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Development of an Integrated *in-situ* Remediation Technology

Topical Report for Task #3.1 Entitled, Emplacement Technology - An Evaluation of Phase IIa and Alternative *Lasagna*™ Emplacement Methods (September 26, 1994 - August 31, 1997)

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The DuPont Company

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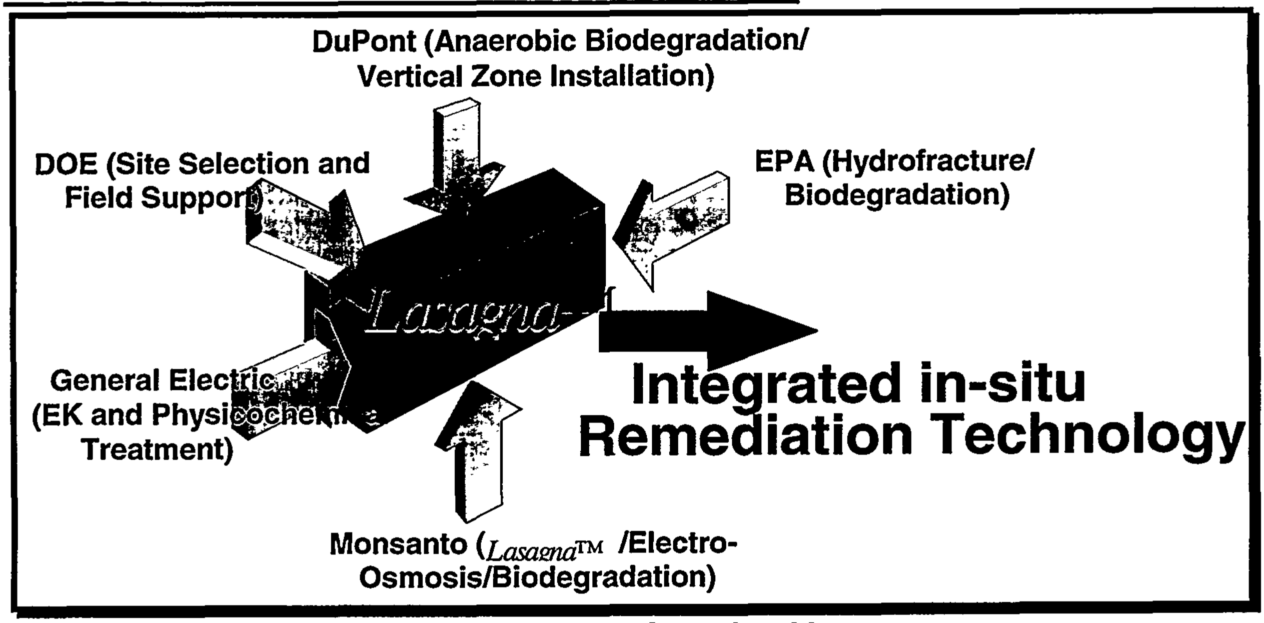

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Topical Report for Task # 3. 1 (January 18, 1996 - August 31, 1997)

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The DuPont Company

Abstract

Contamination in low-permeability soils poses a significant technical challenge to in-situ remediation efforts. Poor accessibility to the contaminants and difficulty in delivery of treatment reagents have rendered existing in-situ treatments such as bioremediation, vapor extraction, and pump and treat rather ineffective when applied to low permeability soils present at many contaminated sites. The technology is an integrated in-situ treatment in which established geotechnical methods are used to install degradation zones directly in the contaminated soil and electro-osmosis is utilized to move the contaminants back and forth through those zones until the treatment is completed. The present Topical Report for Task #3.1 summarizes the electrode and treatment zone emplacement technology developed by the DuPont Company.

B. Acronyms and Abbreviations

DCE	Dichloroethylene
DNAPL	Dense Non-Aqueous Phase Liquid
DOE	Department of Energy
DuPont	E. I. du Pont de Nemours & Co., Inc.
EPA	Environmental Protection Agency
GC	gas chromatography
GE	General Electric Company
LMES	Lockheed Martin Energy Systems
ROD	Record of Decision
RREL	Risk Reduction Engineering Laboratory
SWMU	Solid Waste Management Unit
TCE	trichloroethylene
VC	vinyl chloride

C. Units

C, °C	Celsius, degrees Celsius
cm	centimeters
d, D	days
deg	degrees
F, °F	Fahrenheit, degrees Fahrenheit
f, ft	feet
g	grams
gal, GAL	gallons
h, hr	hours
in	inches
k, K	thousand
kg	kilograms
l, L	liters
lb, lbs	pound(s)
m	meter
mg	milligrams
min	minutes
ml, mL	milliliters
mm	millimeters
ppb	parts per billion
ppm, ppmw	parts per million (by weight)
psi	pounds per square inch
µg	micrograms
µl, µL	microliters
"	inches
'	feet
#	pounds

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E. Background

Statement of the Problem

Contamination in low permeability soils poses a significant technical challenge to *in-situ* remediation efforts. Poor accessibility to the contaminants and difficulty in delivery of treatment reagents have rendered existing *in-situ* treatments such as bioremediation, vapor extraction, and pump and treat, rather ineffective when applied to low-permeability soils present at many contaminated sites.

The Solution

The proposed technology combines electro-osmosis with treatment zones that are installed directly in the contaminated soils to form an integrated *in-situ* remedial process. Electro-osmosis is an old civil engineering technique and is well known for its effectiveness, utilizing very low power consumption, in moving water uniformly through low-permeability soils.

Conceptually, the integrated technology could treat organic and inorganic contamination, as well as mixed wastes. Once developed, the technology will have tremendous benefits over existing ones in many aspects including environmental impacts, cost effectiveness, waste generation, treatment flexibility, and breadth of applications.

Consortium Description

A Consortium has been formed consisting of Monsanto, E. I. du Pont de Nemours & Co., Inc. (DuPont), and General Electric (GE), with participation from the Environmental Protection Agency (EPA) Office of Research and Development, and the Department of Energy (DOE) Environmental Management Office of Science and Technology. The five members of this group are leaders in their represented technologies and hold significant patents and intellectual property which, in concert, may form an integrated solution for soil treatment. The figure on the cover page shows a schematic diagram of the various technologies which the government/industry consortium has integrated for the development of an *in-situ* remediation technology.

Project History

To date, this project has been conducted in two parts: Phase I and Phase IIa. A Management Plan was originally prepared for Phase I of this project by Monsanto and submitted on November 30, 1994. That plan summarized the work plan which was developed in conjunction with DuPont, GE, EPA's Risk Reduction Engineering Laboratory (RREL), Lockheed Martin Energy Systems (LMES), and the Department of Energy. The DOE Gaseous Diffusion Plant in Paducah, Kentucky, was chosen as the site for the initial field tests. The specific contamination site selected at the Plant was Solid Waste Management

Unit (SWMU) 91. For Phase I, the plot selected to demonstrate the process measured 10 feet by 15 feet by 15 feet deep.

CDM Federal Programs Corporation was chosen to provide the on-site support of the field tests which were installed at the DOE site in November 1994. This experiment tested the combination of electro-osmosis and *in-situ* sorption in the treatment zones. Technology development was carried out under the present contract in Phases I and IIa by Monsanto, DuPont, and GE. These studies evaluated various degradation processes and their integration into the overall treatment scheme at bench and pilot scales.

Phase IIa was approved on January 18, 1996. For this phase, a significantly larger plot was selected, measuring 21 feet by 30 feet by 45 feet deep, and significant design changes were also implemented in the materials used to construct the electrodes and treatment zones. While Phase I was conducted to demonstrate the movement of TCE from the soil into the treatment zones, Phase IIa was conducted to demonstrate the full scale remediation of the SWMU 91 site. This latter phase included the use of zero-valent iron metal which degrades TCE to light hydrocarbons and chloride ions. In August of 1997, DOE advised that, based upon the performance of the *Lasagna*™ process during Phases I and IIa, *Lasagna*™ would be the preferred remedy given in the proposed Record of Decision (ROD). When signed, this ROD will be the first example of the use of *Lasagna*™ for the full scale remediation of a TCE-contaminated clay site. ROD approval is expected in calendar-year 1998.

Technical Deliverables

Table E-1 summarizes the four topical reports which have been written to describe the results obtained from the Phase IIa research. This table also shows which organization is primarily responsible for the tasks and for preparing the topical reports. The present topical report summarizes Task #3.1.

Table E-1. List of Topical Reports and Responsible Company

Topical Report	Company
Task #3.1 - Emplacement Technology	DuPont
Tasks #3.2 - Modeling and Iron Dechlorination Studies	GE
Task #3.3 - *Lasagna*™ and Iron Dechlorination	Monsanto
Task #7.2 - Field Scale Test	Monsanto/DuPont/GE

1.0 Introduction

As part of the Phase I effort (see Section E., Background), DuPont was responsible for identifying and initially developing methods for emplacing treatment zones and electrodes for use in the "vertical" *Lasagna*™ process (i.e., with electrodes and treatment zones positioned vertically to promote electro-osmotic flow in the horizontal direction between electrodes). This work resulted in the application of a technique called the "mandrel emplacement method" for emplacement of the electrodes and treatment zones in the Phase I field test. The Phase I topical report entitled *Task 1: Evaluation of Treatment Zone Formation Options* (Shoemaker, et al. 1996) documents this work.

DuPont was also responsible for completing an economic evaluation of the *Lasagna*™ process considering the various findings of the Phase I work. The results of the economic evaluation are documented in the Phase I topical report entitled *Task 5: Cost Analysis* (Quinton, et al. 1996).

The findings from these studies showed that, while the emplacement methods developed and used for the Phase I field test were successful and resulted in good process performance, substantial cost reduction opportunities could be realized with further development. Accordingly, additional emplacement technology development was included as a task under the Phase IIa *Lasagna*™ project proposed to DOE in October 1995, with DuPont again taking the lead.

Two main objectives were identified for the Phase IIa emplacement technology program. The first objective was to develop and adapt the Phase I mandrel emplacement method to incorporate immediate cost reduction opportunities and accommodate the needs of the planned Phase IIa field test. This task involved working with the emplacement contractor to modify the installation equipment used in Phase I to:

- Extend treatment zones and electrodes to the greater Phase IIa target treatment depth (45 feet compared with the Phase I depth of 15 feet), and
- Allow loading of electrode and treatment zone materials directly into the ground either as a dry granular material or slurry (the Phase I design involved encasing these materials in specially fabricated wick drain shells).

Section 2 of this report describes the work performed to achieve this first objective and implement the new technology in the Phase IIa field project.

The second objective was to investigate and develop substantially less expensive (and potentially deeper-reaching) emplacement methods based on wick drain technology and high-pressure jetting technology. This task included adapting the jetting technology for application to *Lasagna*™, with particular focus given to developing the ability to emplace (with some degree of precision) coarse granular matter such as iron, graphite, and/or coke particles. This work culminated in completion of a proof-of-principle field test at an uncontaminated site on property owned by DuPont. Section 3.0 of this report details this effort.

This second task also included an objective of exploring the feasibility of fabricating ready-made *Lasagna*™ technology materials that might be emplaced in a single step during mandrel insertion, similar to the way wick drains are emplaced for geotechnical projects. Included in this task was an investigation of manufacturers and products that might serve as models for "advanced *Lasagna*™ technology materials" based on the wick drain concept. This study was followed by contacts with potential manufacturers to assess interest and solicit support. Results of this effort are detailed in Section 4.0.

The final section of this report (Section 5.0) provides an update of the *Task 5: Cost Analysis* report from the Phase I project, including estimation of costs of the various methods for emplacing treatment zones and electrodes in a full-scale application and evaluation of these costs within the context of the overall *Lasagna*™ process. This latter evaluation was performed using the *Lasagna*™ cost evaluation model developed in Phase I. Based on cost model results, the overall cost effectiveness of each approach under representative scenarios of depth and area treated are compared.

2.0 Phase IIa Mandrel Emplacement

Mandrel emplacement is a technology similar to that used for emplacing wick drains for soil consolidation and driving sheet pile. It is also similar to the vibrating beam technology. In all cases, downforce is used to drive a structural steel member (i.e., mandrel) into the soil using either static, vibratory, or impact pile driving techniques. The mandrel is a hollow steel sleeve through which materials (e.g., wick drains) may be emplaced once the mandrel is driven into the soil to a target depth.

The emplacement process begins by accurately positioning the mandrel over the desired emplacement zone while vertically orienting the mandrel in the two vertical planes. Once in position, an expendable drive shoe is positioned over the leading edge of the mandrel, and the mandrel is lowered slightly into the soil to hold the drive shoe in position. To ensure safe operation, the mandrel is statically loaded before activating the driving mechanism. The drive mechanism is then activated and tuned to the soil conditions for efficient emplacement. Once at the desired depth, the driving mechanism is turned off, and the flowable reactive media is loaded into the internal cavities of the mandrel. After loading the mandrel, the drive mechanism is re-activated to aid the extraction of the mandrel, leaving the drive shoe behind. Reactive media is backfilled into the cavity created by the mandrel. Extraction continues until the desired volume of reactive media has been emplaced and the mandrel is fully extracted. The process can be repeated, overlapping slightly into the previously emplaced reactive zone to create a continuous reactive wall (see Figures 1 and 2).

Depending on the soil type, the unsupported cavity left by the mandrel may tend to close under the pressure of the soil, so the extraction rate should be a function of the pore pressure dissipation curve of the soil and the rate that the reactive media expels from the mandrel. As rule of thumb, the extraction rate should be slower for clays since the pore pressure dissipates slowly; a faster extraction rate is recommended for sands.

2.1 Technology Development

As discussed in the introduction, a pilot test of the mandrel emplacement technology was performed under the Phase I *Lasagna*™ project to a depth of 15 feet. Based on the success of the pilot test, the technology was further developed for full-scale implementation in this project (Phase IIa). The development effort for Phase IIa focused on the following:

- Scaling up the capability of the mandrel emplacement method used during Phase I from a depth of 15 feet to a depth of 45 feet.

- Reducing the emplaced costs for the electrode and treatment zone materials.

The Phase IIa design called for two electrode zones to be emplaced 21 feet apart and three treatment zones emplaced at increments of 7, 12, and 14 feet from each of the electrodes. All of the zones were 30 feet long (see Figure 3) and 45 feet deep.

The pilot-scale treatment zones for Phase I were prefabricated out of geotextile fabrics and a 15-foot by 18-inch by 1-inch drainage mat filled with a measured mass of granular activated carbon. The electrode assembly included a treatment zone and a 15-foot by 18-inch by ¼-inch steel plate as the electrode. As a result, the electrode assembly was heavy and somewhat difficult to handle (see Figures 4 and 5).

These zone assemblies were relatively expensive. Costs for the installed treatment and electrode zones were estimated at $12.88/ft^2 and $18.97/ft^2, respectively. Since a fair amount of labor-intensive fabrication effort was required, scaling up these assemblies was not considered feasible for a full-scale operation. An alternative concept was developed by using materials that could be flowed directly through the cavities of the mandrel. These materials included granular cast iron and granular coke for the electrode and granular iron and sand for the treatment zone. A discussion of the design of these electrodes and treatment zones follows.

2.2 Electrode Requirements and Protocol Development

The granular electrodes were estimated to require a zone hydraulic conductivity of approximately 1×10^{-3} cm/sec to assist with either pumping water into the anode zone to avoid drying or extracting the effluent water from the cathode. Based on modeling of the current distribution, the electrodes also required a "primary" electrode to be emplaced within the "secondary" electrode materials (i.e., coke and iron) to distribute voltage evenly throughout the zone and assist with the electrical connection to the power supply. To achieve these requirements and develop an effective protocol, the electrode materials formula and the electrical connection and associated accelerated corrosion potential were addressed.

2.2.1 Electrode Materials Formula

The initial prescribed design mix for the electrode materials was 50 weight percent (bulk) of 20 mesh granular iron and 50 weight percent (bulk) of a carbon material. The carbon material acted as a conductor, and the iron was incorporated to treat the groundwater. The electrode material mixture had a relatively high hydraulic conductivity to facilitate water management, and the electrical conductivity of the electrode zones was approximately two orders of magnitude higher than the surrounding soil.

The first combination considered was graphite and iron; however, the cost of graphite was a concern so it was not considered beyond the laboratory stage. The second material investigated was granular activated carbon; however, its cost and contaminant absorptive capacity was an issue since contaminant degradation rather than adsorption was an objective of the project. Due to its lower cost and relatively inert status, a mixture of granular iron and a granular cathodic protection coke product was the electrode combination selected. The final proportion of coke was increased to 80 weight percent (bulk) because of the relatively low cost of coke and the small amount of iron actually required to treat the contaminant. Type SWS coke from Loresco was selected as the coke product for Phase IIa. The remaining 20 weight percent (bulk) of 8 to 16 mesh granular iron type 1070 was purchased from Peerless Metal Powders.

2.2.2 Electrical Connection/Accelerated Corrosion Potential

In addition to optimum mixture considerations, an electrical connection was needed from the power supply to the granular materials. The potential for accelerated corrosion of the electrical connection at the air/water interface in the soil was a consideration in this selection. Several concepts for this connection were discussed, ranging from steel cable to iridium oxide coated titanium mesh. Cable was an intriguing choice due to its relatively low cost (i.e., $1/ft for 3/4-inch diameter); however, typical steel cable is lubricated with grease. Since an unlubricated cable could not be located easily and the consensus was that the lubricant would create a poor electrical connection to the iron and coke materials, the cable concept was abandoned for Phase IIa.

The final solution was to use 3/4-inch diameter steel rods that were welded together to achieve a total length of 46 feet. The upper 7 feet was covered with a plastic heat shrink wrapping material to electrically insulate the portion in the unsaturated soil zone, and the rods were inserted every 5 feet along the electrode zone.

2.3 Treatment Zone Requirements and Protocol Development

The electro-osmotic flow rate objective used for Phase IIa was approximately 1 cm/day, thereby requiring a treatment zone of less than 1 inch to provide adequate retention time to treat TCE entering the zone, assuming 100 percent granular cast iron comprised the treatment zone. However, due to mechanical limitations, the mandrel was designed with a width of 2 inches, requiring the treatment zone materials to be mixed with a bulking agent to reduce costs.

2.3.1 Treatment Zone Materials Formula

The initial prescribed formula for the treatment material was 20 weight percent (bulk) of 20 mesh granular iron and 80 weight percent (bulk) of sand. Laboratory test results by Monsanto indicated that these sand/granular iron treatment zones tended to dry out, causing a stoppage of the electro-osmotic flow. To help minimize the drying of the treatment zone, kaolinite clay was substituted for the sand. Kaolinite clay was added at a 60 weight percent water to 40 weight percent clay ratio; however, this ratio provided too much water in the mixture.

A new mixture of 60 weight percent water, 15 weight percent kaolinite clay, and 25 weight percent bentonite clay was tested. Bentonite chips were added as a means to absorb excess moisture in the treatment zone. However, this did not appear feasible because the hydration of the bentonite caused areas to have little iron, and the iron tended to settle out of the mixture. The result would have been treatment zone areas with varying capacities for contaminant degradation.

The final mixture was a 20 weight percent of 20 mesh granular iron type IS purchased from Peerless Metal Powder and an 80 weight percent kaolinite clay type RC-32 (air floated) purchased from Thiele Kaolin Co. A clay to water ratio of 60 weight percent water to 40 weight percent clay was used to create a flowable slurry capable of carrying the iron.

2.3.2 Laboratory Testing

Laboratory tests were conducted of this mixture and revealed that hydrogen gas was generated, causing small fissures in the treatment zone. Some sand was added to the mixture to facilitate the escaping of hydrogen gas. Although adding a maximum amount of sand may have increased the shear strength of the mixture and ensured that materials would not come to the surface, the consortium believed that the hydrogen gas would be kept in the dissolved phase due to the in situ soil pressures and process temperatures. As a result, the final treatment zone mixture remained unchanged, and sand was not incorporated.

2.4 Materials Handling Protocol Development

To develop an effective protocol for materials handling, the form of the materials and delivery system was investigated. One parameter that was important to the investigation was the electrode's hydraulic conductivity, which needed to be approximately 1×10^{-3} cm/sec. Additional criteria based on using a slurry delivery system were that the free water after the slurry settled could not exceed 10 percent, and the iron could not settle significantly in the first 15 minutes after placement.

2.4.1 Material Form

The materials were to be delivered in the form of a slurry to help prevent partitioning of the various materials as they were placed into the mandrel. The slurry form would also help prevent layering from occurring in situ, which was important for the electrode and treatment zones to generate the most uniform electro-osmotic field and treat the groundwater.

2.4.2 Slurry Delivery System

The slurry was proposed to be pumped to the mandrel using a positive displacement style pump. To test this concept, a pump test was arranged with Halliburton at their Duncan, Oklahoma, facility, and a mixing test was arranged at Asphalt Paving, Inc. (API) located in Calvert City, Kentucky. The purpose of these tests was to prove that all of the materials could be mixed and expelled by a conventional rotary-type concrete truck and could be made pumpable.

In Halliburton's laboratory facility, several batches of slurry were mixed. Samples were poured into graduated cylinders to test the settling time of the iron and the free water after settling. The goal was to have a fluid with no apparent settling for 15 minutes and have less then 10 percent free water after 24 hours. A mixture of 40 pounds of Halliburton's proprietary guar gum in 1,000 gallons worked well and was used during the pump test.

Then, a 1- to 2-cubic yard batch of a slurry consisting of 50 weight percent of 20 mesh Peerless iron and 50 weight percent guar gum was mixed, pumped via a Moyno pump through 100 feet of vertical stand pipe, and recirculated. This pump test proved that a slurry delivery system was feasible. A pump test of the 20 weight percent granular iron and 80 weight percent hydrated kaolinite clay (at 60 weight percent water) mixture was not performed because the iron did not settle, and pumping it was anticipated to be equivalent to or easier than the guar gum mix.

2.4.3 Electrical Conductivity

General Electric and Monsanto discovered that, after biodegrading, the guar gum caused an organic film coating on the particles that reduced the electrical conductivity of the electrode materials. However, General Electric showed that this organic film had little effect on the granular iron reactivity. Monsanto concluded that layering the granular iron and granular coke electrode materials would be acceptable, so a separate dry materials handling was developed for the electrode mixture.

The mix test at API's facility proved that mixing the electrode and treatment zone materials was relatively easy using a conventional concrete truck and that both mixtures were easily expelled by the truck (see Figures 6 and 7).

Laboratory tests and the mix test indicated that the kaolinite clay (at a 60 weight percent water to 40 weight percent clay ratio) continued to hydrate; therefore, the treatment zone mixture was too viscous to be poured or expelled by the concrete truck after approximately six hours (see Appendix A). Based on this data, small batches were to be mixed that were sufficient for a morning or afternoon of emplacement efforts.

2.5 Sampling Cassette Protocol Development

A sampling cassette protocol was developed to emplace more cost-effective, retrievable sampling cassettes containing granular activated carbon than used in Phase I (see Figure 8) and emplace the probes using the mandrel technology.

Granular activated carbon sampling cassettes were developed using a geosynthetic well screen filter "sock." The filter sock was threaded over a stainless-steel cable, and granular activated carbon was poured into the sock. The sock was segmented every 12 inches to form a sampling cassette that resembled a string of sausages (see Figure 9).

To emplace the sampling cassettes into the soil, a 2-inch polyvinyl chloride (PVC) well screen was emplaced using a 4 inch by 4 inch by ½ wall thickness mandrel 50 feet long. The retrievable sampling cassettes were inserted into the PVC well screen and secured at the desired depth. Other probes, such as voltage probes, in situ concentration probes, and thermocouples, were also emplaced using this small mandrel.

2.6 Field Equipment Development

Based on the need to emplace electrodes and treatment zones to a depth of 50 feet, a new mandrel design was required, and the mast used during Phase I required modification. In addition, the capacity of the mandrel extraction mechanism used during Phase I was deemed inadequate for the 50 foot depth required in Phase IIa, primarily due to the slow extraction speed and limited pull.

2.6.1 Mandrel Design

Based on the relatively thin treatment zone requirement, a 55 foot long mandrel design was developed using four hollow rectangular tubes having dimensions of 2 by 5 by 3/8 inches. These rectangular tubes were welded together on the narrow sides, and the mandrel was stiffened by two ½- by 6-inch steel plates (see Figures 10, 11, and 12). To help ensure that the materials could easily flow through the tubes in the event of plugging, rectangular ports were cut into the sides of all of the tubes to interconnect the hollow rectangular tubes at the upper and lower 6 feet of the mandrel. The leading edge of the mandrel was fabricated to form fit into the driveshoe and maintained this position via a locating block (see Figure 13). The driveshoe was designed to remain in place upon extraction of the mandrel from the soil.

To evaluate the mechanical integrity of the mandrel design, an analysis of the design for critical buckling stresses and natural frequencies was performed. The critical buckling load was well above the static load of the American Piledriving Equipment (APE) model 180 vibratory hammer; however, the 2nd, 3rd, and 4th natural lateral frequencies coincided with the operating frequencies at various depths of emplacement (see Appendix B). The coincidence of the natural frequencies was judged to be a minor issue, and the design proceeded as conceptualized.

2.6.2 Mast Modifications

To manage the 55-foot mandrel, the mast from Phase I was extended using the same lattice work mast design to achieve a total height of 68 feet. Initially, it also was anticipated that a larger 245C Caterpillar excavator versus the 235C that was used in Phase I would be used (see Figure 14).

A larger vibratory hammer (APE model 180) versus the APE model 150 used in Phase I was selected to ensure sufficient power to drive the mandrel to a depth of 45 feet. The emplacement and extraction forces required for the 15-foot depth for Phase I were generated by a chain and gear drive system driven by a hydraulic motor with a system capacity of roughly 2 tons. This drive system was deemed to have insufficient extraction capacity for the 45-foot depth requirement for Phase IIa; therefore, a cable and pulley system was conceptualized and was driven by a hydraulic winch with a system capacity of 38 tons (see Figure 15).

