LUSTDEM* projects for EPA Region VI, with Dr. Vernon Mast as coordinator. This specific project was located at the Oklahoma Department of Transportation Division VIII headquarters in Perry, Oklahoma.

This report is organized to step the reader through the remediation process which has transpired on the Perry Project. Chapter I addresses why groundwater contamination is a problem, the types of contamination one might encounter, and the specifics of this thesis. Chapters II, III, and IV are background chapters written to inform the reader on the governing regulations and remediation techniques used for clean up in this demonstration project. Chapter V provides a chronology of the activities which have transpired on this project. Chapter VI reviews the current state-of-the-practice horizontal *environmental* drilling technology. This technique is just beginning to gain attention in the environmental industry and an in-depth review was needed. Chapter VII then addresses several key questions an engineer must consider when designing an Air Sparge/Soil Vapor Extraction system, specifically well design decisions. Advantages, disadvantages, and applicability are discussed. Finally, Chapter VIII makes some observations and draws the final conclusions.

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LIST OF ABBREVIATIONS

BPQL – Below Practical Quantitative Limits

BTEX – Benzene, Toluene, Ethylbenzene, and Xylenes

CERCLA – Comprehensive Environmental Response, Compensation, and Liability Act

CWA – Clean Water Act

DD – Directional Drilling

DNAPL – Dense Non-Aqueous Phase Liquids

EPA – Environmental Protection Agency

in situ – in place; on site

IAS – in situ air sparging

HSWA – Hazardous and Solid Waste Amendments

NAPL – Non-Aqueous Phase Liquids

LNAPL – Light Non-Aqueous Phase Liquids

MW – Monitoring Wells

OCC – Oklahoma Corporation Commission

PVC – Polyvinyl Chloride

RCRA – Resource Conservation and Recovery Act

SVE – Soil Vapor Extraction

SW – Sparge Wells

TPH – Total Petroleum Hydrocarbons

UST – Underground Storage Tank

VES – Vapor Extraction System

VOC – Volatile Organic Compounds

CHAPTER I

INTRODUCTION

There are an estimated 2.5 to 5 million underground storage tanks (UST's) in the United States. Over 95% of these tanks hold petroleum products; over 75% will leak according to the EPA within the next 10 years. Leaking underground storage tanks (LUST's) are one of the primary sources of groundwater and soil contamination. These LUST's leak all categories of pollutants including gasolines, jet fuels, solvents, hazardous and toxic chemicals, and waste products. The Environmental Protection Agency (EPA) has placed a strong emphasis on both preventing leaks as well as remediating contaminated sites.

A majority of the released contaminants are volatile or semi-volatile organic compounds. These volatile organic compounds (VOC's) have several characteristics which will determine how they react upon release. The chemicals may be soluble, in which case they will dissolve to some degree into the groundwater and be carried with the groundwater flow (see Figure 1.1). On the other hand, the pollutant may be a non-aqueous phase liquid (NAPL) which will not dissociate into the water. Light non-aqueous phase liquids (LNAPL's), including gasoline and other fuels, are less dense than water and will float on the top of the groundwater (see Figure 1.2). These LNAPL's may be drawn vertically through the soil as a result of seasonal fluctuation or pumping influences on the groundwater table (GWT). Dense non-aqueous phase liquids (DNAPL's), conversely, will fall directly through the groundwater until it is stopped by a confining layer (i.e. shale). The DNAPL's may then flow along the slope of the bedrock (see Figure 1.3). These contaminants are hard to remove, and may even become trapped in depressions below the groundwater, making remediation even more difficult.

Several new remediation technologies are being investigated to clean polluted soil and groundwater sites. These efforts are driven by demands to remediate sites quickly, congenially, and inexpensively. In the past clean up has consisted of excavating contaminated soil and pumping the water to the surface for treatment. Decision flow diagrams are shown for both groundwater and soil remediation technologies (Figure 1.4 and 1.5). To meet the aforementioned driving factors, in situ methods appear to be the best option. It is obvious that excavating soil is disruptive and often impractical. Pump and treat methods of remediating groundwater have been found ineffective and cumbersome. One of the apparent problems with pump and treat is that the contaminant is often left behind in the soil particles below the GWT. Thus, the groundwater may be cleaned, but the residual contaminants remain to pollute the aquifer. Figure 1.6 shows a normal pump and treat system operation. Notice that contaminant concentrations rise quickly after the pumping is ceased. In addition to the technological problems, these methods are very expensive and time consuming.

Over the past decade there have been numerous technology breakthroughs leading to even more research and experimentation. The EPA has encouraged the development and use of these innovative technologies at sites across the U.S. The major advancement has been the increased emphasis on in situ, or in-place, treatment processes. By treating the soil and water in situ, normal activities may continue above ground. By utilizing in situ methods, owners can realize major cost and time savings. Some of the techniques include the following:

For Soil Remediation –

- Bioremediation
- Soil Vapor Extraction
- Soil Flushing
- Vitrification

For Groundwater Remediation –

- Bioremediation
- Air Sparging
- Dual Phase Extraction
- In situ Heating

Not only do these methods reduce time, effort, and money, but they also provide the means to clean many sites which were not amenable to previous methods. While these methods may save hundreds of thousands of dollars and several years at each site, they are still in the infancy stages and have not been subjected to extensive research and/or studies.

ELEMENTS OF THIS THESIS

The basis of this thesis is to study many of the advantages, disadvantages, and concerns of air sparging coupled with varying soil vapor extraction well configuration designs. To better understand the topic, individual chapters are included to introduce the reader to both *air sparging* and *soil vapor extraction* technology (Chapters III and IV, respectively). Initially, a discussion is included on the regulations affecting soil and groundwater contamination (Chapter II).

This report is a result of activities associated with an EPA LUSTDEM remediation project coordinated by OSU at Perry, Oklahoma, for the Oklahoma Department of Transportation. The activities which have taken place at this site are presented in Chapter V. Plans have been made to conduct a workshop at OSU on the design process and findings of this study.

As with any design process, the engineer must match the remediation system design to the specific site. Well design will be a key point to any design. Historically, vertical well configurations have been used for both air sparging and SVE systems. Horizontal trenches are often used for shallow SVE systems, as well. Most recently, horizontal drilling techniques are being adapted from several fields for environmental remediation applications. This provides the engineer the option of using a horizontal well orientation, an option which has not been available in the past. Chapter VI looks at the horizontal environmental drilling industry and the options associated with this technology. Subsequent to Chapter VI, Chapter VII is a discussion on whether the engineer should use horizontal (trenches versus directionally drilled wells) or vertical well orientations for air sparging and vapor extraction systems. Finally, Chapter VIII considers whether a vertical air sparge system could or should be coupled with a horizontal vapor extraction system. A summary and conclusions are drawn from what is presented and what has been seen at the Perry remediation site.

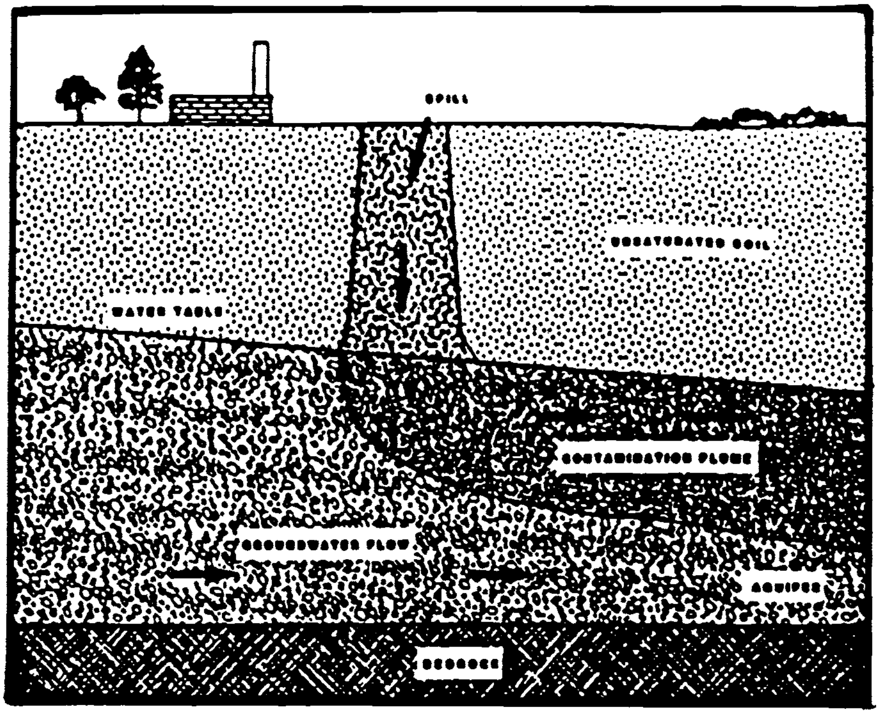

Figure 1.1 – Contaminant plume migrating into the groundwater.

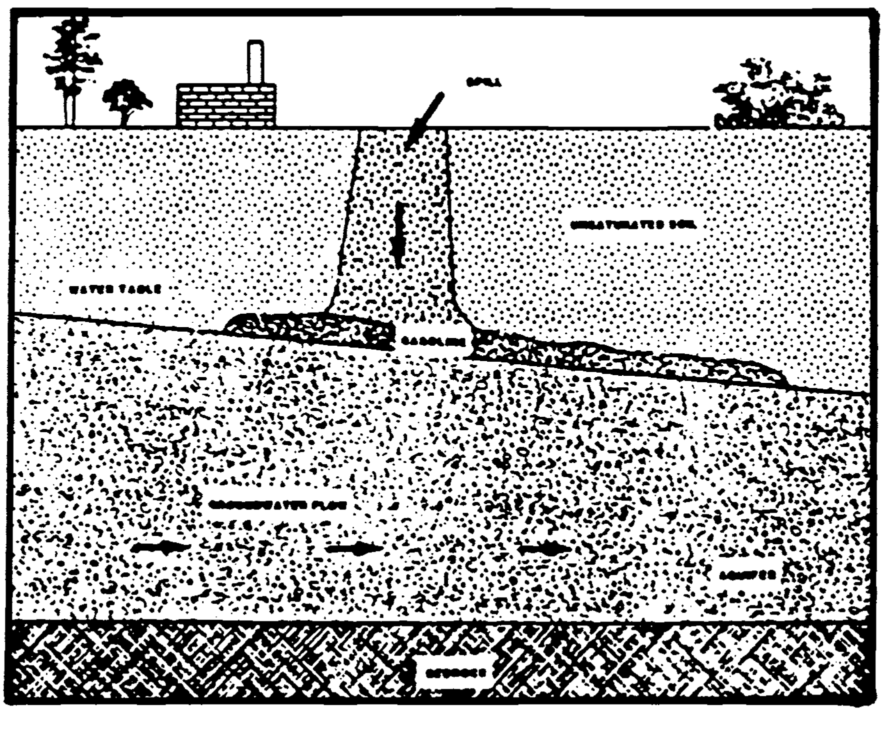

Figure 1.2 – LNAPL Plume as it migrates through the soil to the groundwater.

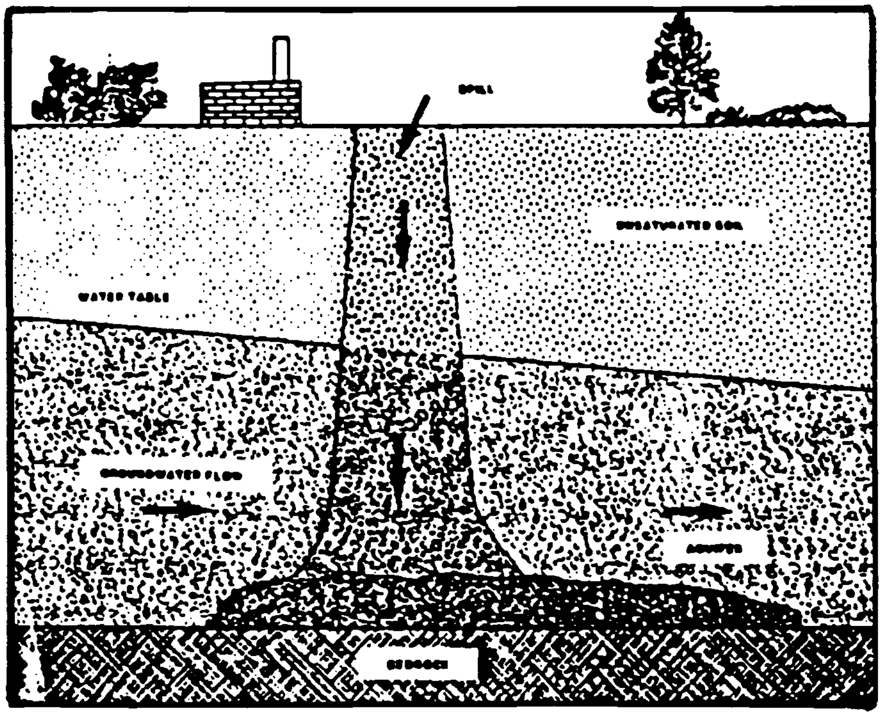

Figure 1.3 – DNAPL Plume as it migrates through the soil to the groundwater.

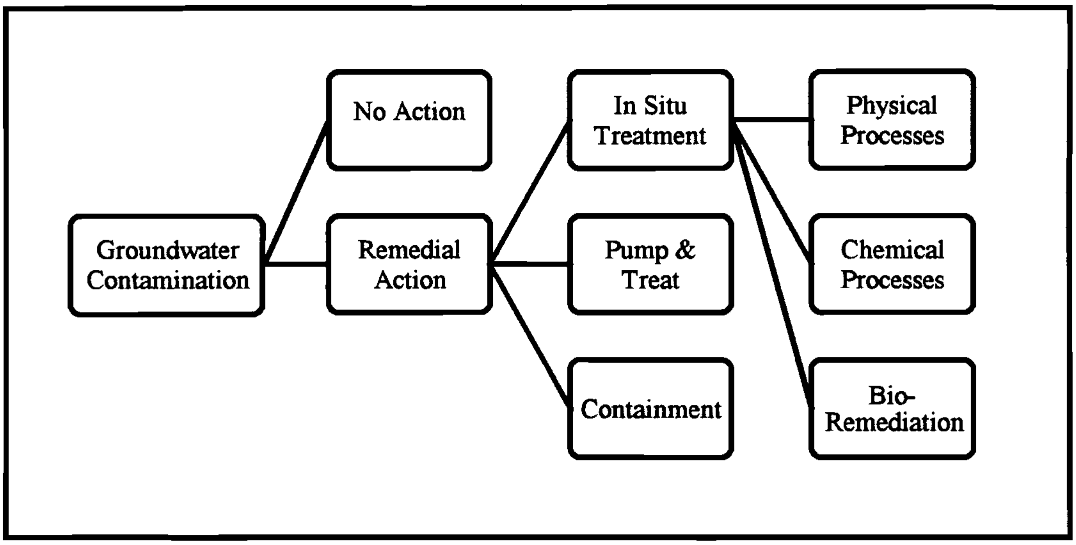

Figure 1.4 – Groundwater Remediation Decision Diagram

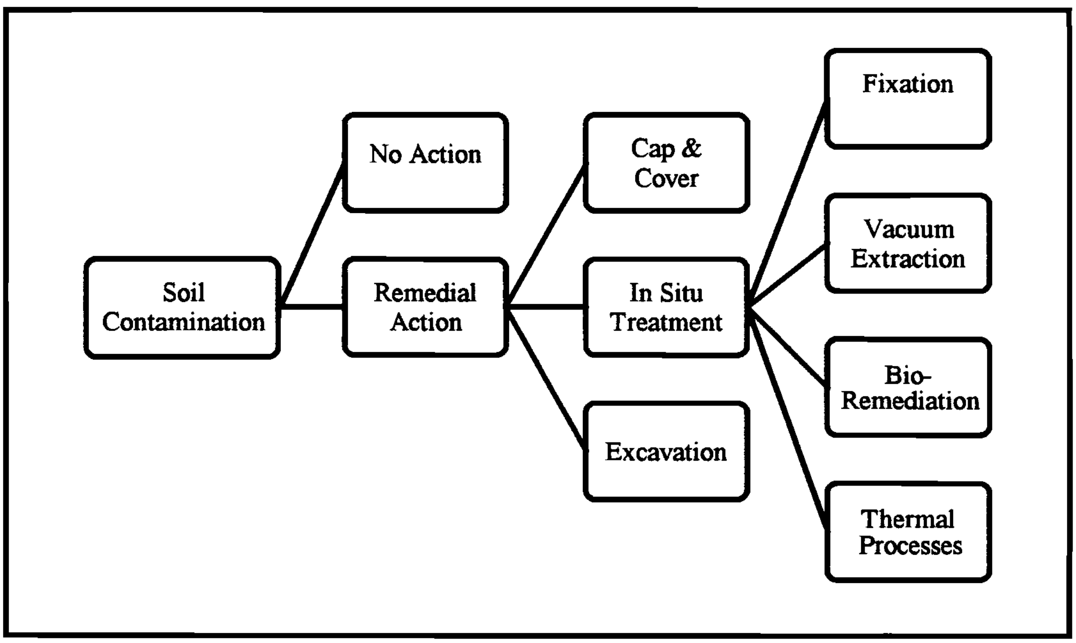

Figure 1.5 – Soil Remediation Decision Diagram

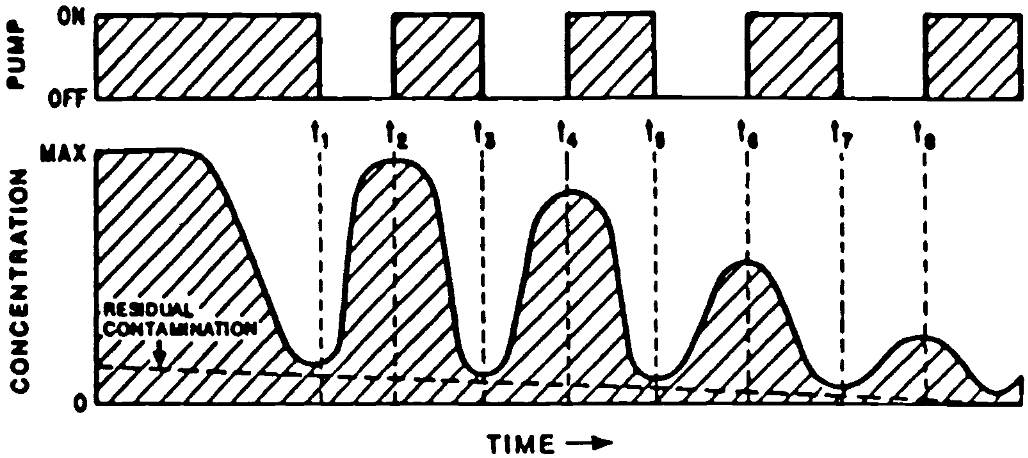

Figure 1.6 – System operation for a typical pump and treat unit.

CHAPTER II

LEGISLATION AND REGULATIONS AFFECTING UNDERGROUND STORAGE TANKS

The corner gasoline station is a fixture of American society. These stations store their regular, super, and premium grades in tanks below ground-level. For years these tanks have been buried without regard for the environment and what may happen in the future. No longer may these tanks, which remain out of sight, remain out of mind. On December 23, 1988, a new set of federal regulations took effect to specifically supervise underground storage tanks (UST's).

The Resource Conservation and Recovery Act (RCRA) was passed by Congress in 1976 as a capstone to the other environmental laws being passed in the early 1970's. These laws were developed to help manage the environmental impacts of an industrialized society. RCRA was amended in 1984 by what is known as the Hazardous and Solid Waste Amendments (HSWA) of 1984. Included in this package of amendments was an area developed specifically for the growing problem of leaking petroleum tanks which were polluting the nation's groundwater. Subtitle I of RCRA addresses UST's.

A History and Background

Underground storage tanks drew national attention in 1983 when television programs such as "Good Morning America" and "60 Minutes" showed examples of communities faced with the problem of leaking UST's. The timing was very opportune in that RCRA and CRCLA both were to be re-authorized in 1984 (Cichon, 1990). At the time the RCRA amendments were being discussed, EPA was developing its own strategies for handling the groundwater pollution problem. However, the EPA was attempting to use the authority of the Toxic Substance Control Act (TSCA) for regulating UST's. When the re-authorization bill for RCRA was proposed, lawmakers included specific statutes addressing UST's.

The proposal gained the support of large, interstate petroleum marketers who sought a consistent set of rules and national standards to preempt the emerging "patchwork" of state laws (Hayward, 1994). The bill passed by Congress stipulated that individual states were to develop their own UST provisions and enforcement plans. These standards were to be at least equal to, or stricter than, the national standards. Currently, while the EPA does not intend to independently check for compliance, it does have approval authority of state enforcement programs.

Subtitle I (eye) was approved in 1984. It required the U.S. EPA "to establish a national regulatory program to control new and existing UST's and associated piping used to store liquid petroleum products and other chemicals defined as 'hazardous substances' under the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA)," (Mast, 1994). The goals of the government regulations were: (Reeves, 1992)

- To acknowledge and correct a long-standing environmental hazards.
- To reduce the chances of future spills and leaks.
- To provide quick hazard containment when spills or leaks occur.
- To establish liability for both past and future incidents.
- To protect public health.

At the time of the original passing of the bill, the EPA did not have a regulation plan or a set of standards ready for implementation. These regulations were not released until December of 1988. The first step in the regulation process was to establish a national inventory of UST's. At that point in time the EPA had no record or evidence to show how many UST's actually existed in the United States. UST owners and operators were required to register their tanks with the state, and an attempt was made to account for the thousands of abandoned sites scattered across the country. The EPA also set preliminary, intermediate, and final compliance dates for the owners and operators to meet the set of standards. The first date was December 22, 1989, for installation of release detection systems on all old tanks. Upgrades of release detection systems for tanks less than 25 years of age must be met by certain intermediate deadlines. And the final compliance date for all tanks to be fully upgraded to all EPA standards is December 22, 1998. If the tanks have not been upgraded by the December 1998 deadline, they will be permanently closed.

While many environmentalists felt that ten years was too long for operators to come into compliance, the EPA had very specific thoughts on the ten year plan. This allowed many small gasoline station owners and small municipalities to ease the financial burden involved with making large capital improvements and purchasing expensive insurance policies. It also allowed the EPA and state regulators time to mature and gather data on a relatively new field. EPA's Ron Brand, director of the office of Underground Storage Tanks:

> "We have worked very hard in the EPA underground storage tank (UST) regulations not to freeze industry and the public into just today's technology. Many people suggest that the EPA should base its regulations on what the industry thinks is best today and then make everyone follow that technology. But industry has shown us that enough changes are going on, enough new ideas are being worked on, that we said no. Today's technology relative to UST's came before the interest now being stimulated by the regulations," (Voluntary, 1988).

Brand believed the 10 year period before final compliance and new regulation release would allow regulators and industry time to learn together what changes should be made in the regulations.

The UST program is unique in that it was the first federal program to utilize TQM (Total Quality Management) in its conception and implementation. The program encourages voluntary compliance and creative solutions, especially in site clean up. The program authors attempted to develop a flexible, decentralized system which avoided top-down management. Not only are the states allowed to set up enforcement programs, but local agencies, such as fire districts, are allowed to pass UST ordinances (Hayward, 1994). This should not over shadow the fact that the EPA still sets the priorities, and *always* has the final say.

