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Horizontal Configuration of the Lasagna™ Treatment Technology

User Guide

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Foreword

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The National Risk Management Research Laboratory is the Agency's center for investigation of technological and management approaches for preventing and reducing risks from pollution that threatens human health and the environment. The focus of the Laboratory's research program is on methods and their cost-effectiveness for prevention and control of pollution to air, land, water, and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites, sediments and ground water; prevention and control of indoor air pollution; and restoration of ecosystems. NRMRL collaborates with both public and private sector partners to foster technologies that reduce the cost of compliance and to anticipate emerging problems. NRMRL's research provides solutions to environmental problems by: developing and promoting technologies that protect and improve the environment; advancing scientific and engineering information to support regulatory and policy decisions; and providing the technical support and information transfer to ensure implementation of environmental regulations and strategies at the national, state, and community levels.

This publication has been produced as part of the Laboratory's strategic long-term research plan. It is published and made available by EPA's Office of Research and Development to assist the user community and to link researchers with their clients.

E. Timothy Oppelt, Director
National Risk Management Research Laboratory

Abstract

This report is a user's guide that discusses the technology and operations unique to the installation and operation of the horizontal configuration of the Lasagna™ integrated soil remediation technology. This technology, called Lasagna™ because of the layers of electrodes and treatment zones, has been developed to combine electrokinetics with treatment zones for use in low-permeability soils where rates of hydraulic and electrokinetic transport are too low to be useful for remediation of contaminants. The technology was developed by two groups, one involving industrial partners and the U.S. Department of Energy and another involving U.S. Environmental Protection Agency and the University of Cincinnati, who each pursued different electrode geometries. This report deals with the horizontal configuration where electrodes and treatment zones are installed by hydraulic fracturing in soil. This report covers a period from October 1993 to August 2001 and work was completed September 29, 2001.

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Acronyms and Abbreviations

Adc	Amperes, direct current
AFB	Air Force Base
AISI	American Iron and Steel Institute
ANGB	Air National Guard Base
bpf	Blows per foot
C	Centigrade
Center Hill	U.S. EPA Center Hill Facility
cm/sec	Centimeters per second
cm	Centimeter
cm^2	Square centimeter
CPVC	Chlorinated polyvinyl chloride
CRADA	Cooperative research and development agreement
DC	Direct current
DOE	U.S. Department of Energy
EK	Electrokinetics
EPA	U.S. Environmental Protection Agency
I.P.	Injection point
kPa	Kilopascal
kW	Kilowatt
m	Meter
NPT	National pipe thread
POTW	Publicly owned treatment works
PVC	Polyvinyl chloride
PVDF	Polyvinylenefloride
RCRA	Resource Conservation and Recovery Act
ROD	Record of decision
S/m	Siemen per meter
SCR	Silicon-controlled rectifier
SIMCO	Southern Iowa Manufacturing Company
TCE	Trichloroethylene
TM	Trademark
UC	University of Cincinnati
UIC	Underground Injection Control
V/m	Volts per meter
Vdc	Volts, direct current

1.0 Introduction

1.1 Technology Description

This report discusses the hardware and operations that are unique to the horizontal configuration of the Lasagna™ technology for in-place treatment of contaminated soil. The general topic of electrokinetic remediation is discussed in other publications. The U.S. Environmental Protection Agency's National Risk Management Research Laboratory (referred to here as EPA) entered into a Cooperative Research and Development Agreement (CRADA) with a Consortium of DuPont, General Electric, and Monsanto companies for this project. The goal was to develop and field test an innovative combination of technologies proposed by the Consortium for in-situ clean up of soils contaminated by hazardous waste (1). Investigators at the University of Cincinnati (UC) collaborated on the effort through the sponsorship of U.S. EPA. The U.S. Air Force is also collaborating with EPA on a large scale demonstration of the horizontal configuration of the technology.

Called Lasagna™ because of its layered configuration, the technology compensates for the low rate of movement of fluids and contaminants in response to an electric field by inserting closely-spaced treatment zones between electrodes. This shortens treatment time because liquids and contaminants have to move only a short distance before reaching a treatment zone. The treatment zones may use a variety of processes for trapping or treating contaminants in place and the electrodes may be emplaced either vertically or horizontally by several different geotechnical processes. Monsanto patented (2,3) the concept of placing treatment zones between sheet electrodes in subsurface soil and then using electrokinetics (EK) to move water (by electroosmosis) and ions (by electromigration) into the treatment zones. When a direct current electrical field is applied to soil it causes all water (and contained contaminants) and ions to move, thus allowing mobilization from fine-grained soil deposits where hydraulic flow alone would not be effective. Placement of treatment zones between sheet electrodes is the critical element in the Lasagna™ process.

Lasagna™ may be implemented in either a vertical or a horizontal configuration. The Consortium members investigated the costs and basic factors of the integrated technology (4,5) and demonstrated it at full scale (6,7) in a vertical configuration using a mandrel/tremie tube system to install electrodes and treatment zones downward from the soil surface (Figure 1-1) for inducing horizontal electrokinetic flow.

EPA agreed to develop and test the horizontal configuration because it offered the advantages of application at greater depths and the ability to use hydraulic flow in addition to electrokinetic flow. EPA also had experience with hydraulic fracturing, a process that can be used in soil to install the horizontal layers of materials needed for the electrodes and treatment zones. Hydraulic fracturing creates layers about 1 cm thick, 6 to 9 meters in diameter, and parallel to the soil surface (Figure 1-2). The hydraulic fracturing process had been adapted (from oil field practices) at the EPA Center Hill Facility for installation of horizontal layers of granular materials in certain types of soils (8-13).

A direct current power supply is connected to the electrode layers, the upper electrode being positive (anode) and the lower electrode negative (cathode). When an electrical field is applied to soil, the water, ions, and other contaminants in soil within the field move uniformly by electroosmosis or electromigration. This allows extraction of contaminants from areas of soil that would be bypassed by hydraulic flow. Liquids are pumped from the cathode to maintain downward flow and enhance EK transport of contaminants and water toward the cathode. Contaminants are degraded as they are brought into contact with the treatment layers by electromigration (ion movement relative to bulk water) or electroosmosis (advective movement of water and contaminants).

One of the likely effects of EK is to move contaminants out of low-permeability zones that would be bypassed by hydraulic flow. See, for example, the laboratory studies with isolated lumps of clay in columns of sand (4). Once in higher permeability zones, contaminants can be transported by the more rapid hydraulic flow. Volumetric fluxes from EK were

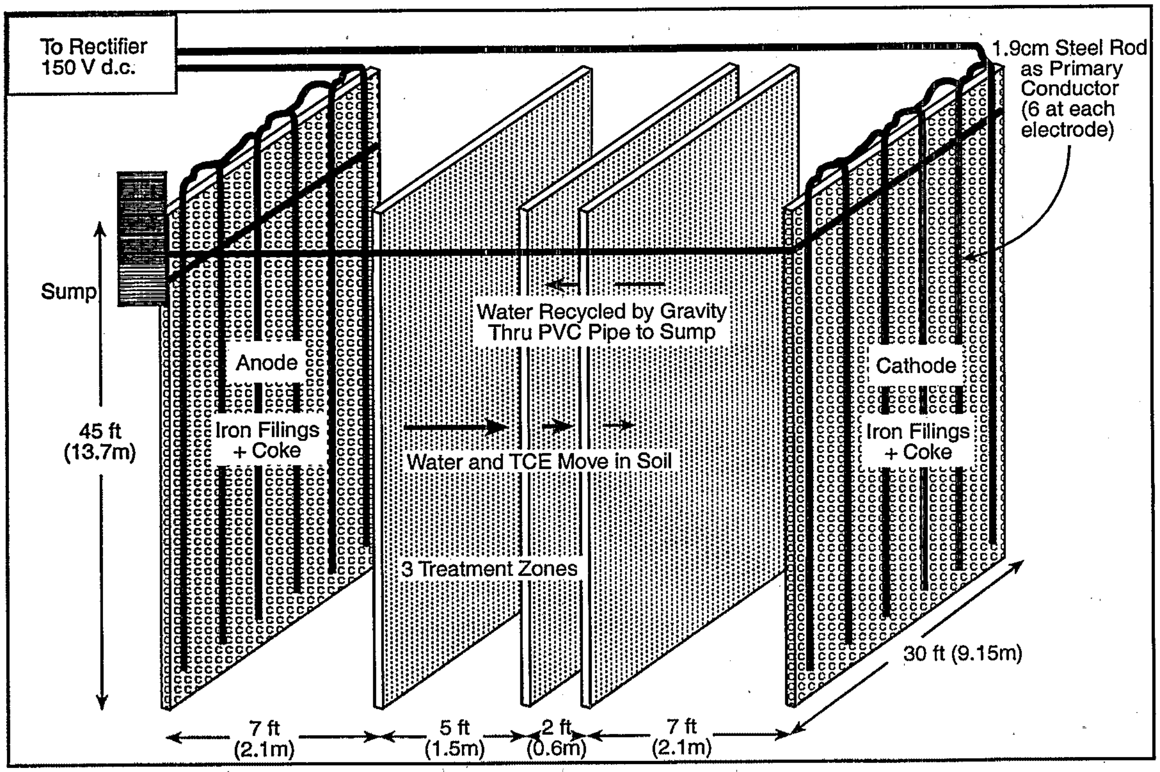

Figure 1-1. Lasagna™ vertical configuration.

on the order of 10^{-8} cm/sec (4) in clay soils. The horizontal configuration can take advantage of both hydraulic and EK transport processes because water is injected at the upper electrode (anode) and pumped out of the lower electrode (cathode). In the vertical configuration, EK is the dominant transport process because both electrodes are at the same elevation.