2.6.3 System Verification

Once the emplacement equipment was mechanically complete, a checkout test of the mandrel system and the materials handling system was conducted at Nilex's office in Englewood, Colorado. As part of this test, personnel from Camp, Dresser, and McKee (CDM); Lockheed Martin Energy Systems (LMES); Paducah Gaseous Diffusion Plant (PGDP); API; Monsanto, and DuPont in addition to Nilex were present to observe potential concerns with the process and conduct a small-scale demonstration of the emplacement processes.

The test utilized the full-scale mast, a 75-ton hydraulic crane (in place of the 245C excavator), a test mandrel simulating the upper 15 feet of the full-scale mandrel, a ½ yd^3 mortar mixer, a cement bucket with an offset dump spout, and a fork truck. The checkout process entailed placing a driveshoe on the leading edge of the mandrel, driving the mandrel to a depth of approximately 10 feet, mixing the desired materials in the mortar mixer, transferring the material from the mixer to the cement bucket, transporting the cement bucket to the emplaced mandrel, transferring the materials from the cement bucket to the mandrel, and extracting the mandrel.

Several electrode and treatment zone emplacements were performed. All of the tests went relatively smoothly, with only minor mechanical issues that were addressed prior to equipment mobilization to the PGDP.

2.7 Site Conditions

The Phase IIa emplacement area was the test site for the Department of Transportation certification of the uranium hexafluoride transportation cylinders. This area is also next to one of the areas at PGDP where cylinders containing 20 tons of depleted uranium hexafluoride are stored. As part of the cylinder storage effort, roadbeds several feet thick were constructed for the heavy transportation equipment. Over the years, this roadbed became quite compacted. The Phase IIa emplacement area extended approximately 50 percent into this roadbed area. It was expected that some loosening of these compacted soils might be needed to allow penetration.

Of more concern was the lack of geotechnical information of the underlying clayey soils and the force required to extract the mandrel at depth of 45 feet. To help address the geotechnical questions, three cone penetrometer tests were conducted by PGDP at locations CPT-1, CPT-2, and CPT-3 (see Figure 16). Cone penetrometer test CPT-1 and CPT-3 were conducted in the main roadbed area. CPT-2 was conducted in an area where significant traffic may have existed during the DOT testing of the cylinders. The cone penetrometer test data and plots of the data are provided in Appendixes C and D, respectively.

To better understand the possible mandrel extraction force needed, LMES collected pore pressure dissipation data. The resulting data was sent to Mr. Dave Woeller of Cone Tech, Inc. for review. Based on the pore pressure dissipation data, the clayey soil at the site appeared to be overconsolidated and would probably rebound and close the cavity created by the mandrel. It was estimated that a theoretical force ranging from 75 to 105 tons might be needed to extract the mandrel (see Appendix E). In addition, it was theorized that if water was applied to the outside of the mandrel to lubricate its surfaces, the extraction force may be cut by as much as 50 percent. Water jets were incorporated into the mandrel design; however, improving the design of the hydraulic cable system on the mast to have sufficient extraction capacity using an excavator was not practical. Instead, a 100-ton hydraulic crane was selected to extract the mandrel and position the mast, thereby eliminating the excavator and its associated costs.

2.8 Emplacement

2.8.1 Preparation

Following the mechanical checkout of the emplacement equipment and processes at Denver, Colorado the mast sections, full-scale mandrel, driveshoes, vibratory hammer, and hydraulic power pack were loaded onto trucks and shipped to the PGDP, along with Nilex's equipment support trailer. Upon arrival at PGDP, the equipment was unloaded and assembled in approximately two days.

In preparation for the Phase IIa emplacement efforts and to improve the effectiveness of the electrodes, the culvert pipe running north and south through the test area was removed. Gravel was spread to level the emplacement area, and the ditch on the southern edge of the area was filled in with gravel to support the crane's outriggers.

2.8.2 Test

After setup was complete, a test emplacement outside the Phase IIa area was performed.

Emplacement depth was limited to approximately 30 feet due to clayey soil adhering to the mandrel. To lubricate the outside surface of the mandrel, a water injection system was used with a 1,500 psig pressure washer and four 1/8 inch diameter nozzles near the leading edge of the mandrel. This modification allowed the mandrel to be driven to the desired depth and extracted. [(The driveshoes worked effectively by keeping soil from entering the mandrel, staying in place via a locating block, and remaining in situ upon extraction of the mandrel (see Figure 13)].

Due to the single lifting point of the crane (see Figure 17), the mast tended to initially either rotate or translate slightly until the mandrel was several feet into the soil. To better secure the position of the mast, the heavy I-beam was set in position as a guide for the mast. The mast was clamped to the I-beam and further secured in position via a heavy lifting strap held taut by a front-end loader (see Figure 18).

2.8.3 Electrode Zones

As the electrode zones were being emplaced, the materials balance was constantly monitored. At the completion of each of the early electrode zone emplacements, excess material was expelled from the mandrel once it was fully extracted from the soil. It was concluded that the soil was rebounding slightly and narrowing the cavity width from 2 to 1.5 inches. To maximize the cavity thickness, the extraction rate was slowed to help ensure that sufficient material was expelled from the mandrel to fill the cavity. In addition, to avoid wasting electrode materials, material volumes were scaled back slightly to fill the volume of the new 1.5-inch cavity.

Electrode materials were delivered to API's facility in preweighed supersacks prior to equipment mobilization and brought to the PGDP as needed. Although transferring the materials from the supersack to the cement truck and mixing the materials went smoothly, continual rotation of the electrode materials resulted in particle size partitioning. To avert partitioning, once the materials were mixed, rotation of the mixer was stopped. The materials were then transferred by the cement truck to the concrete bucket, and the concrete bucket was transported by an all-terrain forktruck to the mandrel. Transfer of the materials into the mandrel was accomplished by activating the gate underneath the concrete bucket, allowing material to flow into the cavities of the mandrel. Sufficient material was stored in a hopper on top of the mandrel for the entire emplacement (see Figures 19 and 20).

Emplacement of the primary steel rod electrodes and 1-inch diameter monitoring wells was accomplished by inserting the electrodes into one of the side cavities at the top of the mandrel before the granular coke and iron were transferred to the mandrel (see Figure 12). This process went smoothly for the primary electrodes, except that they did not stay at the desired full depth during the mandrel extraction process. The primary electrodes retracted approximately 2 to 6 feet, leaving at least 40 feet in situ (see Figure 21). The exposed section of primary electrode rod was cut off near the ground surface. During the emplacement of the 1-inch diameter monitoring wells, the wells tended to retract almost entirely out of the electrode zone; therefore, emplacement of the wells by this technique was abandoned.

2.8.4 Treatment Zones

The treatment zone mixture was mixed in the cement truck and was transferred to the concrete bucket in a similar sequence. Due to the kaolinite clay component, transferring the treatment zone mixture to the mandrel was somewhat "messy," but manageable. As learned in the laboratory, the treatment zone mixture had to be transferred out of the cement truck within 6 hours to avoid excessive dehydration, thereby becoming too viscous to be expelled from the cement mixer.

During the early emplacements of the first treatment zone, approximately 6 to 7 ft^3 of excess treatment zone material remained after the emplacement and was expelled onto the ground once the mandrel was fully extracted. It was concluded that the treatment zone cavity was rebounding inward and reducing the desired 2-inch thickness to approximately 1 inch. In an attempt to remedy this concern, the density of the slurry had to be increased from its original 119 lbs/ft^3, and/or the shear strength of the slurry had to be increased. With limited materials in the field, the iron content was increased, which increased both the density of the slurry and the shear strength.

During several subsequent emplacements, the iron content was increased from 20 weight percent to 60 weight percent iron, while the 40 weight percent clay slurry was held at a constant water-to-clay ratio. The resultant density was approximately 160 lbs/ft^3. Once the treatment zone material protocol was established, only approximately 2 ft^3 of excess slurry typically was expelled at the surface per emplacement. Based on the material balance using the new protocol, the treatment zone was calculated to be 1.5 inches thick.

2.8.5 Emissions and Generated Waste

Volatile emissions were monitored directly at the surface of the emplacement throughout all emplacement efforts. No emission was recorded that warranted an upgrade to respirators or that resulted in halting operations (see Figure 22).

Once the emplacement protocols were established, approximately 2 ft^3 of excess soils were generated per emplacement. With that in mind, this technology should be considered a commercial emplacement method that generates a minimal volume of excess soils requiring possible disposal.

2.8.6 Productivity and Cost

As the emplacement process progressed and was refined, the emplacement cycle times for both the treatment and electrode zones were routinely approximately 20 minutes per emplacement. At this rate, approximately 24 emplacements to a depth of 45 feet were accomplished at the PGDP during a 10-hour work day, with 7 to 8 productive hours including startup, lunch, and shutdown. Cycle times could have been 2 to 3 minutes faster; however, a relatively dense (high blow count) soil zone was encountered at approximately 30 feet that significantly slowed the rate of progress until the zone was penetrated (see Appendix D).

The estimated economics of the pilot-scale test indicate that emplacement alone was approximately \$7.42/ft^2, assuming 24 emplacements per day, an emplaced treatment zone cost of \$13.09/ft^2, and an emplaced electrode cost of \$12.05/ft^2. These costs compare well with the estimated costs prior to Phase IIa as follows: a cost of \$7.85/ft^2 for emplacement alone, \$9.51/ft^2 for the emplaced treatment zones, and \$15.92/ft^2 for the emplaced electrode zones. The cost for the emplaced treatment zone was approximately \$3.50/ft^2 higher than originally estimated because the iron content was increased from 20 weight percent to 60 weight percent during field emplacement efforts. The electrode zone cost is approximately \$4.00/ft^2 less expensive because the original iron content was reduced from 50 weight percent to 20 weight percent and coke is less expensive on a density basis.

2.9 Conclusions and Recommendations

In general, the mandrel emplacement technology worked well. The test demonstrated that this technology can be deployed for clayey soils with a broad range of relative densities. If relatively thin, high blow count soil zones are encountered, this technology can penetrate these zones with a minor impact on production rate.

The following minor recommendations are warranted as a result of Phase IIa emplacement efforts:

- Use a 245C or 375C Caterpillar excavator rigidly attached to the mast or a track-based latticework crane with a steady rest. This method would allow the excavator or crane to position the mast and prevent the mast from swinging (see Figures 14 and 23). In addition, mast verticality would be easier to control since the mast would have less freedom to move due to the additional rigid guide hardware.

- Pump the slurried materials to the mast to reduce some of the transfer time required for slurried materials handling.

- Eliminate the large materials hopper on the mast. The welds on the hopper tended to fatigue and crack after some time due to the vibration and the weight of the materials (see Figure 24).

- Extend the mandrel to gain extra capacity within the mandrel, and use a manlift to lift workers to assist the transfer of materials from the concrete bucket as needed.

3.0 High Pressure Jetting

High-pressure jetting was originally developed in Japan as a means of stabilizing soil to conduct deep excavations near foundations or to improve the load bearing capacity of the soil. For decades, it has been used extensively for grouting and other soil stabilization applications throughout Europe and Asia. In recent years, the technology has become more widely recognized and used in North America. For example, the petroleum industry uses high-pressure jetting of granular materials to improve production performance from a reservoir by cutting through steel casing and penetrating into the formation.

3.1 Technology History and Development

Previously, high-pressure jetting was used to emplace thin intersecting panels in the subsurface to manage groundwater movement. However, interest in high-pressure jetting has increased recently due to its potential flexibility to emplace materials under diverse and extreme conditions. For instance, high-pressure jetting potentially can be used for emplacement to depths over 100 feet and can be used to selectively jet specific zones in the geology. It can also be performed in a non-vertical orientation to grout beneath buildings or other underground obstructions, thereby incorporating the obstruction into the jetted area. Jetting underneath a basement of a building has also been performed.

Because of the flexibility of high-pressure jetting, this technology is being researched for other purposes, such as emplacing granular material in situ treatment zones or fluids for biological augmentation. Research to date shows that high-pressure jetting is a cost-effective alternative for emplacing electrode or treatment zones in those cases where the mandrel approach is inappropriate (e.g., emplacements deeper than approximately 50 feet, obstructions prevent the use of the mandrel, foundations prevent the use of a vibratory hammer).

3.2 Technology Description

3.2.1 Background

High-pressure jetting uses a high-energy fluid stream (i.e., slurry or water) to erode a soil cavity. The jetting stream can be either slurry or water and can be shrouded by air to increase the depth of penetration into the soil. If the high-pressure jetting stream consists of only slurry, the technology is called monofluid jetting; if the jetting stream is shrouded by air, the technology is called double-fluid jetting. Triple-fluid jetting uses water as the high-pressure jetting stream, which is usually shrouded in air with the grout jetted through a third nozzle.

3.2.2 Equipment

The key components of a high-pressure jetting system are as follows: a small- to medium-sized drilling rig that can control rotation and extraction rates of the drill string, a data acquisition system to monitor the jetting parameters, a slurry mixing system, a high-pressure pumping system, a jetting nozzle sub, and a bulk materials handling system.

Various jetting nozzle orientations and quantities are commonly used in construction. The two most common configurations are a single nozzle oriented perpendicular to the axis of the drill string or two nozzles aimed in roughly opposite directions oriented in a similar manner to the drill string.

3.2.3 Process

The first effort of the high-pressure jetting process is to mix up a batch of slurry to be jetted into the soil by transferring grout materials from the bulk material handling system to the slurry mixing system. Once the slurry is mixed, a few test panels are usually emplaced to refine the jetting parameters (i.e., jetting pressure, grout flow rate, rotational speed, extraction rate).

The emplacement process begins by drilling a vertical bore (approximately 6 inches in diameter) to the desired depth. Once at depth, a hardened steel ball bearing is dropped into the drill string to plug the port leading to the drill bit, thus diverting the fluid flow to the jetting nozzles. Then, the high-pressure pump is activated, and the desired operating pressure is eventually achieved. After the jetting nozzles are at full pressure and flow, the drill string is extracted at the desired rate and rate of rotation.

Once jetting begins, excess soil and materials exhaust to the surface through the annulus between the soil and the drill string. The flow of excess materials to the surface is a function of the type of jetting technology (i.e., monofluid, double fluid, or triple fluid). Monofluid jetting usually has the least amount of excess materials being exhausted to the surface; triple-fluid jetting usually results in the greatest materials at the surface. Excess materials are normally collected by digging a shallow surface trench from the drill string to a collection pit or via a vacuum truck. Jetting is usually stopped several feet from the surface to minimize the noise and potential hazards of the high pressure fluid stream.

Types

High-pressure jetting typically creates two types of emplacements, as described below.

Cylindrical

The cylindrical emplacement is the most common and is created by slowly rotating and extracting the drill string during the jetting process. The diameter of the cylindrical shapes can range up to approximately 6 feet.

Thin Diaphragm Wall

This type of emplacement is created by slowly extracting the drill without rotation during the jetting process. For thin diaphragm walls, the length of the wall can range up to 10 feet, and the thickness of the wall can range from approximately 2 inches near the drill string to approximately 6 inches at length, depending on the soil type. A rule of thumb regarding soil type is that clayey or cohesive soils tend to reduce the resultant jetted geometry, whereas a sandy or noncohesive soil tends to maximize the depth of geometry. Clayey formations are simply harder to erode than sandy soils by the high-pressure jet stream.

3.3 Phase IIa Development Activities

The purpose of the Phase IIa development activities was to investigate the technical feasibility of emplacing in situ treatment zones containing granular cast iron using the commercially available high-pressure jetting technology. To determine the feasibility of jetting granular iron, two preliminary tests were conducted. The first test was a pump test to determine the feasibility of pumping granular iron through a high-pressure triplex pump. The second test was performed to further refine the laboratory analysis of using guar gum as a carrier fluid.

3.3.1 Pump Test

Before conducting the pump test, protocols for the guar gum/iron and kaolinite clay/iron slurries needed to be determined. To determine these protocols, tests were conducted by Halliburton at their Duncan, Oklahoma, facility as well as DuPont. The objective of the guar gum/iron tests were to determine the maximum quantity of iron that could be suspended by the guar gum without significant settling. Based on the guar gum tests, approximately 75 percent by weight 20 mesh type IS iron could be suspended. The objective of the kaolinite clay/iron tests was to determine the water content of the kaolinite carrier fluid such that the slurry could be pumped. Based on the kaolinite clay tests, the slurry needed to be approximately 60 percent by weight water and 40 percent clay.

The pump test was conducted at Hayward Baker's facility in Odenton, Maryland. The test included two carrier fluids (i.e., kaolinite clay and guar gum) and two versions of granular iron (i.e., 20 mesh to dust type IS and 50 mesh to dust) to determine the sensitivity of plugging the 4 millimeter jetting nozzles. In addition, the test included all of the equipment that would be used during the field emplacement tests (i.e., mixing tanks, high-pressure pump, jetting rig, jetting nozzle assembly, transfer pumps).

The equipment was set up at Hayward Baker's facility with the nozzle assembly inside of the mix tank to contain the jetted slurry and recirculate the slurry. Once the equipment was set up, a 2 yard batch of Peerless Metal Powders 20 weight percent 50 mesh iron and 80 weight percent kaolinite clay (at a 60 weight percent water and 40 weight percent clay ratio) was mixed. The slurry was then drawn from the mix tank via a precharge pump and pumped to the high-pressure pump. The high-pressure pump then pumped the slurry to the jetting rig.

During the test, the high-pressure pump could build pressure to approximately 2,000 psig. Although 6,000 psig was not attained, slurry was pumped through the nozzles, which did not plug or show indications of wear. It was later determined that the precharge pump was cavitating at the intake hose from the mix tank and starving the high-pressure pump. Thus, the 4-inch intake hose was too small for this slurry, resulting in too large of a pressure drop in the hose. As a result, a 6-inch hose was recommended for the field. (A 6-inch hose was not available at Hayward Baker's facility at the time of this test; therefore, further testing was not conducted.)

3.3.2 Carrier Fluid Tests

After thoroughly flushing the system, a guar gum and iron batch was mixed. The guar gum slurry was first developed in the mix tanks using a ratio of 40 pounds of guar gum to 1,000 gallons of water. After mixing, the guar gum appeared to have built viscosity and Peerless 20 mesh to dust type IS iron was added to the slurry. Grab samples of the mixture were collected and indicated that the viscosity of the guar gum was too low (i.e., visual observation indicated that the iron particles were settling out of the mixture). More guar gum was added to the mixture, which increased the slurry ratio to 60 pounds of guar gum to 1,000 gallons of water. A modest improvement in the particle settling rate resulted; therefore, more guar gum was added to the mixture and increased the slurry ratio to 80 pounds of guar gum to 1,000 gallons of water. With still little improvement in the particle settling rate, an attempt was made to pump the slurry through the jetting system. Again, only approximately 2,000 psig was attained.

To rule out equipment malfunction, the high-pressure pump was inspected. A worn valve seat was determined to be a cause of failing to attain full pressure; however, the wear was caused by standard usage. In addition, one of the nozzles was plugged with iron. Based on these tests, only the Peerless 50 mesh to dust was deemed feasible with the 4-millimeter nozzles since the Peerless 20 mesh to dust type IS iron tended to plug the nozzles. Furthermore, the Peerless 20 mesh to dust type IS iron was much more difficult to maintain in suspension without aggressive agitation. In fact, once the 20 mesh to dust type IS settled out of the mixture, resuspension was not possible with Hayward Baker's current agitation equipment.

Based on these test results at Hayward Baker's facility and the laboratory tests that were conducted at Halliburton, further guar gum carrier fluid tests were conducted by Rhone Poulenc (a guar gum supplier) at their facility in Cranbury, New Jersey. The tests included mixing various quantities of guar gum (i.e., Rhone Poulenc grade jaguar 8600) with various amounts of granular iron to determine the degree of settling over a 15 minute time frame. Two versions of granular cast iron from Peerless were used during these tests: 20 mesh to dust type IS and 50 mesh to dust.

In the tests, the 20 mesh to dust type IS was water quenched iron, which is believed to have caused the guar gum to flocculate, and the iron quickly settled out of the slurry. It was theorized that the water quenching caused various oxides to form on the particle's surface. The oxides then complexed with the guar gum, causing it to flocculate. The resulting mixture was a low viscosity slurry that would not suspend the iron and could not be salvaged chemically.

A viscosity above 3,000 centipoise was required to prevent the 50 mesh to dust iron from settling while a viscosity below 9,000 centipoise was required to maintain a fluid-like slurry. Based on the laboratory work, a slurry protocol for the guar gum slurry was developed as 100 pounds per 1,000 gallons of water. The required pH of the slurry was approximately 7.5 pH after addition of the iron.

Mixing the guar gum and water tended to elevate the pH of the slurry to approximately 2 points above the water's background pH level. Once the guar gum was mixed and the pH was adjusted to approximately 6.5 by adding acetic acid purchased locally in the form of white vinegar, the iron was mixed and slightly elevated the pH approximately 1 point (i.e., final pH of 7.5).

3.4 "Proof of Principle" Field Test

The primary objective of the proof of principle field test was to determine, in a clean field setting, the feasibility of jetting 50 mesh granular iron using commercially available high-pressure jetting equipment. Other objectives involved understanding the geometry of the thin diaphragm and columnar emplacements, determining their iron content after emplacement, and determining their hydraulic conductivity.

3.4.1 Geology and Location

The site of the field test was part of an uncontaminated outcrop and recharge area of the Old Bridge Aquifer. The Old Bridge Aquifer is a member of the Cretaceous age Potomac-Raritan-Magothy Aquifer (PRM), which consists of a southeastward-dipping wedge of sand, silt, and clay sediments. Beneath the Old Bridge Aquifer are the Woodbridge Clay and Farrington sand members.

The Old Bridge Aquifer consists of a deltaic sequence of sand with interbedded silts and clays. The thickness of the aquifer at the site ranges from approximately 100 to nearly 200 feet, depending on topography. In the region of the test area, the Old Bridge Aquifer is approximately 140 feet thick, with 45 feet saturated. The upper 15 feet of the Old Bridge Aquifer were jetted as part of this test (see Appendix F).

The field test location was prepared prior to mobilization by creating two jetting spoils collection pits roughly 12 by 12 by 3 feet. The columns were scheduled for jetting along one side of the pit and thin diaphragm walls along another side of the pit to a depth of approximately 15 feet. As such, both emplacements were to be conducted in the unsaturated zone (see Figure 25).

3.4.2 Equipment

The equipment used for high-pressure jetting can be categorized into three systems: the mixing system, high-pressure pumping system, and jetting rig. The mixing system incorporates, but is not limited to, materials handling equipment, mixing tanks, bulk storage tanks, and a low-pressure pump. The high-pressure pumping system generates the desired pressure (approximately 6,000 psig) and flow rate (90 gpm), depending on the number and diameter of nozzle(s). The jetting rig controls the positioning, orientation, extraction rate, and rotation rate of the drill string. These three systems are interconnected using appropriately sized hose or pipe.

During an early site visit, it was determined that the pressure rating of Hayward Baker's high-pressure hose connecting the high-pressure pump to the jetting rig was insufficient. Although Hayward Baker's standard hose was rated at 5,500 psig with a burst pressure of 25,000 psig, it was routinely operated at 5,800 psig. Operating above the manufacturer's working pressure was not acceptable to DuPont; therefore, a 6,000 psig pressure hose was required.

Hard pipe with a pressure rating of 15,000 psig was connected to the 6,000 psig high-pressure pump, terminating at the pop-off valve (see Figure 26). The high-pressure hose was then connected to the pop-off valve, terminating at the jetting rig (see Figure 27).

Upon arrival at the plant gate, the jetting equipment was inspected by the plant for health and safety concerns and the potential for adverse environmental impacts (e.g., oil dripping from the equipment). The equipment passed inspection and was escorted to the test site. Once at the test site, the equipment was unloaded and the two mixing tanks, generator, precharge pump, and high-pressure pump were set up near the materials staging area to facilitate materials handling (see Figures 28 and 29).

3.4.3 Health and Safety

Once the equipment was setup, a safety meeting was held with key personnel from the plant, Hayward Baker, and the Corporate Remediation Group. The safety of the high-pressure hose was in question, despite the existence of a pop-off valve inline set at 6,100 psig. There was no certification that the hose assembly could withstand the operating pressure even though the hose and couplings were pressure-rated at 6,000 psi, and assembly was performed according to the manufacturer's specifications.

To resolve this issue and allow emplacement efforts to continue, a hydrostatic pressure test was devised using the jetting equipment. The test involved replacing both axisymmetrical nozzles with blank nozzles in the nozzle assembly, thereby plugging the flow of fluid and dropping the ball bearing into the nozzle assembly to plug the flow to the drill bit. The high-pressure hose was then pressurized by the high-pressure pump to approximately 5,800 psig. However, due to a small amount of leakage by the ball bearing in the nozzle assembly, the pressure gradually decreased for over 10 minutes to approximately 5,000 psig. As the pressure decreased, the hose was repressurized. This test method was performed four times, and the hose was inspected for abnormalities in construction or in coupling assembly. After successful completion of this test, the jetting system was approved for use at the plant.

3.4.4 Kaolinite Clay/Iron Materials and Mixing

The kaolinite clay and Peerless 50 mesh iron materials were ordered in preweighed supersacks with plastic bag interliners to prevent the materials from getting wet during shipment and storage. Once the materials were at the test site, they were placed on wooden pallets and covered with waterproof tarps as an additional precaution.

After approval to proceed, a batch of kaolinite clay and iron slurry was mixed. Supersacks of kaolinite clay and iron were handled using an all-terrain forktruck and transferred from the supersack to the mixing tank using the supersack's built-in funnel (see Figures 30 and 31).