It is also the EPA's responsibility to educate owners and operators of proper practice and procedure. Training in corrosion control, installation, inspection, monitoring, and all other aspects is an important responsibility when dealing with UST programs. Mr. Brand commented in an interview that the EPA must do more than just put together 3 inch thick regulation manuals. Changing peoples' behavior requires extra effort which starts with education and support (Voluntary, 1988). The agency hopes to advance this philosophy by creating helpful hand-outs, coordinating with associations like the National Association of Corrosion Engineers (NACE) and the American Petroleum Institute (API), and by funding demonstration projects in each of the EPA regions. Oklahoma State University has been designated as the UST and innovative groundwater remediation demonstration coordinators for the Midwest district. These demonstration projects show owners and operators how to deal with the UST regulations. They also present the most current methods and innovative techniques for installation, monitoring, and remediation. The EPA is making an effort to the make the system as friendly as possible.

The Regulations

The EPA estimates there are approximately 2,000,000 underground storage tanks across the United States at nearly 750,000 sites. Ninety-five percent of the tanks hold petroleum products. They also anticipate nearly 75% of these tanks leaking within in the next 10 years. Additionally, 30% of all leaks are from piping.

What exactly constitutes an underground storage tank? The EPA defines a UST as any tank larger than 1,100 gallons that is 10% or more beneath the ground, including connecting underground pipes. Additionally, the regulations apply only to UST's containing petroleum products or other monitored, hazardous materials (Evans, 1988).

Why are underground storage tanks an environmental concern? It only takes one gallon of gasoline to contaminate 750,000 gallons of water (Davis, 1992). The main concern with storage tank leaks is contamination of groundwater. As many as 50% of municipalities and countless individual water wells in the U.S. depend on groundwater sources. With two million possible polluters, it's easy to see why rules are needed.

Storage tanks are placed underground to avoid the dangers and inconvenience of above-ground tanks. Not only do above-ground tanks occupy space, they are a fire hazard. Unfortunately, as many as 75% of the underground storage tanks are predicted to leak by the year 1998. The problem is multifaceted. Leaks can occur because of corrosion; 80% of the UST's installed before 1991 were single layer, bare steel. Piping systems are also prone to leaks. In addition, improper installation has led to a vast number of leaks.

Subtitle I of RCRA, as amended in 1984, requires the following standards be met by December 22,1998 (Evans, 1988). It should be noted that while the EPA is making every effort to help the owner and to make the process friendlier for everyone, they have set very ambitious goals and stringent standards which tend to make the program much less flexible.

[Note: It is beyond the scope of this paper to go into detail on the specifics of the law. Local UST enforcement agency may be contacted for a more complete presentation of the regulations and expectations of Subtitle I.]

- *Corrosion protection* must be installed. Suggested systems include the sacrificial anode or the impressed current. For installation of new tanks it is suggested that corrosion resistant materials (i.e. fiberglass) be used, at least as a coating.

- *Spill and overfill* prevention must be provided. This is accomplished by one of several ways: an automatic flow shut off when the tank is 95% full, an automatic flow restrictor when the tank is 90% full, or an automatic high-level alarm when the tank is 90% full. In addition, some method must be provided to prevent releases when disconnecting transfer hoses during and after filling operations.

- *Leak detection* is required. There are a number of systems available depending on the type of tank the system will be used on. Detection systems must also address releases by the piping system. Manual inventory or precision testing are often recommended in addition to any system being used.

- "Any installation of new tank systems must be certified, tested, and inspected in compliance with EPA requirements. Additionally, all UST's containing hazardous chemicals are required to have secondary containment...and tanks must be inspected regularly by qualified testers," (Fahey, 1989).

In addition to the standards mentioned, owners and operators must prepare plans of action in case of spills or leaks. The law addresses reporting, permitting, and testing. The UST owner must not only be aware of the federal regulations of RCRA, but also of state regulations, often set by state environmental agencies or, as in the case of Oklahoma, the State Corporation Commission.

FINANCIAL CONSIDERATIONS

Another area addressed by Subtitle I is financial responsibility. Owners are now required to carry insurance policies in order to handle clean up costs should a leak occur. A typical amount would be $1 million policy to cover remediation costs and/or third party injury or property damage (Fahey, 1989). Unfortunately, banks and insurance companies are reluctant to invest in ventures that could assume liability. The uncertain liability situation has hampered owners' attempts to upgrade tanks to meet the new standards. As originally envisioned by Congress, the owners would obtain insurance to protect themselves until they could upgrade to the new standards–around 1998. The lawmakers seemed to have overlooked a few small details, however. Insurance companies refuse to insure tanks until they have been upgraded, thus, defeating one of the key reasons for allowing the ten year enhancement period. Additionally, it puts a strain on the small gas station operator, as was feared in the beginning. Furthermore, the strain of a tidal wave of policy seekers and some poor decision making has put several insurance agents who did offer affordable policies out of business, scaring away other companies who had been considering the idea (Hayward, 1994).

Subtitle I also called for states to establish clean up funds for the remediation of spill sites. These funds are designed to reimburse owners for money spent on clean up efforts. The funds also provide an incentive for owners to report leaks and start remediation programs. These reimbursement programs do work if the owner operates in good faith and makes an effort to work with the system, not against it (Dunn, 1993). Unfortunately, these funds are depleating much faster than the soil and groundwater is being cleaned. While state funds are already running low, the EPA estimates that only 10% of contaminated sites have been remediated. State fund supervisors are making every effort to keep the fund solvent and viable. This is a necessity for many owners and UST engineers as well.

Who is Affected by UST Regulations

Subtitle I has the potential of affecting more people and companies than any environmental law ever passed in the United States. For example, the Clean Water Act when passed by Congress (amendments of 1984) required between 50,000 to 75,000 entities to obtain permits. An estimated 2 million tank owners will be affected by UST regulations (Hayward, 1994). It should also be noted that a majority of these operators have had no prior exposure to federal environmental regulation. This places them at a great disadvantage and in an uncomfortable position, to say the least.

The largest group to be affected by the regulations are gasoline station operators. It is estimated that 50% of all UST's are at gas stations. Unfortunately, 65% of all reported leaks are from retail stations (Evans, 1988). Some predict that the 1998 deadline will not be met by many of these station owners simply because the costs will be too high to make the capital improvements and purchase the insurance necessary. Many feel this is a major threat to the "corner gasoline station." Every effort is being made to assist local operators.

Municipalities and other government agencies (e.g. school systems, state transportation departments) are also affected. These organizations usually run fleet operations, much like national trucking companies do. They must now learn the rules governing their storage tanks in order to remain in compliance. Unfortunately, many of these local government officials are unfamiliar with the technical issues involved. And since the area is relatively new, there are few experienced engineers and contractors familiar with the program. Financial liability becomes a major concern for local governments, especially when one considers this may affect all of the public works, fire departments, police departments–any fleet servicing agencies (Cichon, 1988). Communities must consider their UST management plan and attempt to upgrade to come into compliance so as not to be hit in 1998 with the unpleasant realization of revamping an outdated system in order to continue operations. The issue gained major attention from local governments, as apparent from the numerous articles discussing the pros, cons, and pitfalls of the regulations in journals, such as American City and County and Nation's Cities Weekly, immediately after the amendments were passed in 1988. Public officials are being asked to take on a highly technical field and provide long-term UST management in order to protect public safety and maintain financial stability for their constituency.

Other local agencies and officials who need to be aware of the UST rules include fire-fighters and local hazardous material response units. One of the common occurrences with leaking petroleum is a tendency to seek out low pressure receptors. A prime example is basements. Local units must be aware of how to recognize and handle these situations, and that would include working with the owner of the leaking tank to rectify the situation. Another group affected by the rules are American farmers. Many farmers in the midwest have UST's to store gas and diesel for their trucks, tractors, and other equipment. Although the law exempts farm tanks under 1,100 gallons, farmers may still be in trouble if the tanks leak–they are responsible. If the tank is smaller than 1,100 gallons, it is not regulated by the law; however, the farmer is unable to receive financial help then if it leaks. If the tank is larger than 1,100 gallons, it is covered by clean up funds, but falls under stringent regulations, which many independent farmers can't afford to meet. The result of this situation is that many farmers are being advised (mainly by lawyers) to remove their UST's. This becomes a major inconvenience for the farmer (Davis, 1992).

Real estate agents must also be aware of UST concerns. Ultimate accountability lies both with the property owner and the responsible party, assuming one can be identified. An environmental audit should be performed before the sale or acquisition of any commercial real estate. This may prove invaluable in that contamination may be discovered prior to the sale, thus, allowing both parties to the realize the ramifications of a sale of the property. In some instances the current owner may be held responsible for clean up. In other cases, the price may be adjusted to account for the clean up required after the sale is completed. Ultimately, realtors, buyers, and sellers should be fully aware of the entire picture so as not to be surprised at some point in the future. Additionally, real estate agents should be aware of UST regulations since the ethical responsibility of a good sale is their's (Cook, 92).

CONCLUSION

Underground Storage Tank legislation passed Congress in 1984, and on December 22, 1988, EPA set the regulations into motion. During the years prior to 1988, underground storage tanks had been buried beneath the soil, where they remained out of sight *and* out of mind. After years of corrosion and neglect, these tanks began to leak their harmful oils and toxic chemicals into the soil and groundwater. Recognizing the growing problem, the United States Congress and Environmental Protection Agency developed a new set of standards to curb the current problem and to prevent the problem from recurring in the future.

Subtitle I of the HSWAmendments addresses these UST's. This law will potentially affect more people than any other environmental law passed to date (nearly 2,000,000 owners and operators may be affected). The goal of this law is simple–protect the environment by preventing leaks and spills from UST's and clean up contamination which already exists. The EPA has established ambitious targets and is attempting to assist owners and operators in meeting these goals. And while the program is mandated on the federal level, the implementation and enforcement will be carried out at the state and local levels. Deadlines are drawing near and financial requirements make it difficult at times, but officials remain supportive and optimistic about the program established to regulate our Underground Storage Tank system.

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CHAPTER III

AIR SPARGING TECHNOLOGY: AN INNOVATIVE ALTERNATIVE TO PUMP AND TREAT

INTRODUCTION

The history of groundwater remediation has been centered around traditional pump and treat systems. However, pump and treat is limited in its ability to clean contaminants below certain concentrations and to remediate in an economic and timely manner. Additionally, this process does not address soil remediation in the unsaturated zone. In recent years soil vapor extraction (SVE) has been established as an effective method to remediate volatile components, mainly volatile organic compounds (VOC's), from contaminated soils in a fairly economical manner. Unfortunately, SVE is unable to clean contaminants from the capillary or the saturated soil zones (i.e. below the groundwater table). In situ air sparging (IAS) is a somewhat new technology with a promising outlook for effective, and economic, remediation of VOC's from contaminated groundwater and capillary zones.

Air sparging is a technique in which air is injected below the groundwater table (GWT). As the air rises through the saturated zone, it removes VOC's, by way of volatilization, from the contaminated groundwater. The VOC's can subsequently be removed from the soil by an SVE system, or if only small amounts are present, they simply vent from the soil naturally. Figure 3.1 shows a typical air sparging/soil vapor extraction system. This section discusses several issues related to in situ air sparging. While air sparging has been used successfully for enhancing in situ bioremediation (bioventing), the focus of this paper will specifically be on the use of IAS for the remediation of VOC's (mainly BTEX and other hydrocarbon products) from groundwater and capillary zones.

Fundamental Processes

With contaminated soil and groundwater sites being discovered everyday, new technology is sought to aid in the clean up effort. Air sparging is a relatively new technology used to clean volatile components from groundwater and capillary regions. Unfortunately, air sparging is governed by a combination of complex physical, chemical, and biological processes making it difficult to model.

These volatile components are often the result of gasoline or other petroleum product spills. Often less dense than water, these products will float on the groundwater. Unfortunately, due to capillary action and the seasonal rise and fall of the GWT, the free product is drawn into the groundwater in finger like protrusions, making it more difficult to isolate and clean the site. Remediation of this situation may effectively be accomplished through the use of in situ air sparging. The IAS function is based on volatilization of components as the air rises through the soil.

Theory

Air sparging may be thought of as a crude, subsurface air stripper with the in situ soil serving as the packing material. With sparging, air is injected into the groundwater some distance below the contaminant and allowed to travel vertically and horizontally in a cone like fashion. Air that comes in contact with dissolved or adsorbed phase contaminants will cause the components to volatilize. The air then moves the volatilized particles into the vadose, or unsaturated, zone. They may then be captured by a subsequent vapor extraction system. Figure 3.2 shows typical air flow patterns in both an isotropic and a heterogeneous subsurface with vapor extraction.

Before further discussing the mechanisms controlling the IAS process, the methods of air flow through the soil should be considered. Only recently have researchers reported that air most often moves upward through the soil in channels–not bubbles as originally thought (Johnson, R.L., et al., 1993; Ahlfeld et al., 1994). Originally, geotechnicians thought that air introduced to the groundwater would rise through the saturated zone as a bubble, constantly taking different paths. New evidence shows, however, that channel flow is the more common flow pattern (Ji et al., 1993). Bubbles seem to occur only in medium to coarse gravels (~ 4mm grain size). For smaller grain sizes, finger-like channels tend to form and spread. A recent laboratory study using glass beads to aide visualization confirmed this finding, "For grain sizes of 0.75 mm or less, channel flow dominates...The study showed that the channel flow regime is most likely to occur for air sparging under natural subsurface conditions," (Ji et al., 1993).

Realizing that channel flow is the dominant flow regime, what are the fundamental processes governing this remediation process? As air is injected into the saturated zone, it rises through the soil column in small channels. Thus, contaminants located within the channel itself will be volatilized much like contaminants in the vadose zone under the influence of an SVE system. This process is relatively quick and efficient. Consequently, the more channeling that occurs the more efficient and effective the clean up effort will be. Additionally, organic compounds are the major target of IAS systems, and fortunately, the strippability of these compounds, as influenced by the specific Henry's Law constant, is very high.

Contaminants not directly in the air stream or in isolated zones must move to the air/water interface to be removed. This migration will be by convective-diffusive mechanisms. This is an inherently slow process. It is also the more dominant process since the total channel volume is much smaller than the bulk soil volume. Thus, the system becomes diffusion limited (Johnson et al., 1993; Ahlfeld et al., 1994). As VOC's are swept from the air/water interface, oxygen replaces the contaminant. This begins the air transport through the bulk water. This mechanism is very difficult to predict. As mentioned by Ahlfeld et al. (1994), "The limiting transport mechanism depends on the type of contaminant, density of air channels, and site specific permeability characteristics." By looking at this list, one can see that the site characteristics are constant and the contaminants are predetermined. The only variable is the density of air channels. Unfortunately, this ,too, is more dependent upon site characteristics than system design.

Few well documented case studies have been performed on IAS systems. The air channels take random paths through the soil column. The mass transport mechanisms involved are very complex. Due to these reasons, IAS performance is very difficult to predict. A few modeling attempts have been made for IAS (Ahlfeld et al., 1994; Hinchee et al., 1994). However, due to the number of variables and the complex processes, modeling becomes difficult and pilot studies are the best tools for design of in situ air sparge systems.

DESIGN CONSIDERATIONS

Perhaps the most important step in designing an in situ remediation system is matching the best technology for the specific site. Therefore, it is imperative to have a quality site characterization performed to determine existing geologic and hydrogeologic features, as well as the contamination profile. By reviewing these data, the applicability of available technologies can be gaged.

For IAS systems high permeability soils are preferred since low permeabilities retard air flow. In fact, the presence of clay lenses within the soil structure may cause problems for IAS systems. The air channels will simply go around the layer causing an isolation layer to form above the clay. On the other hand, if the permeability is too high, there will be little horizontal movement of the air flow and a very small area would be influenced (Nyer et al., 1993). Further, homogeneous soils tend to channelize much better than heterogeneous soils (Ji et al., 1993). This will increase the efficiency of the system.

One should also consider subsequent handling of the vapors produced by the volatilization process. Will an SVE system be used, and if so, is the vadose material applicable to SVE systems? SVE design is a separate topic; however, the two systems are complimentary and a combination should be given strong consideration. Another variable to consider is the type of contaminants targeted for remediation. If the particles will not readily vaporize, IAS would not be a good choice. And since dense non-aqueous phase liquids (DNAPLS) will settle through the groundwater to bedrock, sparge systems would again be an ineffective technology.

In situ air sparging is centered around many changing variables, and with no widely accepted models, IAS systems must be designed with flexibility. Many of the operating systems will be adjusted or expanded during operations. Shown here are some of the design parameters, as listed by Nyer and Suthersan (Nyer et al., 1993), for the basic IAS design:

- Radius of the "cone of influence"
- Depth of air injection
- Air injection pressure
- Injection well design
- Injection air flow rate
- Air distribution efficiency

Well Design

Air sparging wells are similar in design to groundwater monitoring wells. Several diagrams are provided in the reference literature. One consideration is the depth of the screen. Common sense states that air injection must be below the lowest suspected contamination level to be effective, but, how far below? Suggestions vary. One must be sure to go deep enough to influence all of the contaminants. But, especially in heterogeneous material, going too deep may allow the air flow (which will take the path of least resistance) to avoid the contaminant plume. The depth at a specific site, of course, depends on the cone of influence (specifically the angle the air takes as it moves upward), the number of wells, and design goals. Another consideration is the length of the screen used for injection. There seems to be some disagreement on this issue. Some writers suggest shorter intervals (~0.5 m) are all that is required, while others maintain longer intervals (>1.5 m) aid the air flow through the saturated zone (Johnson et al., 1994).

Many authors discuss the use of diffusers at the base of the well in an attempt to influence the migration of the air through the soil profile. While diffusers may affect air movement near the well, it is expected that natural soil conditions will dominate air flow regimes within a short distance of entry. Based on this argument, but also realizing that screen openings larger than contiguous pore openings may lead to immediate coalescing of the air stream, the short slotted screens often used for monitoring or water supply wells would be acceptable and economical.

The minimum pressure for air injection must overcome the following: (1) the depth of water standing in the well bore, (2) the frictional losses through the system, and (3) the capillary entry resistance to displace the pore water from the soil matrix encasing the well–

the air entry pressure (Nyer et al., 1993). One must be careful not to over-pressurize the system and cause fluidization of the soil near the injection point. Designers must also consider whether to use continuous air flow or pulsed air flow operations. Researchers point out that pulsing may have some effect on the air channeling through the soil, but the influence is not as much as it had been thought in the past. In fact, pulsing may be a detriment in certain soil types (Alfeld et al., 1994). It is also discouraged during the latter portion of the life cycle curve where diffusion has become the limiting process.

As mentioned previously, the best possible tool for design of an IAS is a pilot study. Pilot tests will help designers determine radii of influence, pump rates, and several other variables specific to each site. This information will subsequently aid in determining well placement and design, pump requirements, and monitoring requirements. If a pilot study is not feasible, data should be sought for similar situations. While the information on how to conduct pilot tests and which parameters to monitor for are beyond this paper, several listed references did contain information on the topic.

Cost Considerations

One of the strengths of the IAS system is the reduced cost over previous techniques. The wells are relatively simple in design, most often utilizing PVC piping and basic pumping systems. This reduces costs considerably. Additionally, air is much easier to pump into the soil than water is to pump out. And when one considers the expense of pumping water for more than 5 or 6 years to sufficiently clean a site, and then to have to excavate large amounts of contaminated soil, the IAS-SVE combination looks very inviting. Money is saved exponentially in shorter closure time alone.

"Air based treatment is by far the most cost-effective closure technology on the market. It can reduce the total cost of equipment acquisition and remedial site operation to half of the typical costs [over recent years]...Part of this cost reduction can be attributed to the technology's potential to bring a site to regulatory closure significantly faster than previous generation technology," (Brown et al., 1992).

Limitations

Like any good technology, if applied in the wrong circumstance or without proper precautions, IAS can fail leaving the designer, and owner, frustrated–and the air sparging reputation damaged. Care should be taken for proper application. Below is a list of potential problems one should be aware of when designing IAS systems.

[These cautions come from three main sources: Nyer and Suthersan (1993); Johnson, Johnson, McWhorter, Hinchee, and Goodman (1993); and The Journal of the Air & Waste Management Association (1992).]

- *Contaminant spreading* - In the same way large pore space fails to force horizontal movement of the air flow, tight soil packing may cause horizontal spreading of contaminants (note that horizontal permeabilities are much greater than vertical permeabilities). This would have the tendency to spread the contaminants, possibly beyond the designers control area. As mentioned before, tight clay layers will also divert air flow horizontally and possibly spread contaminants.

- *Mounding of the groundwater* - A slight mounding of the groundwater level may occur around the air sparging well. The extent of the mounding will depend on the air flow from the well. It has been noted that this may not cause problems for the IAS or SVE systems, but take precaution in that any LNAPL free product floating on the ground-water may be pushed away or become harder to capture and/or control.

- *Vapor movement* - When air is injected, the vadose air pressure rises around the injection point. This allows the potential movement of vapors to nearby, low-pressure receptors (e.g. basements, utility structures, monitoring wells). This may be controlled by a well designed SVE system. Additionally, an SVE system may be needed to capture mobilized compounds discharged near the surface if the concentration is too high to allow natural escape. Whenever IAS and SVE are used in conjunction, the SVE must have a greater air flow rate than the IAS.

- *Geologic and hydrogeologic changes* - Air movement through the subsurface will cause channels to form. In some cases air pockets may form or existing soil structure changes may occur (i.e. fracturing). One should be cautious when shutting off sparge wells in that changes may alter groundwater movement or change the integrity of the soil. Also, if operating pressures were too high, fluidization may have occurred near the well.

- *Monitoring problems* - Unfortunately, the data obtained from commonly designed monitoring wells, the most common means of data gathering and evaluation, are adversely affected by the operations of IAS systems. The monitoring well may act as a low-pressure receptor for vapor gasses. This will taint the results. New monitoring techniques are needed to accurately evaluate the performance of IAS system during operations.

As stated in "An Overview of In Situ Air Sparging" (Johnson et al., 1993), "Despite these problems, in situ air sparging has potential as a remediation tool, when applied in a safe manner and when its limitations are understood. Given its increasing use, it is essential that the technique be examined in detail so that its strengths and weaknesses can be better understood."

SUMMARY

Although it has not been mentioned previously, the enhancement of aerobic biodegradation is a great strength of air sparging. IAS is one of several methods currently used for delivering oxygen (a limiting factor in subsurface biodecay) to the saturated zone. The delivery of oxygen to the zone by IAS air injection stimulates the biodegradation process and becomes an added benefit to IAS systems, even though the main application is air stripping. The delivery of this oxygen is controlled by the same kinetic relationships mentioned previously for IAS.

In situ air sparging is a relatively simple technique which is gaining momentum within the groundwater pollution control field. With the strengths shown throughout this paper, one can see the benefit of using air sparging. With closure times reduced to less than a year in many cases, industry will definitely be looking to take advantage of this system. Obviously, the main considerations for any technology are the site conditions and pollution components to be cleaned up. If the soil permeability is neither extreme (high or low), if there are few heterogeneities, and if the contaminants are readily volatilized, then air sparging will be an excellent technique for remediation. As more studies are performed using IAS systems, the technology will become better understood and more easily applied. Its future is definitely promising.