1.2 Technology status

The Consortium conducted small- and large-scale tests of the Lasagna™ vertical configuration at the DOE Gaseous Diffusion Plant in Paducah, KY. Both tests removed substantial amounts of trichloroethylene (TCE) and demonstrated that the technology was successful and economically competitive with other soil treatment technologies (6,7). After intensive scrutiny by both DOE and the EPA Region IV in several technical meetings during and after the tests at Paducah, EPA Region IV signed a Record of Decision (ROD) in August 1998, specifying the vertical configuration of Lasagna™ as the backup technology for the remaining TCE-contaminated soil.

The parties involved in the work at the Paducah plant believe that the vertical configuration of Lasagna™ offers significant cost advantages for cleanup of low permeability (clayey and silty) soils contaminated with weakly bound (relatively soluble) compounds such as TCE (7). The technology has been proven at several scales in field tests and is available for application from a commercial source, the Terran Corporation in Dayton, OH. It has support from a number of groups who were involved in its development and has the potential to improve the speed and cost-effectiveness of future cleanup activity.

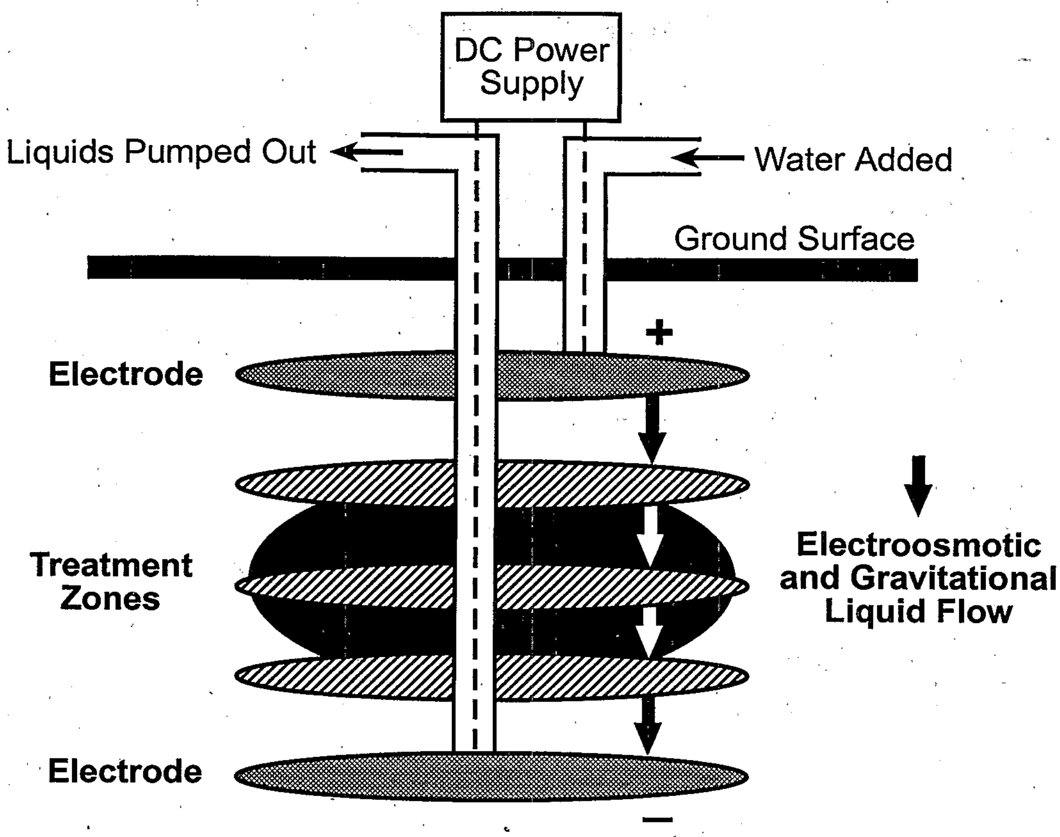

Figure 1-2. Horizontal configuration Lasagna™ cell.

The Lasagna™ horizontal configuration has been tested at small scale and a large-scale test is currently underway. EPA scientists conducted laboratory and field studies and funded assistance agreements with the University of Cincinnati to work on the emplacement and operation of horizontal electrodes and treatment zones using hydraulicfracturing. The Ohio Air National Guard, the U.S. Air Force, and Chemical and Environmental Control Systems (CECOS) International provided materials, infrastructure, and access to sites for work on the horizontal configuration.

Under assistance agreements with EPA, the University of Cincinnati conducted cooperative laboratory work and field studies in clean soils (14,15,16,17) at the EPA Center Hill Facility in Cincinnati, OH and a site near Williamsburg, OH to develop and test the technology and procedures for using horizontal hydraulic fractures as electrodes. Horizontal Lasagna™ cells with zero-valent iron treatment zones and biological treatment zones were also installed and operated, first by UC and later by EPA, in soils contaminated with trichloroethylene (TCE) near Columbus, OH (18,19). This work has developed and tested the use of hydraulic fracturing for installing the layers, making electrical and hydraulic contact with the electrode layers, and methods for operating the Lasagna™ cells. The U.S. Air Force has provided a site and facility support for a large-scale test of the horizontal Lasagna™ process for treating TCE-contaminated soil at Offutt Air Force Base (AFB) near Omaha, NE. The feasibility tests were conducted at this site by UC; the cells were installed by EPA and are currently in operation. The development history, technology and operational experience, and results from pilot studies in contaminated soil were summarized and reviewed; these indicated that it was feasible to implement the horizontal configuration in a field installation (20).

The vertical configuration of Lasagna™ has been demonstrated on a larger scale than the horizontal configuration and the package of skills needed for the vertical configuration are available from a single source (Terran Corp., Dayton, OH). The feasibility of installing and operating a horizontal configuration has been well demonstrated (20); the cost-effectiveness and expected contaminant removal efficiencies are not as well established. The unit operations for implementing horizontal Lasagna™ are available from several different commercial sources; they would have to be gathered into a team to operate an installation.

1.3 Scope of this report

This report discusses the technology and operations that are unique to the horizontal configuration of Lasagna™. The general topics of electrokinetic remediation and hydraulic fracturing are covered elsewhere and are not discussed in this report. See references 21 through 29 for information on electrokinetic remediation and references 8 through 13 for information on hydraulic fracturing. Hydraulic fracturing has been used to create horizontal layers with a variety of materials, and no major problems have been encountered installing horizontal electrodes or treatment zones. The major problems are maintaining flow of liquids and electrical current in the electrode layers.

The remainder of the report covers five significant aspects of use of the horizontal configuration. Section 2 discusses the design, materials, and testing needed for installation of electrodes and treatment zones. The handling of fluids that are added to or removed from electrodes is covered in Section 3. The next major topic, in Section 4, is the conditioning, control, and supply of electrical power to the electrodes. Section 5 discusses monitoring of the process to guide adjustments and maintenance. Section 6 provides some basis for selecting either the vertical or horizontal configuration of Lasagna™ at a particular site.

Very little of the information in this report has been published elsewhere. It is a summary of the authors' experiences with the design, installation, and operation of nine horizontal configuration cells at four different locations over a period of seven years. These have ranged in size from small (10 ft. diameter) research installations to the full-scale (30 ft. diameter) cells that were tested at Offutt AFB, NE. A few data from these cells are presented in this report to demonstrate how such data may be used to identify problems and to assess the progress of treatment. The data are intentionally limited in scope and are not presented to test the hypothesis that the horizontal configuration can effectively treat contaminated soil. That objective will be addressed in a later paper.

2.0 Installing Electrodes and Treatment Zones

2.1 Feasibility testing

It is necessary to conduct a hydraulic fracturing feasibility test at a site being considered for a horizontal Lasagna™ installation because hydraulic fracturing will be used to install the electrode and treatment layers. The ideal approach is to install sand-filled fractures at a location that is either near the area proposed for the horizontal Lasagna™ installation or at least in soils that have the same physical characteristics such as state of stress, particle size distribution, and bearing strength as measured by blow counts. Feasibility testing is most convenient in uncontaminated soil because soil samples must be collected and examined. The information to be gathered during feasibility testing is:

- depths at which horizontal fractures can be created
- fracture inclination
- fracture thickness
- fracture shape (in plan view)

It must be possible to create horizontal hydraulic fractures at the depths of contamination if a horizontal configuration is to be installed. at the site. If test fractures rise to the surface near the injection point (vent) they will be too small and steeply dipping to be useful as electrodes or treatment zones. Fracture inclination (dip) is characteristic of a site and is influenced by soil properties in ways that are not well understood. Fracture inclination is determined by measuring the depth to the fracture at several distances from the injection point. The inclination of fractures is important because it affects the ability to control the spacing between electrode fractures. See Section 2.5 below. The thickness of a fracture is not usually an issue for graphite-filled electrode fractures. Relatively thin (0.5 to 1.0 cm) fractures seem capable of satisfactorily transmitting liquids and electrical power. Fracture thickness may be a critical issue for treatment zones if these need to contain some minimum mass of material. See the Section 2.6 (below) on treatment zones.