It was quickly learned, however, that the flow of kaolinite clay through the funnel needed to be throttled. If too much clay was placed into the small mixing tank, a thin film of clay hydrated on top of the slurry, preventing additional clay from mixing into a slurry. This problem was compounded because the discharge of the circulation pump (i.e., the primary mixing energy source of the small tank) did not have enough energy to entrain the clay into the slurry. As a result, the clay accumulated on the surface of the slurry. To solve this problem, mixing was discontinued in the small tank and was performed instead in the large tank originally intended for bulk storage. The large tank had a large mixing paddle and a high-flow circulation pump to agitate the slurry.

The mixing of the batches for a particular kaolinite clay and iron emplacement was conducted according to the protocol in Table 1. Once the prescribed ingredients were mixed into the slurry, the density of the slurry was measured using a mud balance (see Figure 32).

3.4.5 Kaolinite Clay/Iron Emplacements

After confirming the density of the kaolinite clay and iron slurry at approximately 104.4 lbs/ft^3, the slurry was approved for jetting. The first set of emplacements to be jetted were the columns located to the left of the clay pit (see Figure 25). Three columns were jetted (i.e., one with an extraction rate of 20 cm/sec, another with a rate of 30 cm/sec, and a final column at 40 cm/sec), with rotation rates of the drill string at one-third the extraction rate. The remainder of the jetting parameters (e.g., pressure, flow, nozzle diameter) remained constant. One of the column emplacements was to be isolated, while the other two column emplacements were to intersect to investigate the impact on symmetry and the iron content distribution for intersecting columns. However, during the emplacement of the central column, the jetting spoils came up the borehole of the isolated column, indicating an interconnection. Spoils return to the surface through the boreholes was somewhat dynamic as seen in Figure 33.

The next set of emplacements were the thin diaphragm walls located in front of the clay pit (see Figure 25). The three thin diaphragm walls were jetted (i.e., one with an extraction rate of 50 cm/sec, another with a rate of 75 cm/sec, and a final wall at 100 cm/sec), with no drill string rotation. As with the columns, the remainder of the jetting parameters (e.g., pressure, flow, nozzle diameter) remained constant and one thin diaphragm wall emplacement was intended to be isolated to investigate the impact on symmetry and the iron content distribution for intersecting walls. However, during the emplacement of one of the intersection walls, jetting spoils came up the borehole of the isolated wall, indicating an interconnection.

3.4.6 Guar Gum/Iron Mixing

The first batch of guar gum slurry that was mixed attained a viscosity of approximately 3,000 centipoise after a pH adjustment to approximately 7.5 using 3 gallons of white vinegar (see Table 2). However, after further mixing guar gum and vinegar, the viscosity gradually decreased, despite the constant pH.

It was believed that with the high flow rate of the pump used to circulate the slurry in the large tank and mixing action of the large paddle mixer that the iron would stay suspended. Therefore, the iron was added to the slurry. Once the density was checked and verified, emplacement began.

3.4.7 Guar Gum/Iron Emplacements

The guar gum and iron columns were the next set of emplacements jetted and were located to the right of the guar pit (see Figure 25). The same parameters were used for this emplacement as for the kaolinite clay/iron columns. As with the kaolinite clay/iron columns, one column was intended to be isolated and two columns were intended to intersect. To ensure this outcome, the isolated column was located farther from the intersecting columns than in the previous kaolinite clay/iron column emplacement.

After it was learned that the viscosity degraded due to the high flow rate of the pump overshearing the gum and destroying the guar gum polymer chains, the diesel-driven pump was throttled to an idle during mixing and increased during the jetting process. The next 4 cubic yard batch that was mixed with the pump on idle attained viscosity nicely after adding 3 gallons of white vinegar and mixing in the iron.

The final set of emplacements jetted were the thin diaphragm walls located in front of the guar pit. As with the columns, the isolated thin diaphragm wall was located farther from the other walls than in the previous kaolinite clay/iron wall emplacement to help ensure isolation.

3.4.8 Sample Collection

Throughout the emplacement efforts, samples of the original slurry mixtures and spoils were collected. These samples were analyzed for density and iron content to determine how much iron remained in the soil. Approximately 60 to 80 percent of the jetted volume returned to the surface as jetting spoils.

To increase the chance of core recovery, the emplacements were allowed to equilibrate with the soil moisture for two weeks before coring the emplacements with Shelby tubes. Then, the emplacements were excavated to expose their upper surface to delineate the extent of the geometry and to facilitate sampling location identification (see Figure 34). After delineating the emplacements, Shelby tubes were collected using a hollow-stem auger and a 3-inch diameter Shelby tube (see Figure 35).

The Shelby tube samples were preserved by capping and sealing the cap to the tube with duct tape. The tubes were shipped to a geotechnical laboratory for extrusion and photographic documentation. The geotechnical laboratory also conducted measurements on a limited number of samples (see Table 3).

3.4.9 Sample Analysis

To determine the weight percent of iron that was emplaced, a laboratory technique was developed to extract the iron from the Shelby tube sample. The technique involved using a Gilson model SP-90 automagnet separator to extract the iron from a sample of known initial weight (see Figure 36).

The sample of known weight was washed with water, and the iron from the sample was extracted using the automagnet separator, leaving most of the soil particles behind. For a given wash cycle, the automagnet separator was used several times to extract the iron from the soil particles until no apparent iron was collected by the magnet. The collected iron was then rewashed to further separate soil particles from iron particles of the previously washed sample. This cycle was repeated several times until it was apparent that no soil particles remained with the iron sample. The extracted iron was then oven-dried to determine the weight percent of iron in the sample. The density of the samples, moisture weight percentage, and iron weight percentage for each emplacement type are shown in Figures 37, 38, 39, and 40.

3.5 Field Test Results

The field emplacement efforts have proven that conventional high-pressure jetting technology can successfully jet a slurry of 50 weight percent 50 mesh granular iron and 50 weight percent guar gum or a slurry of 20 weight percent 50 mesh granular iron and 80 weight percent kaolinite clay to a depth of 15 feet in unsaturated soil.

3.5.1 Kaolinite Clay/Iron Excavation

The excavation efforts of the kaolinite clay/iron columns indicate that the columns have apparent diameters that range from approximately 5 to 6 feet for the 20 cm/min column and 4 to 5 feet for the 30 and 40 cm/min columns. However, the outer 1-foot edge of the columns were fragmented, indicating that the actual column diameter might be up to 2 feet smaller in diameter (see Figure 41).

The thin diaphragm walls jetted with the kaolinite clay/iron slurry produced walls that were approximately 2 inches thick and had tip-to-tip lengths of 16 feet for the 50 cm/min emplacement, 14 feet for the 75 cm/min emplacement, and 12 feet for the 100 cm/min emplacement (see Figure 42).

3.5.2 Guar Gum/Iron Excavation

The excavation efforts of the guar gum/iron columns indicate that the columns have apparent diameters that range from approximately 6 to 7 feet for the 20 cm/min column and 5 to 6 feet for the 30 and 40 cm/min columns. Again, the outer 1-foot edge of the columns were fragmented, indicating that the actual column diameter might be up to 2 feet smaller in diameter (see Figure 43).

The thin diaphragm walls jetted with the guar gum/iron slurry produced walls that were approximately 1½ to 2 inches thick and had tip-to-tip lengths of 14 feet for the 50 cm/min emplacement, 12 feet for the 75 cm/min emplacement, and 7 feet for the 100 cm/min emplacement (see Figure 44).

3.5.3 Hydraulic Conductivity

The hydraulic conductivity of the kaolinite clay and iron column emplacements were approximately two orders of magnitude lower than that of the background soil and one order of magnitude lower for the thin diaphragm walls. The guar gum iron emplacements were approximately the same order of magnitude as that of the background soil (3.72×10^{-4} cm/sec). (The hydraulic conductivity of the guar gum/iron thin diaphragm wall was measured horizontally through the wall.)

3.5.4 Thin Diaphragm Wall Iron Content

Based on the laboratory data for the guar gum/iron thin diaphragm wall emplacements, the iron content in the wall exceeded the original iron content of the slurry. This is most likely due to two mechanisms: (1) the near total replacement of the soil matrix with the slurry and (2) the degradation of the guar gum and consolidation of the iron within the wall. As a result, the consolidation of the iron within the wall should be considered during the design stage so that a sufficient wall height remains. If a taller wall can be jetted to compensate for the consolidation or additional slurry can be pumped into the upper cavities of wall, this factor may be negated.

Laboratory data for the kaolinite clay/iron thin diaphragm wall emplacements indicates that the original iron content of the slurry can be obtained in situ. This is most likely due to the near replacement of the soil matrix with the slurry.

Approximately 80 percent of the iron can be accounted for if a mass balance for the iron of the thin diaphragms walls is calculated. Approximately 60 to 75 weight percent of the jetted iron remains in situ within the walls; the balance comes to the surface in the spoils.

3.5.5 Columnar Emplacements

Analysis of the laboratory data for the guar gum/iron columnar emplacements indicates that the original iron content of the slurry can be obtained in situ. However, complete mixing of the soil matrix and the slurry to form a homogenous matrix of soil and iron did not occur (see Figure 45). Incomplete mixing may not be a concern due to the size of the column and the iron amount in the emplacement as long as the pockets of soil do not interconnect to create a pathway through the emplacement.

A mass balance for the iron content in the columnar emplacements is difficult to calculate due to the heterogeneity of the columns. However, based upon the iron content in the spoils, approximately 60 weight percent of the jetted iron may be assumed to remain in situ within the emplaced columns.

3.6 Emissions and Generated Waste

The production of excess spoils is dependent on the soil type, grout type, time required to drill the borehole, and time required to conduct the jetting. With the limited experience to date in quantifying the production of excess spoils, a general estimate for spoils produced during the jetting phase varies from 0.6 to 0.8 times the jetted volume of grout. Finer-grain soils will tend to produce a higher volume of spoils than coarser-grained soils. Similarly, a thick clay-based grout will produce a higher volume of spoils than a leaner clay-based grout. A general rule of thumb is that whichever combination of soil or grout type produces a viscous spoils return tends to carry more spoils to the surface. For instance, jetting with the guar gum based grout tended to produce less spoils than the clay-based grout. The high-fluid dynamic shear rate through the jetting nozzles may have destroyed the polymer chains of the guar gum, changing its high viscosity to that of water. If polymer chains were destroyed, the water-like carrier fluid would have a significantly reduced capacity to carry spoils to the surface. In fact, some of the water could potentially migrate into the formation.

Regardless of the amount of spoils, the excess spoils contain a portion of the jetted iron. This usually would result in the excess spoils being treated and rendered nonhazardous over a relatively short period of time, thereby offering a wider range of disposal options.

High-pressure jetting pilot tests were conducted in an uncontaminated site; therefore, volatile emission measurements were not obtained. However, excess spoils were generated that could potentially produce volatile emissions if contaminants were present. In this case, a spoils control box at the drilling rig was connected to a vacuum truck to manage excess spoils (see Figures 46 and 47). The vacuum exhaust of the vacuum truck could then be passed through an activated carbon scrubber, if needed, to eliminate the volatile emissions.

3.7 Productivity and Costs

Due to the limited experience implementing this technology to date, an average of eight hours out of a 10-hour workday were productive. When system components failed (e.g., a seal in the drill string wore out), productive hours decreased. However, barring significant equipment breakage, repair of the system components proceeded quickly, and production was regained within one hour.

Jetting costs are a function of the site requirements and of the time to conduct the emplacement efforts. Generally, a single high-pressure jetting system costs approximately $7,500/day or more depending on the equipment needs. Costs for premobilization,

mobilization, and demobilization of equipment and crew can range from \$20,000 or more depending on the site location and project requirements (e.g., various support equipment needs such as a vacuum truck or an all terrain forktruck can increase costs up to \$2,000/day).

Based on the analysis by DuPont and for budgetary purposes, the unit cost for emplacement (excluding materials) ranges from \$6/ft^2 to \$9/ft^2 for thin diaphragm walls and \$20/ft^2 to \$27/ft^2 for columns. To estimate the cost of materials, the slurry cost per jetting minute must be determined and multiplied by the time required to jet the needed number of emplacements (see Table 4).

3.8 Conclusions and Recommendations

Based on the limited experience of using the high-pressure jetting technology, it appears to be a reasonably cost-effective alternative to the mandrel technology. In addition, high-pressure jetting offers more flexibility than the mandrel technology for cases where the soils have relative density blow counts above 25 (as measured by the SPT method) or emplacements deeper than 50 feet are desired. Furthermore, high-pressure jetting does not transfer a significant amount of seismic energy to the site, which could be a concern for the mandrel method near foundations or overhead and underground utilities.

To refine the technical capabilities and costs of high-pressure jetting, a larger-scale pilot test(s) of the method is required and would ideally involve the following:

Approximately 24 emplacements, with depths in excess of 50 feet.

Geotechnically delineated site.

Site with underground utilities present.

One of the unique capabilities of high-pressure jetting is the potential capability to emplace a reactive zone to much greater depths. To exploit this depth capability, adaptation of a directional drilling guidance tool capable of measuring the location and orientation of the jetting nozzles is required. Electronically monitoring and recording various jetting parameters is an area recently being addressed in the United States. From a quality control standpoint, a data acquisition system is highly desirable and should be part of all future emplacement efforts.

4.0 Advanced *Lasagna*™ Materials Study

Phase I results indicated that the mandrel emplacement technology is commercially cost effective; however, the prefabricated treatment zones and electrodes used for Phase I were not commercially cost effective due to the labor intensive fabrication process. Therefore, the focus of the Advanced *Lasagna*™ Materials Study was to investigate the potential of automating the electrode and treatment zone prefabrication process to improve cost effectiveness and commercially viability. These new prefabricated materials would then be emplaced using the mandrel emplacement technology.

4.1 Concept Description

The investigation of this concept was focused on commercial manufacturing processes that fabricate relatively thin geotextile composite structures (e.g., bentonite blankets and drainage mats). These materials range from approximately 3/8 inch to approximately 1 inch in thickness and can be fabricated in widths up 20 feet wide and lengths up to 100 feet.

The concept was to use the commercialized fabrication process to manufacture the same geotextile structure, either by replacing the filler material or by incorporating the new *Lasagna*™ materials and delivering the finished product directly to the construction site.

4.2 Concept Development

To investigate the concept further, various manufacturers of geotextile composite structures were contacted, and the concept was reviewed with them. Two challenges became evident. First, the bentonite blanket suppliers are reluctant to foul their manufacturing processes with other filler materials (e.g., granular cast iron) since their primary interest is selling bentonite. Second, suppliers of drainage mats are not equipped to fill their mats with *Lasagna*™ materials since their market focus is geotextile materials.

With the help of Nilex personnel, DuPont explored the technical feasibility of the concept. Preliminary tests were conducted at Nilex's facility in Denver, Colorado, to determine the level of feasibility. Standard ¼ inch thick by 4 inch wide wickdrain material was filled with 20 mesh granular cast iron. It became apparent that filling the wickdrain would cause it to bulge when manipulated, resulting in a product indicative of poor process control. Then, the team conceptualized sewing the wickdrain in a criss-cross pattern prior to filling, but determined that the sewing needle would have a difficult time penetrating through the 20 mesh granular iron.

As a result, this technology effort was deemed not cost effective or commercially viable, and the development effort was stopped.

5.1 Model

The cost evaluation was prepared by developing a cost optimization model of the overall treatment process. The goals of this model were to estimate the three key parameters of a *Lasagna*™ project (i.e., number of electrode rows, number of treatment zones per electrode pair, and the applied electrical potential) and use those values to perform a detailed cost analysis.

The model considers various input parameters such as soil properties, depth of contamination, cost of emplacing electrodes and treatment zones, required purge water volume, time constraints to achieve cleanup, and cost of power. Several example cases were run using the cost model to provide representative cost ranges for applying the technology to clean up TCE contamination in clay. These costs were estimated to range from approximately $45 to $80 per cubic yard of soil for a 1 acre site, with the cost depending on depth of contamination (depth range for the model is 15 to 45 feet) and the time available to complete the remediation (cost range valid for one- and three-year time frame).

Scoping evaluations were performed to determine the effects of dense, nonaqueous phase liquid (DNAPL) on the cost, as more pore water is flushed in DNAPL scenarios. The DNAPL cost scenarios ranged from approximately $70 to $165 per cubic yard of soil for the same 1 acre site. These costs were also dependent on the depth of contamination (range stated above) and the time to complete remediation, which is directly proportional to the pore volumes flushed. The time frame used for the DNAPL scenarios ranged from two to 12 years, with two pore volumes being flushed per year.

To facilitate complete understanding of the cost model, Table 5 lists the abbreviations and respective definitions used within the model. For reference information, Table 6 lists the unit abbreviations involved in this cost evaluation.

5.2 Cost Analysis

The three parameters listed in Section 5.1 (i.e., number of electrode rows, number of treatment zones per electrode pair, and the applied electrical potential) greatly affect the operation costs. This section discusses a cost model based on these parameters that can be used to determine the design that minimizes cost.

- The costs of an electro-osmotic remediation project are divided into three categories:
- Electrode and treatment zone materials and installation.

Fixed costs, including those for the rectifier and power control system, the fluid-handling system, equipment mobilization to install the electrodes and treatment zones, and maintenance.

5.2.1 Installing Electrodes and Treatment Zones

Suppose that N_E equally spaced electrode rows are installed in a site of length Y. This divides the site into (N_E-1) electrode pairs, with spacing between electrode rows (L_E) equal to Y/(N_E-1). If N_T treatment zone rows are equally spaced within the region of each electrode pair, then the spacing between treatment zones (L_T) is

$$L_T = \frac{Y}{(N_T + 1)(N_E - 1)} \qquad (1)$$

The cost for installing rows of electrodes and treatment zones may be expressed as the sum of equipment mobilization expenses (treated here as fixed cost) and costs that are proportional to the area of the installed materials.

The electrode cost excluding mobilization costs (C_E) is

$$C_E = P_E N_E DX \qquad (2)$$

where P_E is the price of electrode material and installation on a per-area basis, D is the installation depth, and X is the width of the site.

Similarly, the treatment zone cost exclusive of mobilization (C_T) is

$$C_T = P_T N_T (N_E - 1)DX \qquad (3)$$

where P_T is the price of treatment zone material and installation on a per-area basis.

5.2.2 Electricity Costs

The cost of electricity may be expressed as:

$$C_e = \underline{P_e \text{ (Soil Volume) (Power Input per Soil Volume)}}$$

$$\text{(Remediation Time)} \qquad (4)$$

where C_e is the electrical energy cost per soil volume and P_e is the price of electricity (e.g., in \$/kWH).

The power input per soil volume is

$$\frac{\text{Power Input}}{\text{Soil Volume}} = \sigma E^2 \qquad (5)$$

where s is the soil electrical conductivity and E is the electrical field gradient. Therefore, the electricity cost is

$$C_e = P_e DXY\sigma E^2 T \qquad (6)$$

where T is the remediation time. The process must continue for enough time to drive the required purge water volume through the soil:

$$T = \frac{\text{Required Purge Water Volume}}{\text{Electroosmotic Flow Rate}} \qquad (7)$$

For the soil between a pair of treatment zones separated by distance L_T,

$$\text{Required Purge Water Volume} = anAL_T \qquad (8)$$

where a is the required number of pore volumes to adequately clean the soil, n is the soil porosity (vol/vol), and A is the cross sectional area perpendicular to flow. The number of pore volumes is determined through laboratory testing of the soil to meet restoration goals. The electro-osmotic flow rate (Q) is given by

$$Q = k_eAE \qquad (9)$$

where k_e is the electro-osmotic permeability.

Combining Equations 7 through 9 yields an expression for the remediation time in terms of the applied voltage and the treatment zone separation distance:

$$T = \frac{\alpha n L_T}{k_e E} \quad (10)$$

which may be rearranged to yield

$$E = \frac{\alpha n L_T}{k_e T} \quad (11)$$

Combining Equations 2, 3, and 4, the total cost of the remediation project (C) is

$$C = P_E N_E DX + P_T N_T (N_E - 1)DX + P_e DXY\sigma E^2 T + C_F \qquad (12)$$

where E is given by Equation 11 and C_F represents fixed costs.

The fixed cost elements in this cost model were estimated using a variety of cost-estimating sources. The input values for fixed costs can be found in Appendix G.

5.2.3 Strategy

Using the cost model developed in Section 5.2, a strategy can be developed to determine the design that minimizes cost. The goal is to select the number of electrode rows (N_E) and treatment zones per electrode pair (N_T) that reduce the total cost (C). Two additional constraints may be important. First, the cost-minimum design suggested by Equation 12 may require an electric field strength that would overheat the soil. Therefore, it is important to consider only those N_E-N_T combinations for which the resulting field gradient calculated by Equation 11 is less than some maximum value (E_{max}). Second, it is possible that the total applied potential that is calculated (the product of E and the electrode spacing) would be higher than acceptable from a safety standpoint. Therefore, an additional constraint would be to insist that $DV \leq DV_{max}$. With these constraints, the strategy for determining the proper design is as follows:

1. Specify

Site and soil properties (D, X, Y, a, k_e, s, n)

Prices of supplies and services (P_e, P_E, P_T, C_F)

Remediation Time (T)

2. Trying different values of N_E and N_T, calculate:

$$E = \frac{\alpha n L_T}{k_e T} \quad (11)$$

where:

$$L_T = \frac{Y}{(N_T + 1)(N_E - 1)} \quad (1)$$

$$C = P_E N_E DX + P_T N_T (N_E - 1) DX + P_e DXY \sigma E^2 T + C_F \quad (12)$$

$$\Delta V = \frac{\alpha n L_T L_E}{k_e T} \quad (13)$$

where:

$$L_E = \frac{Y}{N_E - 1} \quad (14)$$

3. Select the N_E-N_T pair that minimizes C while maintaining

$$E \leq E_{max} \text{ and } DV \leq Dv_{max} \quad (15)$$

where E_{max} is set to 31 volts/m and ΔV_{max} is set to 500 volts for the evaluation conducted.

The cost evaluation uses the costs derived for the mandrel tremie tube emplacement as shown in Appendix G. Table 7 shows the details of *Lasagna*™ optimizations for the one- and three-year cases.

All cases assume that the areal extent of contamination is 1 acre. The contamination was assumed to occur 15 and 45 feet below the surface, with a duration of remedial activity of one or three years. The number of pore volumes flushed (parameter known as alpha) over that time frame was set to two. For the three-year cases, a discount rate of 12% was used to develop present costs for labor and electricity used over multiple years. Other site-specific parameters used in the model can be found in Appendix G.

5.3 Potential Effect of DNAPL on Cost

To determine the effect of potential DNAPL TCE on the cost of a *Lasagna*™ cleanup, an evaluation of the cylinder drop test area at PGDP was completed. The evaluation was initiated because TCE seemed to be exceeding solubility limits at a limited depth horizon within the Phase IIa test plot. Rather than develop a single-point estimate of cost to cover DNAPL removal, the evaluation served as a sensitivity analysis. Using this approach, the soil TCE concentration was varied from relatively low levels (i.e., non-DNAPL) to high levels representative of various quantities of DNAPLs in the soil. The anticipated effect on cleanup cost and remediation time was examined using the *Lasagna*™ cost model spreadsheet. In this way, the inherent uncertainty in estimating mass and residual TCE concentrations were addressed.

5.3.1 Assumptions

For simplicity, many assumptions were made about the *Lasagna*™ system design, the behavior of DNAPL TCE under the influence of electro-osmosis, and the costs associated with long-term operation.

The design was optimized to clean up 100 ppm TCE in soil in one year (flushing two soil pore volumes) under non-DNAPL conditions. In all cases, operation at a flushing rate of two pore volumes per year was assumed based on this design. The costs in Appendix H relating to mandrel emplacements were assumed to be valid for DNAPL zone emplacements.

The primary assumption for TCE cleanup behavior was that the cleanup rate was limited by the solubility of TCE. In other words, the evaluation does not consider the possibility of DNAPL migration under the influence of electro-osmotic flow. (Note that based on recent laboratory and field evidence, this is a highly conservative assumption.) General Electric contributed a simple equation to relate the initial soil concentration (C_{soil}) to the number of pore volumes required (PV_{req}) to complete cleanup:

$$PV_{req} = 2 + ((C_{soil}*(\text{soil specific gravity/porosity}) - C_{sat})/C_{sat}) \quad (16)$$

where C_{sat} is the saturated water concentration (1,100 mg/l for TCE).

For this evaluation, a net (i.e., wet) soil specific gravity of 2.0 and soil porosity of 0.4 were assumed. The equation above is used to calculate the number of pore volumes required to complete cleanup (and, hence, required cleanup period in years) for a range of starting soil concentrations. As a point of interest, this equation also predicts that TCE concentrations in soil greater than 220 ppm is indicative of DNAPL presence. (Please note that this neglects potential sorbed phase and, therefore, is a conservative estimation). From a technical standpoint, the cleanup limitation may be defined by the upper bound soil concentration representing DNAPLs (i.e., maximum soil concentration or an alternate statistical upper bound measure such as a 95% UCL), rather than average concentration. However, the precise measure of cleanup is normally subject to agency negotiation.

Regarding long-term operation costs, specific items were assumed to continue as constant annual costs throughout the required cleanup period (e.g., field labor, maintenance costs, power requirements). For purposes of this evaluation, the ongoing need for a half-time field operator was assumed under the long-term operation scenario. Electricity cost was assumed to continue unabated. In addition, all annual costs were brought back to a present cost basis using a 12% discount rate.

5.3.2 Results

Table 8 presents the results of the *Lasagna*™ DNAPL remediation evaluation. The costs were based on a depth of 45 feet over 1 acre areal extent. Detailed spreadsheets are available in Appendix I, which include the cases for 15 feet.