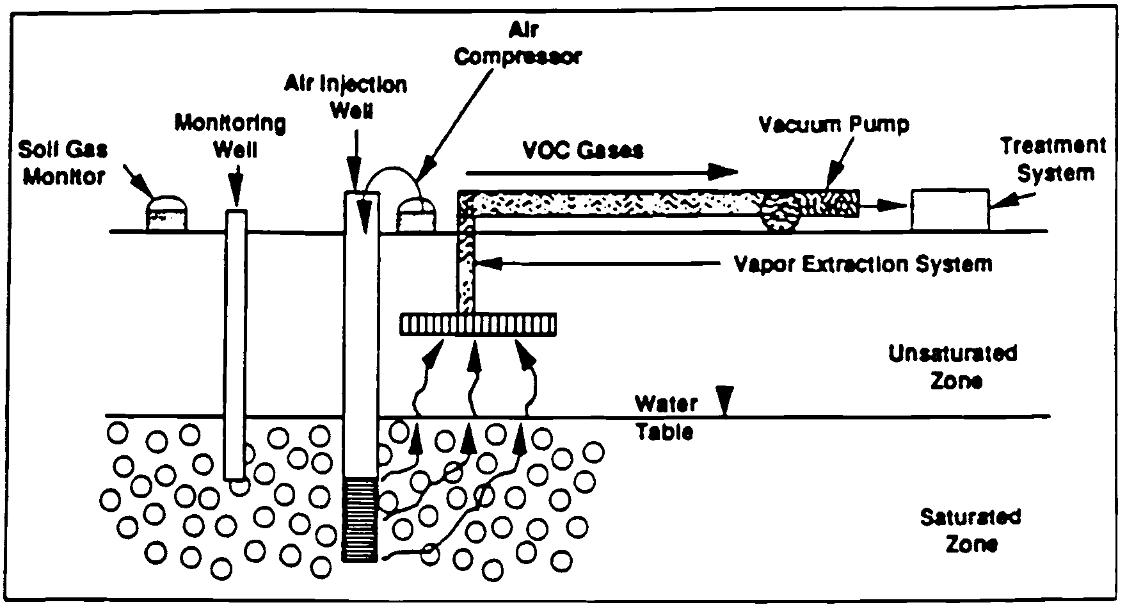

Figure 3.1 – Typical air sparge/soil vapor extraction system using vertical injection and extraction wells (Mast, 1995).

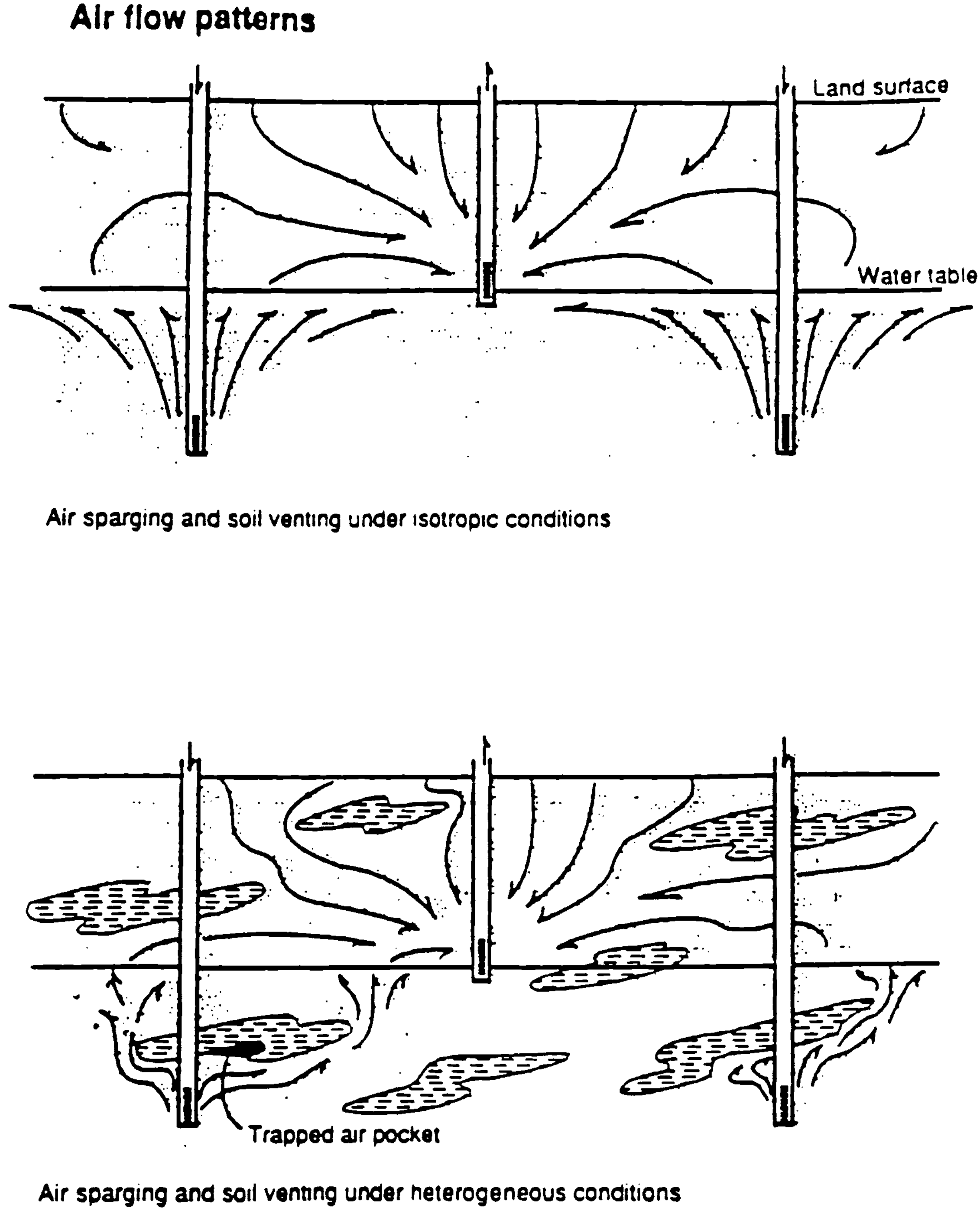

Figure 3.2 – Subsurface air flow patterns for a typical air sparge/soil vapor extraction system (Mast, 1995).

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CHAPTER IV

SOIL VAPOR EXTRACTION TECHNOLOGY FOR SOIL REMEDIATION

INTRODUCTION

With the passing of tough new standards by Congress in the early 1980's, new technologies had to be found to remediate polluted soils around the U.S. The traditional method of handling spills and leaks into the soil and groundwater was through pumping groundwater to the surface and passing it through a subsequent treatment system. Unfortunately, pump and treat has many drawbacks, including its inability to clean the soil above the groundwater table.

Due to the extreme expense, and limitations, of excavating soils for off-site treatment or disposal, in situ treatment methods become mandatory. One remediation method has come to the forefront for the removal of volatile components – soil vapor extraction (SVE). Since its introduction in the mid 1980's, SVE has increased in use, most noticeably at Superfund sites across the U.S. This section discusses the theory behind SVE, design considerations (as applied mainly to remediation of VOC's), and advantages associated with soil vapor extraction.

FUNDAMENTAL PROCESSES

Soil vapor extraction is a remediation technique which moves air through the subsurface in an attempt to volatilize pollutants and draw them to the surface. Vapor extraction systems (VES) are only applicable for volatile pollutants, mainly VOC's, and are only applicable to pollutants in the vadose zone. Once the contaminants reach the capillary zone or the groundwater table (GWT), SVE becomes ineffective and other methods of remediation must be used. A related point, however, is that SVE is an excellent compliment to groundwater remediation efforts since most of these methods do not address the pollutants in the soil above the groundwater table.

Theory

Conceptually, soil vapor extraction is a rather simple technology. The governing ideal is that all solids and liquids partition to some degree into a vapor phase in the presence of air. The amount of substance present as vapor is dependent upon several variables including the volatility of the substance and the temperature, moisture, and pressure of the environment around the material. The volatility of the substance is represented by its vapor pressure and Henry's Law constant. The vapor pressure (analogous to the material's solubility in air) describes how much vapor phase will be present given surrounding conditions. The higher the vapor pressure, the more volatile the substance. Generally, chemicals with a vapor pressure of greater than 0.5 mm of Hg would be amenable to SVE applications (Pedersen et al., 1991).

Henry's Law is also important when discussing volatility. Henry's Law correlates the concentration of a substance in water (in this application, pore water) to the partial pressure (vapor phase present). The proportionality constant which relates the two is known as the Henry's Law constant (k_H); it is unique to each specific chemical. Materials with Henry's constant values above 0.01 (dimensionless) are considered amenable to SVE applications (Pedersen et al., 1991).

Realizing that if the pollutants are indeed volatile, some portion of the substance will exist in the vapor phase in the soil air voids. VES's are designed to pull fresh air into the subsurface and draw the vapor-laden air to the surface for subsequent treatment and release to the atmosphere. The more volatile the substance, the more efficient the removal rate. Basically, vapor extraction systems induce a vacuum in the subsurface by placing a well system near the contaminant. Air blowers at the surface place a vacuum on the wells, thus, drawing the contaminated soil vapors (thus, the contaminant itself) through the wells to the surface. Fresh air is drawn into the soil replacing the contaminated vapor. The contaminants then volatilize into the new, fresh air. This air is removed and the cycle repeats itself.

Limitations

If one assumes that the pollutants present are significantly volatile, and that the pollutant is present as vapor or free product within the void of the soil matrix itself, it is reasonable to assume removal efficiencies of 95 to 100% can be achieved. Unfortunately, this may not always be the case. VOC's and other contaminants may exist in five different locations of the soil matrix (see Figure 4.1). In soil voids, chemicals may exist as (1) free liquid, (2) volatilized vapor, or (3) adsorbed to the surface of the soil particles. Vapor extraction is very effective in removing these constituents. The remaining two sites are (4) dissolved in the soil moisture and (5) sequestered in the middle of the soil particles. Although the process will require much longer, SVE will remove pollutants dissolved in the soil moisture. Removing the constituents from soil moisture is limiting, particularly if a majority of the pollutant is located deep into the capillary zone. Sequestered in the interior of the soil matrix is the most difficult partition to remediate with VES's because the contaminant is not on the edge of the particle where it may be volatilized (Macinnis et al., 1992).

Macinnis and Travis (1992) looked at the effectiveness of VES's when a majority of the contaminant was sequestered in the soil. One important fact to bear in mind when considering SVE is that when organics have been in contact with the soil for several years, a majority of the contaminant will partition into the soil particles. Contaminants bound in the interior must diffuse to the surface for subsequent removal. This will severally limit the efficiency. In this case designers may consider using other technologies to enhance SVE performance. Figure 4.2 shows a nomogram to aid in making the applicability decision.

An obvious limitation associated with SVE application is that the site must allow proper air flow. Air permeability must be carefully investigated during the site characterization process. Sandy soils are obviously better suited for VES applications; clayey soils are less amenable. Clay lenses and other heterogeneities in the soil may present problems by causing dead spaces through which air does not directly flow.

Site Investigation

The first step in developing any remediation effort is performing a thorough site characterization. This step will determine the chemicals pollutants involved, the extent of pollution, and the soil and groundwater properties present at the site. This information is required for the designer to judge which remediation technique will be most effective.

One of the first tasks in the evaluation process is to determine the chemicals involved, including the history and chemical properties of the pollutants. Key characteristics are shown in Table 4.1 (Hutzler et al., 1988). As has been discussed previously, the pollutant's volatility is the main property when considering SVE. Also, one must consider the partitioning of the pollutant within the soil matrix.

Key Properties to Consider for SVE Systems	
Chemical Properties:	
Henry's Constant (k_H)	Solubility
Vapor Pressure	Diffusivity (air and water)
Density	Adsorption Coefficient
Viscosity	Age of the Spill
Soil Properties:	
Permeability (air and water)	Soil Structure
Particle Size Distribution	Organic Carbon Content
Porosity	Soil Moisture
Depth to Groundwater	Location of Heterogeneities

Table 4.1 - Chemical characteristics of the pollutants and soil properties of the site to consider when evaluating SVE. (Hutzler, 1988)

Once the chemical characteristics of the pollutants are determined, one must investigate the soil conditions. The most critical feature of vapor extraction systems is the flow of air through the soil, necessitating a thorough soil study. Several characteristics are vital when evaluating vapor extraction as the remediation technique. A list of these key properties is also included in Table 4.1 above. The soil condition must be taken into careful consideration during the design phase because while the condition may not be favorable for SVE, SVE is somewhat flexible and may still work better than many of the alternative methods. For example, stratification becomes very important because it may limit the areas affected by the air flow (i.e. dead pockets may occur where air flow is not in direct contact, severely limiting the effectiveness). SVE can still be used in stratified soils, but the designer must be very careful when designating the well depths and screen intervals. In fact, stratified soils may enhance the performance by confining the airflow to a very specific region of contamination. It is imperative the designer be aware of the conditions.

Perhaps the most important site test is for the air permeability. An air permeability test is analogous to an SVE pilot test. A typical investigation would consist of establishing one extraction well and then several vacuum monitoring points located at varying distances and directions. A vacuum is placed on the extraction well and data are gathered from the monitoring points on the pressures exerted, the air flow experienced, and the vapor concentrations present (Curtis, 1992). From this test designers can further determine the applicability of SVE to their site. If SVE is being considered, designers must determine a radius of influence (ROI) for a typical extraction well.

DESIGN CONSIDERATIONS

The remediation method whose performance will sufficiently meet the cleanup goals with the least amount of cost, time, or effort is the most appropriate corrective action plan. SVE is one of the most cost effective technologies available. Once the site and chemical characteristics have been determined, the engineer can make a determination if soil vapor extraction is the proper remediation method. As has been mentioned before, the chemical pollutants must be volatile and the soil must allow proper air flow for SVE to be efficient. The engineer can then begin the design process, remembering to allow for flexibility. Figure 4.3 is a diagram which illustrates many of the steps designers must go through during the SVE system design.

System Design

Soil vapor extraction systems move VOC's through the zone of contamination to an extraction well. Therefore, the first design decision is normally the type of well to be used: vertical or horizontal. Vertical wells are far more common with proven track records at hundreds of sites. Horizontal wells have recently been found effective especially at sites with a shallow groundwater table. Figure 4.4 shows several possible well configurations.

Vertical Wells. The most common SVE design utilizes vertical wells to draw vapors from the contamination zone. The wells are similar to groundwater and/or monitoring wells. This makes them economical and easier to install due to standard equipment and expertise in the field. Existing monitoring wells may even be used if they are positioned correctly. Vertical wells are, in fact, one of the only methods available for in situ remediation if the contamination exists at great depths (Curtis, 1992). Vertical wells have been used at depths greater than 150 feet, making it a unique, valuable application.

Horizontal Wells. A less common configuration is horizontal wells. Perhaps a better description would be horizontal trenches, since most often trenches are excavated with SVE piping placed at the bottom of the trench. Compacted clay, bentonite, or geomembrane layers are usually placed above the piping to slow short circuiting from the surface. This is even more important with horizontal wells than vertical wells because trenched pipes are much closer to the surface. In fact, the main application of horizontal wells is at sites with shallow a GWT where vertical wells are not applicable. The trenches allow more area to be covered and may actually speed up remediation. Unfortunately, trenching limitations often limit application to sites where the cleanup is less than 15 to 25 feet below the ground surface. Well orientation will be discussed extensively in later sections.

The next phase of design is well placement. The placement of the wells at the site is based on an estimate of the radius of influence. If a pilot scale study has been performed, the engineer will know with much greater certainty what the ROI will be. This is necessary whether designing a vertical or horizontal VES. The ROI allows the engineer to design a system which theoretically will remediate the entire site. When used as a complimentary technique, the designer must know where to place the wells to stop soil gas movement off-site. Another major concern to the engineer is heterogeneities in the subsurface. These factors all impact the decision of well placement.

Equipment for a VES is very basic and has the advantage of ease of installation. The wells are usually constructed with plastic schedule 40 PVC pipe with appropriately slotted intervals surrounded by a permeable backfill. The wells are connected to a vacuum pump by an above ground manifold system (usually PVC pipe, also). Each well is equipped with a pressure gage and flow meter to monitor control variables. An air-water separator is connected to the manifold to dissociate any water before the air is passed through an emission control unit. Some sites are allowed to simply vent the vapor to the atmosphere. This depends on the contaminants involved and the state's emission regulations.

Operations

Designers must be properly prepared for system startup. Because of the nature of SVE systems, the greatest amount of contaminant removal will soon after start up. Early operation VOC removal rate is usually higher than the rate during later steady state operation. This is due to the initial evaporation of NAPL's. Normal operation will clean at a much slower rate as the VOC's must diffuse and volatilize into the soil gas. In addition, a tailing effect will be seen after the adsorbed phase has been removed and the dissolved phase and sequestered contaminant remains. The aging period has been shown to have a major impact as to the ease of removal. Additionally, soil permeability will have a major effect (Wilson, 1994).

The engineer has several control variables to consider during operation. These include air pressure in the system, flowrate from each well, and pumping duration. Several recent studies have indicated that pulsed pumping may increase VOC removal efficiency as a function of energy expended (Hutzler et al., 1988). Pulsed pumping can be considered for each individual well or for the system as a whole. Pulsed pumping should especially be considered for silty and clayey soils which are more diffuse limited. Wilson (1994) studied pulsed pumping and concluded the following.

> "One can use the soil gas rebound data to adjust the gas flow rate during the terminal phases of the remediation. There is little point in using gas flow rates which yield effluent soil gas VOC concentrations an order of magnitude or smaller than the rebound soil gas concentration after a period of static equilibrium. An alternative approach is to use pulsed gas flow."

Monitoring the system is perhaps the most important responsibility after the system startup. This will tell the engineer how the system is operating. It will also indicate any problems to be addressed. Monitoring will also provide reference data when determining the closure of the program. Rebound gas VOC concentrations may provide a good basis to judge the completeness of the SVE cleanup and aid in the adjustment of vapor flow rates.

Possible Modifications

Engineers in the field have found that several additions can be made to VES's to increase the efficiency. As was mentioned previously, pulsed pumping is an operational variable which tends to increase efficiency. One physical addition to SVE systems would be air injection wells. This would allow engineers to control the air flow across the contaminated zone. It should be noted that these injection wells are different from air sparging wells in that these injection points are in the vadose zone, not the below the GWT.

A related addition which will cut down on short circuiting from the surface is adding an impervious cap to the site. Plastic liners appear to be the most economical approach. Many existing sites such as gasoline service stations have an existing asphalt cap which makes SVE an excellent choice at these sites.

Drawing down the water table is a technique which may make SVE applicable when soil contamination exists below the GWT. Theoretically, a pumping system is designed to pump groundwater (which can be released to a nearby stream or reinjected down gradient following treatment), thus lowering the groundwater elevation and increasing the depth of the vadose zone. As the GWT is lowered the contaminants are left behind, and a VES can then be used to remove the contaminants from the soil.

Two final modifications are heating and/or oxygenating injection air. If the air is heated, it may speed up volatilization by adding energy. Heat has even made SVE possible for some heavier chemicals (e.g. chlorinated solvents) by raising the temperature enough to make volatilization possible. Adding oxygen to injection enhances biological degradation.

Possible Pitfalls

The pitfalls associated with vapor extraction have been presented throughout this chapter. Heterogeneties in the soil matrix may cause stagnated areas which will not clean up. When pollutants are trapped in soil particles (a function of the aging period), SVE may not be the best remediation technology. Short circuiting from the ground surface will decrease the removal efficiency because the air is not forced to move laterally through the contamination zone. A final concern is groundwater upwelling. As a vacuum is placed on the vapor wells, groundwater may be drawn upward. This is of particular concern with shallow groundwater elevations.

SUMMARY

Soil vapor extraction is a relatively simple, extremely popular soil remediation method. A vacuum well induces vapor flow through the unsaturated soil zone. Volatile contaminants will partition into the vapor and be swept away. Heterogeneities in the soil will slow the process. This process is fairly efficient when the air flow is in direct contact with the pollutants. Unfortunately, DiGiulio has found, "Long term performance of venting will most likely be limited by diffusion from soil regions of lesser permeability which are not exposed to direct airflow. The significance of mass transport limitations should be evaluated during venting field tests," (DiGiulio, 1991).

While several technologies exist for soil remediation, soil vapor extraction appears to be gaining favor with environmental engineers because of its simplicity and proven performance. This technology can be modified to enhance performance or aid other efforts. SVE can also be combined with groundwater remediation technologies, such as air sparging, to form a complete site remediation system.

Advantages

- Though based on complex variables, SVE systems are relatively simple in design and very cost effective.
- Soil vapor extraction can be effectively used to remediate a wide range volatile components in a wide range of conditions, (Hutzler et al., 1991).
- SVE has been proven effective through many pilot- and full-scale studies. In fact, SVE may be the most successful soil treatment technology available (Pedersen et al., 1991).
- The systems are flexible enough to allow rapid changes in design and operation in order to optimize the removal rate, (Hutzler et al., 1991).
- Vapor extraction systems are relatively low in cost for design, installation, and operation. This is due both to simplicity and the use of existing equipment, (Curtis, 1992).
- Site disturbance with SVE is minimal and the environmental impact low. This makes it applicable to a great many sites that would not be amenable to other methods, especially at sites with asphalt/concrete caps, or near buildings.
- Large volumes of soil can be readily treated.
- SVE can remediate sites at great depths (>150 ft) which may not be accessible by other means, (Curtis, 1992).
- SVE cleanup durations are generally short when compared with other technologies.
- VES's remove the contaminants from the environment so that they can be properly destroyed or handled, as opposed to trapping them in place or relocating the pollutants elsewhere.
- Vapor extraction systems are generally only a part of an overall remediation system. Because of the low cost, easy installation and operation, and low site disturbance, SVE is a excellent addition to an overall remediation strategy.

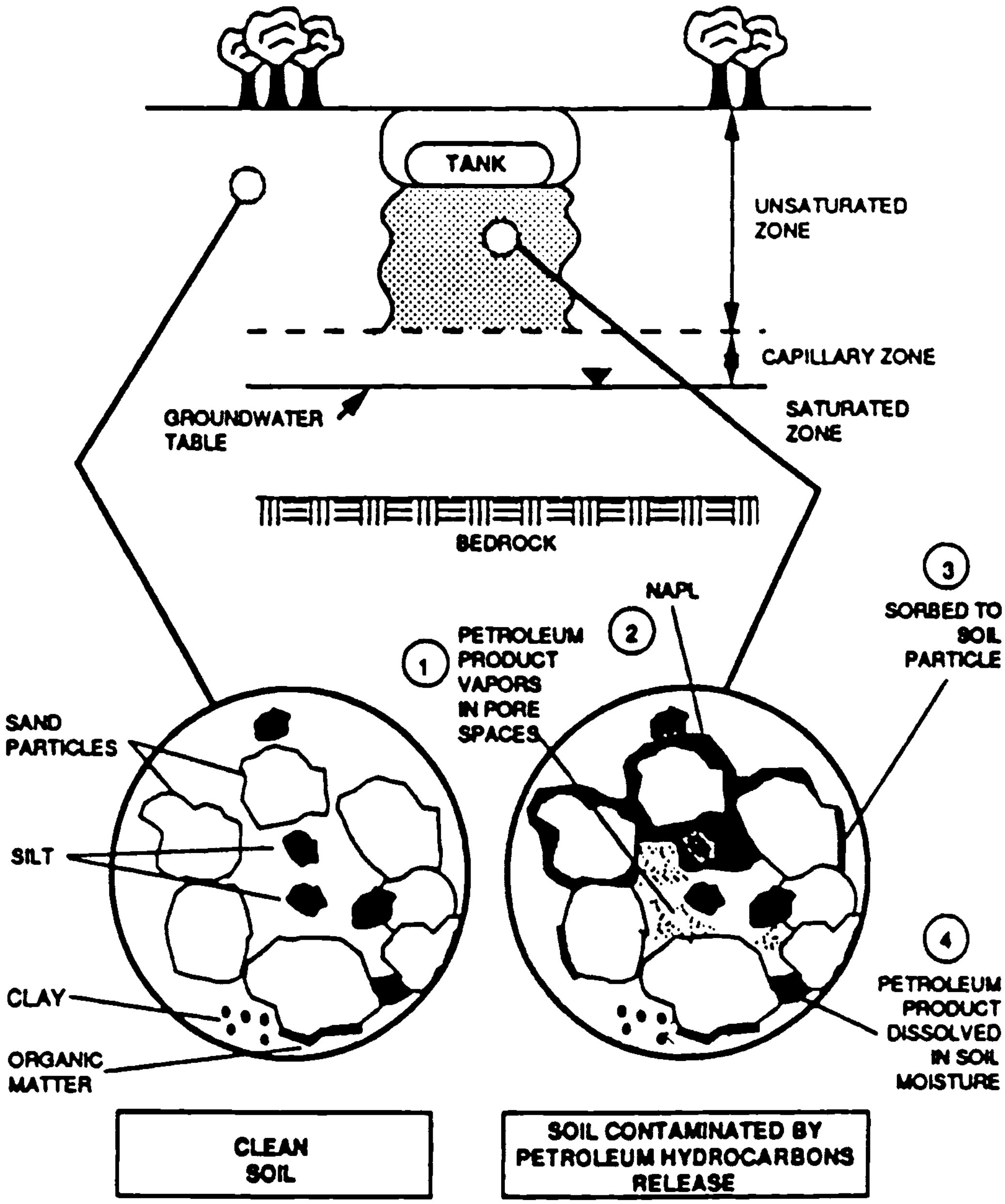

Figure 4.1 – Contaminant location in the soil matrix (Pederson, 1991).