Hydraulic fractures are rarely symmetrical. The ratio of the longest dimension to the shortest may range from 1.1 to 1.8, with 1.2 being the most common value. If test fractures are highly elongated, the shape will be a consideration in determining the number of cells that will provide coverage of the contaminated area. Fracture shape is inferred from measurements of the changes in ground surface elevation after a fracture is installed. In most soils the surface uplift will approximate the thickness of the subsurface fractures with the highest point some distance from the injection point.

2.2 Pre-installation soil sampling

Care must be taken during any pre-installation soil sampling to avoid creating places where materials can vent/flow to the surface during hydraulic fracturing. Thus, any pre-installation soil sampling will have to balance the competing needs to gather information about contaminant distribution in soil and the requirement to prevent venting during fracturing. Fracturing can be conducted successfully in the vicinity of bore holes that have been completely plugged. In the horizontal configuration cells at Offutt AFB there were several locations that had been sampled and backfilled with bentonite pellets a year earlier; these did not vent to the surface (leak) during installation of the electrode and treatment zone layers. We do not know any way of predicting when bore holes have been completely plugged; therefore it is desirable to avoid pre-installation soil sampling in the area where a horizontal cell will be installed. Site records should also be used to identify sampling locations from previous investigations. If other factors are equal, small borings by machines such as a Geoprobe may be less of a problem than the larger hollowstem auger borings.

2.3 Access wells for electrodes

The casing for electrode access wells must be made of a non-conductive material because the casing will be in a strong electrical field and could short circuit between the electrode layers or conduct electricity to the surface where it would be a hazard to personnel. The most likely material for such casing will be polyvinyl chloride (PVC) or chlorinated polyvinyl chloride (CPVC). CPVC retains strength at higher temperatures. We have not yet encountered any temperature-related problems with PVC electrode well casing and it has been used successfully in a number of installations (14, 15, 16, 17, 18, 19, 20).

The casing should be at least 3 inches nominal diameter for the cathode well to allow space for pumps, sensors, and electrical connections to fit inside it; the anode casing may be smaller, depending on the type of electrical connection to the granular graphite and the sensors employed. The casing should also have flush (smooth) threaded joints and be either schedule 80 or 120 because it will be driven some distance into the soil. It is advisable to select the size of the casing after all the other down-hole components have been identified and their sizes are known. If there is very little extra space it would be useful to add devices to hold components to one side to allow space for those installed later.

The upper electrode (anode) should be installed first, then the treatment zones, and finally, the lower electrode (cathode). This recommendation is not unique to Lasagna™; it applies to any installation where horizontal hydraulic fractures are placed one above the other (8). When a hydraulic fracture is propagating outward from the injection point and encounters an existing boring, even one that is thought to be well sealed, there is a risk that the fracture will vent to the surface. When a casing has been driven directly into soil or into an undersized hole, a good seal is created and there is only a slight risk of another hydraulic fracture venting upward along the side of the casing. This risk can be avoided entirely by always creating a new fracture below the depth of any existing fracture. The other potential problem with fracturing at the depth of an existing casing is the shadow effect (see Figure 2-1). When a growing fracture encounters a vertical casing or other large object it propagates around it but often does not close upon itself on the other side of the object. This is a minor problem for an electrode fracture because a sheet electrode will create a satisfactory electrical field even if the electrode has some holes in it. (Chen, Jiann-Long, Personal Communication) It could be a more significant problem for a treatment zone since water and contaminants could pass through the shadow zone or hole without being treated.

Most soils in which horizontal hydraulic fractures can be created are relatively stiff, on the order of 15 blows per foot (bpf) with a 140 pound hammer dropping 30 inches onto a 2-inch split spoon sampler. In such soils, PVC casing of sufficient size for electrode wells cannot be driven without some preparation of the hole. We have successfully installed PVC casing by beveling the leading edge and pushing the casing into a hole approximately the same size as the outside diameter of the casing. This hole is terminated about 4 feet above the depth at which the fracture will be created. The casing is sealed into the soil and driven the remaining distance by boring inside the casing either by hand or with a drill rig. A hole is bored about a foot ahead of the casing, the casing pushed or hammered to refusal, and then another short hole is bored ahead of the casing. This is repeated until the casing has reached the depth at which the fracture will be created. Boring inside the casing and driving it into an undersized hole insures a seal between the casing and soil and prevents leakage up the outside of the casing during fracturing. Although schedule 80 or 120 PVC casing is both strong and rigid, it has enough flexibility to conform to slightly irregular holes and provide a good pressure seal. When the casing has been driven to the desired depth, an open (un-cased) hole should be bored about 4 inches deeper to allow space for notching the soil and creating the hydraulic fracture.

The soils at Offutt AFB were extremely soft, 1 to 2 bpf. In these soils, a hollow stem auger was advanced about 10 feet from the surface in order to bypass and seal off the sandy materials near the surface. The casing was driven inside the auger the remaining distance using a hydraulic hammer. The end of the casing was sealed with a pointed plastic plug pushed about 4 inches deeper with a drill rod once the casing had been driven to the desired depth.

These methods for installing access wells require some skill and experience. An obvious and apparently simpler approach would be to drill a hole larger than the casing and then grout the annulus between the casing and the soil to prevent venting to the surface during hydraulic fracturing. Even when a seal could be maintained by using a non-shrinking grout, the installation resulted in problems with notching the soil at the bottom of the hole or with the fracturing process itself. Eventually we abandoned this approach and used some variation on a driven casing to install electrode wells.

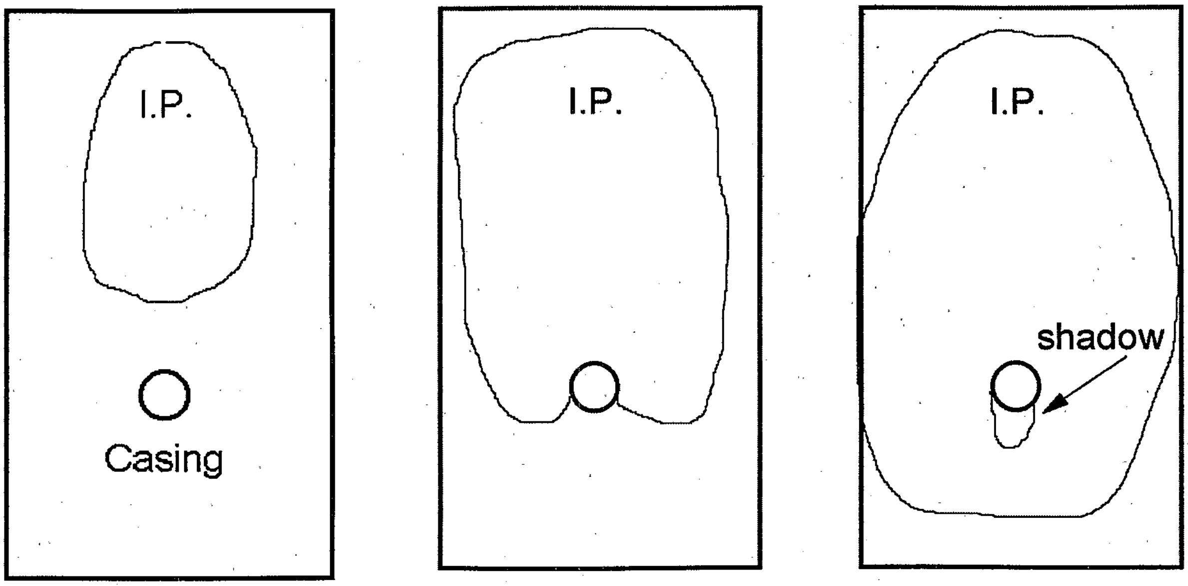

Figure 2-1. Plan view of hydraulic fracture propagating from injection point (I.P.) toward casing; shadow (unfractured area) develops behind casing

2.4 Electrode material

In the large-scale demonstration of the vertical configuration (7), the electrodes were 1.5 inch (3.8 cm) sheets of 50/50 by volume iron filings and Loresco coke with 1.9 cm steel rods driven into the electrode material at six locations to make electrical connection. The electrical conductivity of the electrodes was 4.5 S/m, about 200 times greater than the electrical conductivity of the surrounding soil.