5.3.3 Discussion

As shown, project cost is expected to increase in cases where the initial soil concentration increases above approximately 100 ppm. The overall project cost increase is directly attributed to ongoing labor, maintenance, and electrical cost. Note that recent laboratory work reported by General Electric strongly suggests that DNAPLs will migrate in response to electro-osmotic flow, albeit at a fraction of the rate of water migration. In the two tests reported, the apparent DNAPL migration rate was one-sixth and one-eighth of the water migration. If one were to assume a conservative field DNAPL migration velocity of one-tenth the water migration rate, the cleanup cost for any DNAPL case would cap at approximately the 2,500 ppm case shown in Table 8 (i.e., about $7 million for this generic 1-acre, 45-foot-deep case).

6.0 References

Athmer, et al. 1996. *Large Scale Field Test of Lasagna™ Process* (Topical Report for Task #12 and 13). In "Development of an Integrated In Situ Remediation Technology." DOE Contract No. DE-AR21-94MC31185.

Brodsky, P.H., and S.V. Ho. 1995. In Situ Remediation of Contaminated Soils. U.S. Patent No. 5,398,756, issued March 21, 1995.

Shoemaker, et al. 1996. *Evaluation of Treatment Zone Formation Options* (Topical Report for Task #1). In "Development of an Integrated In Situ Remediation Technology." DOE Contract No. DE-AR21-94MC31185.

Quinton, et al. 1996. *Cost Analysis* (Topical Report for Task #5). In "Development of an Integrated In Situ Remediation Technology." DOE Contract No. DE-AR21-94MC31185.

Table 1. Mixing Protocols for Kaolinite Clay and Iron Slurry Batches

Parlin Iron/Clay Batches

			Diaphram	Diaphram	Diaphram	Column	Column	Column	
			50 cc/min	75 cc/min	100 cc/min	20 cc/min	30 cc/min	40 cc/min	
			13 feet deep	13 feet deep	13 feet deep	9 feet deep	13 feet deep	13 feet deep	
			90 gpm	90 gpm	90 gpm	90 gpm	90 gpm	90 gpm	
			7.92 minutes	5.28 minutes	3.96 minutes	13.72 minutes	13.21 minutes	9.91 minutes	
			713 gallons	475 gallons	357 gallons	1234 gallons	1189 gallons	892 gallons	
			3.5 yards	2.4 yards	1.8 yards	6.1 yards	5.9 yards	4.4 yards	
		Batch Size	4.0 yards	3.0 yards	2.0 yards	6.0 yards	6.0 yards	5.0 yards	
		95#/cu.ft.							
		2,565 #/yd.							
Iron/Clay	Wht %	#/ 1 yard	# (gal)	# (gal)	# (gal)	# (gal)	# (gal)	# (gal)	total #
H2O	48	1,231 (148)	4,925 (590)	3,694 (443)	2,462 (295)	7,387 (886)	7,387 (886)	6,156 (738)	32,011
Clay	32	821	3,283	2,462	1,642	4,925	4,925	4,104	21,341
Iron-50	20	513	2,052	1,539	1,026	3,078	3,078	2,565	13,338
	clay	bag usage							
		batch 1	1@ 1670# minus 28#	1@1395# plus 247#	1@1670 minus28# ea.	1@1395 plus247#	1@1395 plus247#	1@1670 minus28# ea.	
		batch 2	1@ 1670# minus 28#	1@1395# minus 574 net minus 327 from bag 2		1@1395 plus247#	1@1395 plus247#	1@1670 minus28# ea.	
		batch 3				1@1395 plus247#	1@1395 plus247#	1@1395 minus574# from	
	Iron-50	bag usage	1@2000# plus 52# Split in 1/2 batches	1@2000 minus 461# split in 2/3-1/3 batches	use from extras	1@3500# minus 422# split in 1/3	1@3500# minus 422# split in 1/3	1@2000 minus 565# split in 3 batches	

Table 1. This table shows the mixing protocols for the kaolinite clay and iron slurry batches.

Table 2. Mixing Protocols for Guar Gum and Iron Slurry Batches

Parlin Iron/Guar Batches

			Diaphram	Diaphram	Diaphram	Column	Column	Column	
			50 cc/min	75 cc/min	100 cc/min	20 cc/min	30 cc/min	40 cc/min	
			13 feet deep	13 feet deep	13 feet deep	9 feet deep	13 feet deep	13 feet deep	
			90 gpm	90 gpm	90 gpm	90 gpm	90 gpm	90 gpm	
			7.92 minutes	5.28 minutes	3.96 minutes	13.72 minutes	13.21 minutes	9.91 minutes	
			713 gallons	475 gallons	357 gallons	1234 gallons	1189 gallons	892 gallons	
Guar@100#/1000 gallons			3.5 yards	2.4 yards	1.8 yards	6.1 yards	5.9 yards	4.4 yards	
		Batch Size	4.0 yards	3.0 yards	2.0 yards	6.0 yards	6.0 yards	5.0 yards	
		104.4#/cu.ft.							
		2,819 #/yd.							
Iron/Guar	Wht %	#/ 1 yard	# (gal)	# (gal)	# (gal)	# (gal)	# (gal)	# (gal)	total #
H2O	49.4	1,392 (167)	5,570 (667)	4,177 (500)	2,785 (334)	8,355 (1000)	8,355 (1000)	6,962 (835)	36,205
Guar	0.6	17	68	51	34	101	101	85	440
Iron-50	50	1,409	5,638	4,226	2,819	8,456	8,456	7,047	36,644
	Iron-50	Bag usage							
		batch 1	1@3500 minus 681#	1@3500 minus 681#	1@2700# plus 119#	1@3500 minus 681#	1@3500 minus 681#	1@2700 plus 119#	
		batch 2	1@3500 minus 681#	1,409# from buckets		1@3500 minus 681#	1@3500 minus 681#	1@2700 plus 119#	
		batch 3				1@3500 minus 681#	1@2000 plus819 from buckets	1,409# from buckets	

bag count			clay	guar
Iron	10	3500	2	8
	3	2700	0	3
	4	2000	3	1

Table 2. This table shows the mixing protocols for the guar gum and iron slurry batches.

Table 3. Sample Locations and Geotechnical Tests Conducted

GeoSytems Consultants, Inc.

Laboratory Assignment and Data Summary Sheet

Project Numbe 97G151 Project Name Parlin NJ Site Date Assigned/d ######

Project Engine C R Calabria Client DuPont Page 1 of 4

Boring No.	Samp eType	Depth (feet)	M.C (%) ASTM D 2216	LL/PL ASTM D 4318	Density ASTM D 4718	Spec.Grav. ASTM D 854	Partcl.Size (sieve) ASTM D 422	Partcl Size (hydrm) ASTM D 422	TX k_h ASTM D 5084 (cm / sec)		Remarks
1G	column	8' - 10'	17.1		113.79		*	*	k_v	3.65×10^{-4}	
3G	column	8' - 10'	14.7	NP	115.90		*	*	k_v	1.68×10^{-3}	
9G	wall	8' - 10'							x		x = no sample to test
10G	wall	8' - 10'	17.8	NP	143.91	3.70	*	*	k_h	5.15×10^{-4}	
15G	wall	3' - 5'			133.82		*	*	k_h	7.66×10^{-5}	
17G	wall	8' - 10'		NP	143.10		*	*	k_h	1.38×10^{-4}	
18G	wall	8' - 10'					*	*	x	no sample to test	x = no sample to test
12G	wall	13' - 15'	18.7		129.00		*	*	k_h	6.25×10^{-4}	
5	column	8' - 10'	16.4		127.72		*	*	k_v	7.77×10^{-6}	
11	wall	13' - 15'	28.3		122.5				k_h	2.13×10^{-5}	
8	wall	8' - 10'	23.6		113.1 x						
14	wall	8' - 10'	17.5		122.5						
15	wall	8' - 10'			xx						
Other Soil bag		13' - 15'			113.70		*	*	k_v	3.72×10^{-4}	

Notes. 1) prepared tube log for each sample
2) photographed each sample after extrusion

Shelby Tube Sections

A	B	C
top		bottom

Vised Work Scope Based On Changes Per Your Telephone Conversation 7/31/

Table 3. This table shows the sample locations and geotechnical tests that were conducted.

Table 4. Selected Cost Items Required for Preliminary Estimate

Input Site Parameters	Case 1 Diaphragm	Case 2 Diaphragm	Case 3 Diaphragm	Case 4 Column	Case 5 Column	Case 6 Column
Drilled Depth In Feet	100	100	100	100	100	100
Jetted Height In Feet	60	100	60	60	100	60
Centers Between Boreholes In Ft	8	8	8	3	3	3
Barrier Length In Feet	800	4000	1900	800	4000	1900
Number of Crews Per Day	1	2	2	2	2	2
Equip. and Crew Cost Per Day	$6,700	$13,400	$13,400	$13,400	$13,400	$13,400
Calulated Jetting Details						
Jetting Time / Empl., Minutes	36.58	60.96	36.58	60.96	101.60	60.96
Drilling Time / Empl., Minutes	16.67	16.67	16.67	16.67	16.67	16.67
Total Time / Empl., Minutes	73.24	97.63	73.24	97.63	138.27	97.63
Calc Emplacements / Day	6.55	4.92	6.55	4.92	3.47	4.92
Cost Basis						
Number Of Emplacements	101	501	239	268	1334	634
Number Of Test Emplacements	4	4	4	4	4	4
Projected Emplacements / Day	4	6	8	6	4	6
Number Of Jetting Days	26.70	85.59	30.84	46.05	321.26	108.19
Jetting Contingency Days	4.01	12.84	4.63	6.91	48.19	16.23
Setup And Teardown Days	3.00	3.00	3.00	3.00	3.00	3.00
Additional Site Testing Days	1.00	1.00	1.00	1.00	1.00	1.00
Total Number Of Days	35	102	39	57	373	128
Costs Estimates						
Emplacement	$232,547	$1,372,587	$528,778	$763,154	$5,004,254	$1,720,834
Mob/Demob.	$50,000	$100,000	$100,000	$100,000	$100,000	$100,000
Per Diems	$25,596	$146,205	$58,045	$82,533	$525,633	$182,589
Materials						
Support Equipment	$121,609	$597,705	$232,474	$333,920	$2,169,620	$748,439
Total	$429,852	$2,216,497	$919,298	$1,279,507	$7,799,507	$2,751,862
Cost per Ft^2	$8.96	$5.54	$8.05	$26.66	$19.50	$24.14

Table 4. This table shows many of the cost items that need to be included as part of a preliminary estimate.

Table 4. Selected Cost Items Required for Preliminary Estimate (Continued)

Jetting Cost Estimates

Assumptions			
Extraction Rate	(cm/min)	(in/min)	
Columar Walls	30.00	11.81	
Thin Diaphragm Walls	50 00	19 69	
Equip. and Crew Cost / Day			
Single Fluid	$6,000		
Double Fluid	$6,700		
Triple Fluid	$6,700		
7 Person Crew Per Diems	$700		
Double Fluid System			
Grout Pumping Rate In gpm	90		
Number Of Days To Setup	2		
Number Of Days To Teardown	1		
Number Test Emplacements	4		
Number Of Additional Test Days	1		
Contingency On Jetting Days	0.15		
Slurry Mixture (C:B wt%)	1:1		
Lbs Of Clay / min.	13.4		
Cost Of Clay In $/Lb	0.3		
Lbs Of Cement / min	536		
Cost Of Cement In $/Lb	0.06		
Lbs Of Water / min	536		
Cost Of Water In $/Gallon	0.012		
Density Of Slurry In Lbs/Ft^3	90		
Drilling Rate In Ft/Min	6		
Time To Relocate In Min	20		
Productive Hours / 10 Hr Day	8		
Production efficiency	0 6		
Support Equipment			
Excavator, $/Day	500	During Entire Program	
Dump Truck, $/Day	0	During Entire Program	
All Terrain Forktruck	600	During Entire Program	
50 Ton Crane $/Day	1200	During Setup And Teardown	
Two Vacuum Trucks, $/Day	2400	During Entire Program	
6 Roll-Offs, $/Day	0	During Entire Program	
Dozer, $/Day	0	Number Of Days At The End Of The Program =	2
Frac Tank, $/Day	0	During Entire Program	

Table 5. Cost Model Acronyms and Abbreviations

Acronym/ Abbreviation	Definition
A	cross sectional area to perpendicular flow
a	pore volumes (dimensionless)
C	total cost of remediation ($)
C_E	electrode cost, excluding mobilization cost ($)
C_e	electrical energy cost ($)
C_F	fixed costs ($)
D	installation depth (feet)
E	electrical field gradient (V)
E_{max}	maximum field gradient (V/M)
Fe	iron
GE	General Electric Company
k_e	electro-osmotic permeability $(cm^2/V)(s)$
Ir	iridium
ISTZ	in situ treatment zone
L_e	distance between electrode zones (meters or feet)
L_T	distance between treatment zones (meters or feet)
n	soil porosity [vol/vol (dimensionless)]
N_E	number of electrode rows (dimensionless)
N_T	number of treatment zone rows (dimensionless)
O	oxygen
P_E	price of installed electrode ($/ft^2)
P_e	price of electricity ($/kWH)
P_T	price of installed treatment zone ($/ft^2)
Q	electro-osmotic flow rate (m^3/S)
s	soil electrical conductivity (mS/cm)
T	remediation time (years)
V_{max}	maximum potential (V)
X	site width (feet)
Y	site length (feet)

Table 6. Unit Abbreviations

Unit Abbreviation	Definition
cm	centimeters
sq cm	square centimeters
cu yd	cubic yards
ft	feet
g	grams
gal	gallons
gpm	gallons/minute
hr	hour(s)
in.	inches
kW	kilowatt
kWH	kilowatt-hour
lb, lbs	pound(s)
m	meter
mS/cm	milliSiemen/centime ter
sq ft	square foot
yr(s)	year(s)

Table 7. Lasagna™ Costs by Years to Remediate Site

Years to Remediate Site	Emplacement Cost ($/ft²) (Elect/TZ)	Depth (ft)	A/C Distance(ft)	TZ Distance (ft)	Field Potential (volts)	Gradient (v/m)	Cost ($/yd³)
1	$10.14/$8.61	15	52.5	4.8	493	30.8	$79
1	$8.35/$6.82	45	52.5	4.8	493	30.8	$59
3	$10.14/$8.61	15	70	8.8	402	18.8	$67
3	$8.35/$6.82	45	70	8.8	402	18.8	$43

Table 8. Lasagna™ DNAPL Remediation Evaluation (45-foot-deep scenarios)

Soil Concentration (ppm)	Required Pore Volumes	Years to Clean Up	Estimated Project Cost	Cost/yd³ (1-acre basis)
100	2	1	$4.3 million	$59
600	4	2	$5.2 million	$71
1,000	6	3	$5.8 million	$78
2,500	12	6	$7.0 million	$96
5,000	24	12	$8.3 million	$112

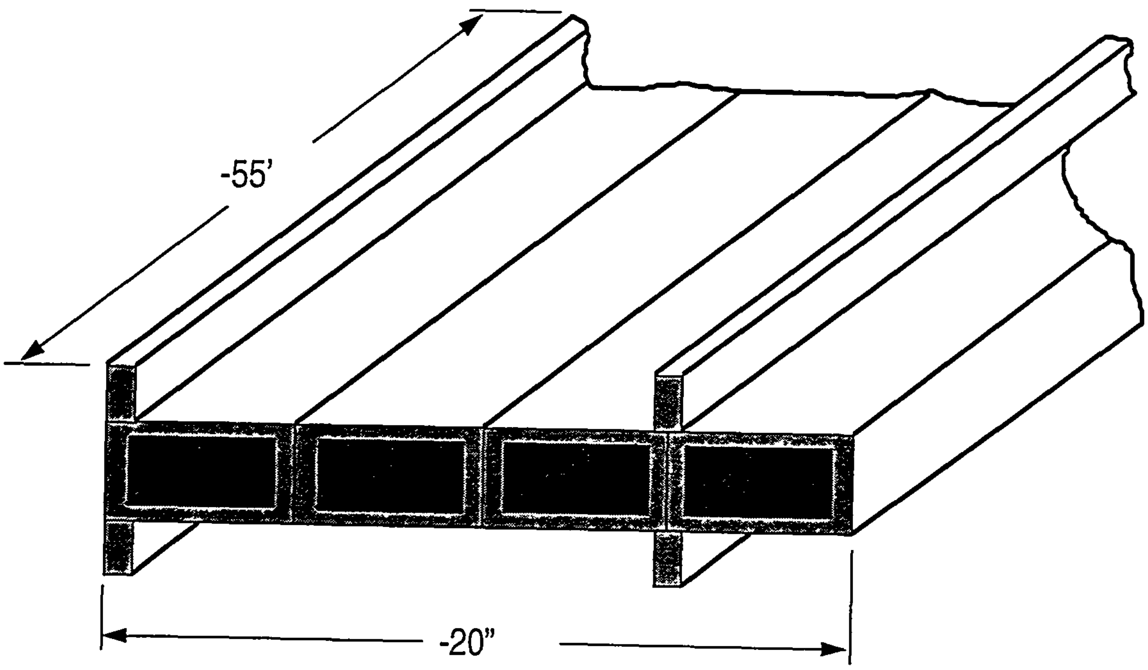


Figure 1. Illustration of Mandrel Concept Used for Phase IIa

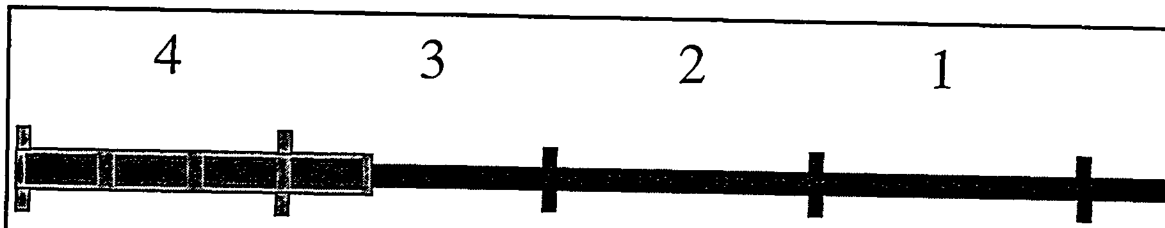


Figure 2. Illustration of Serial Emplacement Sequence Concept for Phase IIa with 25 Percent Overlaps into Previous Emplacement

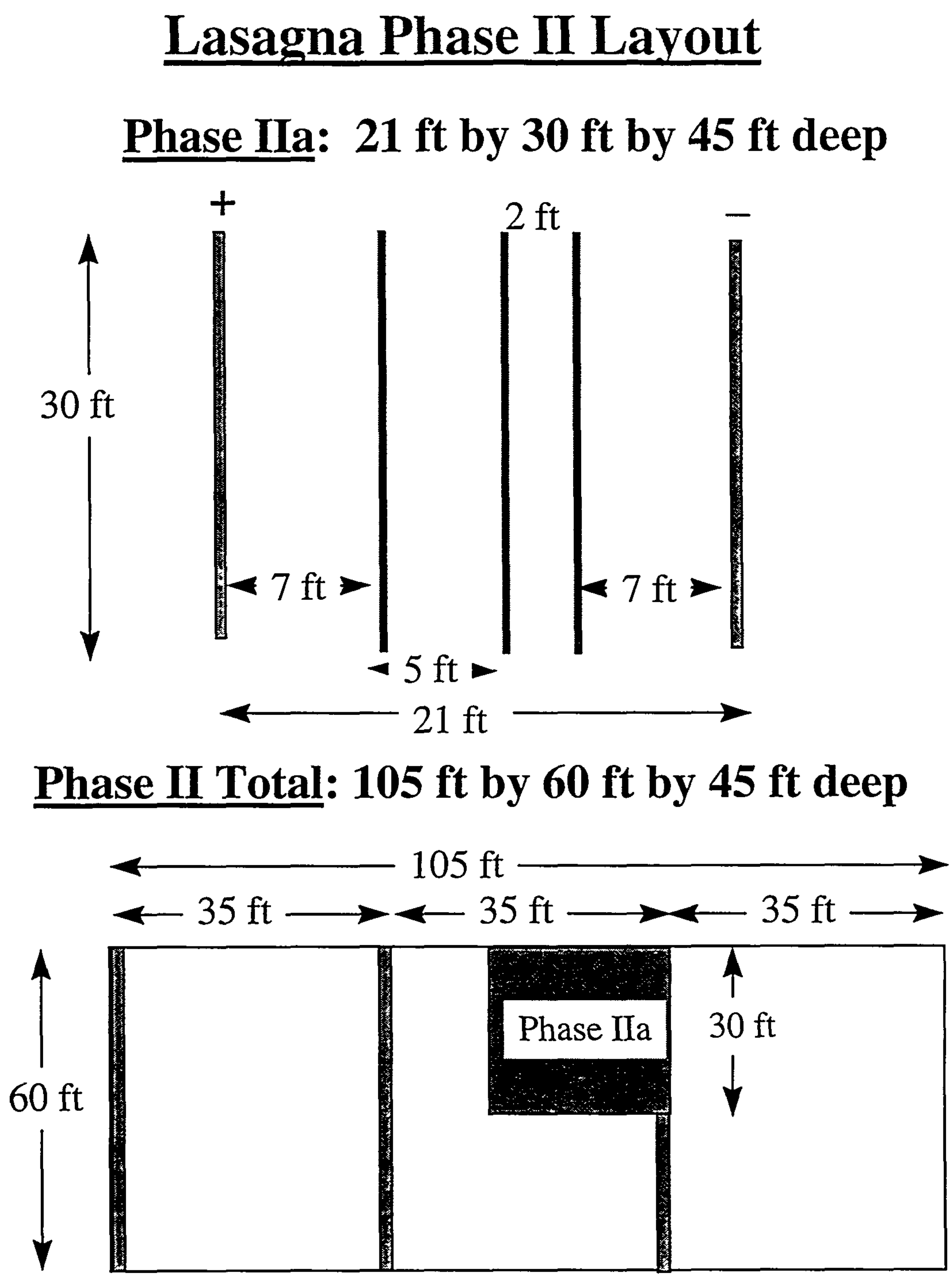


Figure 3. Illustration Representing Electrode and Treatment Zones Emplaced as Part of Phase IIa Effort

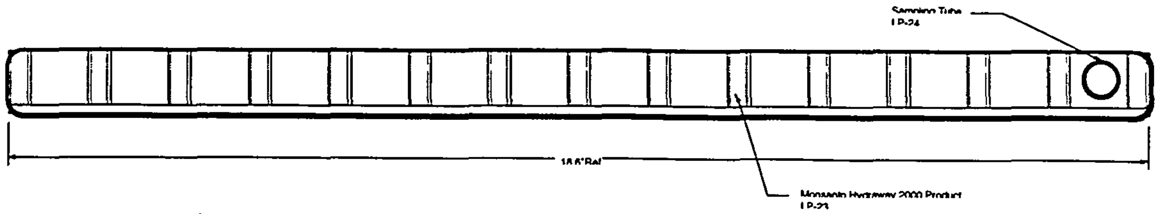


Figure 4. Illustration of Treatment Zone Design Used for Phase I

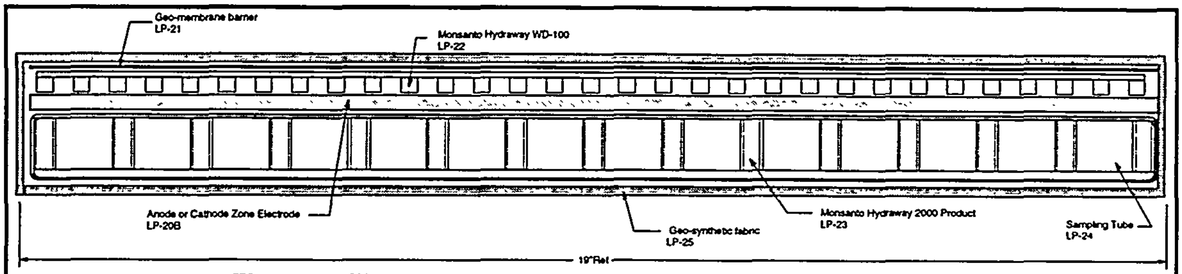


Figure 5. Illustration of Electrode Design Used for Phase I

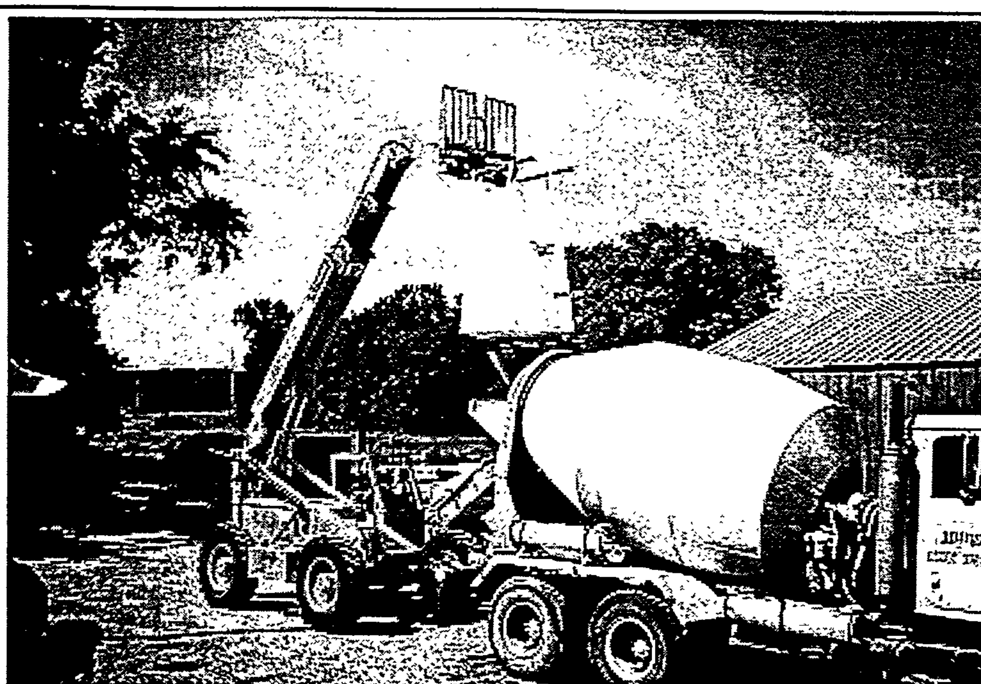


Figure 6. Photo Showing Supersack of Kaolinite Clay Being Loaded into Concrete Truck Using All-Terrain Forktruck