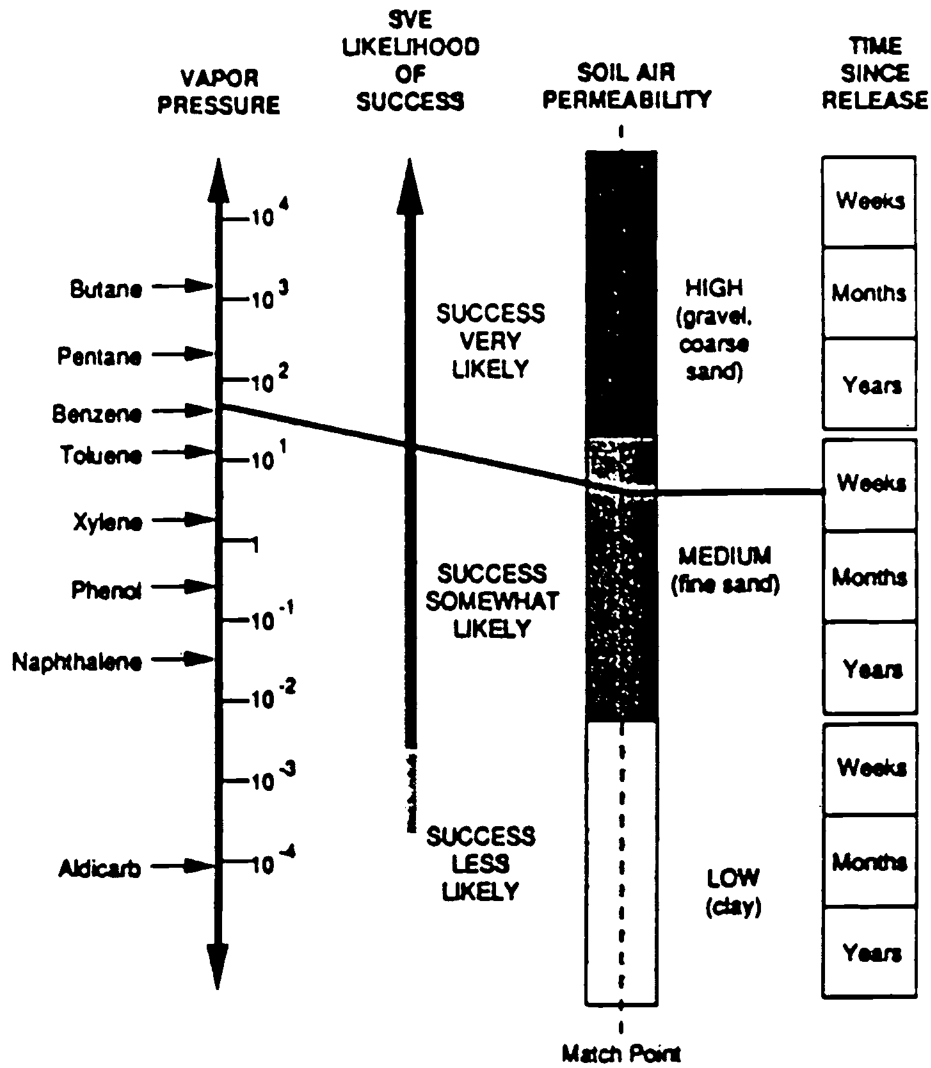

Figure 4.2 – Soil vapor extraction applicability nomograph (Pederson, 1991).

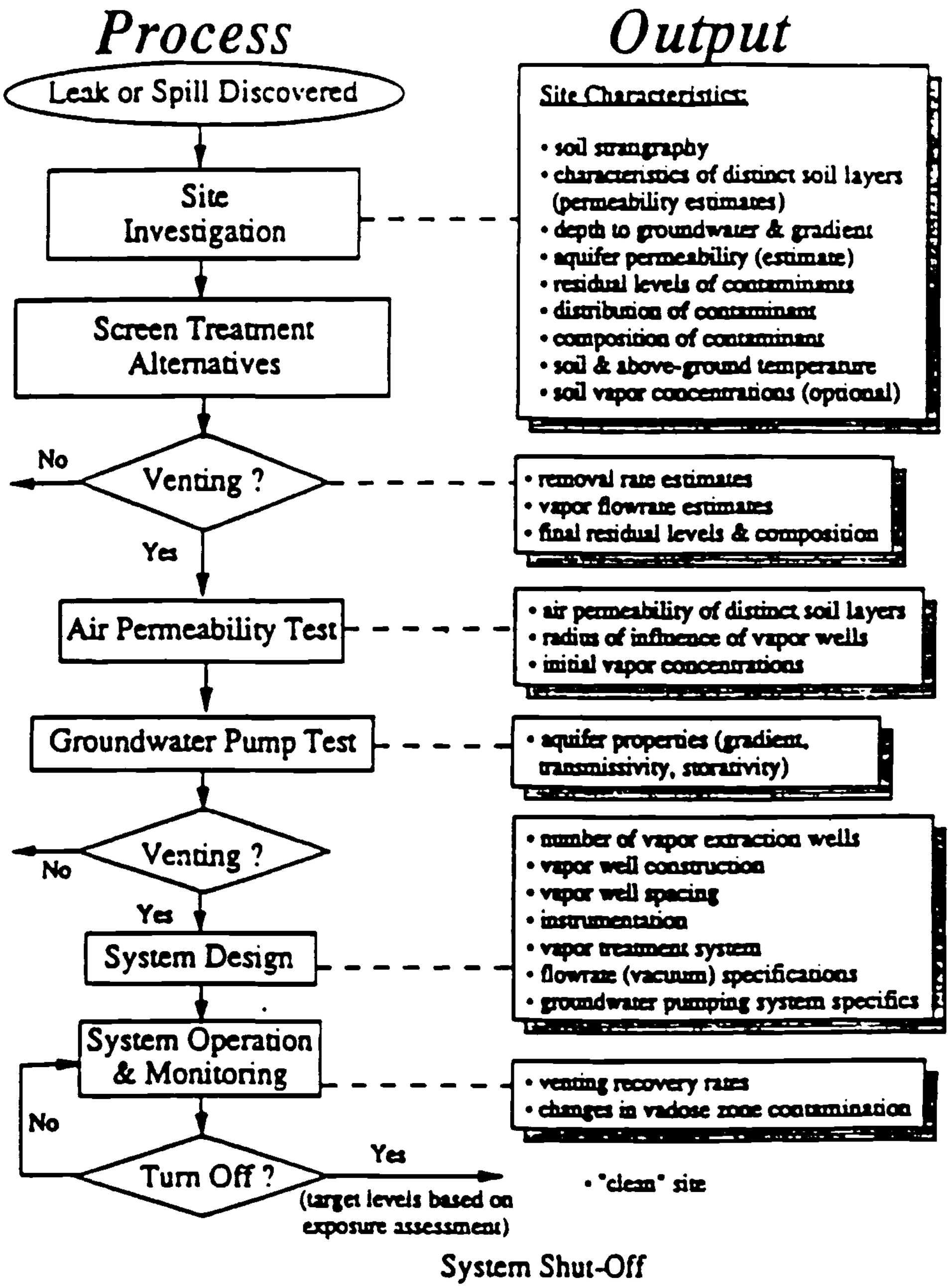

Figure 4.3 – Soil vapor extraction system design procedure (Johnson et al., 1991).

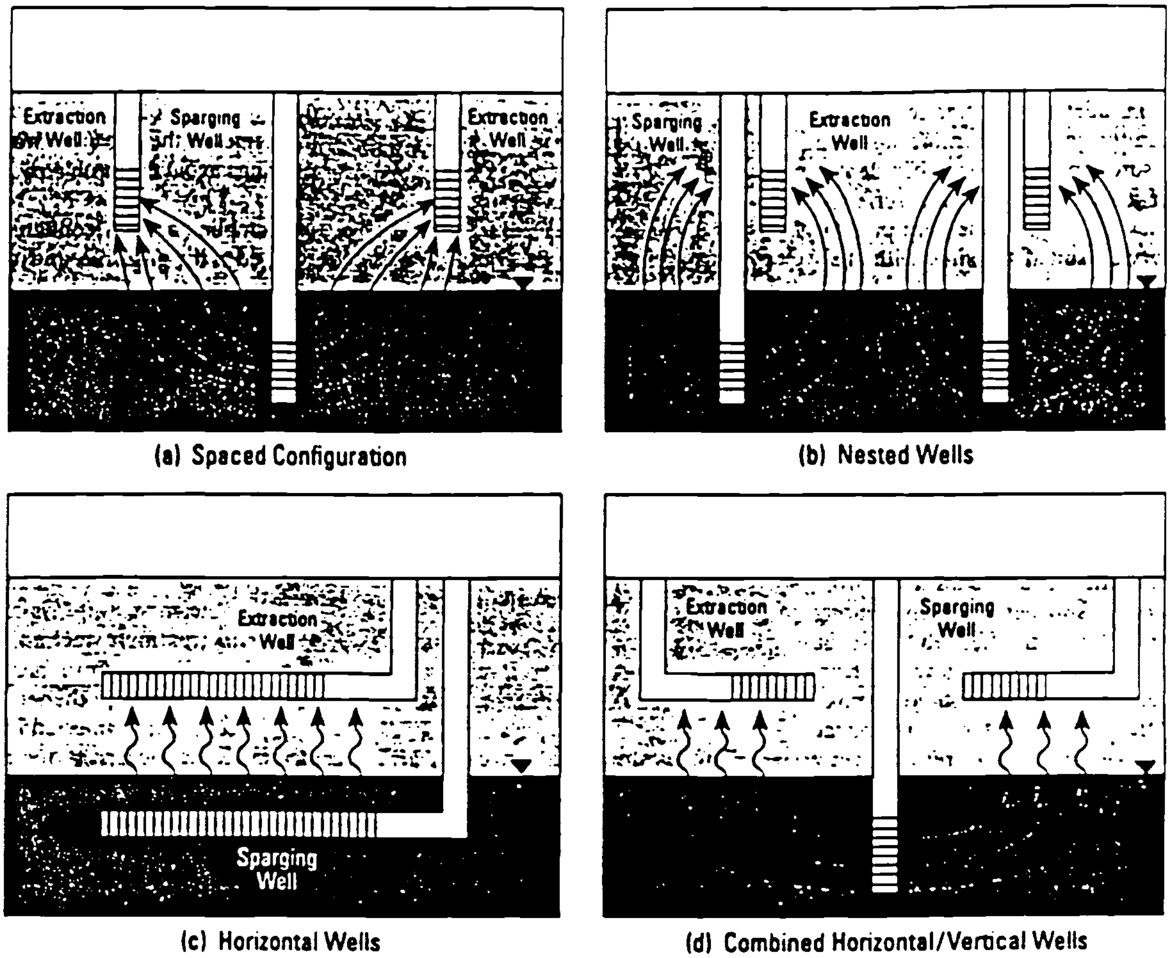

Figure 4.4 – Possible soil vapor extraction well configurations (Pederson, 1991).

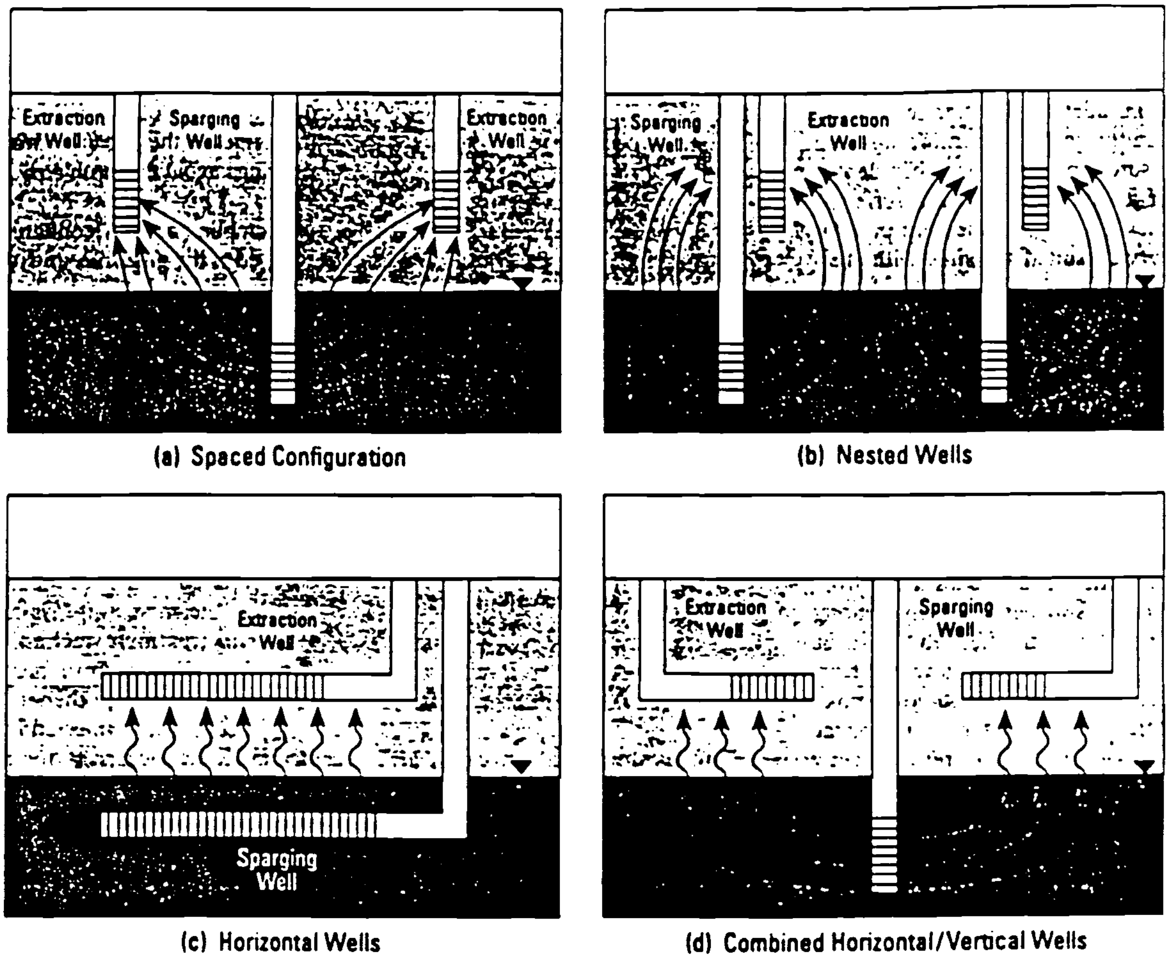

Figure 4.4 – Possible soil vapor extraction well configurations (Pederson, 1991).

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CHAPTER V

PERRY-SITE BACKGROUND INFORMATION

The EPA has been placed with the responsibility of overseeing the clean up of America's groundwater and overlying soils in accordance with RCRA's Subtitle I (regarding underground storage tanks). Fortunately, not only is the EPA looking to set forth the regulations, they also intend to expose owners and operators to the latest practices and procedures for remediation. The agency hopes to advance this philosophy by conducting studies, creating helpful guidance reports, and by funding demonstration projects in each of the EPA regions. Oklahoma State University has been designated as the UST and groundwater remediation demonstration coordinators for the Midwest District. The EPA sees training as an important responsibility when dealing with UST programs. These aforementioned demonstration projects actually show owners and operators the most current techniques and innovative technologies for remediation. These projects are designated as *LUSTDEM's*, or *L*eaking *U*nderground *S*torage *T*ank *Dem*onstrations.

The primary reason for these projects, in addition to education, is to study and develop new techniques which will reduce the time and money associated with remediation, while yet meeting the required levels of quality. The main requirement is that the technique must be innovative. Historically, remediation techniques have been lengthy, costly, and labor intensive. In situ techniques have many advantages over off-site treatment, including reduced cost and less disturbance. An objective for the study is to collect well-documented cost performance data.

History of the Perry Site

The Oklahoma Department of Transportation (ODOT) maintains numerous maintenance facilities across the state. At these facilities the vehicles are fueled and maintained. The gasoline and diesel fuels are stored in standard underground storage tanks. At the ODOT Division IV headquarters in Perry, Oklahoma, on May 10, 1993, authorities discovered a possible leak in the product line between the tank battery and the pump island. This chapter will present the history, characteristics, and steps which followed.

The Perry facility has a typical tank battery consisting of the following: a 12,000 gallon unleaded gasoline tank, a 12,000 gallon leaded (regular) gasoline tank, a 12,000 gallon diesel tank, and a 1,000 gallon kerosene tank as shown in Figure 5.1. The tank battery consists of standard steel UST's and is located beneath gravel in the otherwise asphalt parking and storage area of the facility. On May 10, 1993, a leak detection alarm indicated a leak in the product line between the tank battery and the southwest pump island. After verifying the validity of the alarm, an environmental management firm was retained to conduct emergency response and initial abatement activities at the site. The line was uncovered, the leak located, and the waste identified as gasoline. The pipeline of concern was disconnected, drained, and replaced. The heavily contaminated soils around the line were removed and recycled as fill material for a roadway subgrade. Further investigation revealed approximately 27inches of floating free product in a tank battery manhole. Subsequently, 130 to 140 gallons of gasoline were removed by pumping from the manhole.

SITE CHARACTERIZATION

To determine the extent of contamination at the site, an initial site investigation was performed on September 8-10, 1993. Originally, nine soil borings were drilled with one soil sample and one groundwater sample collected from each well. These samples were analyzed for benzene, toluene, ethylbenzene, total xylenes (BTEX), and total petroleum hydrocarbons (TPH). Tests showed no contamination in the soil. The groundwater samples, however, did show contamination. Four of the bore holes were converted to monitoring wells. To better determine the extent and location of the plume, five more monitoring wells were installed with samples taken in December, 1993.

Figure 5.1 shows the location of the monitoring wells (MW) and the UST's. Table 5.1 lists the maximum contaminant levels allowed at the site as set by the Oklahoma Corporation Commission (OCC), the governing body for UST regulation in the state of Oklahoma. Table 5.2 displays the groundwater contamination levels found at the site. The results in Table 5.2 were used to map the benzene and TPH plumes at the site which are shown in Figures 5.2 and 5.3, respectively. Benzene will be used as the major trace pollutant, thus, the benzene plume map was developed. As mentioned, no evidence of soil contamination was found, or the levels were below measurable levels.

Required Clean Up Levels (Category II)					
Parameter	b	t	e	x	TPH
Soil (ppm)	5	400	150	1000	500
Water (ppm)	0.05	10	7	100	10

Table 5.1 - Minimum clean up levels at OCC remediation sites.

Contamination Levels (mg/l)					
Parameter	**b**	**t**	**e**	**x**	**TPH**
MW - 1	9.160	1.920	*	1.890	17.30
MW - 2	*	*	*	*	*
MW - 3	35.100	30.100	2.680	14.300	120
MW - 4	*	*	*	*	*
MW - 5	*	*	*	*	*
MW - 6	*	*	*	*	*
MW - 7	*	*	*	*	*
MW - 8	0.384	*	*	*	3.113
MW - 9	*	*	*	*	0.114
* - BPQL, Below Practical Quantitative Limits					

Table 5.2 - Groundwater sampling results, as of October, 1994.

Soil boring logs were prepared during the soil boring procedure according to standard protocol. Classifying the soils and determining the subsurface profile is an imperative step of characterizing the site. The first five feet at Perry was typically a dark brown, low plasticity clay (CL) with some sand and silt. From five feet to ten feet, the soil is a red brown to dark brown, low plasticity, clayey silt (ML) with friable sandstone. From ten to fifteen feet is generally red brown, low plasticity silt with friable sandstone. A tight clay layer was observed at approximately twenty feet below the ground level. A typical soil boring log is included (Figure 5.4). The main characteristic to note from the boring log is that the soil is fairly permeable and mainly sandstone.

Another important characteristic is the groundwater elevation. The elevation at the top of each of the well casings was taken with respect to a reference point. The distance to the groundwater table (GWT) was then measured for each of the monitoring wells. From

Seasonal Groundwater Elevations (ft)					
Monitoring Well	**Top of Well Casing**	**Depth to GWT**	**Water Table Elevation**	**Depth to GWT**	**Water Table Elevation**
	(Relative)	**8 Sept. '94**	**8 Sept. '94**	**23 Feb. '95**	**23 Feb. '95**
MW - 1	95.60	8.75	86.85	10.19	85.41
MW - 2	98.88	11.98	86.90	13.01	85.87
MW - 3	96.76	10.00	86.76	12.66	84.10
MW - 4	97.80	11.32	86.48	12.50	85.30
MW - 5	96.11	9.49	86.62	10.95	85.16
MW - 6	97.16	10.00	87.16	12.28	84.88
MW - 7	96.66	10.96	85.70	12.18	84.48
MW - 8	96.81	12.11	84.70	13.22	83.59
MW - 9	96.90	11.54	85.36	12.68	84.22

Table 5.3 - Groundwater table elevations for each monitoring well.

these results, a preliminary potentiometric map showing the direction of groundwater flow was developed. This map is shown on Figure 5.5. As time passed, the GWT elevations were monitored to determine the seasonal high and low. The highs and lows are presented in Table 5.3.

The hydraulic conductivity (k) of the soil was tested in three wells. The results ranged from 2.52 x 10^{-5}cm/sec to 67.3 x 10^{-5}cm/sec. An average of 23.2 x 10^{-5} cm/sec was chosen. Likewise, the average interstitial velocity for this site was calculated to be 3.84 x 10^{-3} ft/day. However, when compared with the spread of the plume, this estimate appears to be very low. Analysis of the plume over the first 240 days showed a velocity of about 0.4 ft/day. This may be due to the initial mounding effect of the product release on the aquifer. Additionally, the backfill in the tank battery was composed of sand and small cobbles leading to a higher infiltration rate, and thus, a higher initial conductivity.