This kind of material could not be used for electrodes in the horizontal configuration because of problems related to the thickness of the electrode. Hydraulic fractures may be several cm thick near the injection point (electrode access well) but usually decrease in thickness to 0.5 to 1.0 cm at several meters from the well. The material in a fracture of this thickness must conduct both water and electricity for the horizontal configuration Lasagna™ cell to function properly. Several different sizes of carbon materials were tested as potential electrode materials (20). Graphite, 20 x 35 mesh size, was used most frequently. Its unloaded hydraulic conductivity was 1.2×10^{-3} cm/sec (14). This has been sufficient for adding or removing liquids from an electrode and for minimizing blockage of hydraulic flow by gases generated in electrolysis. The wet electrical conductivity ranged from 55 to 630 S/m at confining stresses from zero to 30 kPa. (20). This electrical conductivity was great enough to provide a sharp contrast between the electrical conductivity of the electrode fracture and surrounding soil and to allow electrical connection between the power supply and the electrode at only one point, in the electrode well.

Graphite is the most satisfactory material we have tested. Its electrical conductivity is high enough to create a strong contrast between the electrical conductivity of the electrode fracture and the surrounding soil, so that most of the electrical power will be conducted through the electrode fracture and only one contact point between the electrode fracture and the power supply is needed. Larger particle size (e.g. 10 x 20 mesh) might provide better water flow and release of electrolysis gases. Particle size is not an issue for hydraulic fracturing. We have created fractures using material that passed a 1/4" (0.64 cm) screen and recovered the larger particles in soil samples 12 feet (7.4 m) from the injection point. As the particle size is increased, the grain-to-grain contact may decrease enough to reduce the bulk electrical conductivity.

If the use of a larger particle size is being considered, tests of wet electrical conductivity are recommended and some of these tests should be under confining stresses similar to the (soil) overburden stresses at the depths where the electrode fractures will be installed.

2.5 Electrode spacing

The distance between the electrodes affects the intensity of the EK effect and the speed of the treatment process. There are four factors to consider in selecting the spacing between electrodes for the horizontal configuration:

- Lack of control of fracture slope
- Relationship between electric field strength (V/m), and processing time
- Heating limits on power supplied to an electrode
- Treatment zone installation

The majority of hydraulic fractures exhibit some slope upward as they propagate away from the injection point. This slope may range from 0.8 to 25 degrees. Unpublished data from the University of Cincinnati suggest that at the 95% confidence level the slope of any fracture at a particular site will be within 10 degrees of the average slope for all fractures at the site. The slope appears to depend strongly on conditions at the site; which site conditions affect the slope are not known. Soils with sharp contrasts in particle size (texture) are the exception. In these soils, fractures will often propagate along the contact between two layers of soil when there is a difference in particle size. If the soil layers are horizontal, the fractures will follow the layer and remain horizontal. In any case, the slope of the fracture cannot be controlled; soil conditions control the slope. If soil conditions change within relatively short vertical distances, fractures at the same location may have different slopes at different depths. Thus the distance between two electrode fractures may increase, remain the same, or decrease as distance from the injection point increases.

The rate of movement of liquids and ions is directly proportional to the electric field strength, the applied voltage divided by the distance between the electrodes. Treatment time is affected by the rate of movement. There is a direct relation between electric field strength and treatment time in the vertical configuration where EK is the primary transport mechanism. The relation is less clear in the horizontal configuration because both hydraulic flow and EK are present as transport mechanisms. An electric field strength of 50 V/m is often recommended as a starting point for design but lower field strengths may be sufficient in the horizontal configuration because EK mobilizes contaminants from low-permeability zones and may need to move them only short distances before they encounter gravitationally induced hydraulic flow. See Alshawabkeh et al. (24) for a discussion of electrode design and treatment time and a graph of treatment time versus electric field strength.

Heating in the well for the electrode may limit the power that can be supplied to a horizontal configuration Lasagna™ cell and, hence, the maximum electrode spacing. See Section 4.2 (Temperature Protection) below. In the vertical configuration (Figure 1-1) the top of the electrode is accessible and a sufficient number of connection points can be inserted to supply and distribute the power without problems. In the horizontal configuration (Figures 2-2 and 2-3) the space in the electrode well is limited and power is supplied to the graphite fracture at a single point. Even under optimum conditions this is a small contact point and will have a finite capacity to transmit power without overheating.

In the horizontal cells at Offutt AFB we were using a power supply that fixed the applied voltage and allowed the current to float i.e., vary in response to conditions in the cell (see Section 4.1 below). Voltage was adjusted by changing the connections on a multi-tap isolation transformer. We initially set the potential at 68 volts which corresponded to an electric field strength of 44 V/m and the cell drew 72 amperes. After several days the cathode connection began to overheat so the potential was reduced to 49 volts which corresponded to 32 V/m and the cell operated satisfactorily for a long period, drawing 50 amperes. Selection of electrode spacing must take into consideration the amount of power that can be supplied to the cell.

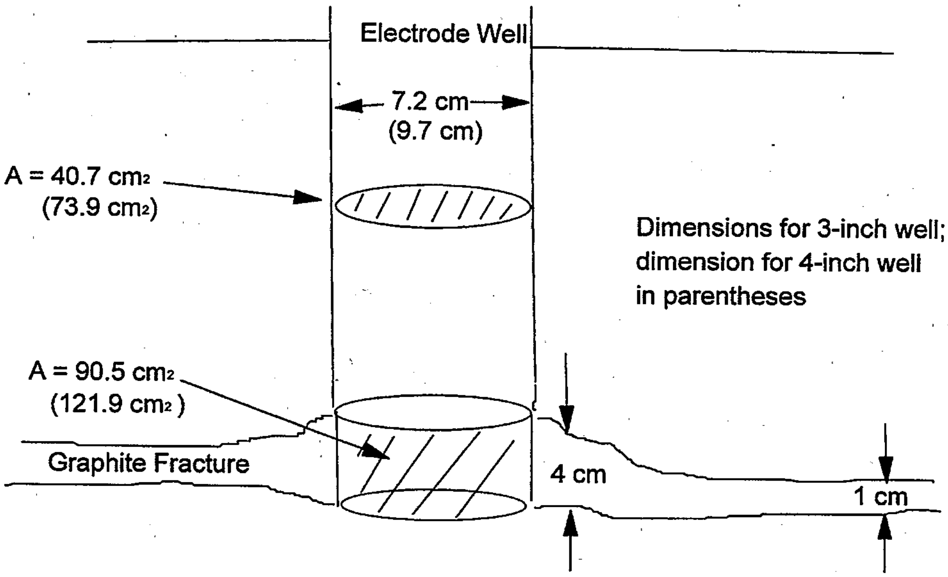

Figure 2-2. Electrode Well Dimensions

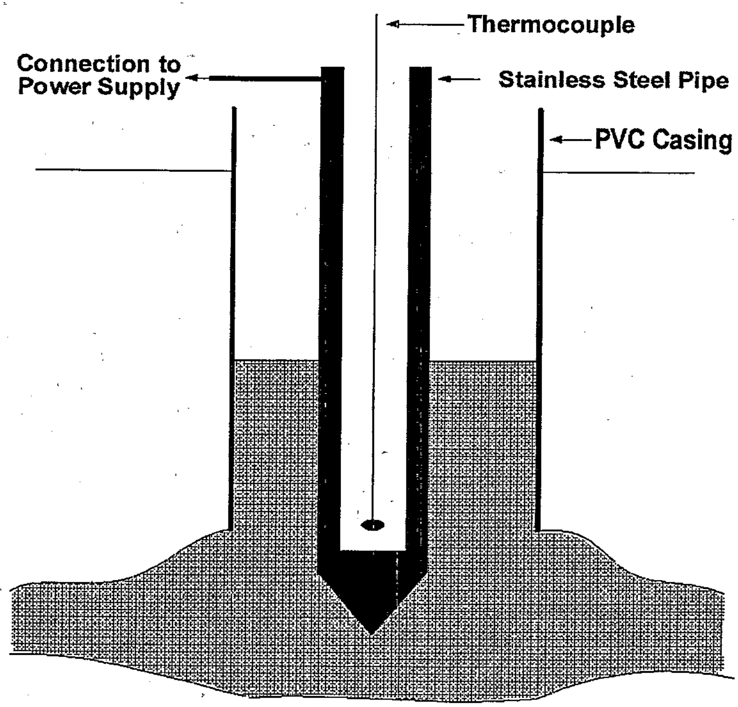

Figure 2-3. Connection to Graphite Electrode Fracture. Connection and PVC Casing Drawn to Scale

The final consideration in selecting the distance between electrodes is the space needed for installation of the treatment zones. As noted in Section 2.6 (below), the minimum vertical spacing between hydraulic fractures is between 9 and 12 inches (23 to 30 cm). The amount of material in a treatment zone (fracture) will be limited by the thickness of the fracture, and the thickness can be modified only slightly changes in the hydraulic fracturing process. If the treatment scheme requires a certain mass of material (e.g. zero-valent iron), there must be enough space between the electrode fractures to install the number of treatment fractures that will contain the needed total amount of treatment material.