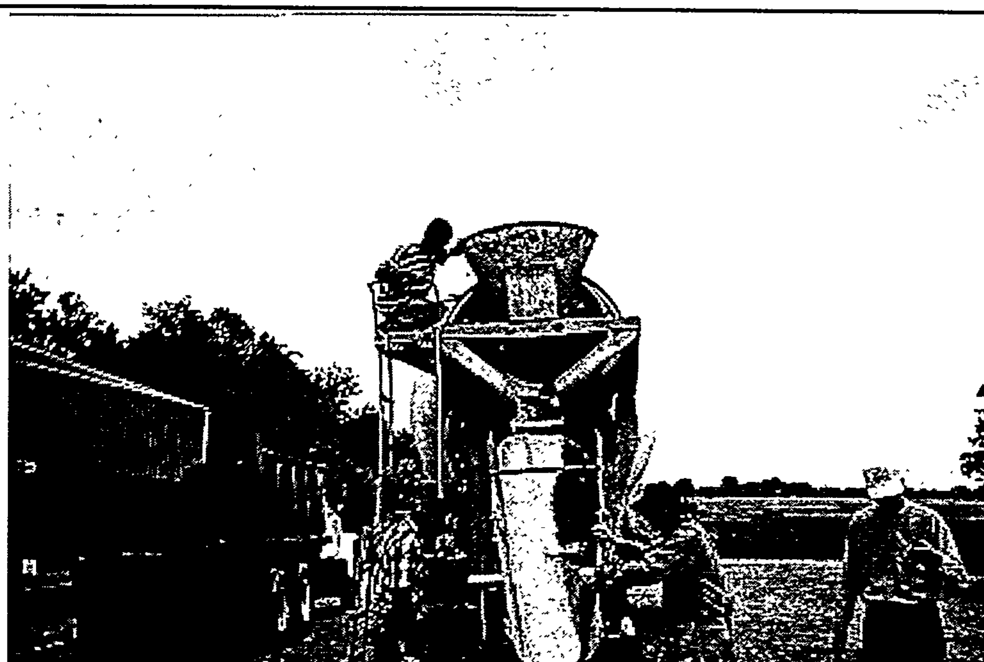


Figure 7. Photo Showing Treatment Zone Materials Being Discharged by Concrete Truck

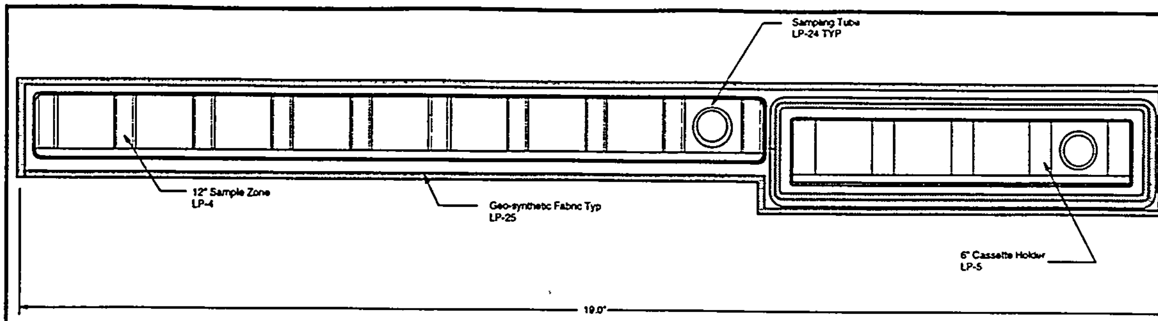


Figure 8. Illustration of Sampling Cassette Developed for Phase I

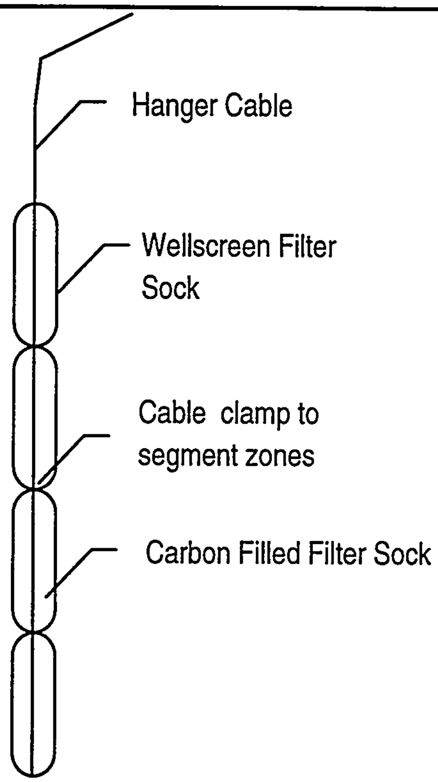


Figure 9. Illustration of Sampling Cassette Developed for Phase IIa

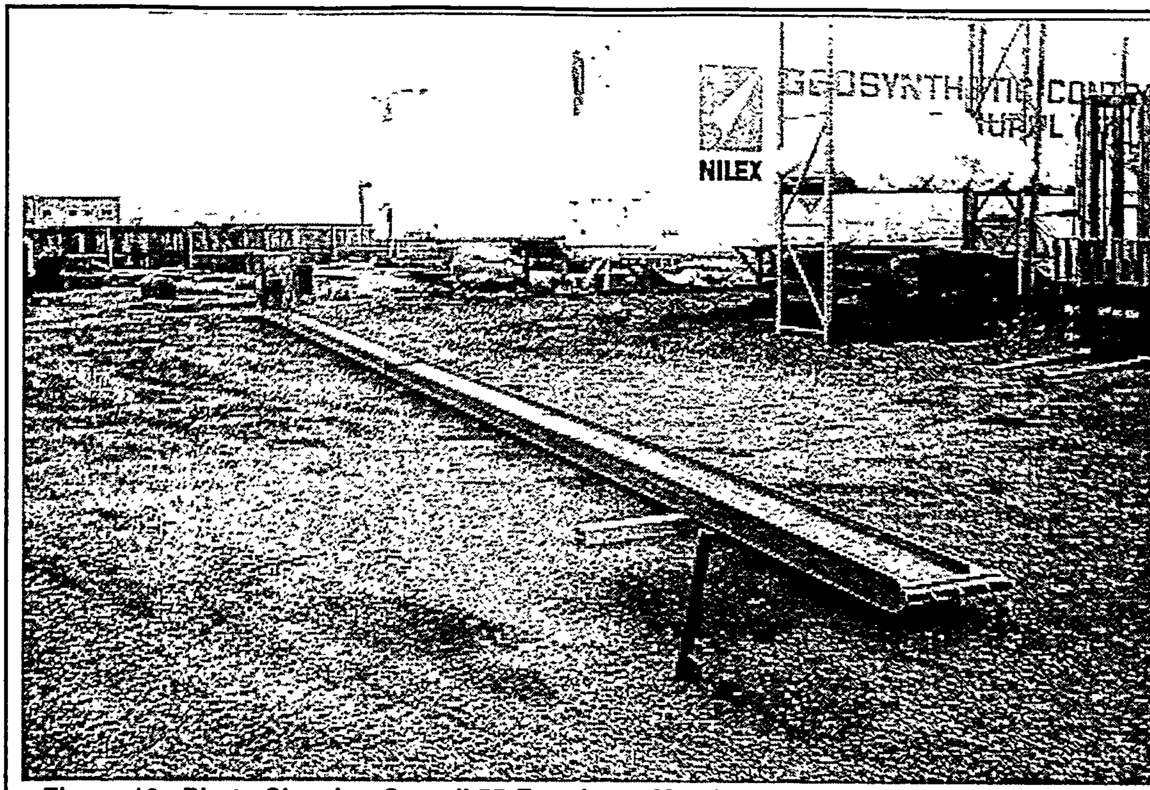


Figure 10. Photo Showing Overall 55-Foot Long Mandrel Constructed from Rectangular Tubing and Longitudinal Stiffening Plates (Materials Hopper at Top)

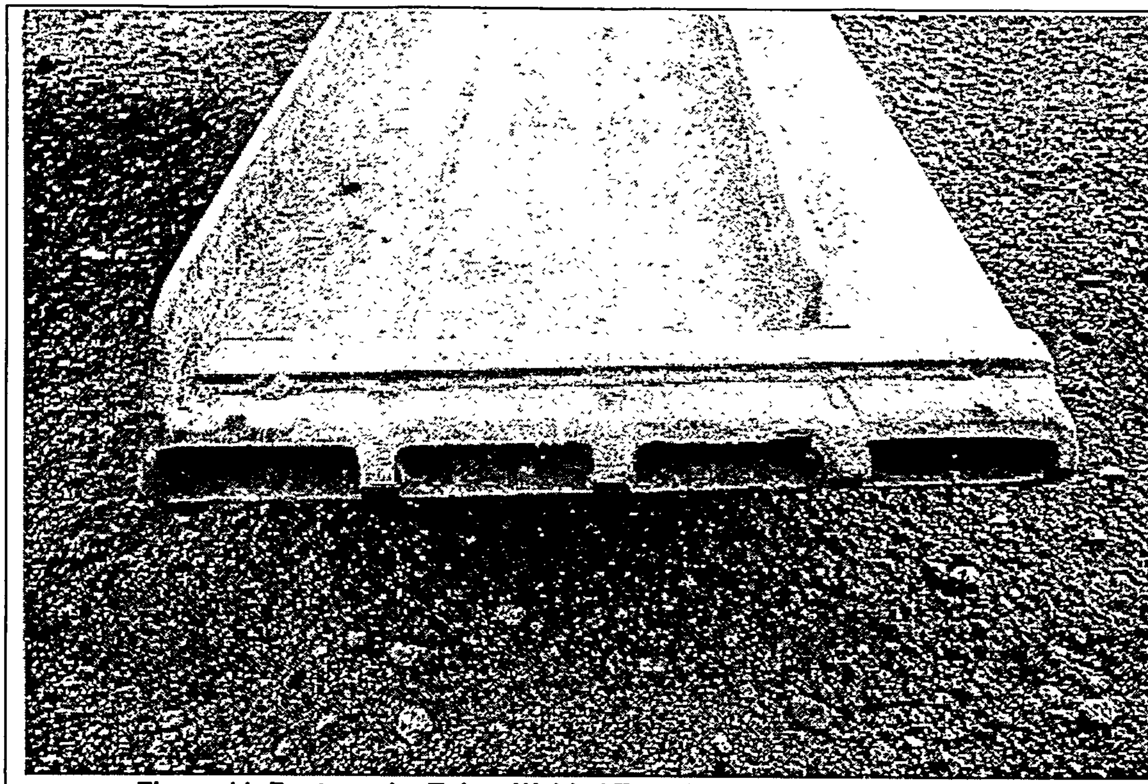


Figure 11. Rectangular Tubes Welded Together and the Stiffening Plates

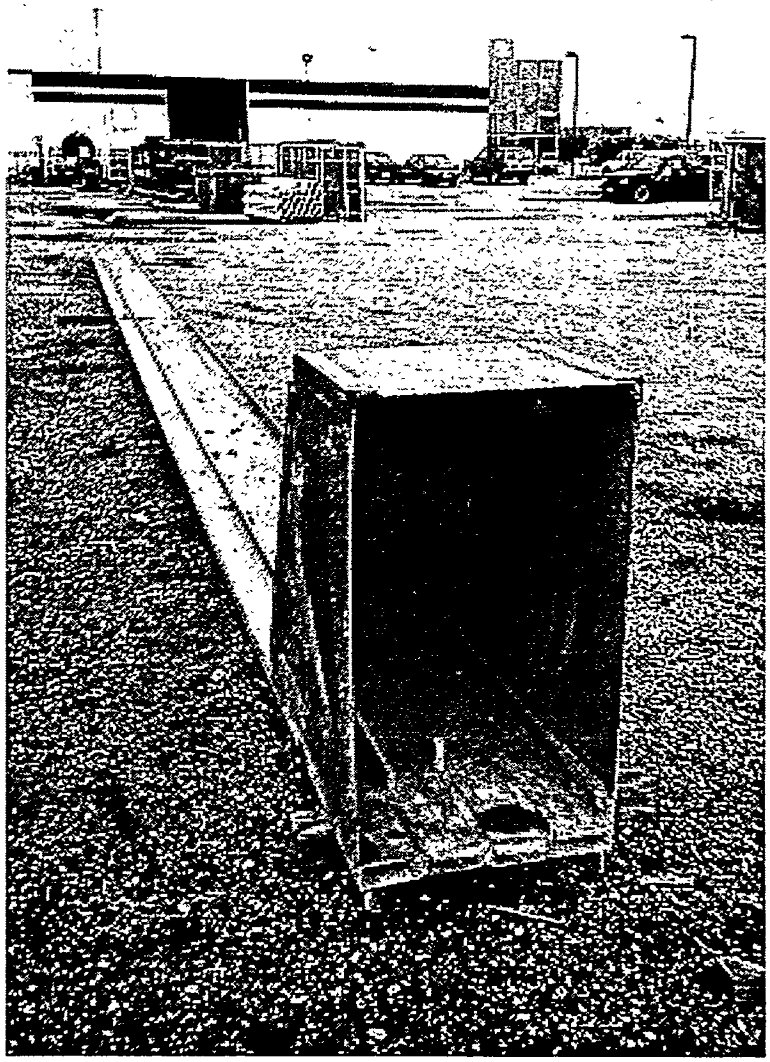


Figure 12. Inside of Hopper

Figure 13. Lower Cost Driveshoe Used for Phase IIa

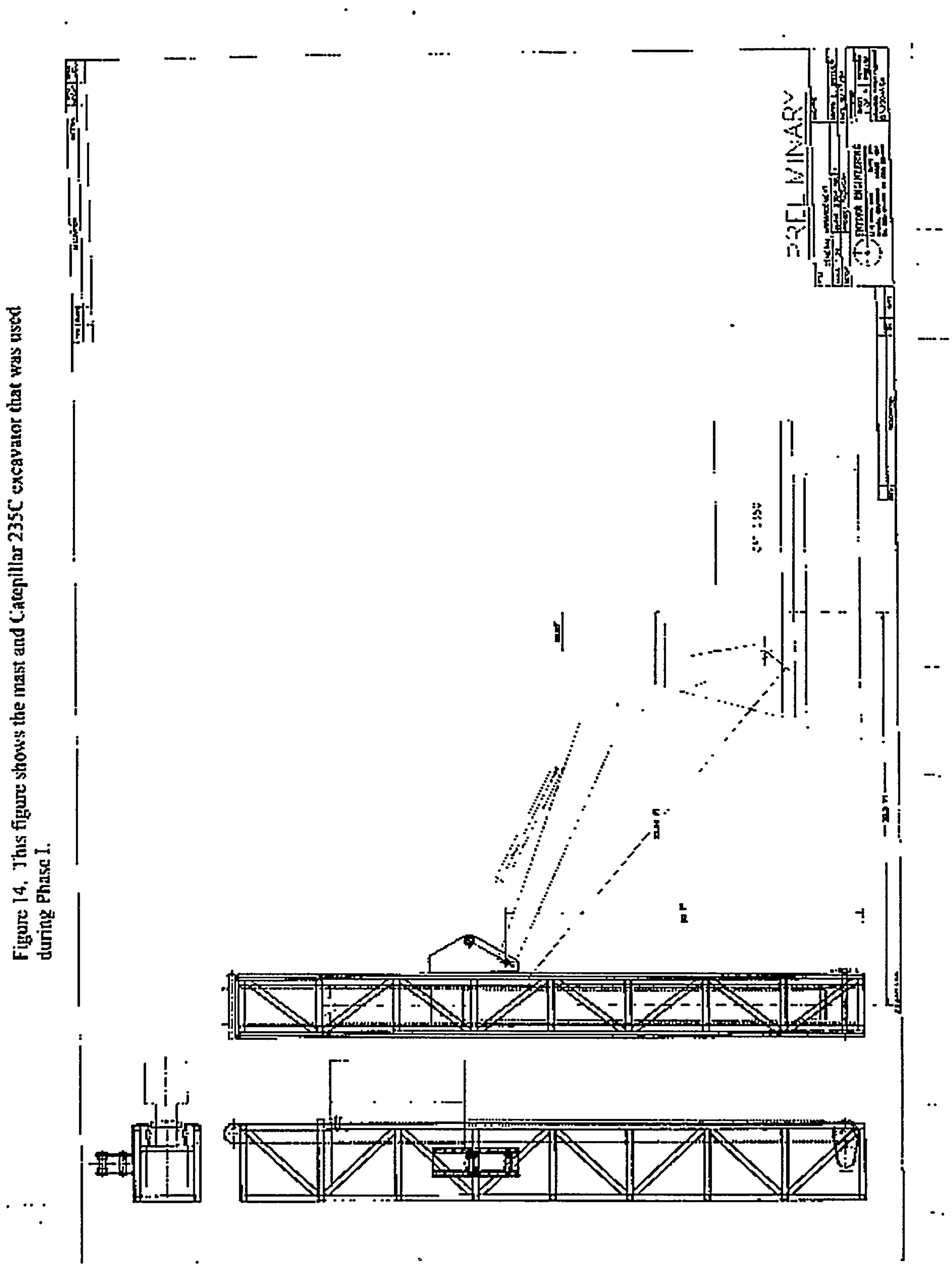


Figure 14. Mast and Catepillar 235C Excavator Used During Phase I

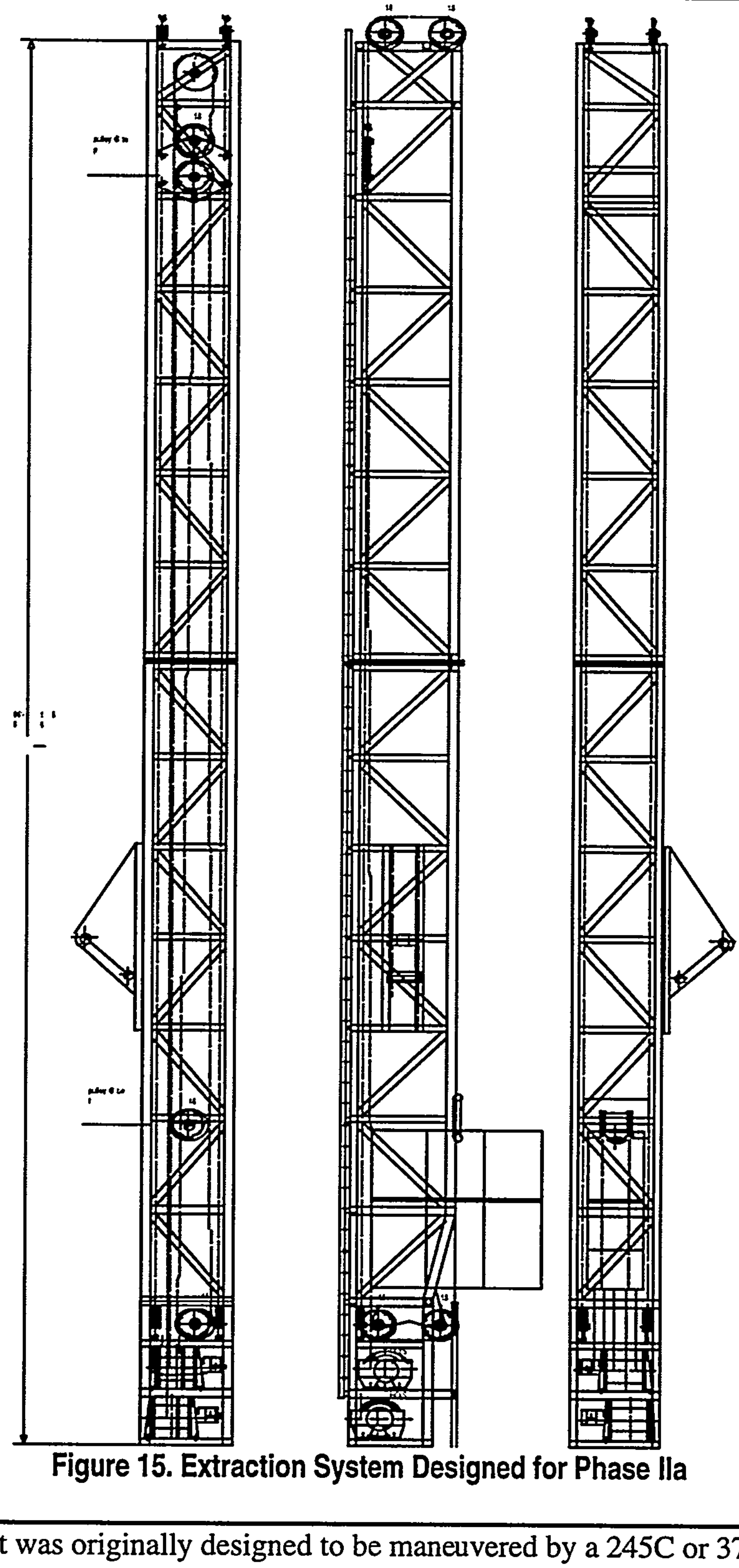


Figure 15. Extraction System Designed for Phase IIa

Note: The mast was originally designed to be maneuvered by a 245C or 375 Catepillar excavator and attached at the triangular mounting plates.

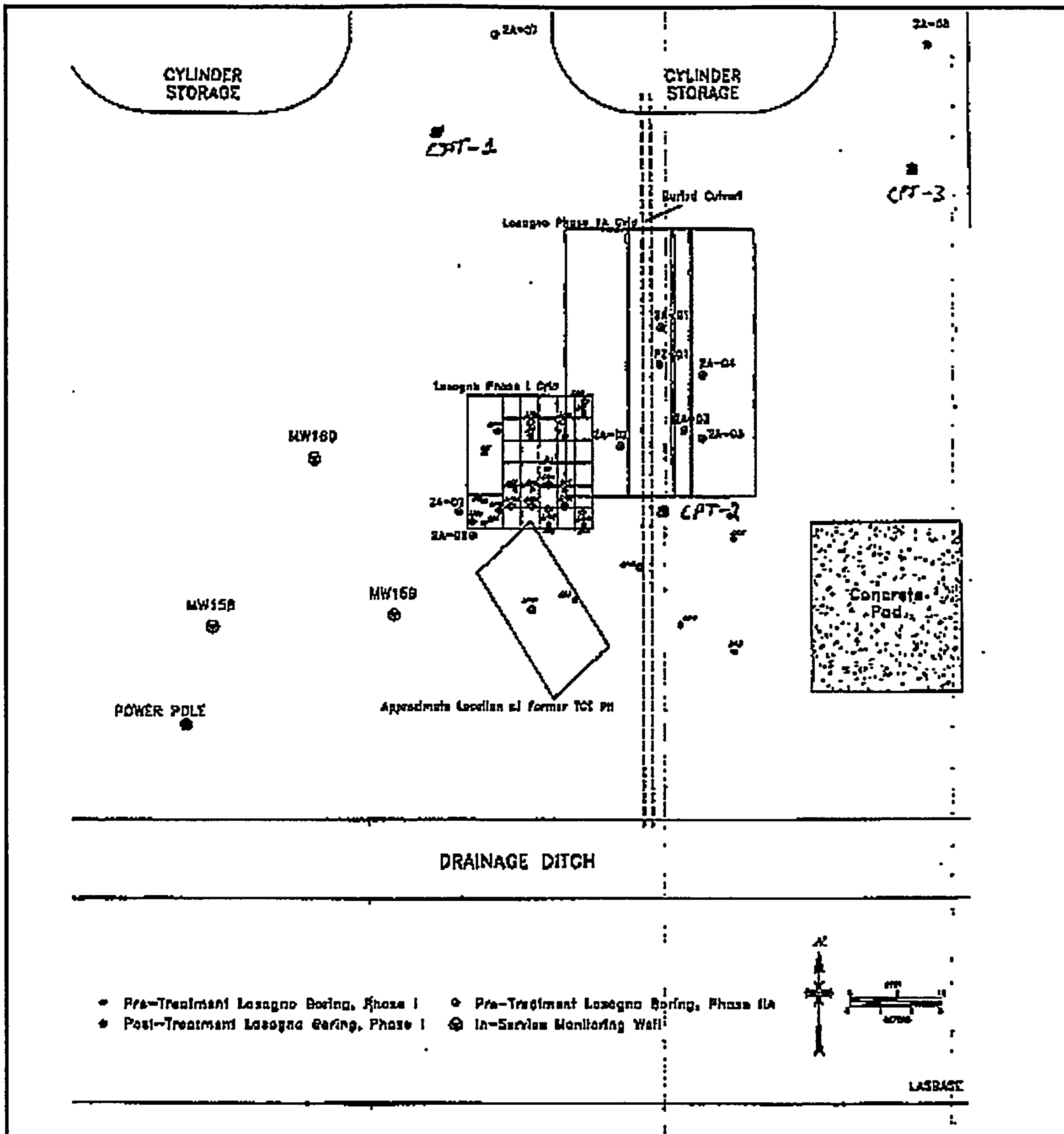


Figure 16. Illustration Showing Locations of Cone Penetrometer Tests Surrounding Phase IIa Area