PRELIMINARY DESIGN

In January of 1994, the Civil and Environmental Engineering Department of Oklahoma State University was selected by the EPA, in conjunction with OCC, to act as an overseer of the ODOT- Perry Office remediation effort. At this point the project was designated as a LUSTDEM site for EPA Region VI. Dr. Vernon Mast, P.E., was to head the effort of implementing an innovative remediation technique. Originally, OSU's role was one of coordination and consultation. As the project evolved, OSU was charged with preliminary design, and ODOT took over implementation.

The project team consisted of the following individuals: Casey Shell, ODOT field maintenance engineer and engineer of record for the project; Dr. Vernon Mast, professor at OSU in environmental geotechnology and an experienced remediation consultant; Mr. Don Spurrier, P.E., OSU engineering extension office; Derrick Bandelier, Valerie Rogers, Anthony Apple, Kevin Koerner, and A. Karim - graduate assistants at OSU.

Air Sparging, in conjunction with *Soil Vapor Extraction*, was chosen as the innovative technology for this study. Several factors led to this decision. The soil matrix at the site is mainly a homogeneous sandstone with good permeability. This is an extremely favorable characteristic which allows vapor movement through the soils for the SVE. However, SVE alone is not considered innovative. Air sparging is relatively new, and in combination with SVE, is innovative. Additionally, the contamination was found in the groundwater, not in the vadose soil. Air sparging remediation focuses on cleaning the groundwater. The SVE system will simply remove the volatilized contaminants created by the air sparge flow. If the system is found to be effective and cost efficient, a demonstration workshop will be presented by OSU in order to share with owners and operators in the area the advantages, possibilities, and design considerations associated with this technique. All design and operation matters must be approved by the OCC for this project before implementation. The EPA is also kept abreast of the progress.

The preliminary design was completed in April, 1994. Derrick Bandelier, in partial fulfillment of his degree requirements, summarized the preliminary design in a report titled, Preliminary Design of Soil Vapor Extraction and Air Sparging System: ODOT Maintenance Facility, Perry, Oklahoma. This original design was intended merely as a beginning foundation to spark questions and provide a base; modifications were expected as information became available. Vertical air sparging and vapor extraction wells were chosen for this preliminary design. The system was laid out according to the SVE well placement. The positioning of the wells was based on a suggested standard of 30 foot spacing, on center. The wells were placed so as to theoretically cover the entire contaminant plume. Additional wells were laid out in front of the groundwater flow to prevent the pollutants from migrating beyond influence of the systems. The grid of wells was laid out on equilateral triangles instead of the usual square grid. This was to prevent dead spaces at the center of any four wells (if one considers the influence to be circles, not squares). This design is shown in Figure 5.6.

The vertical air sparge wells were placed at the intersections of the SVE well influences. The air sparge wells were kept well within the SVE influence so that the VOC's will not be forced beyond the remediation zone (Figure 5.7).

PILOT STUDY

When evaluating the system, the design was deemed excessive. To evaluate remediation designs, engineers must look at the overall effectiveness first and foremost. Also important, though, are the cost effects, constructability, and applicability to the site. It was presumed that first design would have sufficiently cleaned the site; however, the design was not cost effective nor constructable. The system was over-designed. A pilot study was needed to gain valuable information for a more effectively designed system.

On June 21, 1994, a pilot test was performed. A sparge well and vapor extraction well were installed and tested to better establish influence radii. The test procedure is documented in the listed referenced material (Apple, 1994; PEM, 1994). The results indicated a radius of influence of over 30 ft. for the sparge well. Likewise, a vacuum radius of over 40 foot was noted. These values were extremely high, making the site appear even more suitable to the selected action plan. These high values can be attributed to the asphalt cap over the region. The results were later used to develop a more feasible design.

The site showed favorable results to both systems. In addition to the ROI's, VOC emissions from the SVE system were monitored. The data revealed that, indeed, VOC levels increased shortly after turning on the sparge system, indicating that the air sparging was volatilizing contaminants from the groundwater. Conversely, VOC levels returned to original emission levels when the sparge system was turned off. Another effect was also observed–upwelling occurred in monitoring wells one and five. This fact is significant when considering future design and system start-up.

For remediation efforts such as this one, pilot studies are a valuable tool for proper, cost effective design. The information gained can be used to more accurately complete a final design. The data can also be used to better predict future happenings, problems, and, most importantly, results. All of the preliminary information, site characteristics, and pilot study results were utilized in developing a final design and beginning the operations.

MODIFIED DESIGN

The pilot study confirmed that air sparging in concert with SVE was a viable method of remediation. The study also provided new, site-specific performance data for both the IAS and SVE. This new information was utilized to modify the design. The preliminary design was based on standardized guesses. The new design was customized to the Perry site for better efficiency and performance.

The most prominent change in the design was the change from vertical extraction wells to horizontal trenches. While the comprehensive rationale behind this decision is the subject of a subsequent chapter, it should be noted that the decision to use horizontal wells was based on the horizontal wells providing equivalent results at a much lower cost and much easier constructability. Additionally, horizontal wells are an innovative configuration for which the EPA would like to see more data collected. Trenches were laid out to encompass the air sparge well field in order to prevent migration of the contaminant vapors. The trench layout is shown in Figure 5.8.

The IAS well locations were also reconfigured to account for the corrected ROI. Seven air sparge wells were needed to achieve the desired coverage. This is 64 wells fewer than the original 71 well design. The air sparge locations are also shown on Figure 5.8. These wells were installed on February 23, 1995, according to the plan. The diffusers were placed five feet below the seasonal low GWT elevation, as triangulated from historical data.

In addition to the location of the sparge wells and the SVE trenches, the design of the actual wells are also critical. A typical section for each is included (Figures 5.9 and 5.10). The designs are fairly standard. Contractors will be fairly familiar with installation procedures which reduces cost and increases the ease of installation.

This modified design was submitted to the OCC and approved for installation. ODOT authorities began the process of procuring control equipment and well materials. ODOT engineer Casey Shell approached The Charles Machine Works, maker of Ditch Witch™ equipment, about securing trenching equipment for the horizontal trench installation. An official at CMW, upon hearing the needs of the ODOT site, suggested that horizontal directional drilling may be a better option for this remediation effort. Authorities at ODOT and OSU considered the advantages and disadvantages associated with directional drilling. These considerations are presented in the subsequent chapters.