2.6 Treatment zones

Treatment zones may be installed with or without permanent access wells depending on how the zone will function. The biological treatment zone at Rickenbacker Air National Guard Base (ANGB) (19) was connected to the surface by several wells for injecting gases in the center of the zone and venting around the edges. This treatment zone required periodic additions of methane to stimulate the methanotrophic microorganisms that had been inoculated into the zone to degrade trichloroethylene. For a treatment zone that requires a permanent connection to the surface, it is best to leave the injection well in place and use it for access to the zone. There is often a problem in installing an access well after the fracture has been created. Smearing of soil at the junction between the well and the fracture can be difficult to remove when the fracture is at a substantial depth and smearing will block the transfer of liquids and gases between the access well and the fracture.

The zero-valent iron treatment zones at Rickenbacker ANGB (18) and at Offutt AFB (20) did not have permanent access wells because the treatment process did not require any. For treatment zones such as these, a well may be installed for creating the treatment fracture and then removed. Another successful approach uses a direct push soil sampler as the access for creating the fracture. We used an Earthprobe 2000 on a SIMCO drill rig but other samplers such as a Geoprobe may be used in a similar fashion. The Earthprobe has an outer casing about 1.25 inches in diameter. The outer casing and an inner rod with a point to seal the bottom end of the casing were driven together to the depth for fracturing. The inner rod was pushed a few inches deeper to create a cavity below the casing for notching the soil and injecting the treatment zone material. The top end of the casing was threaded for 1.25 inch male pipe thread so the fracturing well head could be attached. After one treatment zone was installed, all materials were removed from the outer casing by flushing with water, the inner rod was replaced and the casing and rod driven to the depth for the next treatment zone. When all treatment zones had been installed, the Earthprobe casing was removed and the hole backfilled with bentonite pellets. Other methods for pumping fluid grouts are available and would likely work as well as the bentonite pellets.

The total mass of treatment zone material installed by hydraulic fracturing is limited by the installation process more than is the case for treatment zones in the vertical configuration. The thickness of an individual fracture can be increased slightly by adjusting the viscosity of the gel and increasing the solids content of the mix but most fractures will be about 1 cm thick. The vertical spacing is also limited. In many soils, fractures can be installed with 9 inches (23 cm) vertical spacing but it is safer to install them at intervals of 12 inches (30 cm) or more to avoid unplanned intersection of the fractures. Given these physical limitations of the process, it may not be possible to place sufficient mass of treatment zone material in soil to achieve the desired residence (contact) time in the treatment zone for water and contained contaminants before they reach the cathode and are removed from the treatment system. If this is a problem the system can be shut down (both the power and pumping from the cathode) periodically to increase residence time in the treatment zone or the fluids can be passed through a filter/treatment system after they are pumped from the cathode.

Whether the hydraulic fracturing machine operates in a batch or continuous-mix mode, there will be a system for feeding solids into the mix. When working with iron powder or filings for a treatment zone, care must be taken to clean the solids feed system thoroughly after fracturing. Some granular iron will remain in the system and will gradually corrode though contact with moisture in the air and fuse into a solid mass. A year after we installed the Lasagna™ cells at Offutt AFB, we were installing some sand-filled fractures and encountered a major problem with the machinery jamming and stalling the pump engines. When the feed system was disassembled we found that solidified masses of iron powder had reduced the feed path to about 5% of its normal size. The iron was removed by breaking it up with a crow bar. It came out easily in chunks from 1-inch thick to the size of a hand. It would have been much easier and more convenient to have cleaned the feed system before the iron fused into a solid mass.

3. Fluid Management in Electrodes

The horizontal configuration (see Figure 1-2) is most efficient if the anode is the upper (positive) electrode and the cathode the lower (negative) electrode. With this arrangement of electrodes the EK and gravitational fields move water downward and have an additive effect. For this process to function, water must be supplied to the anode and removed from the cathode, both of which are porous. If water is not removed from the cathode, the EK will cause water to accumulate at the cathode and gradually build a hydraulic head that opposes movement by EK and stops the process (14, 15, 16). Water movement must be maintained because it transports contaminants to treatment zones.

When the anode is installed below a water table, water will be supplied naturally and no additional water is needed. In our installations, the water table was near the anode level but provision was made for water supply because of anticipated seasonal fluctuations. A pressure transducer was set in the well and connected to a system for maintaining the water level at a point above the transducer. The set point was adjustable to allow tests of the effect of water level on temperature in the well.

Adding excess water to the anode increases the risk that contaminants will be transported laterally out of the cell as well as vertically downward through the treatment zones. The depth of water maintained in the anode well should be selected based on the potential for such lateral transport. Several piezometers in the cell just above the anode fracture and another piezometer outside the cell at the same depth will provide the information needed to calculate the lateral hydraulic head gradient (driving force). Multiplying the lateral hydraulic head gradient by the lateral hydraulic conductivity gives the lateral flow rate. An acceptable lateral flow rate is specific to each site, depending on considerations such as distance to adjacent uncontaminated soil, monitoring wells, and the need to track the mass balance of contaminants. Once an acceptable lateral flow rate has been estimated, it is possible to back-calculate to determine an acceptable water level for piezometers in the Lasagna cell. Note that piezometers must be installed in soil outside the electrode because water levels measured in electrode wells are not a reliable measure of water levels in soils at the same level. Gases are generated in both electrodes by electrolysis of water. This gas generation interferes with water movement in the cathode to a greater extent than in the anode because the gas production is greater (20). The set point for the water level in the anode well must be adjusted until the water level in the piezometer(s) in the cell is achieved. A pressure transducer in a piezometer might be used to control water addition to the anode well but some kind of control system would still be required in the anode well to prevent over-filling which would present an electrical hazard or running dry which would interfere with the electroosmotic process and cause overheating of the anode.

In the cathode well another pressure transducer measured the water level and a pneumatic bladder pump (Cluxton Instruments, Inc.) was used to lower the liquid level and induce flow from the cathode into the well. There are many other pumps that serve equally well. See, for instance, the pump on page 60 of reference (28). The only requirements are that the pump materials be resistant to high temperatures and pH that may be as great as 10. See the list of temperature and pH-resistant materials in Section 4.2 (Temperature Protection). This pumping of cathode fluids insures that EK flow will not be blocked and contaminants will continue to move through the treatment zones.

Water pumped in from soil surrounding the cathode also counteracts the resistance heating at the contact between the cable from the power supply and the granular graphite in the electrode fracture. Because fine graphite particles caused problems in the pump check valves and in the volume measuring system above ground, a screen was wrapped around the pump intake. To prevent clogging of this pump screen, water was injected periodically inside the screen to back-flush it. We noted temperature increases in the cathode well that coincided with the pump screen flushing cycle (Figure 3-1). We speculate that the temporary increase in fluid level in the well blocked inflow from the graphite electrode and resulted in the observed temperature spikes. The interval between pump screen flushes was gradually increased from 30 minutes to 6 hours; this kept the pump operating and greatly decreased heating associated with the pump cycle.

Gases are generated in the electrode fractures due to electrolysis of water. Oxygen is generated at the anode and hydrogen at the cathode with the volume of hydrogen being twice that of the oxygen. These gases block pore space

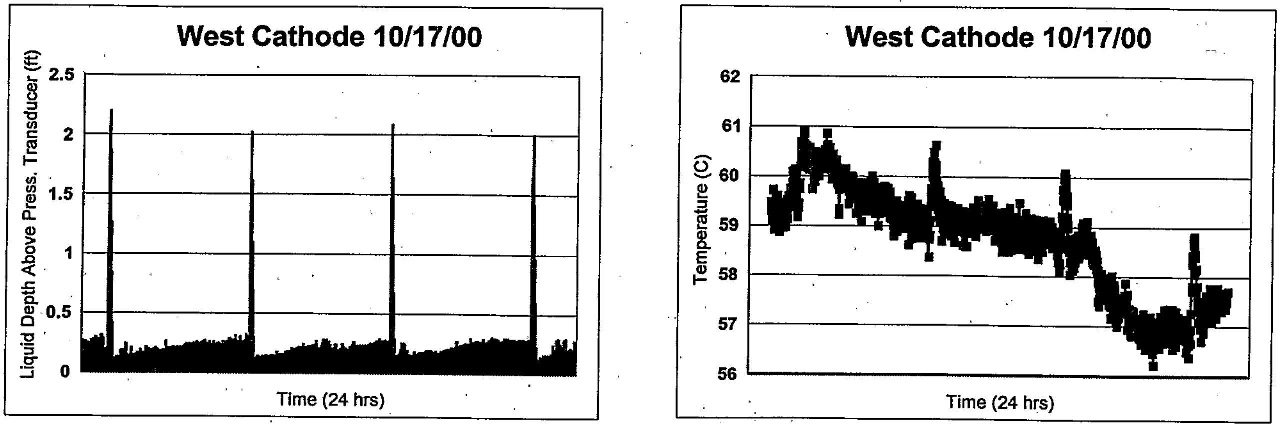

Figure 3-1. Simultaneous Increases in Fluid Depth and Temperature in a Cathode Well

in the electrodes and reduce their fluid transmissivity. The installation at Offutt AFB is at twice the depth of previous horizontal configuration cells (20). We speculate that the increased depth is the reason why restriction of fluid flow by gases is less of a problem than at previous installations but we do not yet have data to test this hypothesis.