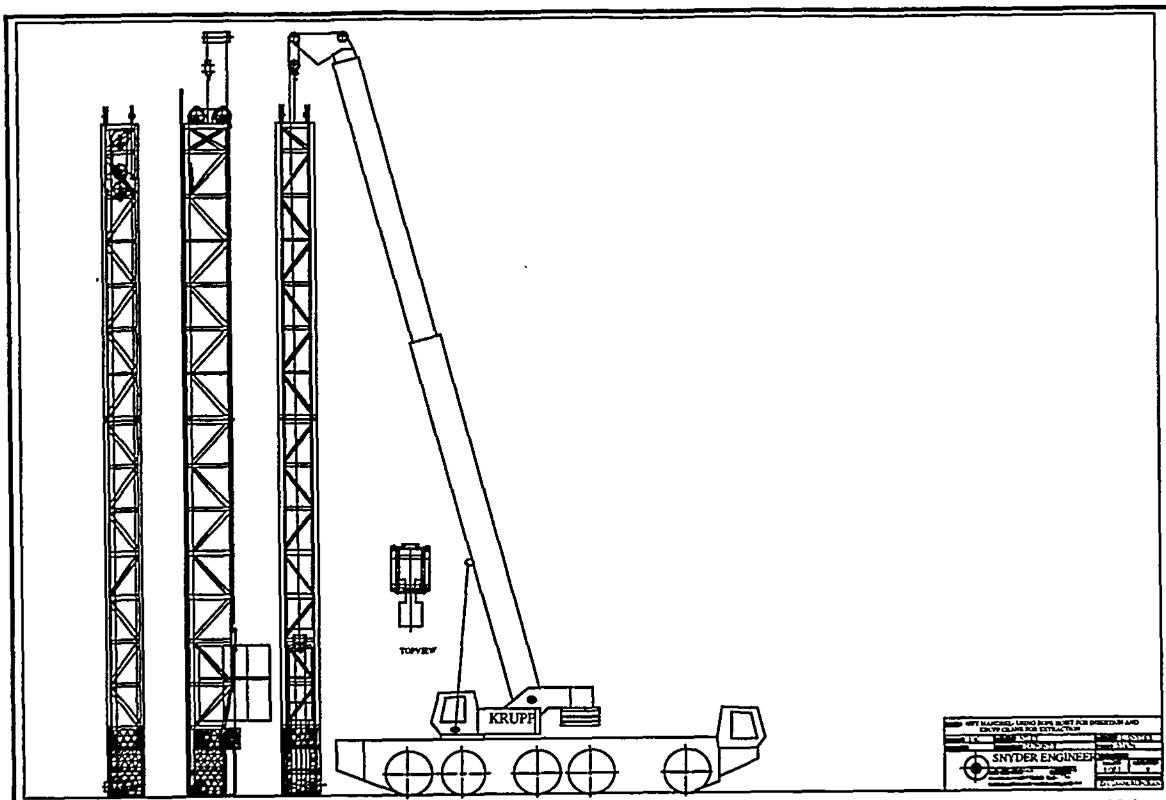


Figure 17. Illustration of Hydraulic Crane and Mast Showing the Two Cables, One for Lifting Mast and One for Extraction of Mandrel

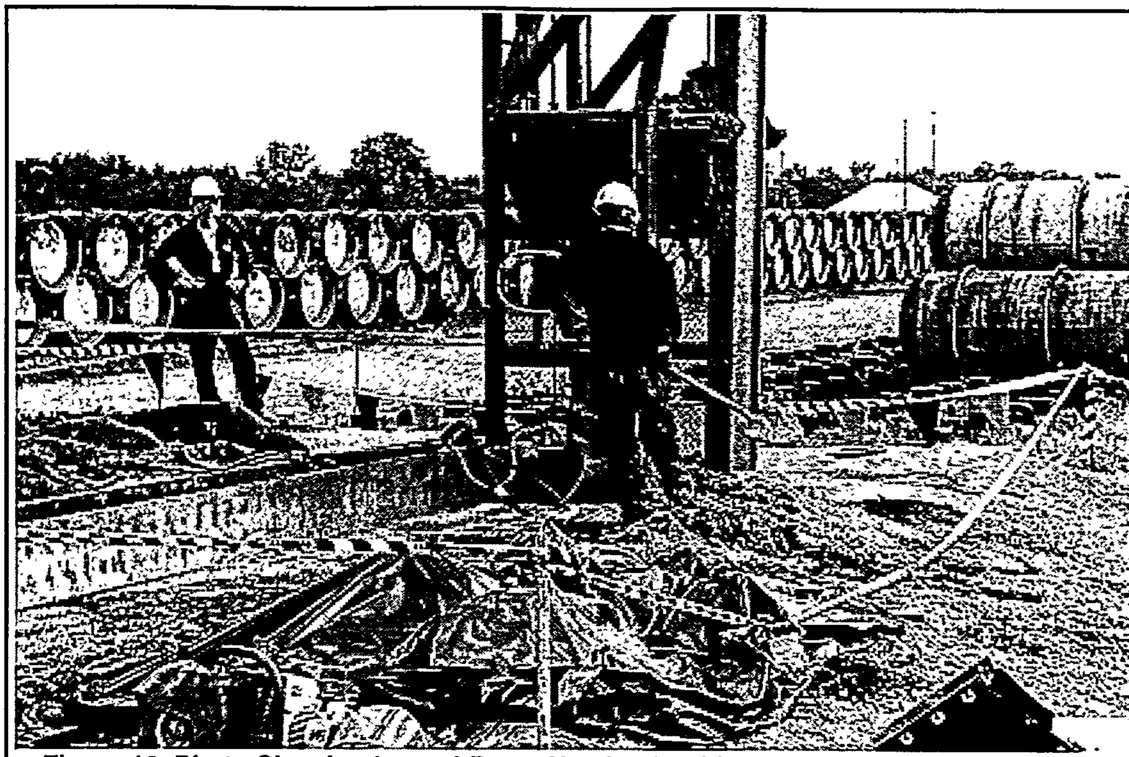


Figure 18. Photo Showing Large I-Beam Used to Position Mast and Heavy Strap Used to Help Hold Mast in Position against I-Beam

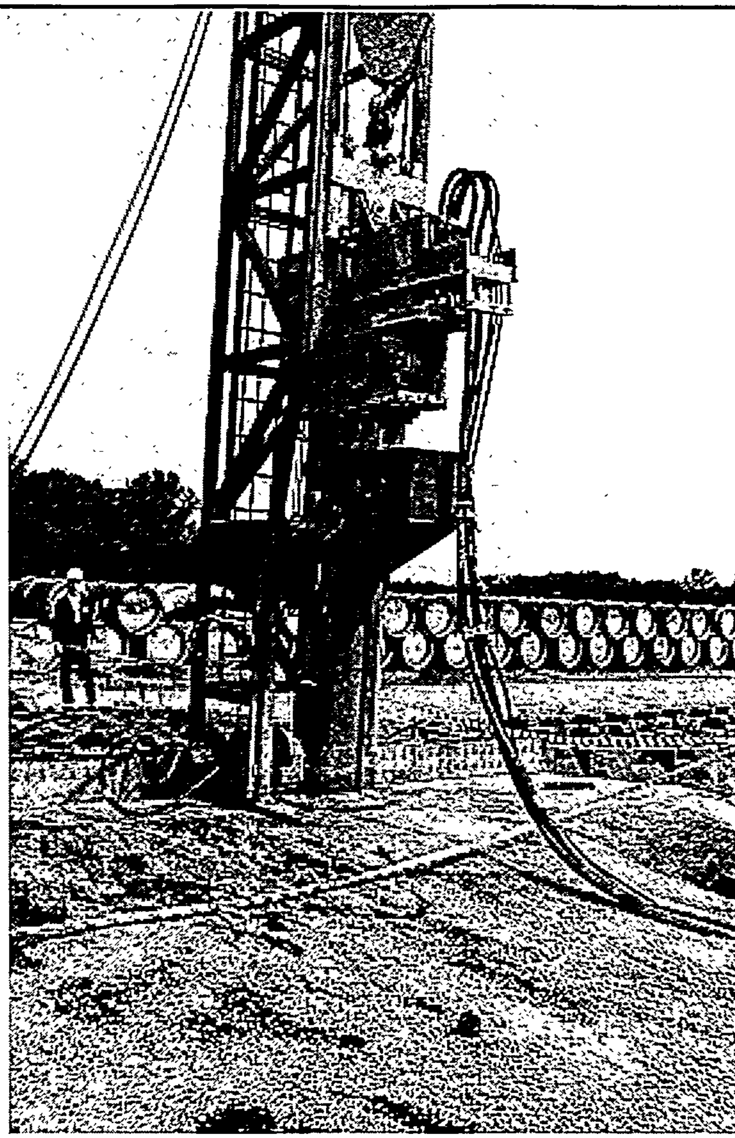


Figure 19. Mandrel Emplaced To Depth and Ready to Receive Materials.

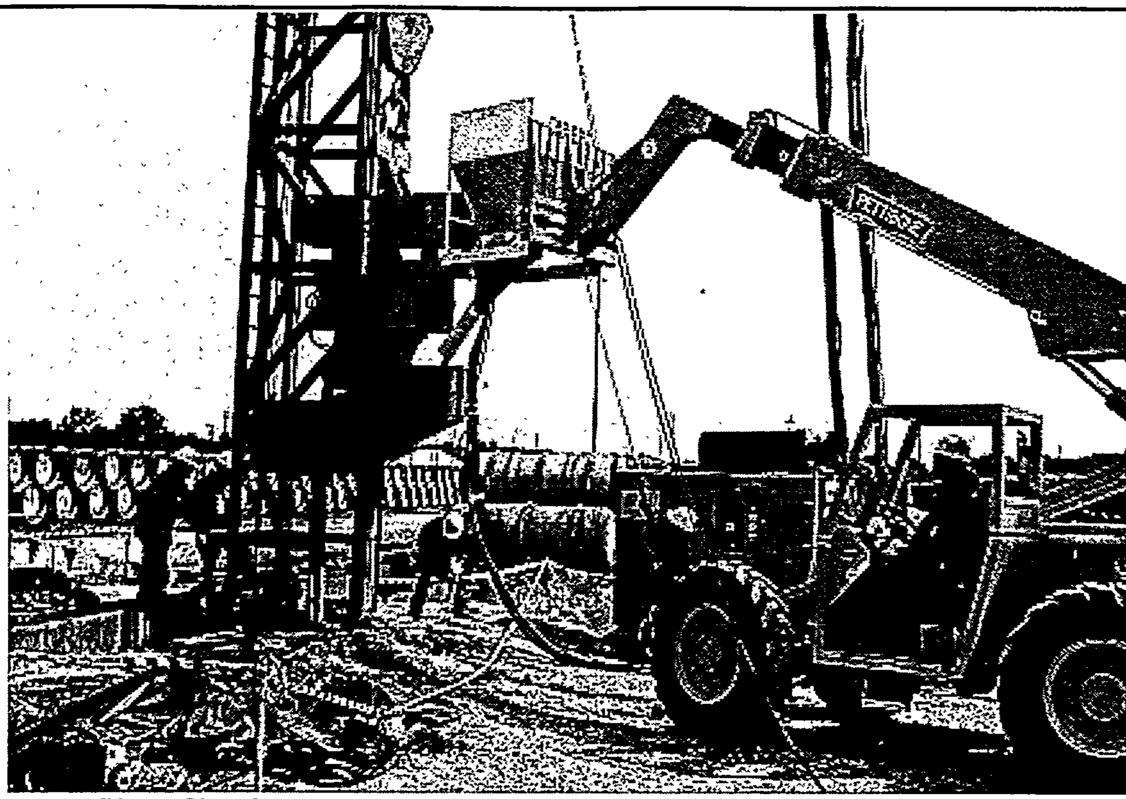


Figure 20. Photo Showing All-Terrain Forktruck and Concrete Bucket in Position as Materials Are Transferred to Mandrel

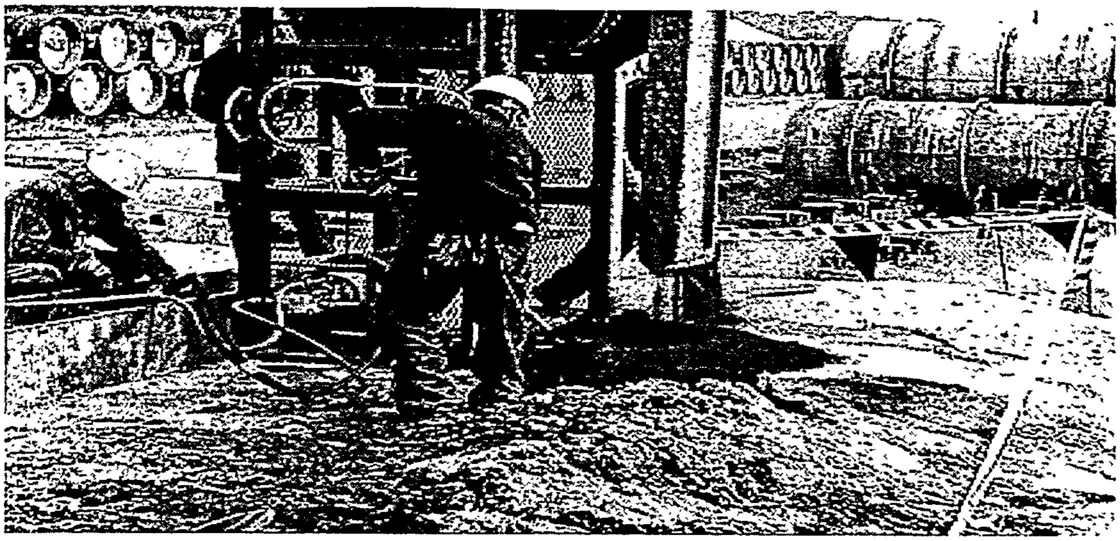


Figure 21. Photo Showing Mandrel Fully Extracted from Soil with Excess Electrode Materials Discharging on Ground

(Note Primary Electrode Extending above Surface)

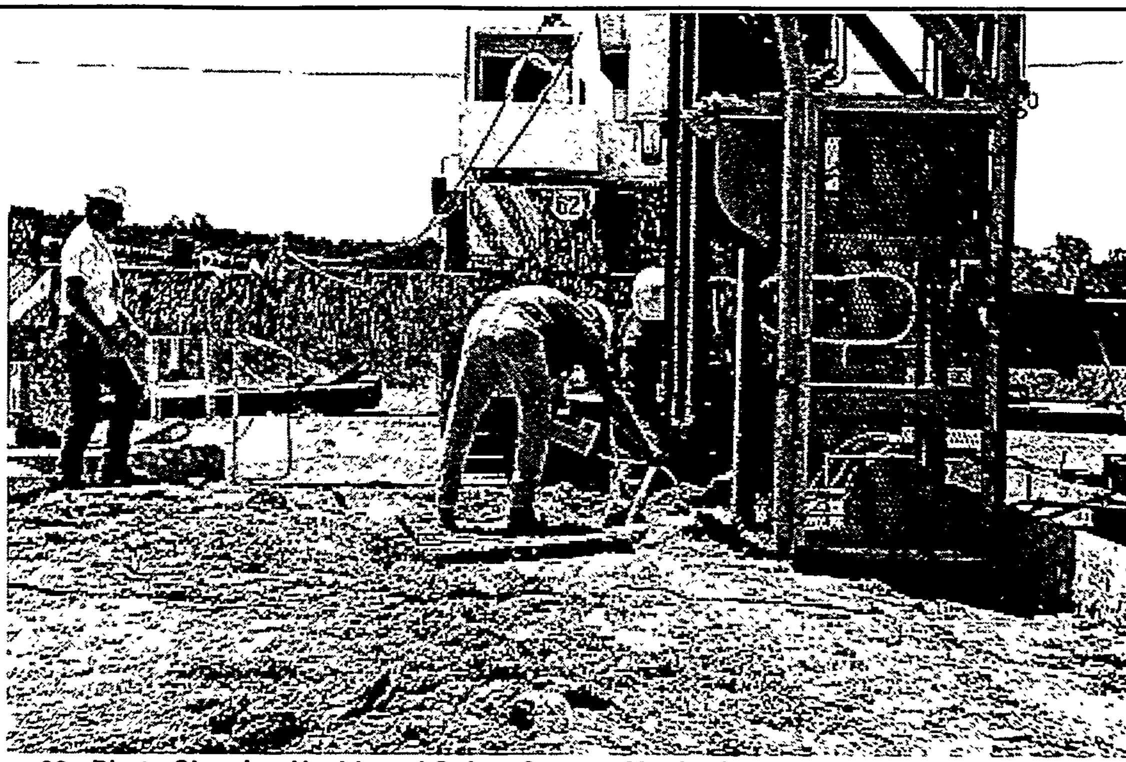


Figure 22. Photo Showing Health and Safety Contact Monitoring any Volatile Emissions Directly at Soil Surface

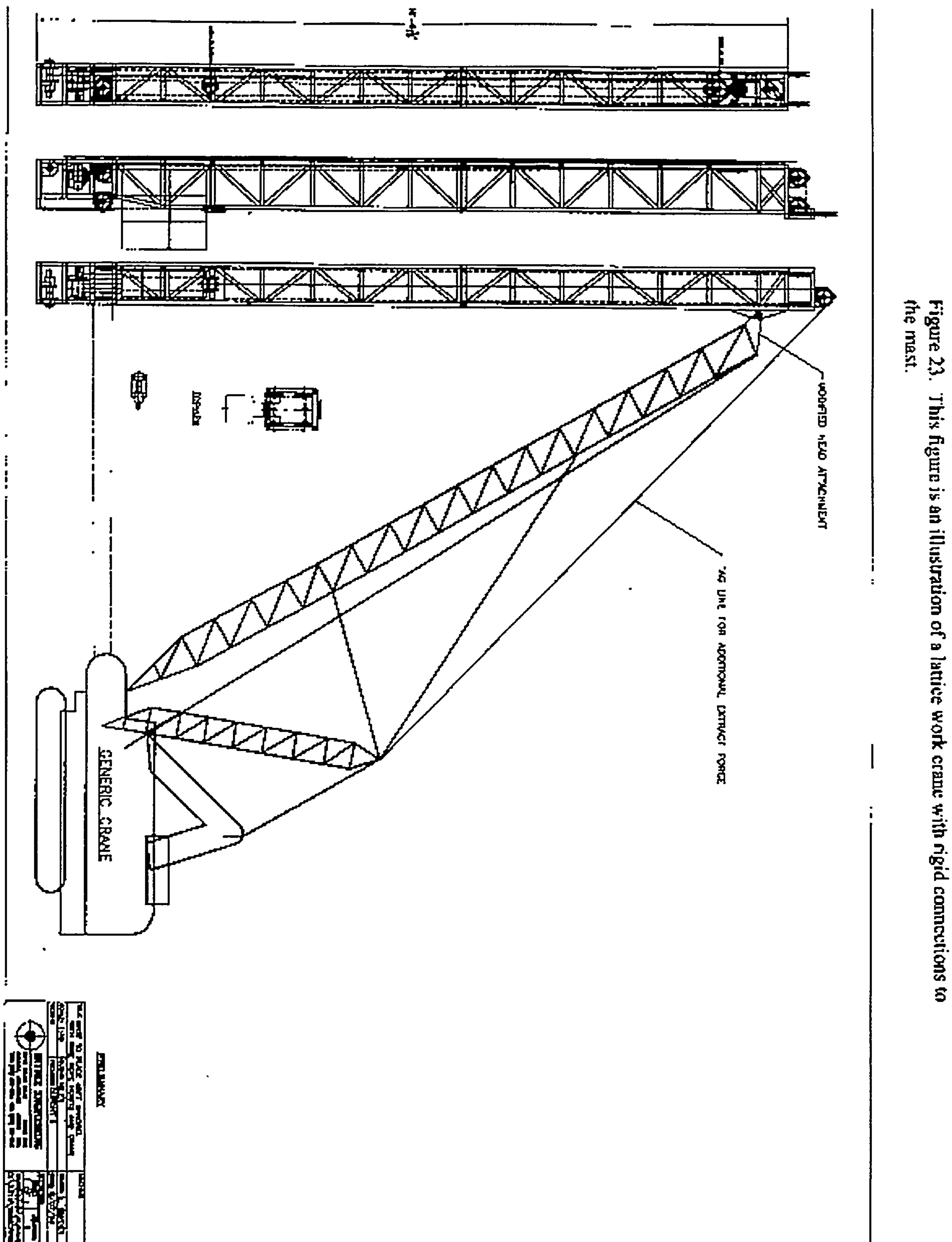


Figure 23. Illustration of Lattice Work Crane with Rigid Connections to Mast

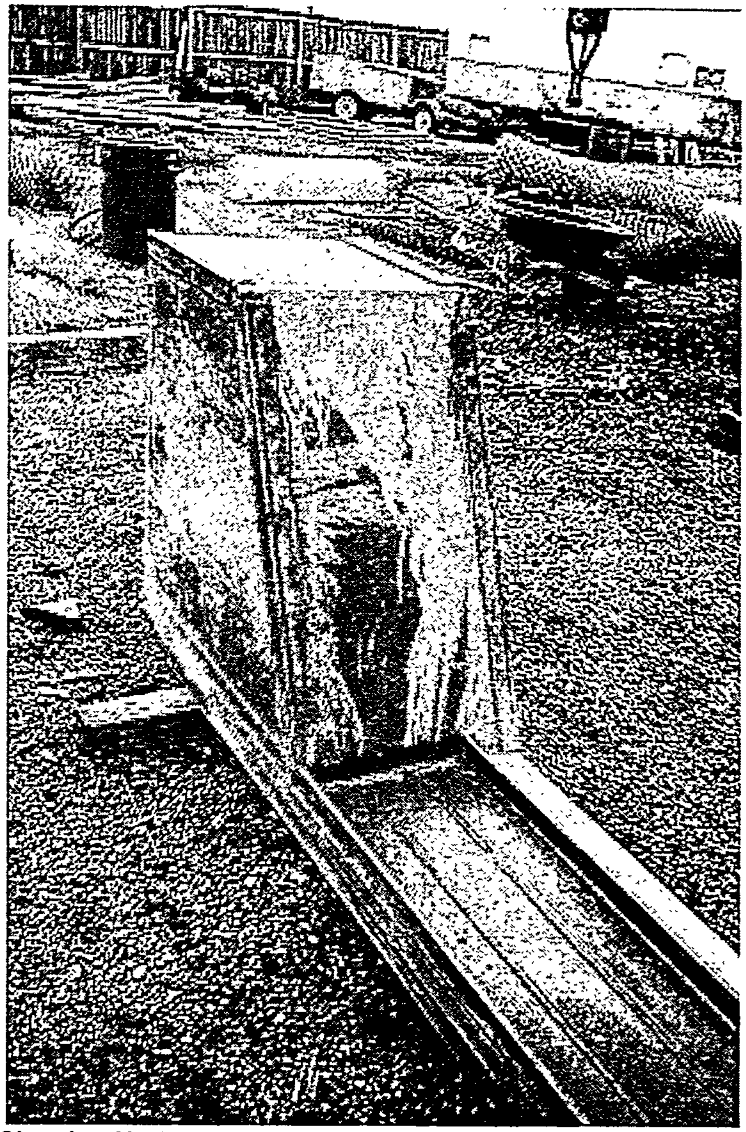


Figure 24. Photo Showing Underside of Mandrel Hopper Where Cracks Occurred (Cracks Were Welded, Followed by Welding an Angle Iron over Corners)

Figure 25. Illustration of Proposed Spoils Pits and Layout of General Locations of Emplacements

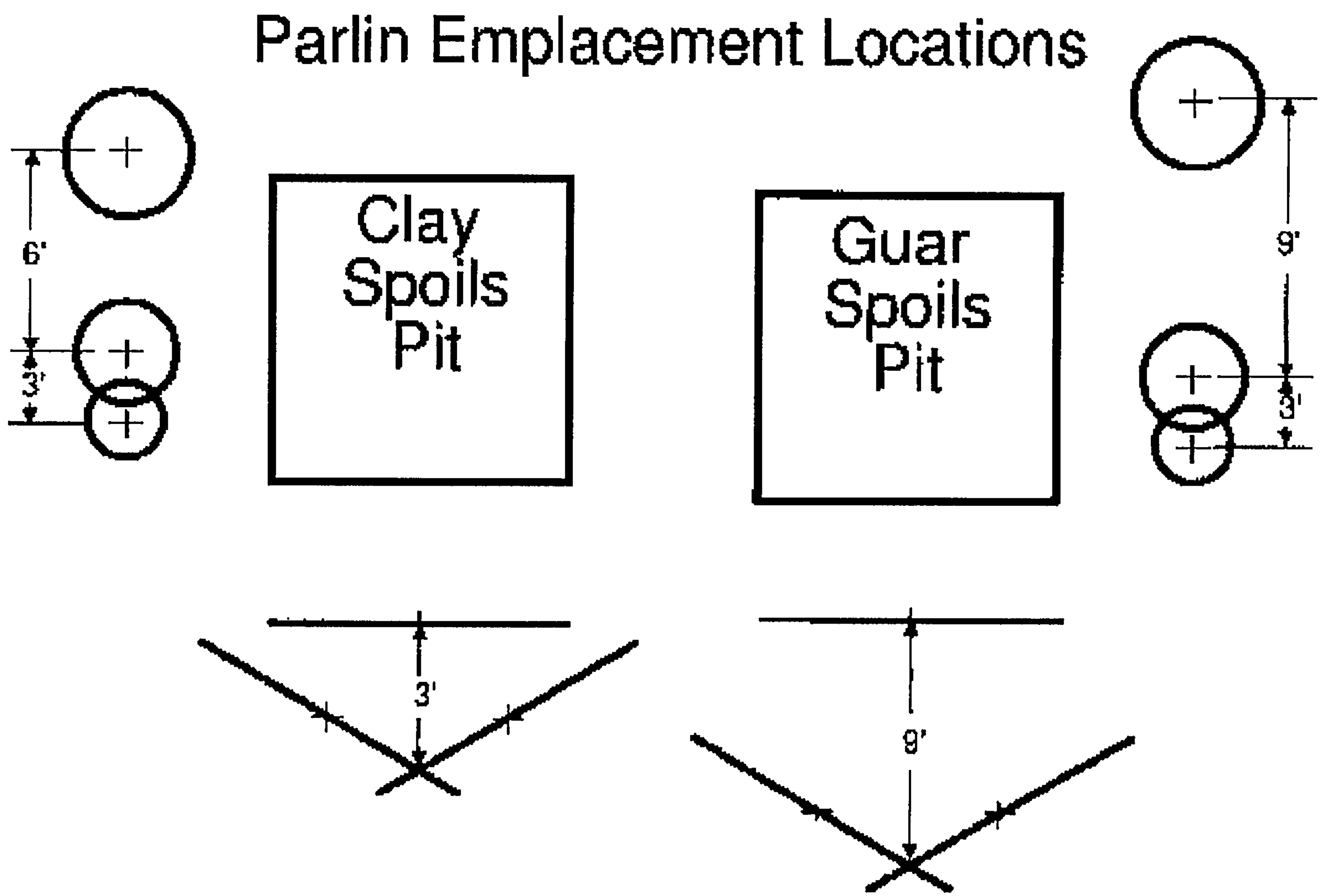


Figure 25. This figure is an illustration of the proposed spoils pits and the layout of the general locations of the emplacements.