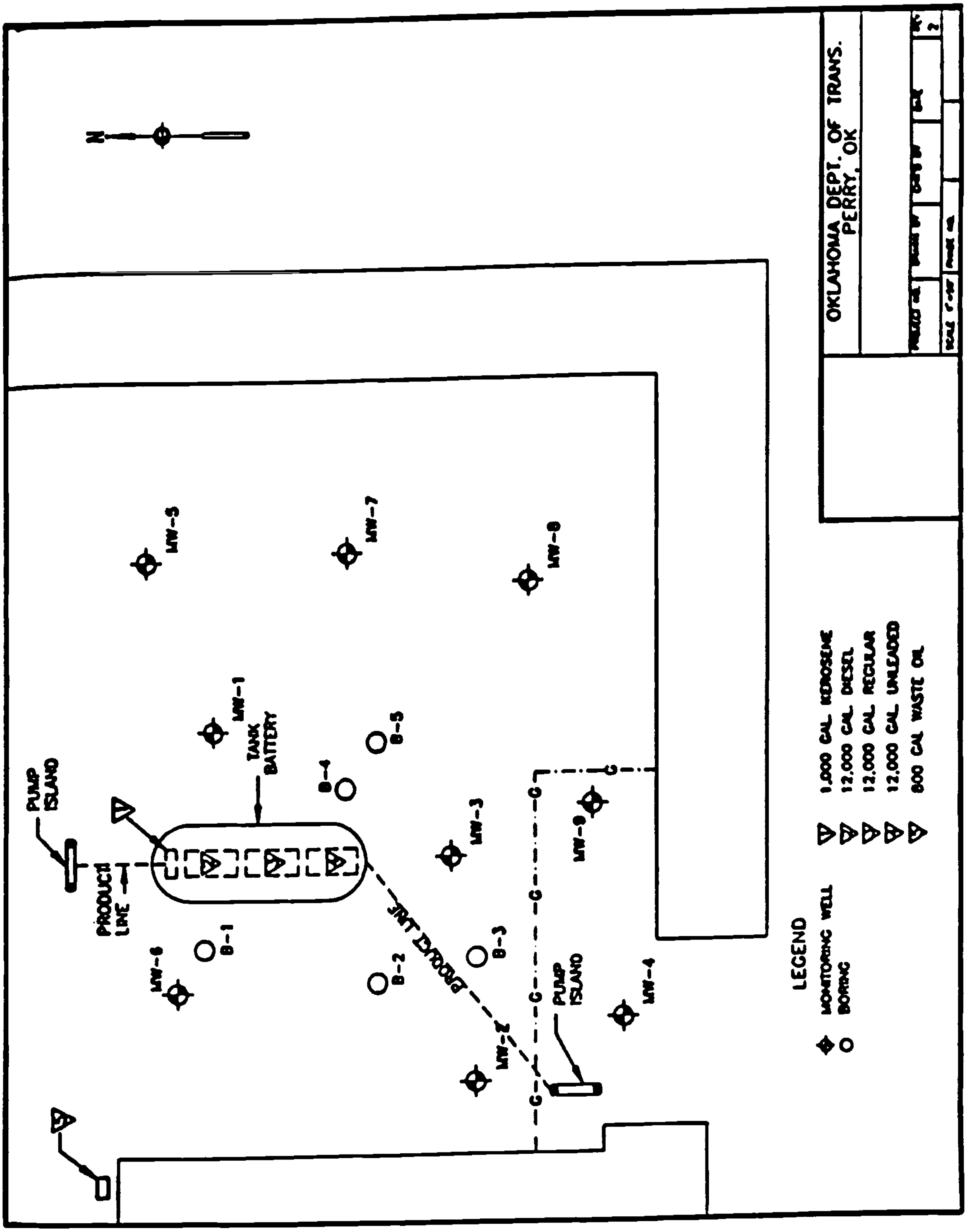

Figure 5.1 – Perry Site Layout

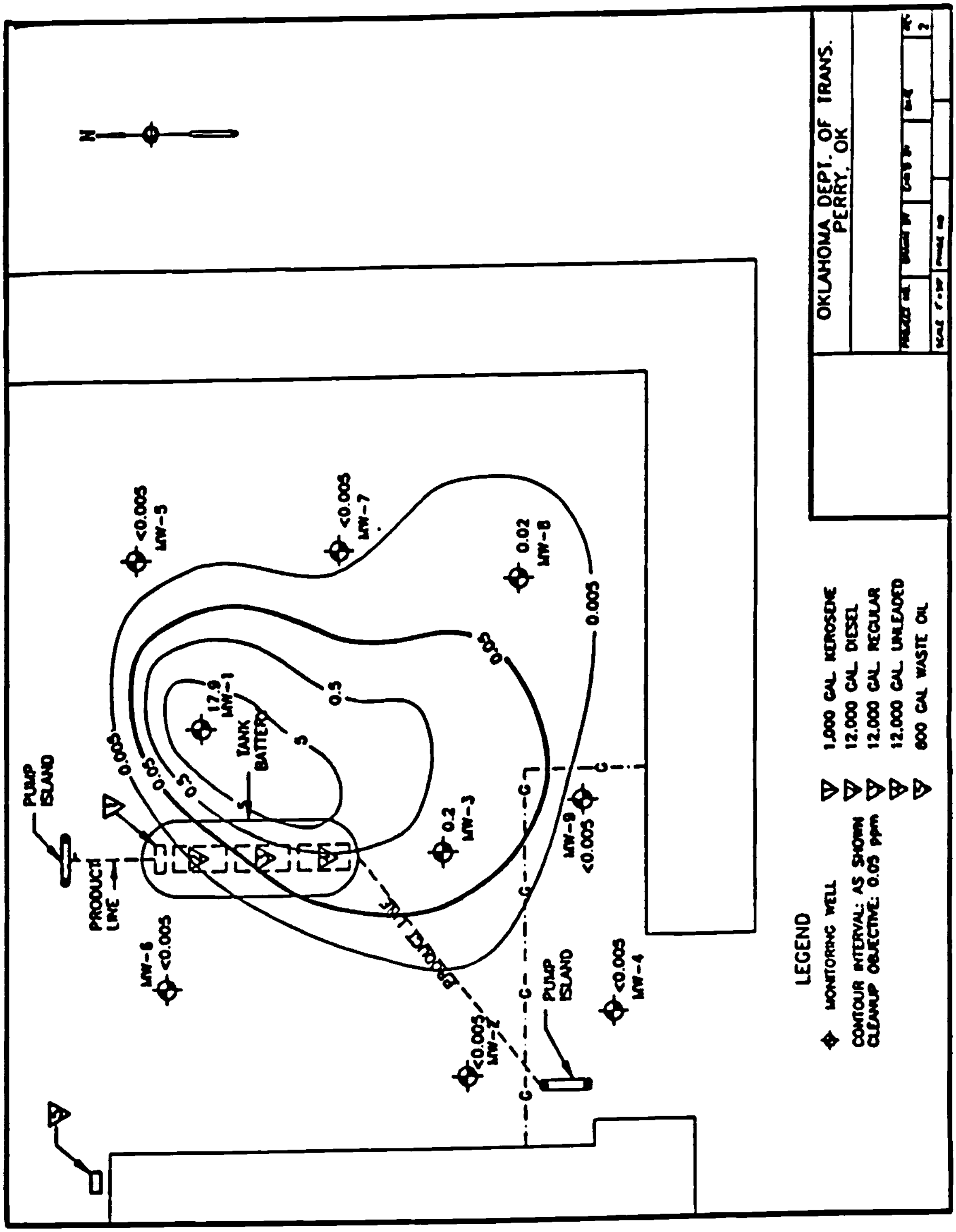

Figure 5.2 – Projected Benzene Plume

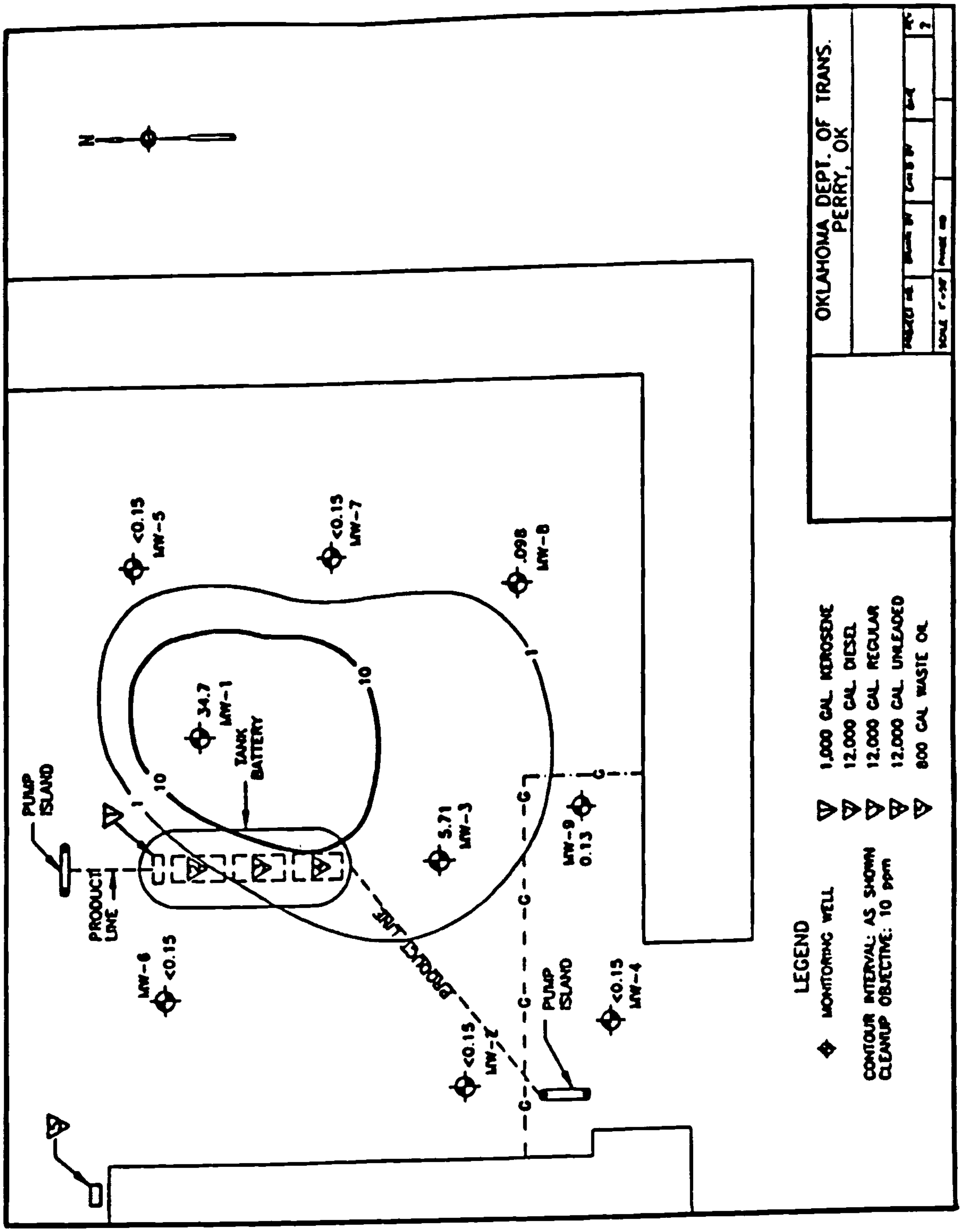

Figure 5.3 – Projected TPH Plume

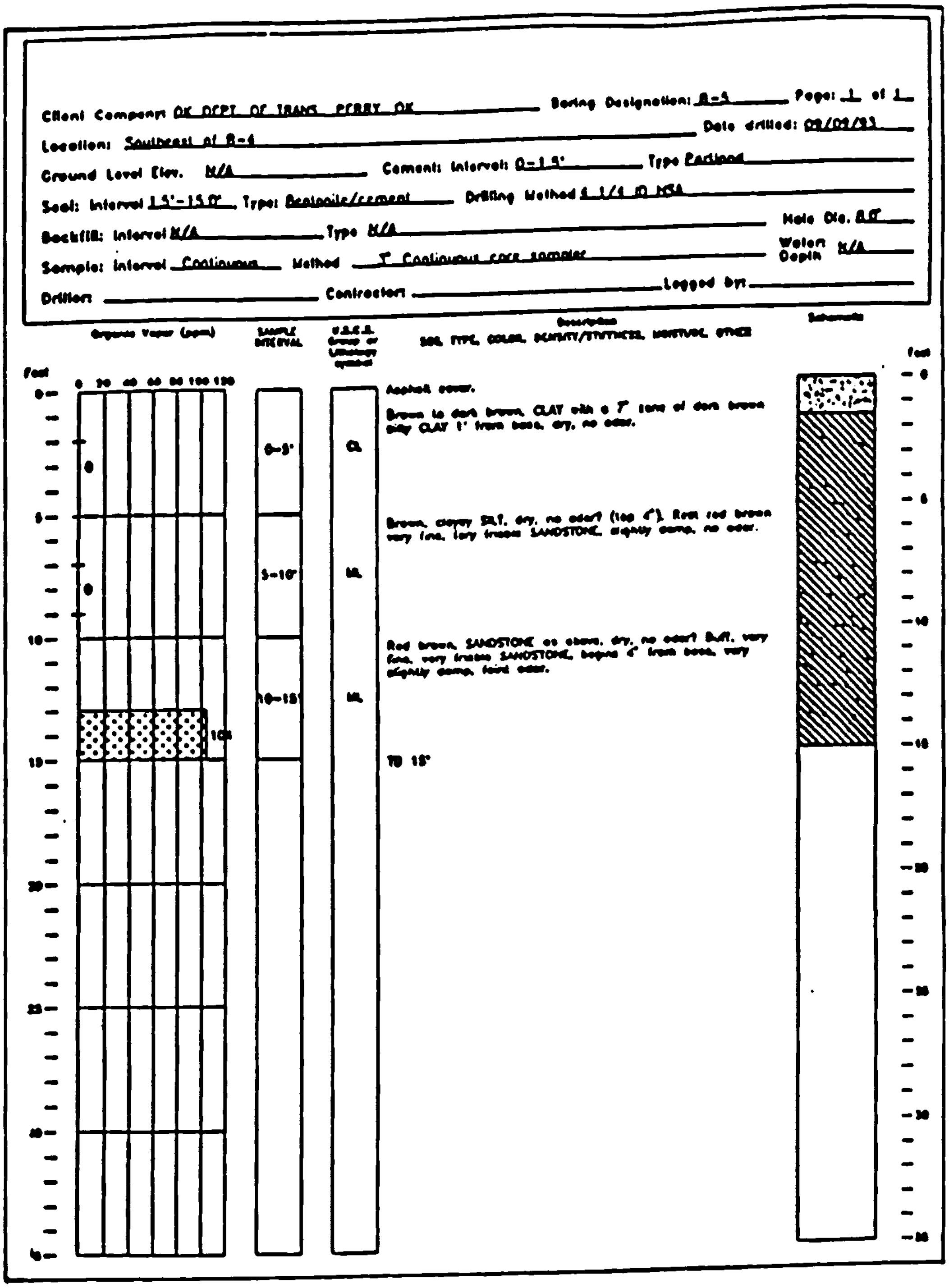

Figure 5.4 – Typical Boring Log

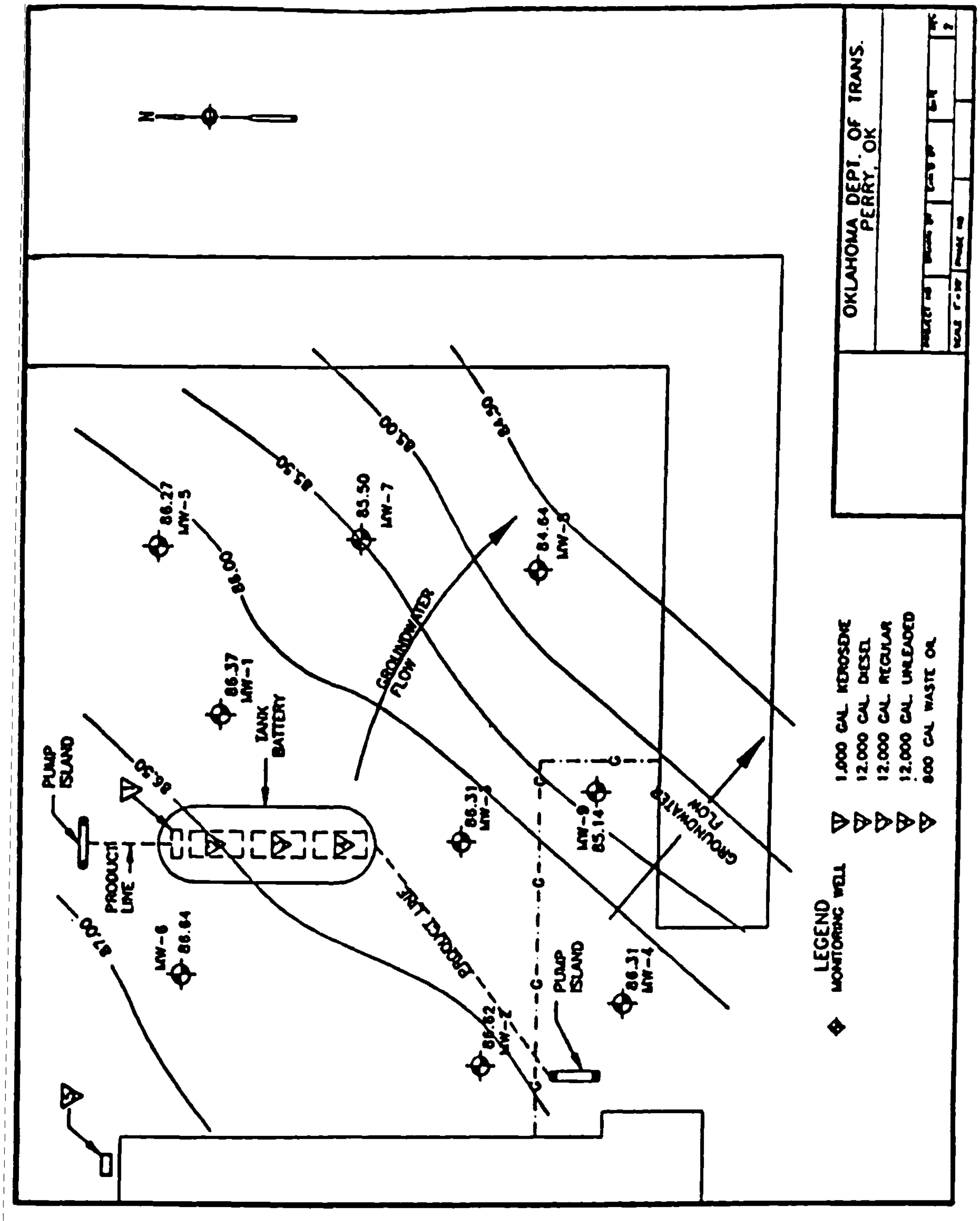

Figure 5.5 – Groundwater Flow and Potentiometric Surface Map

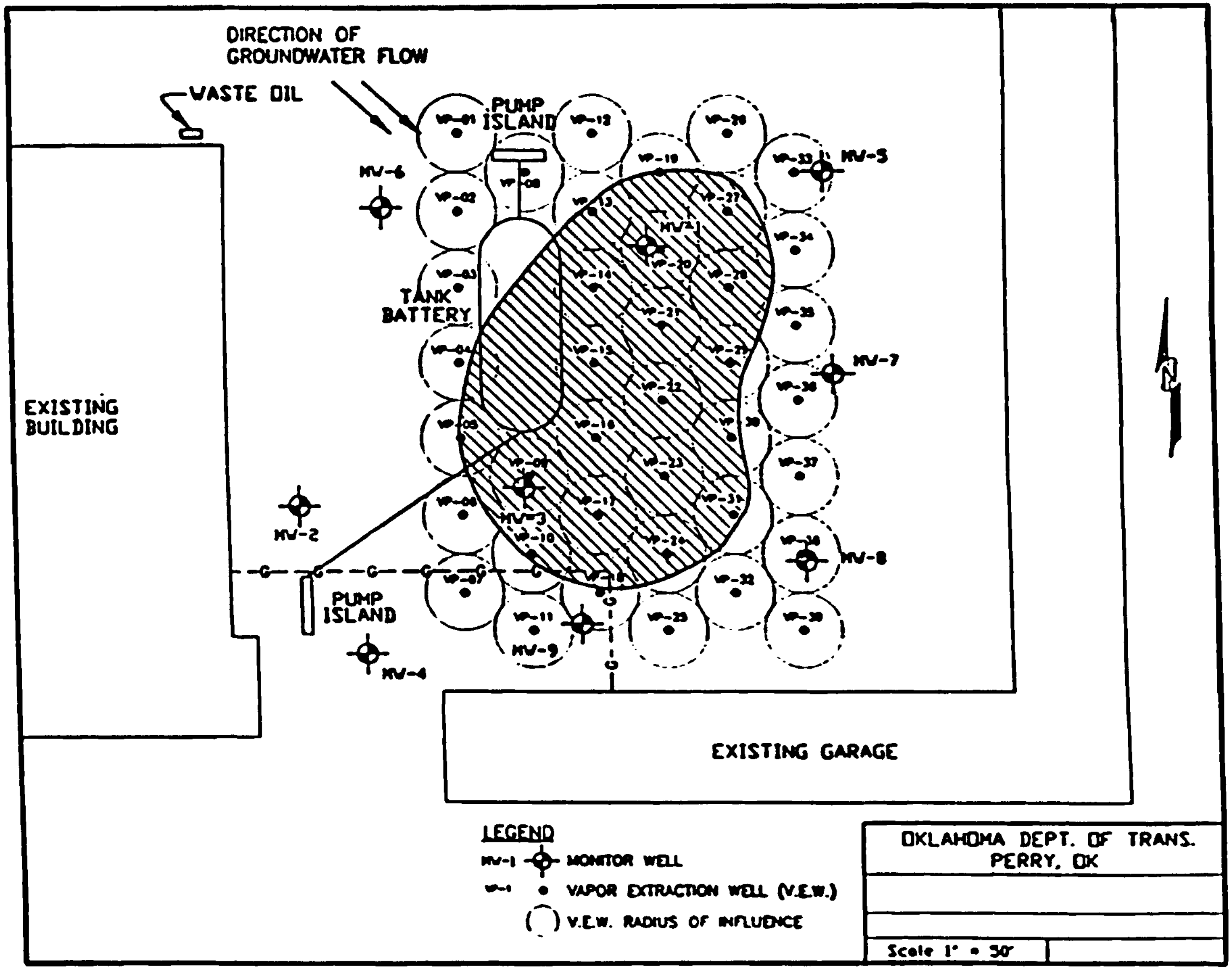

Figure 5.6 – Original SVE System Design

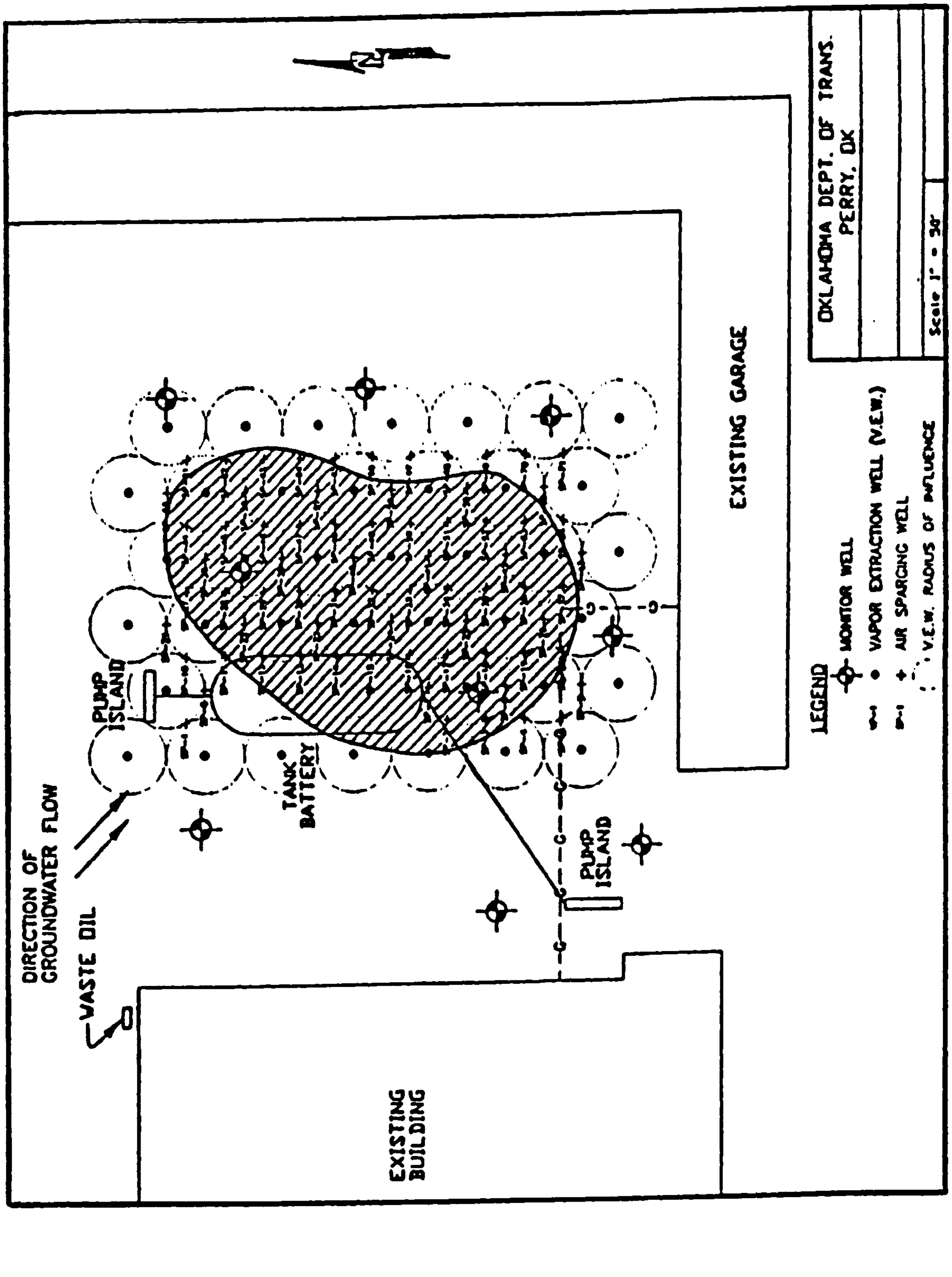

Figure 5.7 – Original Air Sparging System Design

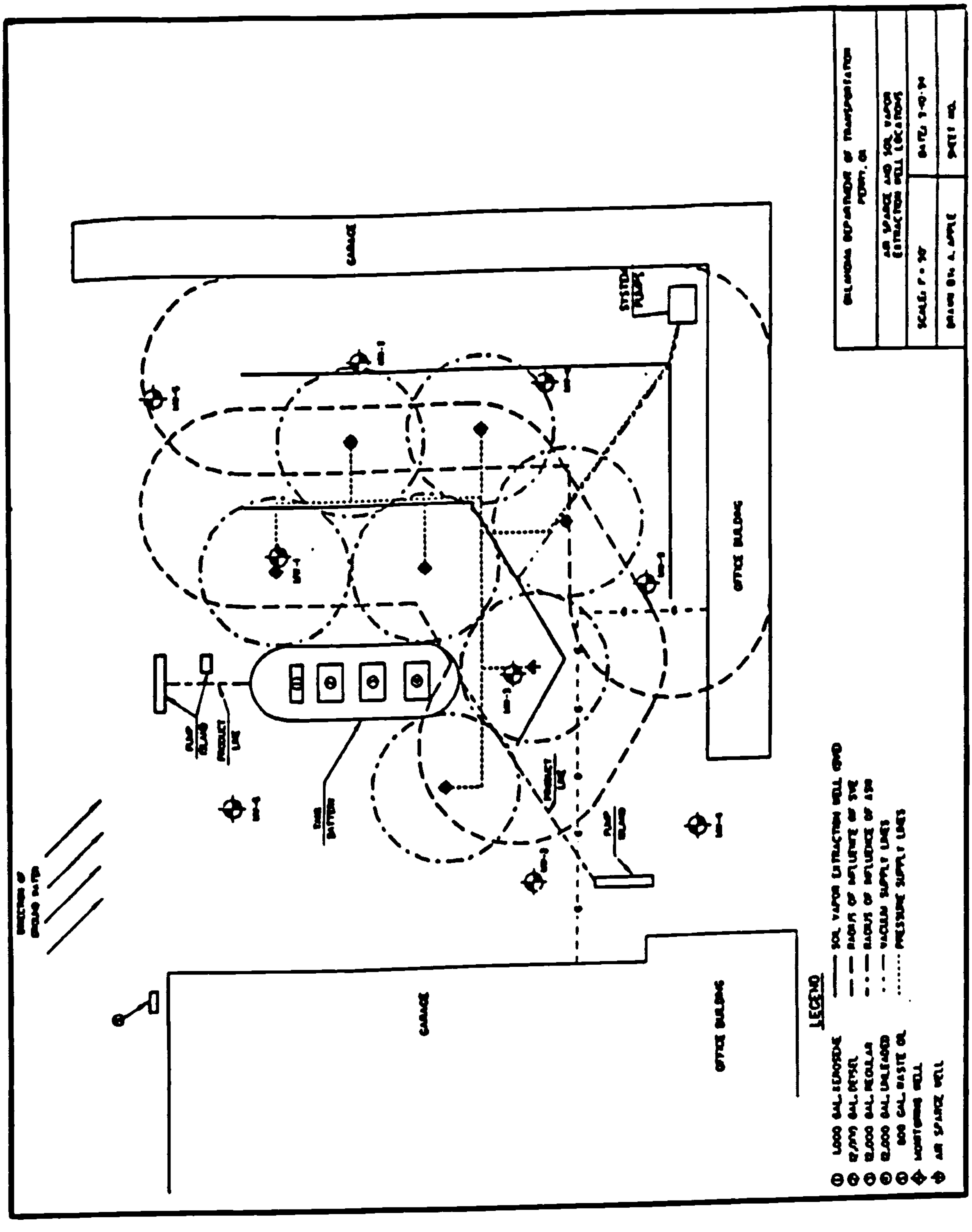

Figure 5.8 – New Air Sparge Well Locations and Vapor Extraction Trench Layout

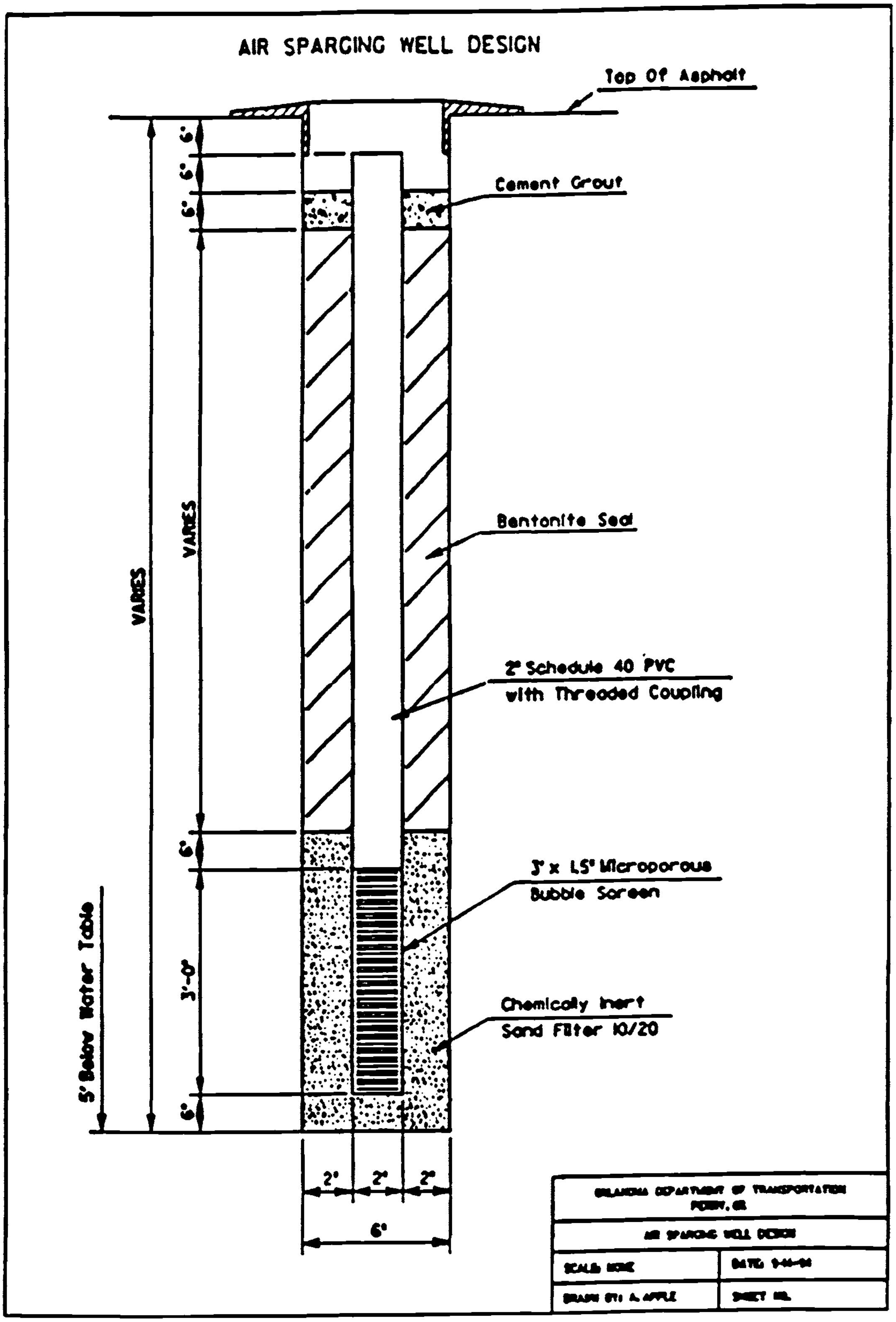

Figure 5.9 – Typical Section of Air Sparging Well

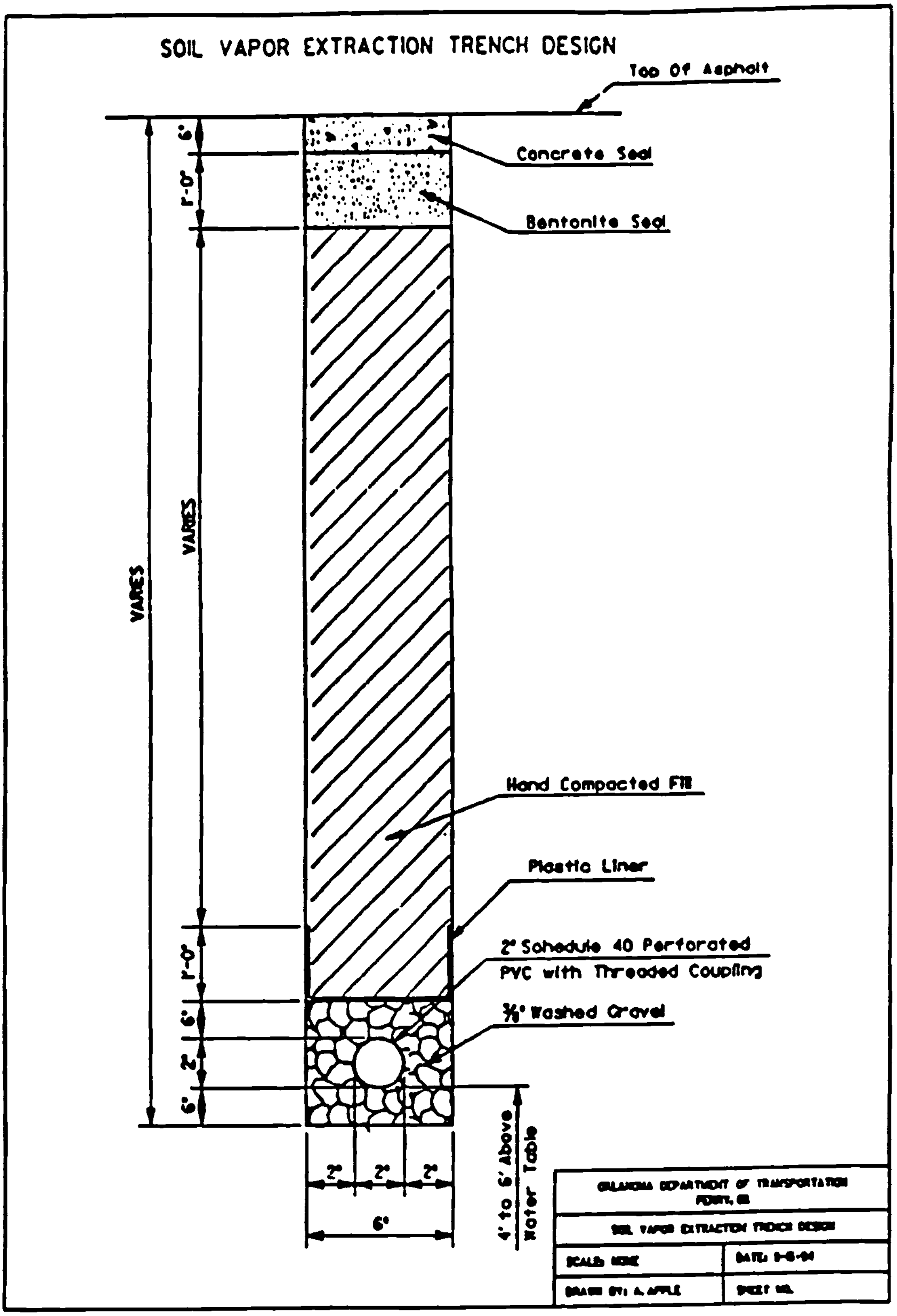

Figure 5.10 – Typical Section of SVE Trench Well

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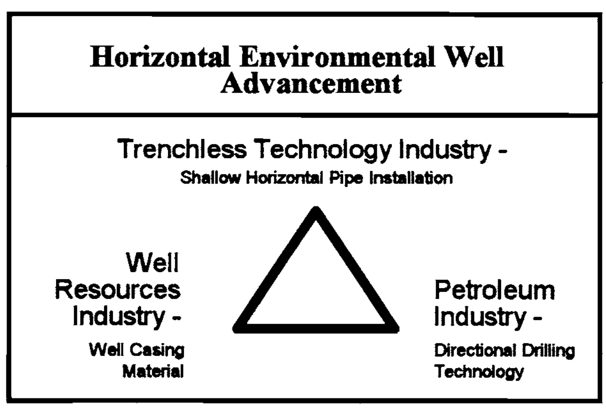
CHAPTER VI

ENVIRONMENTAL HORIZONTAL DIRECTIONAL DRILLING TECHNOLOGY

Horizontal drilling technology has been evolving rapidly in the oil and utility industries over the past twenty years. Horizontal wells offer the oil industry additional oil recovery over the traditional vertical well orientation . Similarly, the utility industry has used horizontal drilling (also referred to as directional drilling, or DD) to revolutionize utility line placement. Recently, environmental engineers have found that this technology may offer several benefits to soil and groundwater remediation efforts as well. This section will look at the history, technology, and options associated with horizontal drilling.

A BRIEF HISTORY OF HORIZONTAL ENVIRONMENTAL WELLS

Environmental engineers are looking to utilize horizontal drilling technology to assist environmental remediation efforts. To aid the development of this technology, knowledge is being drawn from three established industries; no one industry has all of the answers. The petroleum and utility industries bring expertise in directional drilling equipment and techniques. The water resource industry is developing well construction materials which will withstand the rigors of horizontal installation. From the combined efforts of these industries, horizontal drilling for environmental purposes may provide numerous options in the near future.



source: Wilson & Kenda, 1994

In the petroleum industry, horizontal drilling has been used to increase reservoir contact area, thus enhancing well productivity. The first well was completed in 1942 (Joshi, 1991). During the 1980's directional drilling use increased dramatically, both for enhanced oil recovery and exploration activities. During the 1970's the trenchless technology industry borrowed the knowledge of horizontal drilling and modified it for the installation of pipelines and utilities beneath buildings, paved surfaces, and bodies of water. The major advantage they gained from DD was subsurface installation without surface feature disturbance. Pipes have been placed beneath nearly ever major river in the United States. Borehole diameters as large as 60 inches and runs several thousand feet long have been used for river crossing borings. Utility installations are usually performed using smaller, simplified drilling rigs; but, the procedure is similar.