In the vertical configuration demonstration (Figure 1-1), fluids were recycled from the cathode back to the anode. This was accomplished with a gravity drain located slightly below the original ground surface. Since the fluids were never brought above the ground surface, the treatment was completely in situ. Thus the operation was not subject to the provisions of the Resource Conservation and Recovery Act (RCRA) or the Underground Injection Control (UIC) program which would have required removal/destruction of contaminants before fluids were re-injected into the anode..

In the horizontal configuration demonstration at Offutt AFB we are not recycling fluids from the cathode to the anode because of concern about plugging the graphite pack in the well and the anode fracture. The space in an electrode well is quite limited (Figures 2-2 and 2-3) and is easily plugged if the fluid pumped from the cathode contains particulates, precipitates, flocs etc. We have observed these in previous small-scale studies (14-19) and have experienced problems with recharge of fluids into the anode due to plugging.

Fluids pumped from the cathode are considered groundwater. Groundwater itself is neither a solid waste nor a hazardous waste. When the groundwater contains hazardous constituents above health-based levels, it is subject to all applicable RCRA requirements. If groundwater is passed through a filtering system (e.g. activated carbon) and all constituents are reduced below health-based levels, the groundwater no longer contains hazardous wastes and does not have to be managed as hazardous under RCRA. The recharge of treated cathode fluids to the anode would still be regulated by the UIC program and the state or municipality will have their own requirements that have to be met for discharge to a publicly owned treatment works (POTW) or storm sewer. We have found the requirements for discharge to a POTW (40CFR304.1 - 304.6) to be less restrictive than those for the UIC program (40CFR144-148).

4. Electrical Power Management

A direct current (dc) power supply is connected to the Lasagna™ cell (see Figure 1-2) to induce EK transport, electroosmosis for water and electromigration for ions. When an electrical field is applied to soil, the water, ions, and other contaminants in soil within the field move uniformly. This allows extraction of contaminants from areas of soil that would be bypassed by hydraulic flow, the majority of which occur in large pores and channels between soil structural units. (21, 22, 23,24).

4.1 Power supply

A series of power supplies were built for the different sites, increasing in size from 9 kW in the beginning tests at Center Hill (16), to 40 kW at the Offutt AFB site. These power supplies share four common elements: (1) a fused safety disconnect switch connected to the utility line power, (2) some type of controller, (3) an isolation transformer and (4), a rectifier to convert to direct current. These power supplies were custom-built to keep costs down, save time, and because no suitable units were available commercially. The sizes of the power supplies vary because of the increasing scale of the field tests.

The controller in the 9 kW power supply was an electromagnetic coil design, using a saturable reactor coil, that could be adjusted to set the current (Adc) delivered to the Lasagna™ cell. The potential (Vdc) was allowed to change in response to the effective resistance of the cell. Operation in this constant-current mode was selected because much of the bench scale work done by others used constant-current mode (21, 22, 23, 24) where it was unclear how much current would be drawn from the power supply. This experiment had not been conducted previously in an open system field test without boundaries. This type of magnetic coil design is very robust, and could operate without damage to the power supply, even with a direct short in the cell. This first power supply used single-phase 208 Vac line power. This design was chosen to minimize the cost of the expensive magnetic elements. A three-phase design would have provided smoother direct current output but would have cost about three times as much because three controllers (saturable reactor coils) would have been required.

When the size of the power supply was scaled up, the saturable reactor became less useful as a controller. The redesign substituted an electronic silicon controlled rectifier-type (SCR) power controller for the electromagnetic coil. This change was made because of the prohibitive cost of a larger coil, because the SCR controller was expected to provide more precise control, and because it had the added feature of operating in either constant-current or constant-potential mode. This controller includes a current limit circuit to prevent damage to the unit by a short circuit at the cell. The design was modified to use 208, 230, or 240 Vac, depending on what was available at a particular site. Operation in constant-potential mode, rather than constant-current mode, became the preferred method, since the constant voltage gradient appeared to stabilize the system. The maximum current supplied by the power supply has ranged from 40 to 200 Adc depending on the size and number of Lasagna™ cells that were being operated.

For the Rickenbacker ANGB site at Columbus, OH (18,19) the design included a thermocouple at the connection to the graphite fracture in the electrode well. This was connected to a control circuit in the power supply that shut down power when the temperature in the electrode well reached 80°C and restored power when temperature decreased to 75°C. This prevented boiling in the electrode wells and fluidization of the granular graphite with subsequent loss of electrical contact. The power supply for Offutt AFB includes a similar temperature controller, and a computer data acquisition and control system, with remote operation.

The third element, the multi-tap isolation transformer, is usually not provided in an off-the-shelf rectifier power supply. It is essential in this application for several reasons.

- It is required to separate the system from the utility line power, so that the potentials at the cell could "float" as needed with respect to far-field ground

- It reduces the available short-circuit current from the utility line to a safer level and greatly reduces the hazard of electric shock to workers at the site
- The multi-tap feature also allows adjustment for maximum efficiency, which is important when using an SCR-type controller

The fourth element, the full wave bridge rectifier, was designed with over-size diodes, and over-size cooling fins, and fans, to make it robust enough for the changing conditions at field sites. Computer-grade capacitor banks with about 0.4 Farad capacity are used to smooth the output wave to direct current.

4.2 Temperature protection

Electrical resistance is inherent in the system. The major resistance will be where electricity is applied to the graphite in the electrode well and at the grain-to-grain contact between graphite particles in the electrode fracture. Heat will be generated at these points and if left unchecked will result in boiling of fluids in the electrode well. This boiling disrupts the grain-to-grain contact and the electrical contact between the graphite and the power supply. Once contact is lost it may be quite difficult to reestablish.

Over-heating is avoided by monitoring temperature and shutting off or reducing power when temperature approaches some critical value. Our experience suggests that shutting off the power between 75°C and 80°C will be satisfactory. The temperature sensor should be placed as close as possible to the contact between the power conduit and the graphite pack. When we used stainless steel pipe for the power conduit, the thermocouples were placed inside the pipe as near to the bottom as possible (Figure 2-3). When the thermocouples were placed too high in the pipe the temperature at the critical point reached boiling before power was reduced and the electrical contact was lost.

The temperature and pressure monitors, pumps, and any other monitoring or control equipment to be placed in the electrode wells, must be fabricated using materials that are resistant to high temperatures and to the extremes in pH (2 to 10). We have used type T copper and constantan thermocouples to measure temperature in all our installations. This type is most accurate in the range 0 - 100°C (30). Other materials that have been used in horizontal configuration installations include:

Teflon for the thermocouple insulation
Chlorinated Poly Vinyl Chloride (CPVC) for the pump body
Poly Vinyldenefloride (PVDF) check valve body
VITON® seals
Polypropylene tubing and screen
Nylon cable ties
Neoprene hose
Polyolefin heat shrink tubing
Poly Vinyl Chloride (PVC) insulated 105°C rated electrical cable

All these materials are heat resistant to 100°C, and are very resistant to extremes of pH. Materials such as duct tape and standard PVC electrical tape should not be used in electrode wells.

4.3 Connections

As noted above, the point at which the cable from the power supply connects to the graphite fracture (electrode) is subject to contact resistance, local heating, corrosion, and loss of electrical energy. After working with a variety of materials and designs we have settled on stainless steel pipe as the connection that is easiest to fabricate, install, and maintain. American Iron and Steel Institute (AISI) type 304 stainless steel is most readily available but AISI type 316 is more resistant to the corrosive environment, particularly in the anode. We used nominal 3/4 inch schedule 120 pipe in type

316 stainless steel. There was enough space inside the pipe to allow insertion of a thermocouple completely to the bottom to monitor temperature at the contact between the stainless steel and the graphite pack. The wall thickness was sufficient to allow the cutting of alternating male and female inch National Pipe Threads (NPT) so sections of the pipe could be screwed together with flush joints. The flush joints gave slightly more space and made it easier to place pumps, pressure transducers, and water lines in the well after the stainless steel pipe connection had been driven into the graphite pack. See Figure 2-3 for a scaled diagram of the stainless pipe inserted into the graphite pack in an electrode; this diagram illustrates the limited space in an electrode well.

The threaded joints in the stainless steel pipe also made it easier to remove and replace pumps for periodic servicing. Our installations had a fixed enclosure over the electrode wells with the inside clearance limited to about 5.5 feet. This made threaded connections necessary in order to add and remove the pipe in sections of 5 feet or less. It there had not been a fixed enclosure over the electrode wells, the pipe connection could be in longer pieces or even one piece if the depth to the graphite was less than 20 feet.