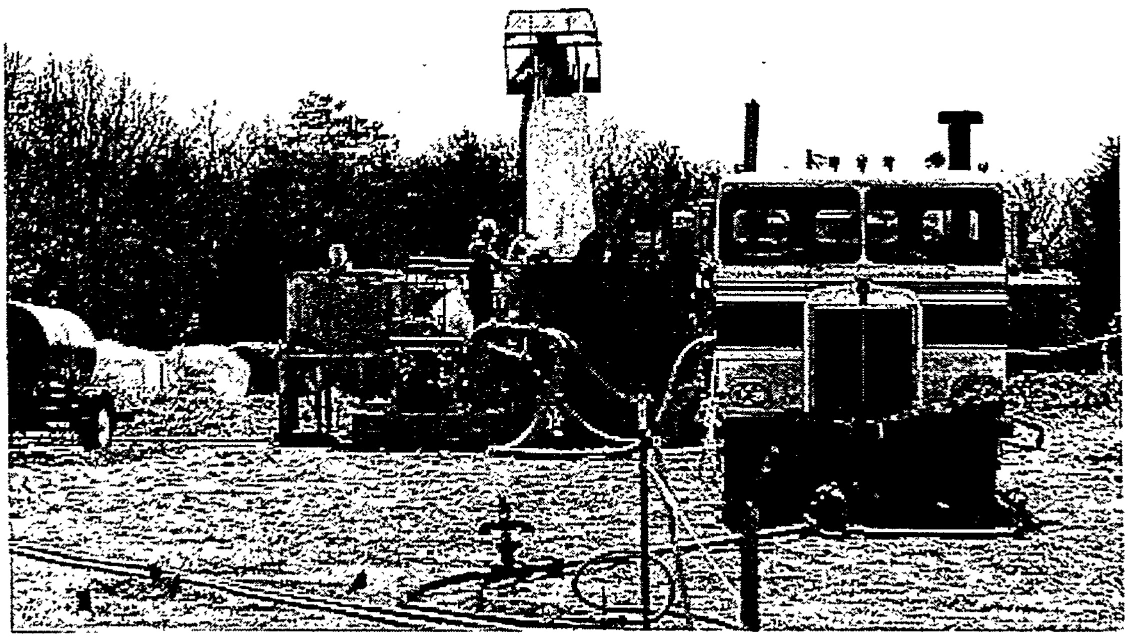


Figure 26. Photo Showing Hard Pipe, Pop-Off Valve, and High-Pressure Hose Connection

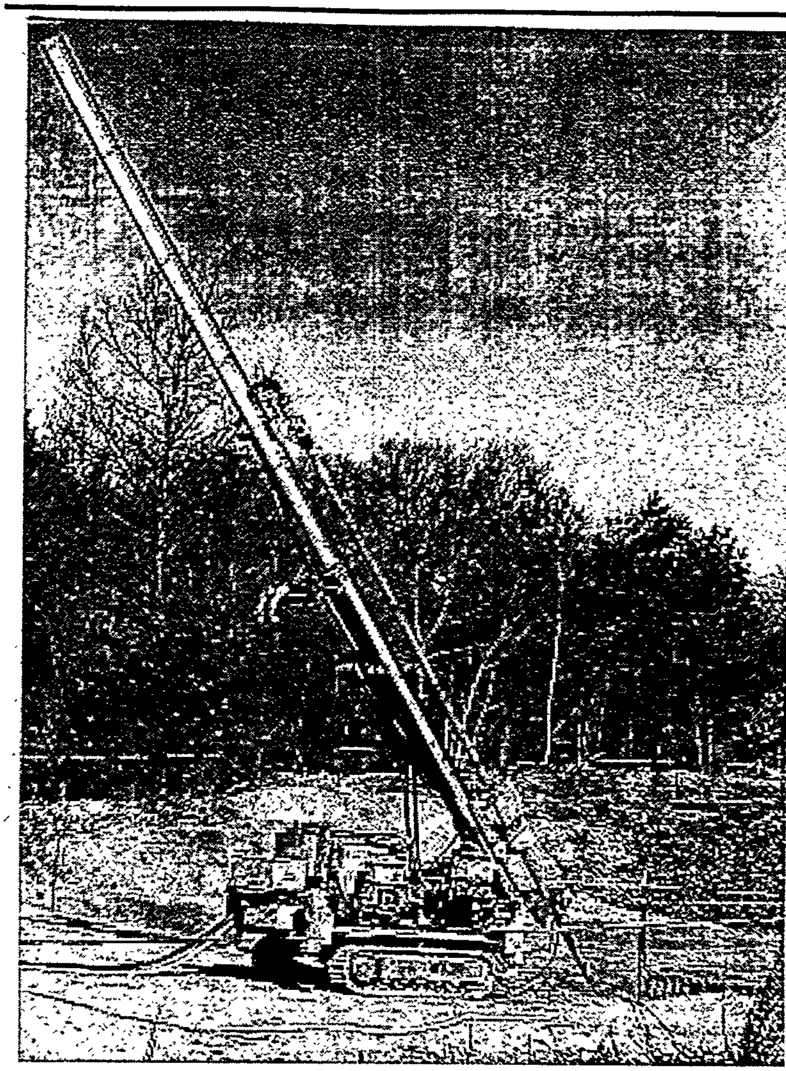


Figure 27. Photo of Jetting Rig Used During Emplacement Tests

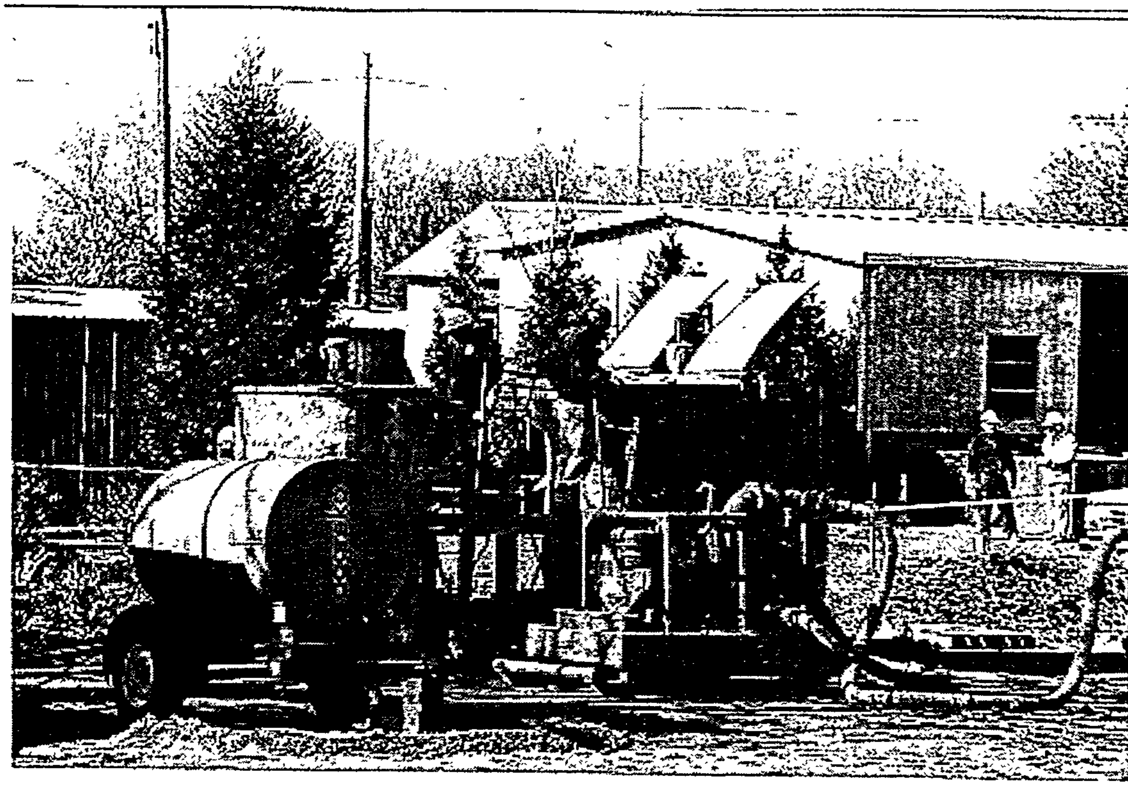


Figure 28. Photo Showing the Two Mix Tanks, Precharge Pump for High-Pressure Pump, and 6-Inch Hose Leading to High-Pressure Pump

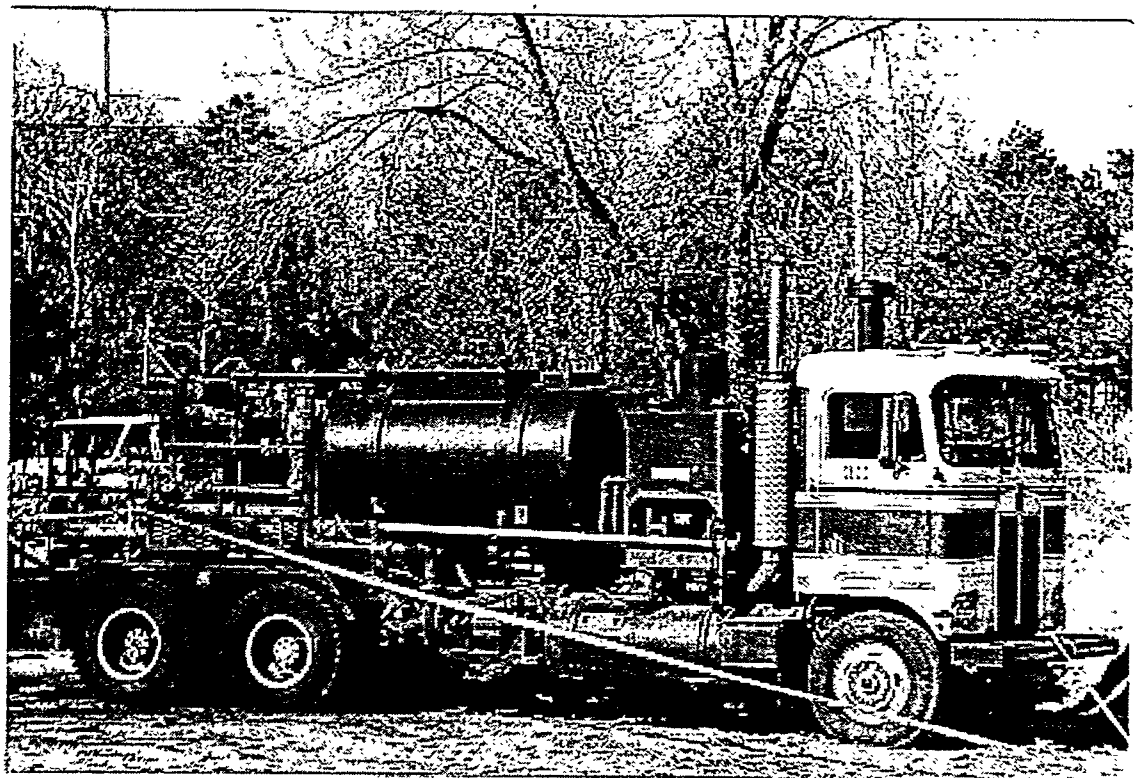


Figure 29. Photo Showing High-Pressure Pump Mounted on Truck Designed for Cementing Oil Wellbore Casings

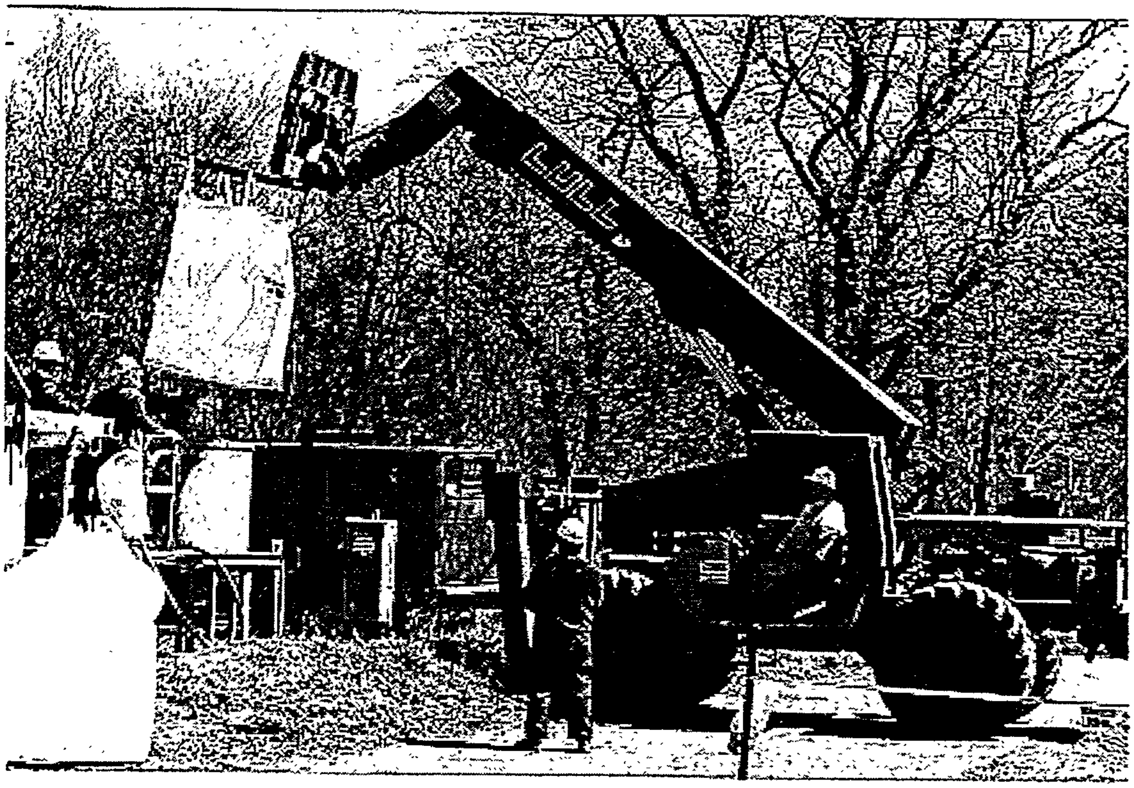


Figure 30. Photo of All Terrain Forktruck Positioning a Supersack of Kaolinite Clay over Mixing Tank and Opening the Supersack's Built-In Funnel

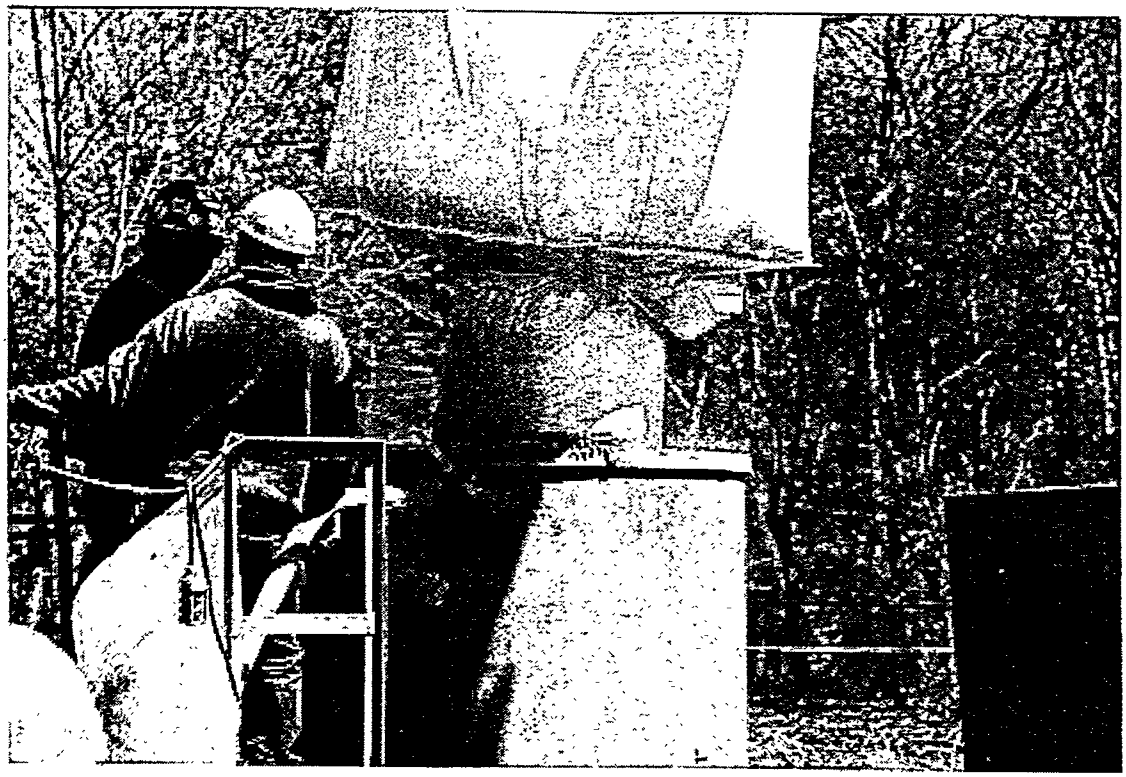
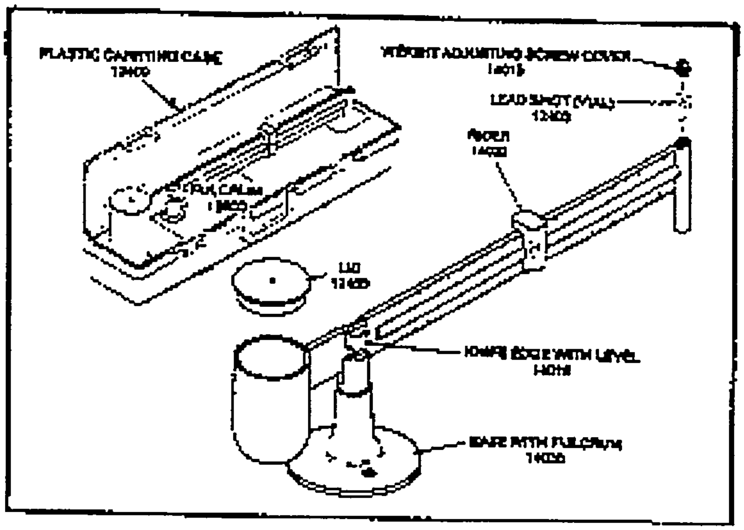


Figure 31. Photo of Supersack's Built-in Funnel



Fann Instrument Company
P O Box 4350
Houston, Texas, U.S A. 77210
Telephone: (713) 987-4482
Toll Free: (800) 347-0450
Fax: (713) 987-4358

Figure 32. Photo Showing Mud Balance Used to Confirm Density of Slurries

Figure 33. Photo Showing Nature of Spoils Returning to Surface Through Borehole

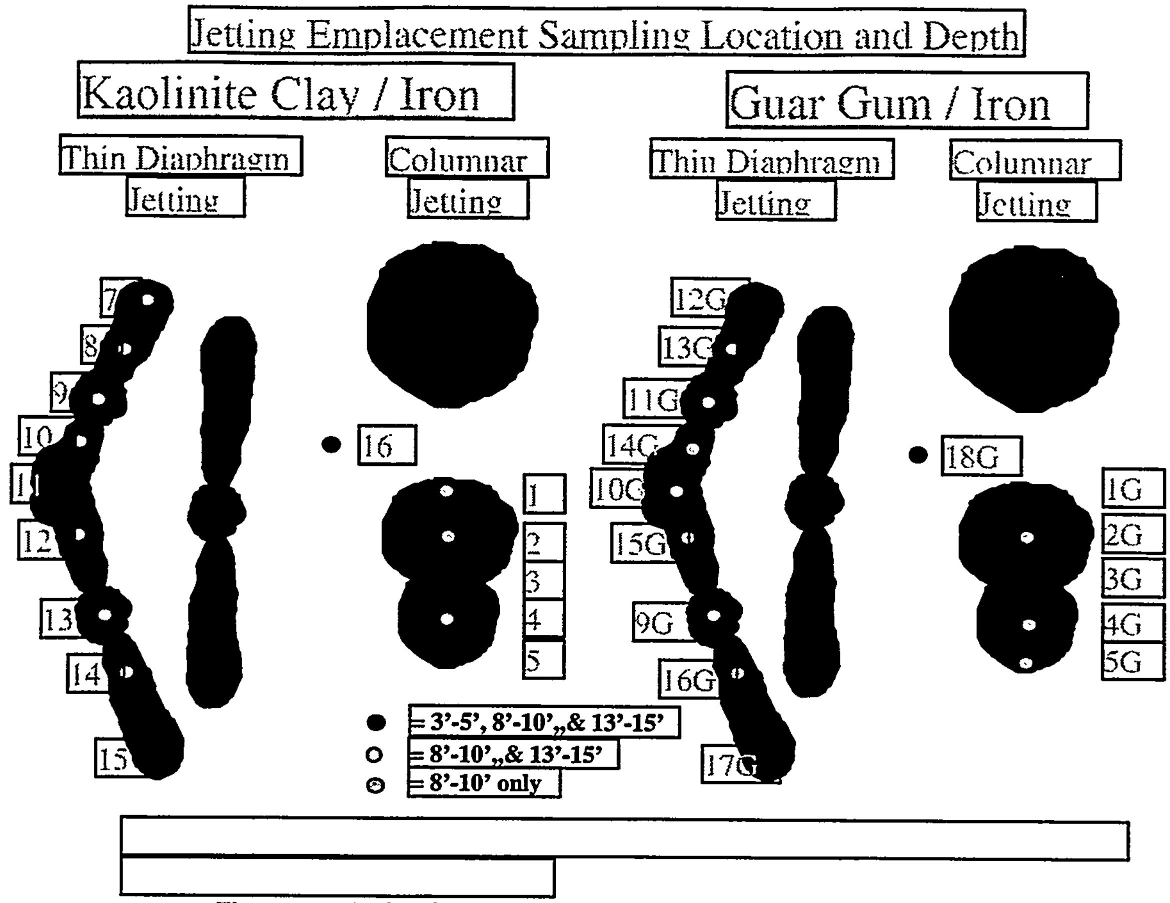


Figure 34. This Figure Shows the Sampling Locations of the Shelby Tubes and the Depths of the Samples

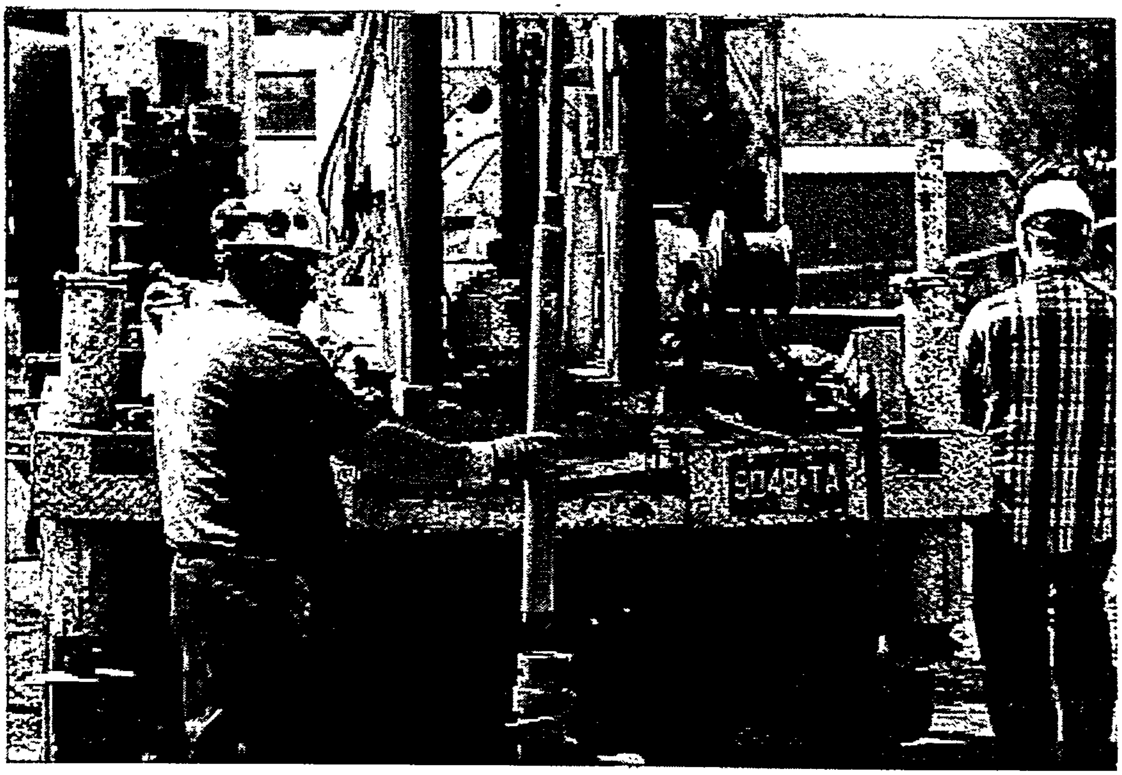
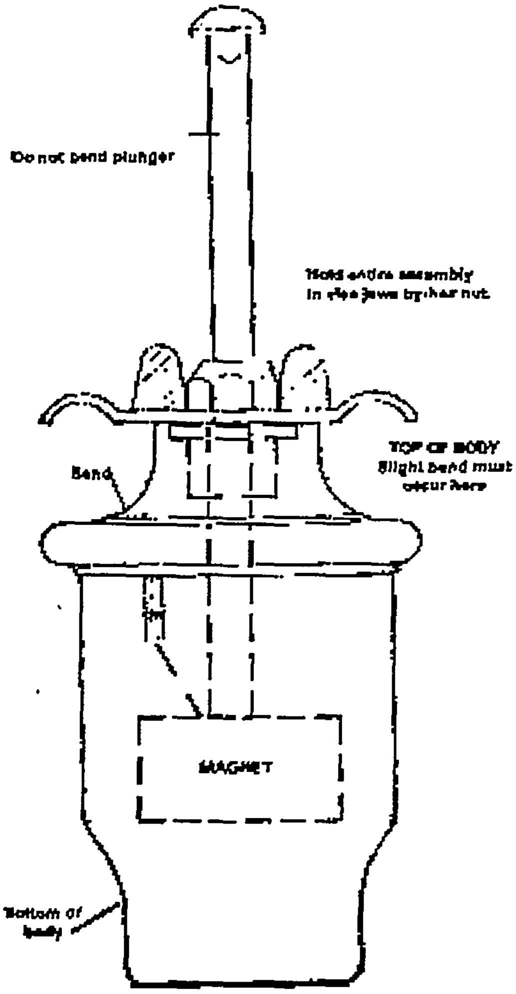


Figure 35. Photo Showing Shelby Tube Being Extracted from within Hollow-Stem Auger

GILSON MODEL SP-90 AUTOMAGNET SEPARATOR



REPAIR OF ABUSED OR DROPPED UNITS

1. Lift Automagnet to eye level and sight the plunger angle-incline.

2. Prepare to bend top of body in opposite direction of plunger-incline.

3. Insert Automagnet in vice jaws and hold by the hex nut. DO NOT PUT VICE JAWS ON THE PLUNGER.

4. Grasp the bottom of the body with the palm of the hand and bend top of body (slightly and gently) to make plunger in line with the main body, or so that the interior magnet assembly does not touch the sides of the bottom section.