The potential for use in the environmental field was recognized in the late 1980's. The wells have been used for injection and extraction purposes at both government and private commercial sites across the country. The first environmental horizontal well installation was at the Department of Energy Savannah River Site in 1988. Drilling and installation methods are under continuing adjustment to meet the needs of environmental applications. DD offers many of the same advantages to environmental engineers as it does for other industries.

> "Most important is the capability of boring with great accuracy. Wells can be installed under paved surfaces, including parking lots, streets and highways; buildings; other surface obstructions; and beneath streams or lakes. Because starting pits are not required, the drilling operation is launched from the surface. Horizontal drilling causes minimal surface damage, produces little secondary contamination, and eliminates cross contamination of vertically stacked aquifers." (Griffin, 1995)

Horizontal vs. Vertical Well Productivity

Directional drilling techniques are now being used to install injection and extraction remediation wells where installation of trenches, or even vertical well systems, may not have been possible in the past. In addition, these wells may provide a distinct advantage over vertical wells because of their geometric orientation. Contaminant plumes are often horizontal in nature due to the horizontal hydraulic conductivity (K_H) being much greater than the vertical conductivity (K_V). The plume is restricted vertically, but is allowed to spread horizontally. Because of this characteristic, horizontal wells allow much greater contact area within the plume for either injection or extraction. One preliminary field test has shown that horizontal wells may increase remediation efficiency five-fold, mainly due to geometry (Looney et al. 1991). This number is similar to the average increase from horizontal wells versus vertical wells in petroleum recovery (Joshi, 1991).

The contact factor is also an important point to consider if the contaminant is under a building or some other obstruction; a horizontal well allows direct contact with the contaminant versus indirect flow from a peripheral vertical well system. Horizontal wells offer several advantages and disadvantages over traditional vertical wells which will be explored in greater depth in the next chapter (see page 91).

Horizontal Well Drilling and Installation for Environmental Projects

The use and installation of environmental wells is quite different from traditional horizontal wells in several important ways. Techniques in the other industries are not as concerned with the amount of skin damage associated with the drilling method. However, for environmental applications it is important to disturb the existing soil as little as possible. This allows better fluid flow to or from the well. Also, in environmental applications one does not wish to introduce unnecessary foreign material to the subsurface. Some drilling techniques use extensive amounts of drilling fluids (which may or may not have been designed as "environmentally sensitive"). These fluids are not a desirable additive and will tend to change the texture of the surrounding soils. Other foreign additives which may be introduced inadvertently are grease and other lubricants associated with the drilling machine itself. These concerns are being researched and modified for environmental applications.

Another difference in environmental applications is the well material being used. Environmental wells must be cost effective. This often precludes expensive, but durable, metal piping. With vertical well installation the casing is introduced into to a drilled hole with little resistance experienced by the pipe. Conversely, horizontal wells undergo great stress during installation due to drag friction caused by the soil closing in on the casing. This stress is increased by the addition of fluid during the drilling process. The mud which is created creates a large suction force which increases the stress as the casing is pulled through the borehole. The stress often necessitates the use of high-strength pipe material (e.g. HDPE, fiberglass). The historically preferred casing material, slotted schedule 40 PVC, has been shown to fail under the extreme tensile stress. The water resource industry, having some background experience to draw upon, is working to develop better materials for this application.

Possible Pitfalls

Horizontal drilling is not without its concerns. A major concern is harmful disturbances to the subsurface. Fracturing may occur allowing drilling fluids or contaminants to migrate to uncontaminated regions. Additionally, the drilling fluid may cause damage to underground utilities, change soil texture, or run along trench lines beyond the control area.

Care must be taken during drilling so that the borehole does not infringe upon underground structures, breach utilities, or compromise soil stability (Horizontal News, 1993).

A point of distinction between utility drilling and directional drilling is that utility drilling specifies a depth while directional drilling specifies a horizon located at a specific depth. This slight distinction is important because the distance from the surface to the wellbore may change along the length of the borehole, especially with dipping bedding planes or a rolling surface topography. This requires accurate surveying and documentation during drilling to ensure accurate well placement (Horizontal News, 1993).

Horizontal well completion is very different than vertical well completion. One must note on the detail whether the vertical distance or the measured depth is specified. The vertical depth is from the surface to a point directly below. The measured depth is measured from the surface entry point along the wellbore. Slanted boreholes present unique problems with grouting and sealing the well. Without the aid of gravity, well completion is difficult, especially along the extended, curved section prior to the horizontal screen section (Horizontal News, 1993).

One point which might limit the use of directional drilling is the depth of the desired well. As the depth increases with horizontal wells, so to does the cost of installation. This is mainly due to the need for more sophisticated guidance equipment and more expensive drilling tools. Also, a greater depth to the screen section requires more space at the surface for step off distance. A final thought is that very few contractors are currently trained, equipped, and experienced in directional drilling techniques. The process is new and it will take time for contracting firms to evaluate the business and determine whether they desire to enter this market. State regulators too must adjust to the new procedure.

Well Drilling and Installation Procedures

The drilling and installation methods chosen for a horizontal well must be amenable to the established site characteristics and the desired function of the well. One must decide on which wellbores should be used: a continuous borehole or a blind borehole. There are currently three separate drilling methods used for directional drilling. The engineer may specify using a compaction tool, down-hole mud motor, or jetting tool to drill the pilot hole. Each option will be discussed briefly.

Horizontal Drilling Methods – *boreholes options*

Continuous Boreholes. Continuous boreholes extend to the surface at two locations. The drill rig is set up at the borehole entrance. A pilot hole is drilled downward through the curved section. The curve angle will straighten back to horizontal as the hole approaches target depth and desired screen location. The pilot hole is then drilled through the horizontal screen section. At the other end of the specified screen area, the hole will curve upward and extend to the surface (see Figure 6.1). The pilot hole may then be enlarged to the desired diameter by pulling an opener (reamer) back through the hole. The well materials are pulled into place from the exit end. The drag friction from this procedure places the well casing under extreme tensile stress, as mentioned previously.

This method has the advantage of providing two surface access points to the subsurface well casing. Additionally, the drilling methods required to construct a continuous borehole may require less drilling fluid (especially important for SVE applications). Also, the pipe installation through a continuous borehole is often easier than through its counterpart, a blind borehole. One disadvantage to continuous boreholes is that the borehole length will be longer which may or may not add to the expense.

Blind Boreholes. Blind boreholes, in contrast to continuous boreholes, have only one surface access point–the shaft entrance. The wellbores will terminate at the target depth rather than turning back up to the surface (see Figure 6.2). The casing is then installed by one of three methods. A washover pipe may be installed after the pilot hole is drilled. The well casing is then installed inside the washover pipe and the washover pipe removed. In the open wellbore method, the borehole is drilled and cased to the end of the curve. A pilot hole is then drilled through the horizontal section, reamed out, and the screen pushed in. Of course, this method is only applicable in soils which will allow the reamed hole to remain open. In the final method, a pilot hole is drilled and then the casing is pulled into the hole as the hole opener is pushed through.

Blind wellbores have the advantages of only needing one surface point (the entrance), only one curve must be negotiated in drilling the hole, and short-radius blind boreholes require less step-off distance in front of the screened section. However, blind wellbores make long well completion difficult.

Horizontal Drilling Methods – *drilling tools*

Compaction Tools. For compaction drilling, a curved (or wedge-like) drill bit is used to push its way though the soil. The bit is much like a duck bill or a wood chisel. The shaft pushes the bit through the soil. The curve on the bit forces the assembly in a curved path. The bit and shaft spin to allow the path to advance straight forward. A major advantage to this method is that a small amount of water is often the only drilling fluid used to cool and lubricate the bit. Unfortunately, this method provides little wellbore stability and is, therefore, only applicable in soils which provide intrinsic wellbore stability. This is a tool designers are focusing on modifying for environmental project applications.

Down-Hole Mud Motors. With mud motor assemblies, a rotating motor is attached to the end of the drill string (shaft). Drilling fluid is pumped under pressure through the string to the motor causing the motor to drill its way through the soil. Different drill bits may be attached according to the site conditions. The speed and power of the motor is controlled by the pressure of the fluid.

Mud motors allow drilling into some formations not accessible by compaction bits because of both the grinding bit action and also the ability to shore the sides of the wellbore by the addition of stabilizing materials (mainly a bentonite slurry). Additionally, shorter radii can be achieved with mud motors over the other two drilling methods. Disadvantages associated with mud motors include excess soil cuttings and superfluous amounts of drilling fluids being added causing changes in the surrounding host formation

Jetting Tools. Jetting tools use hydraulic pressure to cut their way through the subsurface. This method is limited to the applications where adding excessive amounts of drilling fluid is not a problem. For environmental projects, this is not a desirable method.

Skin Damage

Skin damage is damage and alterations to the soil formation on the edge of the wellbore and is one of the largest concerns of directional drilling for environmental applications. The problem with skin damage is that changes to the texture of the soil hampers the flow of air and groundwater through the formation to or from the well. The damage is caused by both the drilling method used and the addition of drilling fluids. Damage can be physical and/or chemical in nature. Compaction of the soil particles changes the soil density and pore space directly surrounding the borehole. Foreign particles added during the drilling process may also fill pore spaces. Soil cuttings are also left in the wellbore. These are each examples of physical changes. Chemical changes of the soil are caused by changes in pH, redox potential, and ionic mixing with drilling fluids. Precipitation or dissolution of minerals in the host formation may result reducing permeability and pore space.

The term 'skin damage' implies that the damage is strictly to the walls of the well-bore. This is not the case. Damage will continue into the surrounding formation as far as the drilling fluid and other undesired material can travel. Compaction drilling becomes a desirable method to use because this method uses a minimum amount of drilling fluid. Often water is the only fluid needed, and is only used to cool and lubricate the bit. Obviously, any method which minimizes the addition of fluid which can extend in to the formation is advantageous. However, with compaction drilling the bit does just as the name implies–it compacts, or pushes, the soil out of its way. The drill cuttings are left in the hole and pushed into the sides of the wellbore. This compaction is aided by even the smallest amount of drill fluid. The result is a thin, high-density compaction layer surrounding the wellbore.

Drilling fluids are the other major cause of skin damage. The fluid is chemically engineered to meet the specific need of the drilling method and is selected to meet the site conditions. Drilling fluids are used for numerous reasons (Wilson et al, 1993).

- Clean drill cuttings from the drill bit and the lead end of the wellbore
- Transport the cuttings to the surface
- Cool and lubricate the drill bit and drill string
- Provide wellbore stability (by either adding stabilizer or creating a mudcake)
- Control subsurface pressures
- Drive down-hole mud motors

Intense research is currently underway to develop new drilling fluids which will minimize the effects of adding these fluids to the host soils (Dale, 1995). Additionally, environmental engineers have questioned the composition of these fluids and whether they should be used at all for environmental clean up efforts because of their own chemical make up. This is a major criterion for the researchers–develop environmentally sensitive drilling fluids which eliminate any further contamination.

Figure 6.3 pictorially shows the physical and chemical skin damage which can result. Mud cakes are often created on purpose to maintain the wellbore walls. The mud cake can later be removed during well development; however, the mudcake should form quickly during construction to prevent migration of carrier fluids and solids further in to the host formation. Fluids and solids which penetrate into the so-called transition zone are difficult or impossible to remove from the formation.

The important point to remember about skin damage associated with directional drilling is that it can not be eliminated (disturbance will occur), but one should strive to minimize it. This is best accomplished by reducing the amount of drilling fluid used. Although compaction drilling bits compact surrounding soils, it is still a desirable method due to the minimal amount of added fluid which can penetrate into the formation.

WELL DESIGN

As with any design process, the engineer must know the objectives of the project. Use of horizontal environmental wells can be for numerous activities, including:

I. Groundwater extraction for –
   - Free Product Recovery
   - Pump and Treat Remediation
   - Creation of a Hydraulic Barrier
   - Groundwater Table (GWT) Depression

II. In Situ Vapor Extraction/Injection –
   - Air Sparging
   - Soil Vapor Extraction
   - Delivery of Nutrients for Bioremediation
   - Thermal Desorption
   - Bioventing

The design of the wells will be determined by the desired use. It is possible to use the system for more than one use over the life of the project. This must be taken into account during initial design. Often a preliminary use will be specified for early remediation, then a second technique will be used to refine the clean up.

Once the objectives and uses of the system have been determined, the specific design criteria may be set. Taking into account the site conditions, the engineer in conjunction with the contractor, must determine the drilling method to be used. Next, the screen location and length must be set. The location of the screen is most dependent upon plume location and the use (e.g. injection or extraction). Other design criteria to be set include screen material, slot size, and diameter; riser casing material and size; filter pack considerations; and well bore path to the screen (Wilson et al., 1993).

Well Screen Location

For horizontal wells the location is specified by an azimuth, inclination, and vertical depth to the top of the screen. As mentioned, the location of the well is set according to the location of the plume, the use, and the site conditions. Contaminant plumes are often spread horizontally. Gravity will pull contaminants vertically through the soil. However, the natural tendency of the soil is to pull the contaminants horizontally. Conductivity of the soil is stronger in the horizontal direction than in the vertical direction. That is $K_X \geq K_Y > K_Z$. The well screen will be placed to optimize the system with these conductivities in mind. The groundwater flow direction is also important (the groundwater flow does not have to be in the K_X direction). Wilson et al. (1993) suggests that the optimum placement for an environmental horizontal well will be perpendicular to the K_X direction. For wells designed for groundwater extraction or liquid injection (e.g. nutrient addition for bioremediation), a perpendicular line will take the greatest advantage of the high conductivity. The line must then span the entire width of the plume because conduction will not carry to or from the ends of the line when it is oriented perpendicular to the main conduction.

The measured depth to target is also needed to specify a well location. The measured depth to target is the distance along the wellbore from the surface entry point to the target zone. This is opposed to the vertical depth, or screen depth, which is the vertical distance from the surface to the well screen.

The engineer will most often specify a straight, horizontal screen section through the target zone. However, lateral curves through the subsurface may be chosen to compensate specific characteristics of the plume or the soil profile. Compound curves in the screened zone must be taken into account when specifying drill methods and well material.

Well Material

The horizontal well screen is designed according to the function of the well and the drilling/installation method to be used. Wells used for extraction will have different requirements than wells used for injection. The slot size will be based upon the soil characteristics. For most environmental applications, a sand pack is specified to aid the even flow of air to or from the well. Unfortunately, installing a filter pack around a horizontal well is nearly impossible. Methods for installing a filter pack around horizontal wells have been developed but are not refined.

One option available is to use a pre-packed well screen. Pre-packed piping has been manufactured to meet the high-strength requirements of horizontal well installation. Additionally, these pipes come in several diameters and slot sizes. Use of pre-packed filters will be more costly than normal slotted pipe, and probably more difficult to install. Pre-packed pipe will require a longer radius of curvature, increasing the wellbore length.

As discussed previously, the strength of well materials is extremely important. The environmental engineer must look first at which materials will provide the tensile or compressive strength needed to meet the installation requirements. Also important is the radius of curvature for the pipe. Often the stronger pipe is also stiffer preventing it from navigating short curves drilled through the subsurface. After satisfying the strength and radius requirements, the planner must consider the cost of the pipe and also availability. The casing will be specified by material, inside diameter, and slot size.

Other Design Elements

The angle between the drill stem and the ground surface at the entry point is referred to as the entry angle, or approach angle. The angle can be between 7° and 90°. The angle will be set to coordinate with the desired screen elevation. Deeper wells will require a steeper approach angle to reach the remediation zone sooner. A more common occurrence is a flat angle for shallow well installations. The drilling rig also influences the entry angle. The most common approach angles are less than 30°.

The curved portion of the wellbore is defined by a radius curvature. Shorter radii signify tighter curves. A short radius is less than 150 ft. A medium length radius is between 150 to 800 ft. Greater than 800 ft. is considered a long radius (Wilson et al., 1993). Tight curves require highly flexible casing, but higher strength material to withstand the friction of installation. Medium and long radii of curvature are desirable over shorter radii due to the reduced drilling and installation stress on the string and casing. Also, longer radii can be drilled by a variety of drill rigs, possibly reducing the cost. However, the increased radius will lengthen the wellbore length, thus increasing the drilling cost. This increase in cost must be weighed against the reduced risk incurred during well installation.

The step-off distance is the horizontal distance from the beginning of the horizontal section back to the borehole entrance point. The step-off distance is extra distance which would not be needed if the drilling machines could drill down and turn a 90°. Surface structures may limit the length of the step-off distance. A mandatory shorter step-off distance will dictate a short radius of curvature, and thus the associated concerns of the casing material. When the step-off distance is not fixed by site conditions, the distance will vary according to the approach angle and radius of curvature of the borehole. The drilling contractor may be given the liberty to determine the step-off distance, approach angle, and radius of curvature if surface obstructions or surface area are not a concern.

CONCLUSIONS

For years the environmental industry has relied on vertical wells and shallow trenches in the design of remediation systems. While vertical wells do have distinct advantages, horizontal wells also provide unique options. Directional drilling has been used for years in the petroleum, utility, and construction industries. Since the first horizontal environmental well was installed in 1988, efforts have been underway to modify directional drilling techniques for use in environmental remediation.

David D. Wilson of Independent Environmental Consultants, Arvada, Colorado, estimates only 20 contractors currently use directional drilling for remediation work on a regular basis, but that number will increase shortly. The number of environmental wells installed in the last half of 1994 was more than triple the total number of horizontal wells completed since the first tests in 1987 (Griffin, 1995).

Horizontal wells offer several advantages for remediation. Horizontal wells can be drilled beneath surface structures and paving, providing direct contact with the contaminant plume without major alteration to existing surface structures. For many applications horizontal wells provide an advantage because of their associated geometry. While horizontal wells appear more expensive based upon installation costs, reduced hardware and operation costs and reduced clean up time may provide reduced future expense.

In summary, horizontal wells provide new options to environmental engineers designing groundwater and soil remediation systems. Directional drilling techniques, equipment, and materials are being modified to meet environmental needs. And while this technology is not suited for every situation, it will provide new opportunities now and in the future.

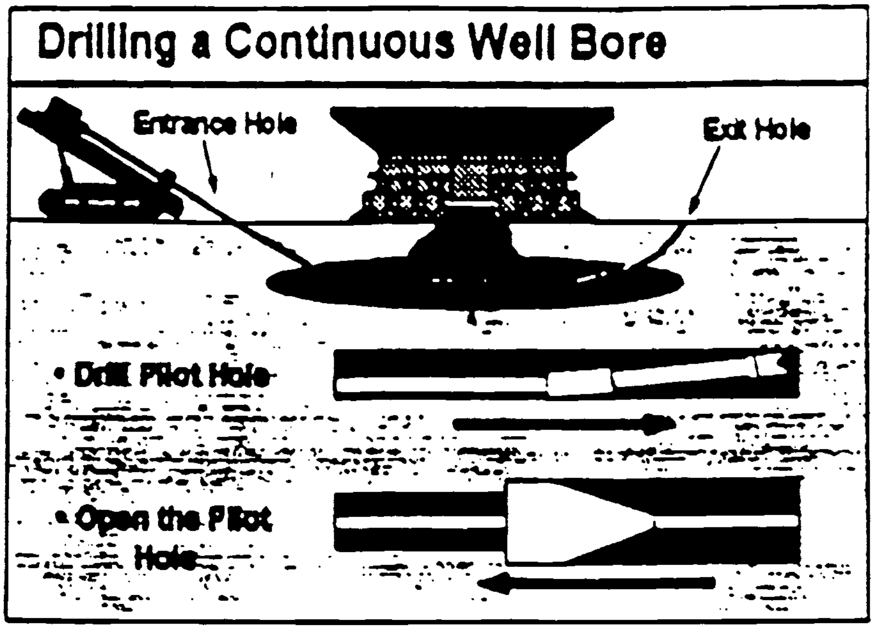


Figure 6.1 – Continuous borehole plan view (Wilson, 1993a).

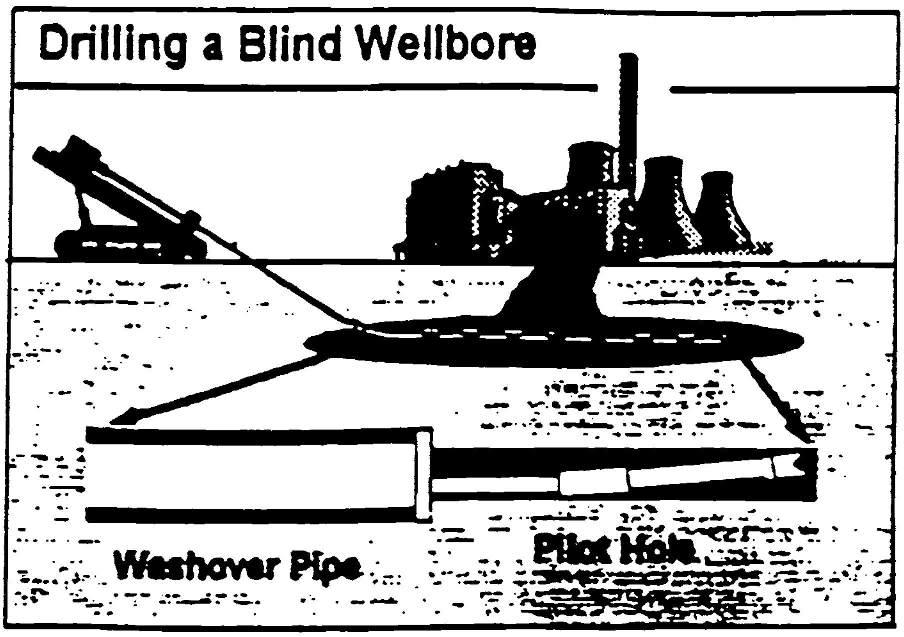
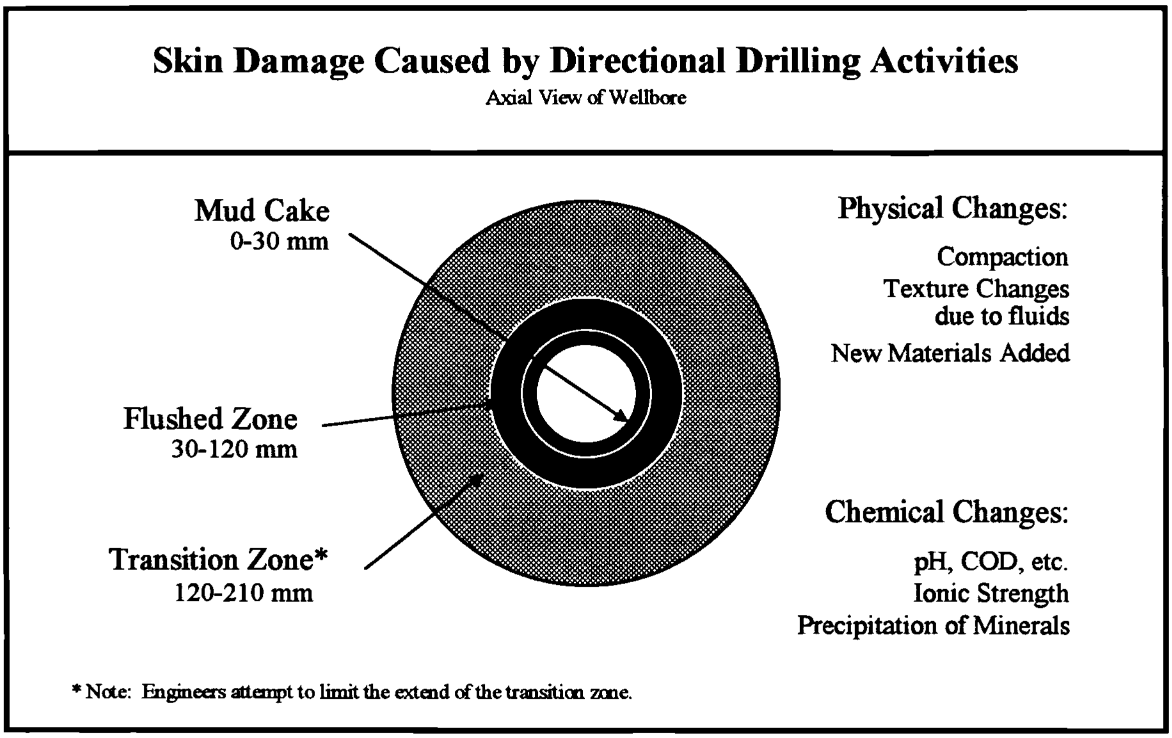


Figure 6.2 – Blind borehole plan view (Wilson, 1993a).



source: Wilson and Kenda, 1994

Figure 6.3 – Cross-section view of skin damage area resulting from directional drilling activities.