In reference (20) it was concluded that stainless steel connections for the cathode are relatively trouble-free while stainless steel connections for the anode would require periodic maintenance. Subsequent experience supports this conclusion. Cathode connections at Offutt AFB operated for long periods with no major increases in temperature. When they were removed for inspection they showed no corrosion and only a small amount of mineral and graphite deposition that was easily removed with emery paper or a steel brush. The performance of anode connections was more erratic. In one cell the AISI type 304 schedule 40 stainless steel connection operated for over a year during which time the current decreased from 54 to 42 amps at 48 volts DC and the temperature increased by only about 20C. In the other cell, which drew only about 25 amps, two consecutive AISI type 316 schedule 120 stainless steel connections corroded completely in less than two months each. We speculate that industrial chemicals present in the soil around the anode were involved in the increased rate of corrosion. Increases in temperature and decreases in current gave clear advance warning that the anode connections were about to fail.

Another type of electrode connection was used successfully on a number of installations. This was a solid graphite rod (tip) that was machined to a point on one end and drilled and tapped on the other. See Figure 8 in reference (20) for a model of this type of connection. The cable from the power supply was soldered to a short copper rod which screwed into the base of this graphite point. The cable and rod were inside a CPVC pipe to insulate the connection. The CPVC pipe screwed into the graphite tip around the copper rod and cable to seal out electrode fluids from the connection. See also Figure 3 in reference (17). These graphite connections were durable, but they had to be pounded, rotated, or withdrawn at intervals ranging from a week to two months to reestablish contact and reduce resistance. These graphite connections cannot be driven with as much force as the stainless steel pipe. When inserted after fracturing, the graphite into which the connections were driven was the softer (less compact) material in the upper part of the access well. We also experimented with suspending the contact point in the access well and injecting the graphite around it during creation of the graphite fracture electrode. Both types of connection worked well but still required periodic maintenance.

The electrical contact will usually be driven or pushed into the graphite pack to make connection. The upper portion of the graphite pack is usually softer and less compact than the pack near the point where the graphite fracture intersects the well. This softer material will provide a less satisfactory contact point and exhibit greater electrical resistance and heating than the deeper material. A convenient way to determine when the contact is satisfactory is to connect the power supply and observe the increase in current as the contact is driven deeper into the graphite. When there is little change with increasing depth of insertion, the contact is satisfactory. At that point the temperature in the connection should be observed for several hours. A sharp and continuing increase in temperature (ca. 20C per hour) indicates contact resistance and an unsatisfactory contact.

When fracturing has been completed some graphite may have to be removed from the well but this should be done carefully and after careful consideration of the effects. First, allow the graphite to settle and consolidate in the access well for at least 24 hours. Then measure the distance to the surface of the graphite and note whether the graphite surface is below the static water level. If this point is more than 6 feet (1.8 m) from the fracture level, we recommend removing some graphite to minimize resistance to fluid flow. It is recommended that about 4 feet (1.2 m) of graphite pack be left in the electrode well. In the cathode well, the level of the graphite must be below the static water level because liquids are pumped from the cathode to maintain downward flow in the cell.

For reasons we do not understand, the electrical connection in some electrodes will gradually degrade with the electrical current decreasing and temperature in the electrode increasing. When this happens, first try pounding the connection slightly deeper into the graphite pack and rotating it slightly. In several cases this has re-established electrical contact for a few months. If this is not successful then re-fracturing is necessary. Withdraw any pumps, sensors, and electrical contacts from the electrode well, remove as much of the old graphite as possible, and pump in a small amount (about 100 lbs) of new graphite. In every case where we have done this it re-establishes electrical contact for an extended period.

Other applications of electroosmosis for remediation of contaminated soil have used electrode systems that were buffered against pH changes. These systems appear to avoid the problems with loss of electrical contact and corrosion at the anode that we encountered. See references (28, 29) for examples of these connections.

5. Process Monitoring

Conditions in the horizontal Lasagna™ cell must be checked periodically to determine whether the process is proceeding satisfactorily and to provide a basis for adjustment and maintenance. The critical parameters are potential (voltage), current, temperature and fluid levels in the electrode wells.

The discussion of monitoring of electrical potential and current (Vdc, Adc) in a horizontal Lasagna™ installation assumes that the power supply controls potential and allows current to float in response to the resistance in various parts of the cell. A fixed current/floating potential power supply was used in some of the early work but we have the most experience with using the fixed potential design. The fixed potential design was used in most of the work because the fixed potential gradient in soil between the electrodes appeared to stabilize conditions in the cell.

Potential was adjusted by changing the connections on the multi-tap isolation transformer, selecting a value that would provide minimum heating problems at the electrode connections and maximum efficiency, which is important when using an SCR-type controller. Potential was measured regularly on the output side to assure that the power supply was functioning as intended. No problems with control of potential have been noted. The computer monitoring system at Offutt AFB recorded potential, current, temperature etc. once per minute. These files were downloaded daily to the computer in Cincinnati. The apparent potential varied less than 1.0 volt. Some of this variation is noise inherent in the system, as discussed below. When potential was measured at the power supply with a multimeter the variation was less than 0.1 volt.

Potential is also measured in the soil between the electrode fractures in the cell. If the soil electrical properties are uniform between the electrodes and if there is good (low resistance) contact between the cable from the power supply and the graphite in the electrode well, a plot of electrical potential versus depth will be roughly linear. See Figure 5-1 for an example of a satisfactory (linear) voltage profile in soil. This is the desired condition. A uniform potential gradient between the electrodes insures that water and contaminants are being affected as much as possible in all parts of the soil. A uniform potential gradient also indicates good contact at the electrodes and a low risk of overheating and disruption of grain-to-grain contact in the graphite.

Figure 5-2 illustrates another type of information that may be obtained from voltage measurements in soil. The voltage probe from which these data were obtained was located about 12 feet from the injection point at the center of the cell. The electrode fractures were installed at approximately 18 and 24 feet. The sharp increase in voltage above 16 feet indicates that the upper electrode (anode) fracture has risen (dipped upward) as it propagated away from the injection point. This phenomenon (steep up-dip) is observed in many hydraulic fractures.

Potential in soil is measured by driving a plastic casing, with its lower end sealed, below the depth of the lower electrode (cathode). This casing has stainless steel screws through the wall at 6-inch (15 cm) intervals up the casing over the interval corresponding to distance between the electrode fractures. The outer end of the screw contacts the soil; a slider is inserted inside the casing to contact the inner end of the screw. A multimeter is connected to the slider and measures the potential difference between each screw and the cathode of the nearest cell (Figure 5-3). A plot of these measurements versus depth shows the average slope (potential gradient) and any deviations from linearity (see Figures 5-1 and 5-2).

When a fixed-potential power supply design is used, then current (Adc) varies inversely with resistance in the cell. The majority of changes in resistance occur at the contact between the cable from the power supply and the graphite fracture. Monitoring current thus becomes one of the primary means for assessing the state of this connection. Decreases in current to a cell give advance warning that the connection is deteriorating and such decreases are invariably followed by increases in temperature. Detecting this behavior before the temperature approaches the boiling point provides an opportunity to clean and reestablish the connection before it deteriorates enough to do irreversible damage to the packing and grain-to-grain contact of graphite in the electrode well and the electrode fracture in the vicinity of the well.