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CHAPTER VII

DESIGN CONSIDERATIONS OF VERTICAL VERSUS HORIZONTAL WELL CONFIGURATIONS

A number of factors are considered when an engineer is designing an air sparging/ soil vapor extraction remediation system. The engineer must design a system, based upon established criteria, which will effectively meet state and federal remediation standards. Having reviewed the technology behind in situ air sparging (IAS) and soil vapor extraction (SVE) in chapters III and IV, one is aware that the major decisions of an IAS/SVE system design are concerned with well design. One of the first decisions to be made is the orientation of the wells, vertical or horizontal. Tradition has dictated the use of vertical wells. However, horizontal wells are now being considered for both methods. This chapter provides insight and draws conclusions about the advantages and disadvantages of the different options.

Specifically, three questions are posed:

1. Should vertical or horizontal wells be used for air sparging?
2. Should vertical or horizontal wells be used for soil vapor extraction?
3. If a horizontal orientation is to be used for SVE, should a trench design or a directional drilled well be used?

To answer these questions, one must consider the hierarchy of criteria to be used. Thus, the parameters (driving factors) are discussed. Subsequently, the questions are considered individually by presenting the advantages, disadvantages, and applications associated with the specific options.

Decision Drivers

When engineering an environmental remediation system, the design is based upon the goals and desired result of the clean up. As with any design, the engineers' decisions are governed by established criterion, decision drivers. A discussion of these parameters is important to understand how the decisions and suggestions in this section are determined.

The first and foremost driver is technical feasibility. The method chosen must produce the desired level of remediation. This encompasses several questions. First, will the chosen method be able to meet the desired remediation level? Next, will the design system perform the desired function? Is the system amenable to the specific site conditions as established in the site characterization? For example, an engineer may have soil contamination in a soil profile layered with clay lenses. As the engineer considers soil vapor extraction, the first question should be, "Will SVE sufficiently remediate the site to meet the required standards?" In this case, SVE is the method being considered. The next question might be, "Will vertical wells perform the desired vapor extraction?" A vertical well configuration, then, is being posed for the system. Finally, "Will vertical SVE wells perform well in a layered soil profile?" This question addresses the site conditions. The method of remediation must be deemed feasible for further consideration.

If more than one method is technically feasible, one must use further criteria to make the decision of which method. The next driver is usually cost – the chosen method must be cost effective. When determining which method is most cost effective, one must consider all associated cost–present and future, direct and indirect–with each method. Since remediation efforts are strictly a cost center and no return is produced, firms attempt to spend the minimum dollar amount required to meet government standards.

Another parameter is congeniality. From the owners standpoint, this point may be as important as any other factor. The engineer must consider ease of installation, how it will affect daily activities at the site, and both permanent and temporary alterations to the site. Obviously, removing all of the concrete parking at a shopping center to instigate a soil flushing system, although feasible, would not be desirable. Constructability will play a major role in engineering a final design, especially for SVE well design.

Efficiency is a final driver. This criteria is closely related to total cost. The more efficiently the system runs the more savings that can be realized. Also under efficiency, one must consider all uses for the system. For example, can or will the system piping be used for more than one use over the life of the project.

To summarize the decision process, feasibility is the top criterion. After determining feasibility, cost, congeniality, and efficiency are considered in determining the best remediation method for a specific site. Moreover, no two sites are alike and each must be considered on its own needs and characteristics.

QUESTION #1 – VERTICAL OR HORIZONTAL AIR SPARGING

Vertical and horizontal wells each have applications where one option will be clearly preferable over the other to meet the specific needs of the project. In these cases cost, congeniality, and feasibility have little influence. Horizontal wells must be used to pass beneath buildings and other permanent structures on the surface. Horizontal boring allows one to reach under these obstructions without destroying them. Vertical wells must be used when the contamination is found at great depths. Horizontal wells become impractical as the depth increases. Vertical and horizontal well configurations for air sparging each have distinct advantages and disadvantages which should be considered.

Perhaps the main advantage of vertical air sparging wells is the added control. Each well is outfitted with a valve and gage to control air flow rates. Assuming the system consists of several wells, this feature provides particular advantages. One can control the air flow to each well which is especially applicable with different levels of contamination. To increase the efficiency of the system, engineers may wish to reduce the flow to fringe areas where the contaminant concentration is less. Additionally, by varying adjacent well flow rates, the engineer can increase the agitation, and in essence create a pulsing action at each well as opposed to pulsing the entire system. Pulsing individual wells can create greater agitation because of the overlap of the radii of influence of adjacent wells. Pulsing the entire system would reduce and return each ROI in unison.

While the engineer has no control over where air goes once it is supplied to the well, with vertical wells they do have assurance, by monitoring flow gages, that each well is supplying air flow. This is a perceived problem with horizontal wells: there is no assurance that air is being supplied over the entire length of the screen. With horizontal wells fines and mud may clog the screen slots during the installation process, thus preventing air flow to certain sections. Furthermore, air will take the path of least resistence once it is introduced to the screened section of the well. This may mean the air will entering the soil at the near end of the screen and not even reaching the far end of the casing. There is no way to know for sure whether these problems exist. A related point is that an air diffuser and a sand pack may be used with vertical wells. These features are believed to allow better air introduction to the subsurface than slotted pipe.

Other advantages associated with vertical wells include being able to vary the depths of each well and being able to reach great depths. By being able to vary the depths the engineer can tailor the well field to the specific site characteristics, including groundwater elevations and soil profiles. This becomes difficult with horizontal wells because one cannot vary the screen elevation to much extent due to the large radii of curvature associated with the pipe and drilling equipment. Additionally, the cost of horizontal drilling is greatly affected by the depth of the well. The price will become limiting if the well must extend deeper than 50 ft.

The contaminant plume will always extend horizontally in the downgradient direction, as K_H is greater than K_V. Horizontal wells allow the engineer to run a lateral screened section through the plume for greater, direct contact with the pollutants. For extensive plumes this may be a more economical choice than a vertical well field. With respect to cost, a larger ROI for the vertical wells will require fewer number of wells needed and a more cost competitive system compared to horizontal wells. For air sparging clayey soils tend to force the soils laterally (until channelization allows the air to move upward). Thus, in clayey soils vertical air sparge wells have a distinct economic advantage due to the increased ROI.

Designers must look at the overall plan for the site. Horizontal wells may not be desirable for the air sparging portion of remediation, but a horizontal well may be desired for groundwater and free-product extraction initially or bioremediation efforts after the air sparging. In this case the horizontal orientation may be acceptable for air sparging as well.

Field studies are still needed to test the overall efficiencies and compare the advantages and disadvantages of vertical versus horizontal air sparge wells. One specific question will be concerned with which geometry will be preferable: the cone field of vertical wells or the extended triangle of horizontal wells. This and other questions are still in need of study.

Question #2 – Vertical or Horizontal Soil Vapor Extraction

Experience has shown both vertical and horizontal vapor extraction wells are effective and acceptable for SVE systems. Again, each orientation has its own applications for which it is better suited than the other. At this point the discussion will focus strictly on the well orientation, vertical or horizontal. With the horizontal SVE configuration, two options are available: a trench system or directionally drilled wells. This choice is covered in the next section.

Vertical wells have traditionally been the most used design. It is the only option feasible for deep contamination sites. Also, in layered soil profiles a vertical well can extend downward through several layers increasing its suitability, whereas a horizontal well would be confined to draw vapors mainly from the layer in which it is located. Vertical wells are similar in design to monitoring wells which makes installation immensely easier, assuming the specified well location is accessible at the surface. Additionally, a sand pack may be placed around the well favorably influencing air flow to the well.

When considering whether to use vertical or horizontal soil vapor extraction wells, one must consider the depth of the watertable. For shallow GWT's (<15 ft.) vertical SVE wells are impractical – horizontal wells must be used. Horizontal wells will minimize upwelling of the groundwater and allow greater coverage in shallow regions.

An important point to bear in mind regarding vertical versus horizontal wells will be the geometry of the capture (influence) zone. To better evaluate this consideration, one must consider the purpose of the SVE well system. Assume, as is often the case, that the well system is being designed to capture vapor laden air from an air sparging system. The vapors will be migrating upward and the purpose of the SVE system is to act as a capture net to prevent the vapors from migrating off-site or reaching the surface. To accomplish this, a solid horizontal (perpendicular) plane of influence is needed. Vertical wells in theory produce circular capture zones around the wells. For a solid plane to be created, the ROI's must overlap. If the system is not properly designed or the soil is more restrictive in certain pockets, gaps can be caused at the center of the circles. This can be minimized with proper design, but a horizontal well may be preferable due to the perpendicular plane being a solid sheet (assuming the well screen is not restricted). Figure 7.1 shows the two configurations.

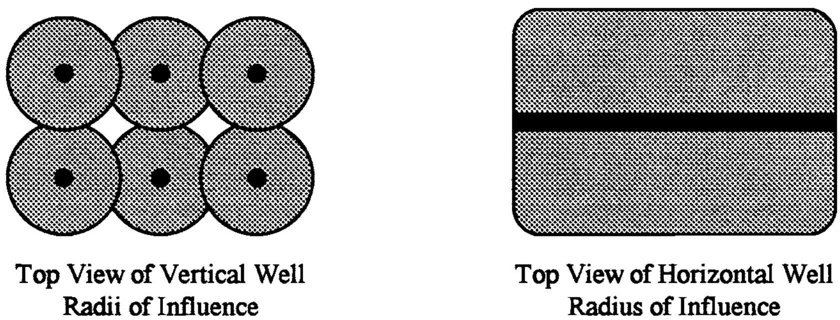

Figure 7.1 – Theoretical capture zones for SVE well configurations.

This argument assumes that the vertical length of screen (and, thus, the vertical depth of the capture zone) is not important, but rather the horizontal cross-section determines efficiency. This will not be the case, as mentioned, in layered soils where vapors must be drawn from several horizontal sections to prevent migration off-site. Added vertical depth may also be advantageous in heterogeneous soils where one should not rely on one horizontal plane being able to capture all of the vapors.

QUESTION #3 – TRENCH OR DIRECTIONAL DRILL FOR HORIZONTAL SVE

If the decision is made to use a horizontal soil vapor extraction system, the engineer must decide whether to use a horizontal trench system or a directionally drilled horizontal well. Trench design is the established technology which, among other items, adds a factor of certainty. A trench system is easier to install and allows flexibility in the layout over directional drilling. By flexibility, it is meant that one can turn corners and curves, or change the depth much easier than with directional drilling. A sand pack may be placed around pipe which will help keep clay and silt particles away from the slots of the screen section. Sand pack installation is virtually impossible with a horizontally drilled pipe. A pre-packed filter pipe must be used for directional drilling, but this increases cost significantly and adds design constraints. Additionally, trench design avoids adding fluids to the subsurface, as is the case with all horizontal drilling methods. Trench installation will also allow the engineer to inspect the condition of the pipe, especially the clearness of the slots. Horizontal wells must be accepted without substantial proof of condition.

While trenching is the traditional method, directional drilling offers many new advantages. Conventional trenching equipment can only extend to a depth of 7 to 9 feet below the surface. To go deeper, a backhoe would be needed. Backhoe excavation is a slow process and causes excessive damage to the site. A backhoe bucket is a minimum of 16" wide. When a 2" to 4" diameter pipe is to be used in the trench, 16 inches is excessive. However, directional drilling can reach greater depths and still provide the desired horizontal orientation.

Horizontal drilling eliminates the problem of sealing off a trench. It is nearly impossible to seal the edges and top of a trench pit. Air may then escape along the edge of the pit due to the lower resistance. Additionally, the cap on top of the trench must be able to reproduce the existing surface conditions. This is especially difficult at sites where vehicles will be traveling over the top of the trench. The cap must maintain the integrity of the pavement and prevent against permanent damage. With horizontal boring the only surface features are the entry and exit (for continuous boreholes) pits. These points are not large (usually less than a 5 ft. x 5ft. square) and can be situated in the least conspicuous area.

When the remediation is completed, a trench must be rehabilitated in an attempt to return the site to original conditions. This is nearly impossible. First, the subsurface texture cannot be returned after a trench has been excavated, especially in clayey soils. No amount of compaction will return the site to pre-trench conditions. Additionally, no cap or patch to an asphalt or concrete pavement will be able to regain the original integrity. Since boreholes are completely beneath the surface, no alterations (other than the hole itself) occur to the soil profile or breach of the surface features.

Directional drilling allows a well to be drilled below buildings and other surface obstructions where trenches cannot. Moreover, directional drilling also allows another major advantage – the elimination of "Commerce Disturbance". When a trench line is being excavated or placed, normal activities at the site are altered. At sites with vehicular traffic (i.e. filling stations) this may be a major concern. With horizontal drilling, normal activities may continue uninterrupted. This is an extremely important congeniality point to consider.

Trenching creates an indirect, often overlooked, problem – what to do with the excavated soil. The soil will most likely be contaminated. Horizontal boring drastically reduces the secondary waste. A plug of contaminated soil may be pushed out in front of the reamer on the pull-out of the drill string, but this will be much less material than with trench construction. Disposal of contaminated soils will add greatly to the cost. Select material must also be found to replace the excavated soils, again increasing the cost. Furthermore, unearthing polluted soils is not an option in certain areas because of air emission constraints.

Cost Considerations of Trenching vs. Directional Drill

According to officials with Ditch Witch, directional drilling installation costs range from $25 to $75 per foot for normal drilling to a depth of approximately 50 ft. Deeper depths will increase the cost due to the added cost of sophisticated guidance equipment. Additionally, horizontal wells require stronger well materials than the traditional Schedule 40 PVC. This will increase the horizontal well cost. Pre-packed filter pipe will also add significantly to the cost. These factors combine to make the horizontal well installation cost greater than the cost of a similar trench system. However, when a complete cost analysis is performed, one may find directional drilling more economical.

While excavation and piping costs are cheaper for trench systems, they do have several added charges. The excavated soil at a contaminated site is itself likely contaminated. This secondary waste must be disposed of properly. With the loss of this soil, select backfill material must be used. A bentonite layer and cap to match the surface will also add cost. An indirect cost at sites where traffic travels over the trench is the probable repair to the cap 6 to 12 months after installation. A future cost will be rehabilitation and repair to the site upon closure.

Considering all associated costs with each method, directional drilling is cost competitive with trenching. The engineer should not rule out horizontal drilling without proper consideration. The cost associated with each site will be unique.

CHAPTER VIII

SUMMARY AND CONCLUSIONS

PERRY-SITE CHANGES AND ACTIVITIES CONSIDERING HORIZONTAL DRILLING

OSU and ODOT officials used the information gained from the pilot study to complete a modified design. The pilot study had confirmed air sparging in concert with SVE was a viable method of remediation. The new design was customized to the Perry site for better efficiency and performance. After learning of the advances made in the use of directional drilling for environmental remediation wells, designers agreed a horizontal well rather than the designed trench was a desirable option for the Perry site.

The decision to switch to a horizontal well rather than the trench was based on several key points. One main concern with the trench design was how to seal the trench top while maintaining integrity of the asphalt cap. Traffic in this area is heavy and includes large maintenance equipment. Engineers were concerned with the traffic over the patchwork causing buckling at the edges. Directional drilling eliminates this problem in that the paving is not disturbed. Additionally, the directional drill reduces disturbance to the soil which is desirable for any remediation effort.

The design was modified to reflect this change. The depth of the vapor extraction well was set approximately 2 feet above the seasonal high GWT. This corresponded with the top of a sandstone layer, thus the line was drilled just above the rock layer. An alteration was also made along the southernmost SVE line. Originally, the line was halted just short of a gas line which extended out from the building. The gas line is an estimated 3 feet below the surface. Since the horizontal well will be deeper than 8 feet below the surface, the well may pass safely below the gas line. This allows the SVE system to extend closer toward the pump islands, the site of the original leak. This extension would have only been possible with the trench system if the trench were excavated and packed by hand around the gas line. Drilling allows the wellbore to pass below without concern.

Ditch Witch was the contractor secured to install the horizontal well system. They used the opportunity to train and demonstrate their drilling equipment to new owners and operators, while providing OSU an opportunity to test a horizontal well system (a truly innovative feature) as a part of the demonstration project. The original trench system would have provided a less expensive alternative, which would have been the desirable option to ODOT officials. The cost factor to ODOT would out-weigh the congeniality factor and other advantages. To other firms, the added cost may not have been enough to exceed the added advantages.

On February 27, 1995, Ditch Witch drilled the first borehole at the Perry facility. The line extended from the north edge of the remediation zone south through a connection pit and beyond the office building before surfacing. Slotted Schedule 40 PVC pipe had already been purchased for the trench design. While Ditch Witch officials were skeptical of the PVC withstanding the rigors of installation, an attempt was made to pull the pipe through the wellbore. As expected, the schedule 40 PVC failed in tension only a short distance into the hole and high density polyethylene (HDPE) pipe was recommended as a casing material.

Findings and Conclusion

With the passing of tough new standards by Congress in the early 1980's, demand increased for new technologies to remediate polluted soils and groundwater around the U.S. The traditional method of handling spills and leaks has been to pump the groundwater to the surface and to pass it through a subsequent treatment system. Unfortunately, pump and treat has many drawbacks, including its inability to clean residual contaminants below the groundwater table and a failure to address pollutants in the unsaturated zone.

Several innovative and proficient remediation technologies have been developed since the mid 1980's. Air sparging and soil vapor extraction are two of these methods. SVE is an established technique, while air sparging is somewhat newer and still being tested. Both technologies show signs of being efficient, cost-effective in situ remediation methods.

Air sparging is a procedure which introduces air through a well to the saturated zone some distance below existing groundwater contamination. As the air rises through the contaminant plume volatile components of the pollutant will volatilize into the air stream and be swept upward for removal. As this process continues, contaminant levels are reduced by the volatilization.

Soil vapor extraction operates on the same principle in the vadose zone. Air is drawn through the soil, volatilizing contaminants found above the groundwater table and capillary zone. This system may be used to capture vapor laden air from an air sparging process, thus aiding the groundwater remediation effort as well. The vapors are then brought to the surface for treatment and/or release.

Proper system design with all goals and requirements in mind is imperative for the efficient remediation of any contamination site. Air sparging coupled with soil vapor extraction addresses both contamination in the groundwater (where it is most critical and most often located) and the over-lying soils. To use such a system, the contaminants must be sufficiently volatile and the soils should be fairly homogeneous and permeable. This paper has shown that if the site and contaminants are suitable to these methods, IAS/SVE is very capable, cost-effective, and simple to design, build, and operate.

When designing an air sparging/soil vapor extraction system, the engineer's first major design decision must be on well configuration. From the arguments presented, the following may be concluded: *Vertical air sparging wells with horizontal soil vapor extraction wells should be given top consideration for well orientation.*

Vertical air sparging wells provide the engineer with added control not available with horizontal wells. With horizontal wells, the engineer will have no control of entry points of the air to the subsurface, other than the knowledge that air is flowing through the pipe. With vertical wells, he knows exactly where the air is being introduced and how much is flowing to that point. Flow rates may then be controlled or pulsed at different points across the remediation site with much greater ease and certainty. By varying air flow rates of adjacent wells the operator may increase agitation and in essence pulse each individual well, as opposed to the entire site, simultaneously.

Another major advantage to vertical air sparge wells is the ability to tailor the design to the specific site and pollutant characteristics. The diffuser depth is a very important specification for air sparge designs. Vertical wells allow the designer to place the diffuser of each well at a very specific elevation according to seasonal groundwater elevations, characteristics of the soil profile, or location of the contaminant plume. Additionally, vertical wells are easy to install, are much cheaper than directional drilling, can be extended deeper if needed, and can be constructed with a sand pack and diffuser. Vertical air sparge wells provide a number of significant advantages over horizontal wells.

Horizontal soil vapor extraction wells, on the other hand, appear to provide the advantage over vertical SVE wells. While vertical SVE wells do have their time and place (mainly in layer soils), horizontal wells appear to provide an advantage mainly due to their geometry. The capture zone of horizontal wells will provide a barrier to the surface. Vertical wells may allow dead zones which would allow air to pass, and they extend vertically through zones not needed in a capture system. It should be noted that this discussion is assuming that the SVE system is complimentary to an air sparge system and its main purpose is to capture air sparge off-gas. In cases where the SVE system's main purpose is remediate thick layers of soil contamination, vertical wells may indeed be better suited.

For sites with a shallow groundwater table, horizontal wells are the only option. Vertical wells would cause extreme upwelling and the radius of influence would be relatively small raising the number of needed wells. Horizontal wells are the accepted standard in shallow vadose regions. Notwithstanding, the engineer should still consider horizontal SVE at deeper depths. Horizontal drilling technologies have recently been adapted for environmental applications. This is making possible the use of horizontal wells at deeper depths than was possible previously.

Once one has decided to use horizontal vapor extraction wells, he or she should consider directional drilled wells should be considered as opposed to a trench design. The main parameters in making this decision will be cost and constructability (ease of installation). The effectiveness of the drilled well will be equivalent to the trench line in most cases.

The cost of installing a horizontal environmental well will be much greater than that of a trench. However, if one takes into account secondary waste disposal, cap construction, as well as future repair, the two methods are very similar in price. If the two designs are similar in feasibility and price, one considers congeniality factors. Directional drilling does not require the disturbance or destruction of existing surface features such as pavement. Not only will this maintain the integrity of the remediation cap (very important for SVE remediation efforts), it prevents permanent damage to the owner's property. Besides preventing damage to the site, horizontal drilling eliminates commerce disturbance. With most remediation projects taking place at gasoline filling stations, it is important for engineers to avoid hampering, or even halting, daily activities. This will save the owner lost earnings which should also be considered in the cost analysis. Finally, as boring produces less destruction at the site, it also produces less secondary waste. If the site is truly polluted, any excavated soil will have to be dealt with. Directional drilling techniques can leave the soil in the borehole, greatly reducing the amount of secondary waste.

In summary, vertical air sparging coupled with horizontally drilled soil vapor extraction is a unique remediation design which is simple, effective, constructable, and cost-efficient. These are the exact features needing to be met in today's environmental remediation field.

VITA

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