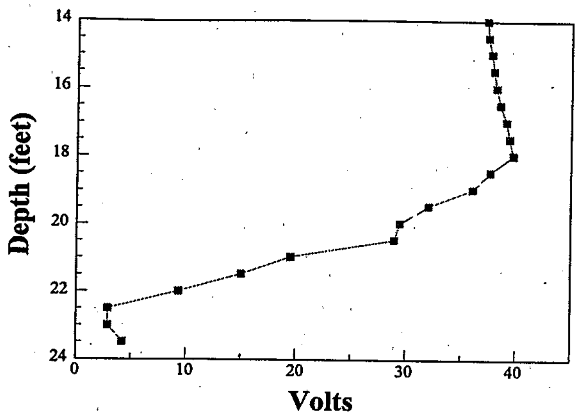

Figure 5-1. Linear Voltage Profile in Soil

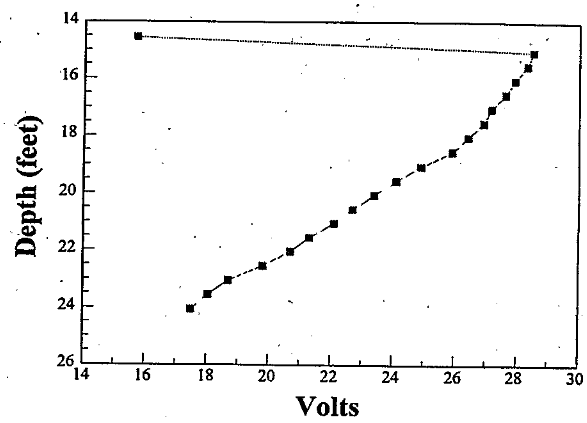

Figure 5-2. Voltage Profile in Soil

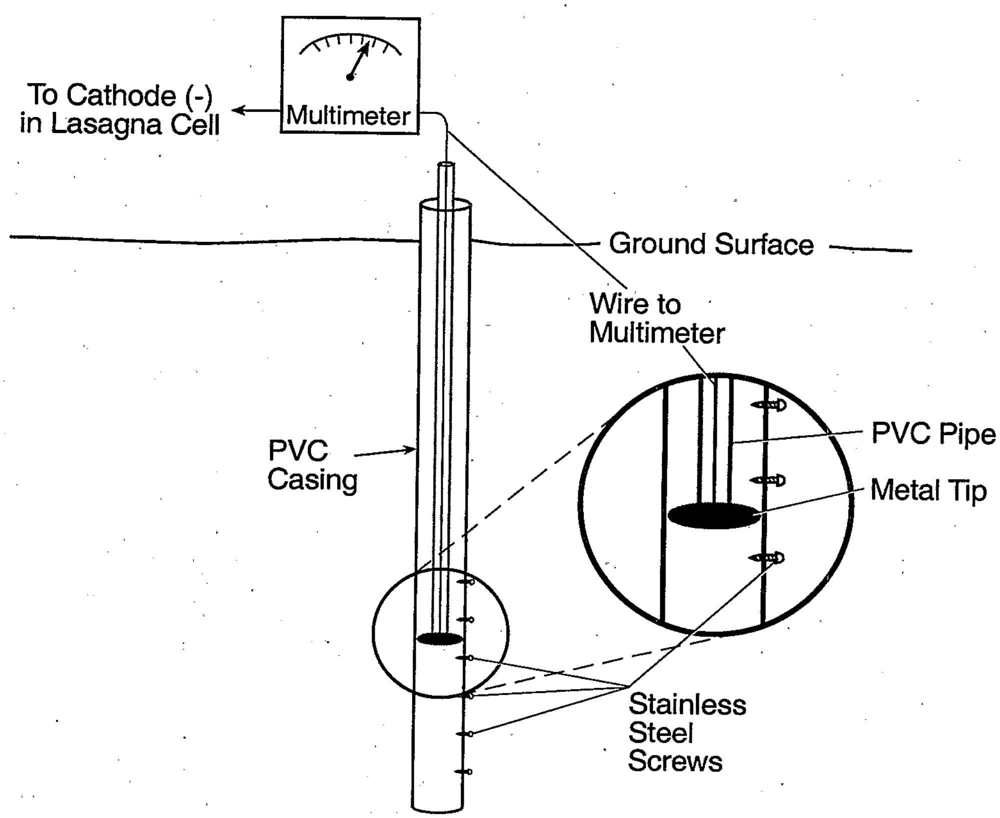

Figure 5-3. Voltage Probe

Monitoring temperature in the electrode wells is also a way to assess the condition of the connection between the power conduit and the graphite electrode fracture. When temperature rises sharply, the connection is deteriorating and resistance is increasing. However, the primary importance of temperature is its effect on the granular graphite in the electrode well and electrode fracture. As indicated above, boiling disrupts the grain-to-grain contact and makes it difficult to reestablish a satisfactory (low resistance) connection. Temperature is monitored primarily so this problem can be avoided. As also noted above, temperature should be measured as closely as possible to the contact between the power conduit and the granular graphite in the electrode well.

Fluid levels are monitored in all electrode wells to determine the need for adding or removing fluids and to check the operation of systems for accomplishing this. The cathode (lower electrode) wells are pumped to remove fluids accumulating due to EK transport of water through soil. If this is not done, a hydraulic head would gradually develop that opposes EK transport and either halts it or greatly reduces efficiency. Water is added to anode (upper electrode) wells to replace that which is moved downward by EK. Water levels in the anode well should not be increased so far above static (far-field) levels that a groundwater mound develops and transports contaminants laterally out of the Lasagna™ cell. We used down-well pressure transducers for monitoring fluid levels; other systems could be used to accomplish the same thing.

While all this process monitoring could be done manually by personnel at the site, it is highly advantageous to be able to accomplish this automatically and have access to the information from a remote location. Automatic monitoring makes it possible to develop on-site control systems that will, for instance, turn off power if temperature is too high, add water to maintain desired levels in anode wells, or transmit alert messages if fluid levels in the cathode wells rise too high.

When process monitoring is accomplished automatically, the signals from current, temperature, and voltage sensors may be noisy (vary erratically) for several reasons. Very long cable lengths, the need to use isolation interface modules (to protect the computer or data acquisition system from accidental direct connection to high voltages at the field site), and an open framework of the data acquisition rack and power supply, may all contribute to noise. When a multimeter is used to monitor current , it is connected to the current shunt of a power supply and noise reduction techniques are incorporated in the multimeter. This arrangement provides a signal that is much more stable than a signal from a multimeter connected through an isolation interface module and data acquisition rack on a computer or other data acquisition system. For indirect, noisy connections it is advisable to use software to calculate a running average over a 5- to 7-second period so the true value of temperature, current, or potential is not obscured by variation that is an artifact of the system design. See the temperature data in Figure 3-1 for an example of a noisy signal.

6. Technology Niche

The applicability, in general, of electrokinetic extraction is discussed in reference (24). An electric field is much more effective than a hydraulic gradient for moving contaminants in fine-grained soils of low hydraulic conductivity. In coarse-grained soils of high hydraulic conductivity, the hydraulic gradient is a more effective driving force. In heterogeneous soils, an electric field in conjunction with a hydraulic gradient can achieve nearly complete removal of contaminants where the hydraulic gradient alone could not. See, for example, the laboratory studies of electrokinetics in sand columns containing isolated lumps of contaminated clay (4). Although contaminant transport rates and efficiencies are strongly affected by soil type, electrokinetic extraction can be used, with some modification, in most soils. If the contaminant exists as a strongly sorbed phase on the soil particle surface or as precipitates in the soil pore, this may be a significant limitation.

The following are some conditions which affect the usefulness of the Lasagna™ horizontal configuration relative to the vertical configuration. They provide some basis for selecting the configuration that will be most effective in a particular setting.

In normally consolidated soils with no significant stratification (layering), the vertical configuration is the obvious choice. Hydraulic fracturing is unlikely to be successful and the horizontal configuration cannot be installed. When there is doubt about soil properties, install some test fractures. The installation at Offutt AFB is a case where the soil was normally consolidated and very soft, but fracturing was successful in a part of the soil profile.

Where soil is contaminated completely to the surface, and is relatively shallow, either configuration can be made to work. The horizontal configuration would use a metal mesh on the surface as the anode and a graphite fracture electrode as the cathode. This was used successfully at the Columbus, OH site (18, 19). The shallower the contaminated soil the easier it will be to insert the electrodes and treatment zones for the vertical configuration. Where contamination is deep and is overlain by uncontaminated soil, the horizontal configuration has an advantage because the electrodes and treatment zones can be placed just where they are needed.

When the contamination extends from the surface to great depth, either configuration could be workable. If the horizontal configuration is used, it could be necessary to install a number of pairs of electrodes to treat the entire interval, operating them sequentially with the cathode (lower electrode) being used as the anode for the lower cell when treatment is completed on the upper cell. This sequential arrangement is necessary because the spacing of the electrodes must be such that the applied voltage results in a gradient of 0.3 to 0.6 V/cm. The design of the power supply and heating at the electrodes may limit the voltage that can be applied.

The vertical configuration can use only the electric field to transport water and contaminants; the horizontal configuration uses both the electric field and gravity. Water is added to the upper electrode (anode) and liquids are pumped from the lower electrode (cathode). In soils with a wide distribution in pore size or some remaining free product (liquid phase contaminant), the horizontal configuration has an advantage because it can use the pumping from the cathode to remove free product before turning on the power to use EK. As indicated above, one of the likely effects of EK is to move contaminants out of low-permeability zones that would be bypassed by hydraulic flow. Once in higher permeability zones, contaminants can be transported by the relatively more-rapid hydraulic flow. Only the horizontal configuration can take advantage of hydraulic flow as a transport mechanism.

An additional consideration in choosing between the vertical and horizontal configurations is the need to operate completely in-situ. A vertical configuration can be installed so that liquids can be pumped from the cathode and reinjected into the anode without ever being brought above the land surface. This meets various regulatory requirements pertaining to disposition of waters containing hazardous constituents. The top of a vertical configuration anode is accessible for dealing with any plugging problems resulting from reinjection of cathode fluids. In the horizontal configuration most of the anode is below ground and inaccessible. Cathode fluids must be treated to remove particulates and flocs that would plug the interface between the bottom of the anode well and the anode. It is difficult to accomplish this entirely below land surface. If fluids are brought above land surface they must be treated to remove contaminants in order to comply with regulatory requirements and permits obtained for reinjection of the fluids.

Finally, where surface disturbance needs to be avoided, the horizontal configuration has a definite advantage. The well heads and associated equipment are a relatively small installation; most of the control apparatus can be placed at some distance from the well heads. All of the electrodes and treatment zones are below the ground surface and are left in place after completion of treatment.

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