5. SEPOR, Inc. will not accept responsibility for any adjustments made by the operator.

6. GILSON COMPANY will not accept responsibility for any adjustments made by the operator.

Figure 36. Sketch of Tool Used to Separate Iron Particles in the Sample from Soil Particles

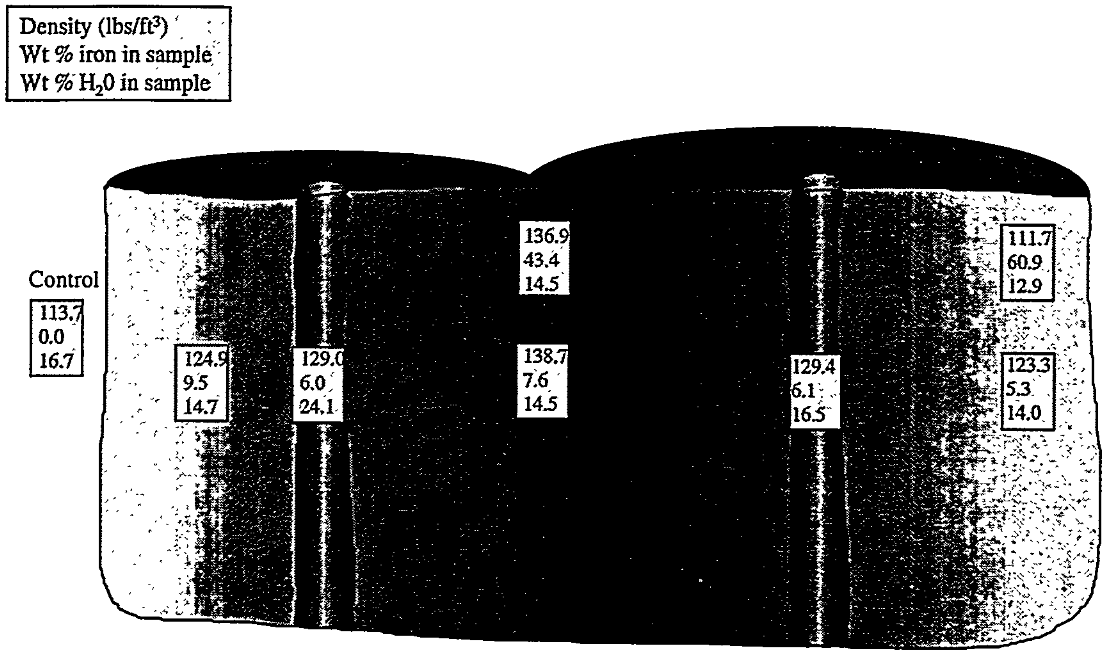


Figure 37. Drawing Showing Laboratory Iron Extraction Results for the Columnar Emplacements Using Kaolinite Clay/Iron Slurry

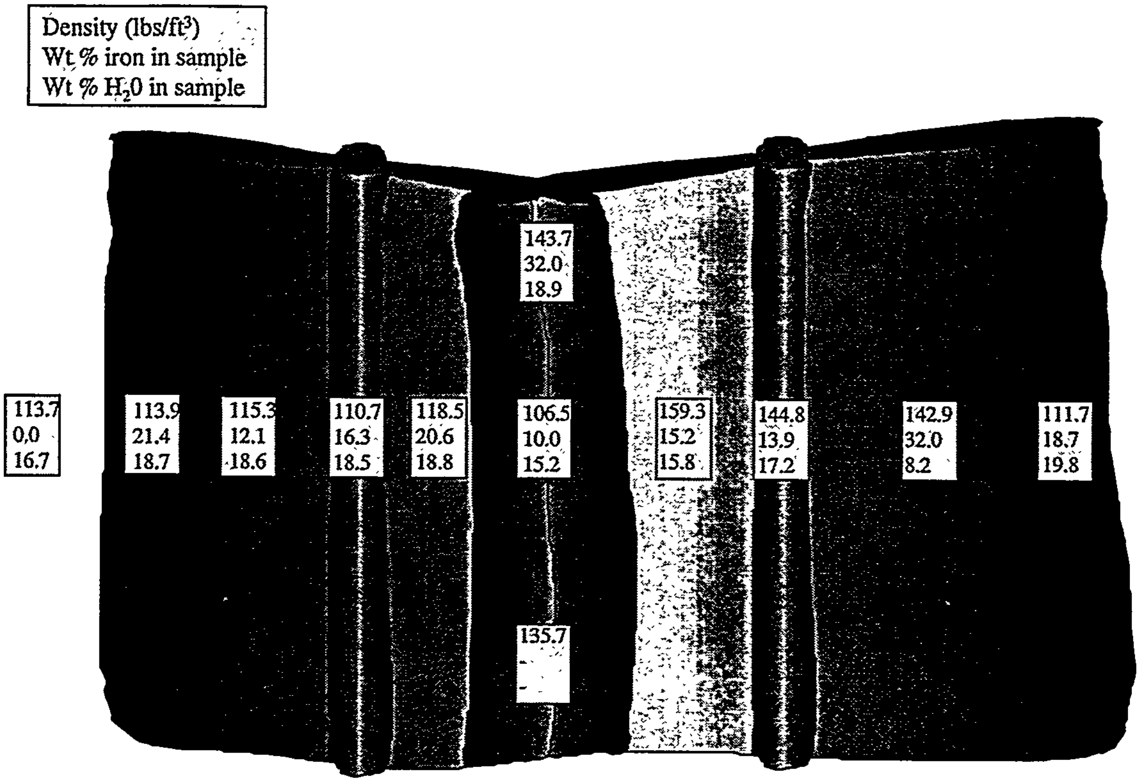


Figure 38. Laboratory Iron Extraction Results for the Thin Diaphragm Wall Emplacements Using the Kaolinite Clay/Iron Slurry

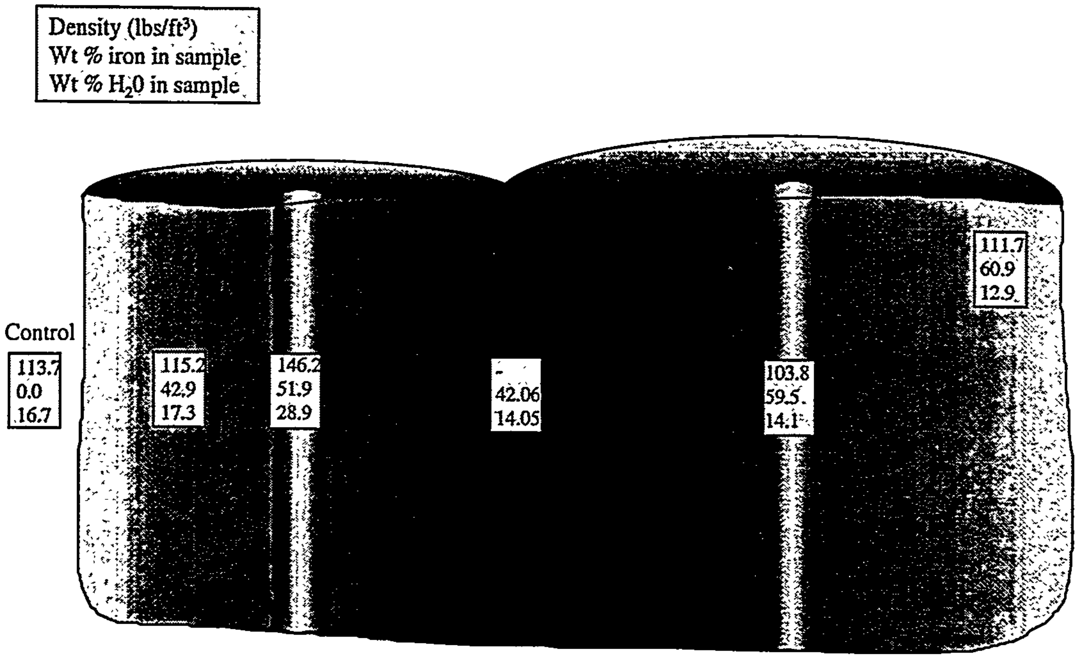


Figure 39. Laboratory Iron Extraction Results for the Columnar Emplacements Using the Guar Gum/Iron Slurry

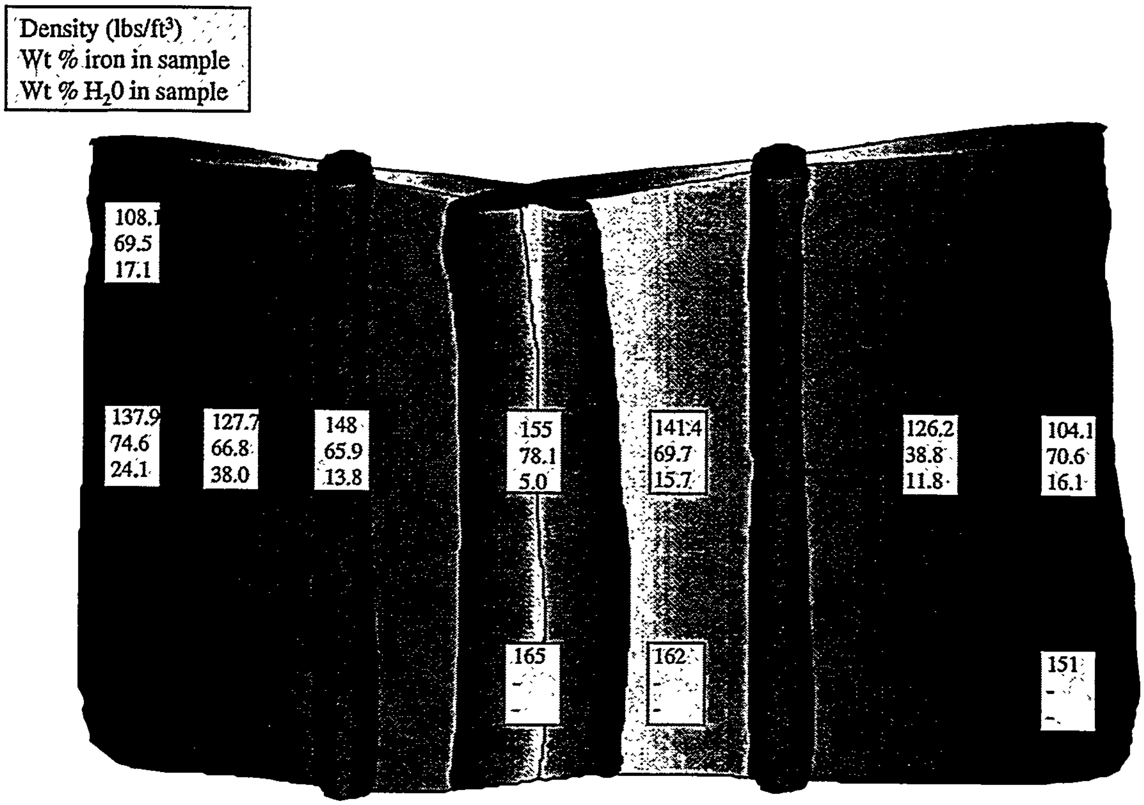


Figure 40. Laboratory Iron Extraction Results for the Thin Diaphragm Wall Emplacements Using the Guar Gum/Iron Slurry

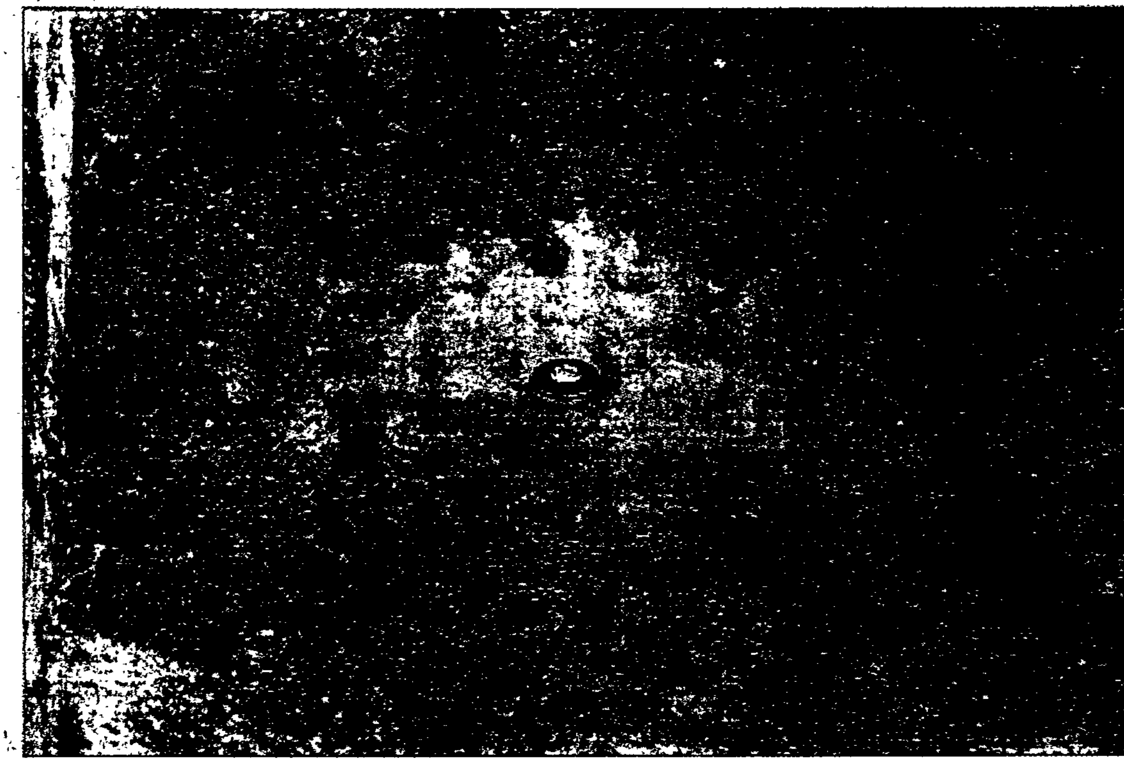


Figure 41. Photo of Upper Surface of Kaolinite Clay/Iron Column Showing Injection Well Boring (Indicated by Tape Measure) and the Somewhat Heterogeneous Column Matrix

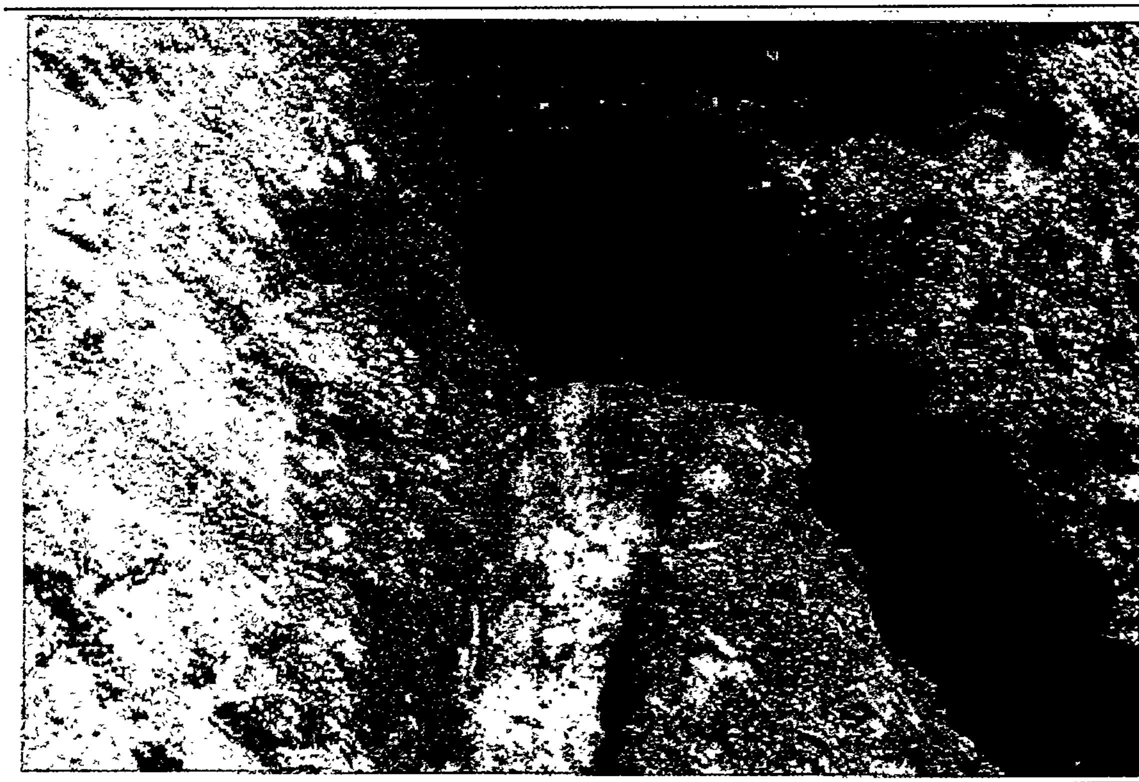


Figure 42. Photo Showing Isolated 50 Cm/Min Kaolinite Clay/Iron Thin Diaphragm Wall Intersecting 100 Cm/Min Thin Diaphragm Wall Near Their Tips

Figure 43. Photo of Isolated 20 Cm/Min Guar Gum/Iron Column

Figure 44. Photo of Isolated 50 Cm/Min Guar Gum/Iron Thin Diaphragm Wall Showing Injection Point at Right and a Vertical Wall at Tape Measure

Figure 45. Photo of Upper Surface of Column Showing Injection Well Boring (Indicated by Tape Measure) and Heterogeneity Of The Column's Matrix

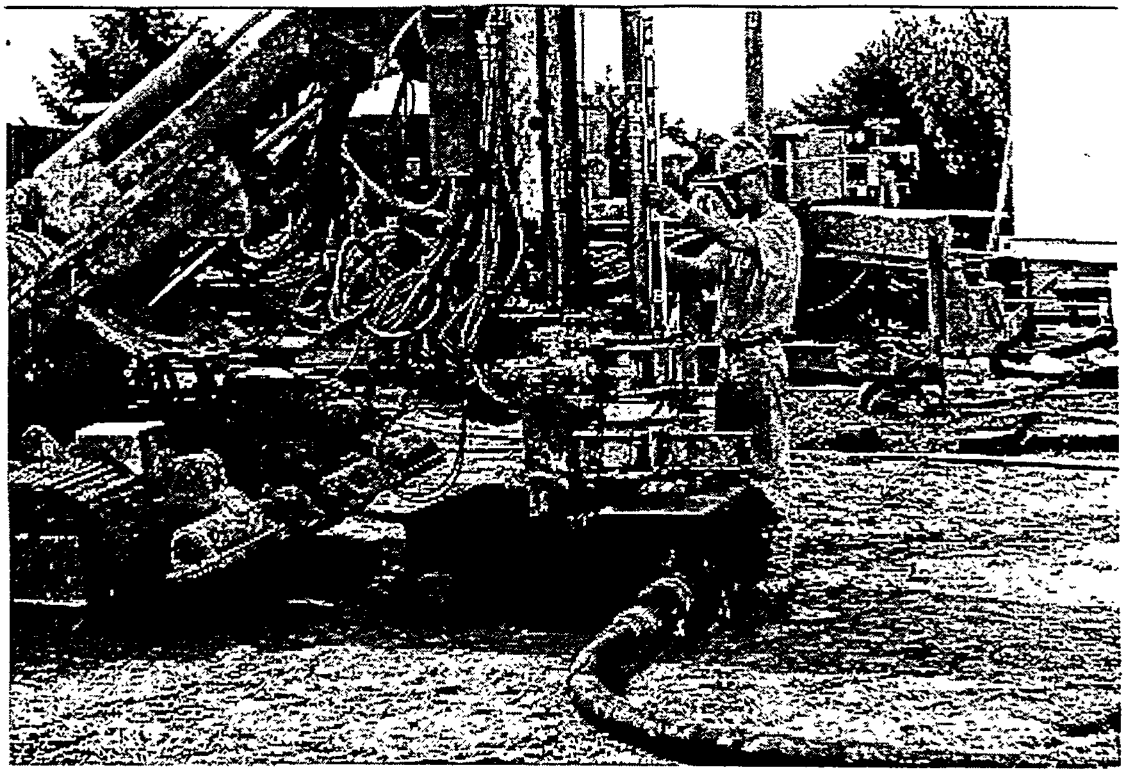


Figure 46. Photo Showing Spoils of Control Box Used to Collect and Control Excess Spoils at Jetting Rig

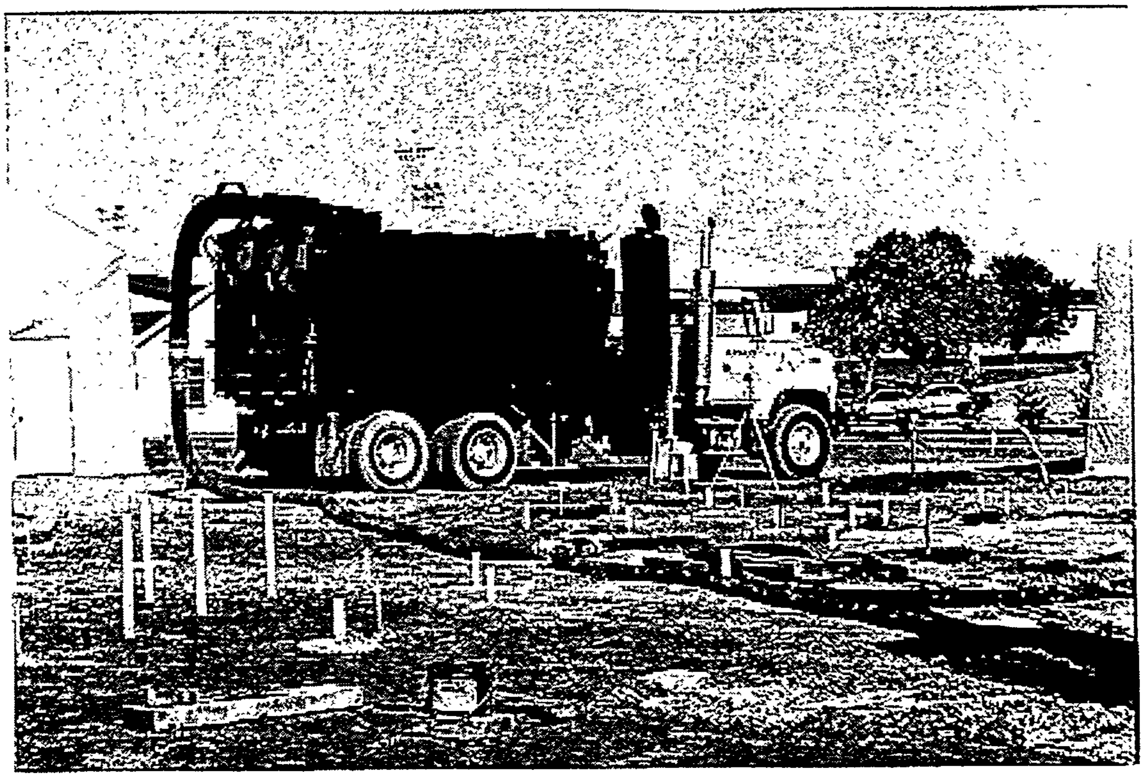
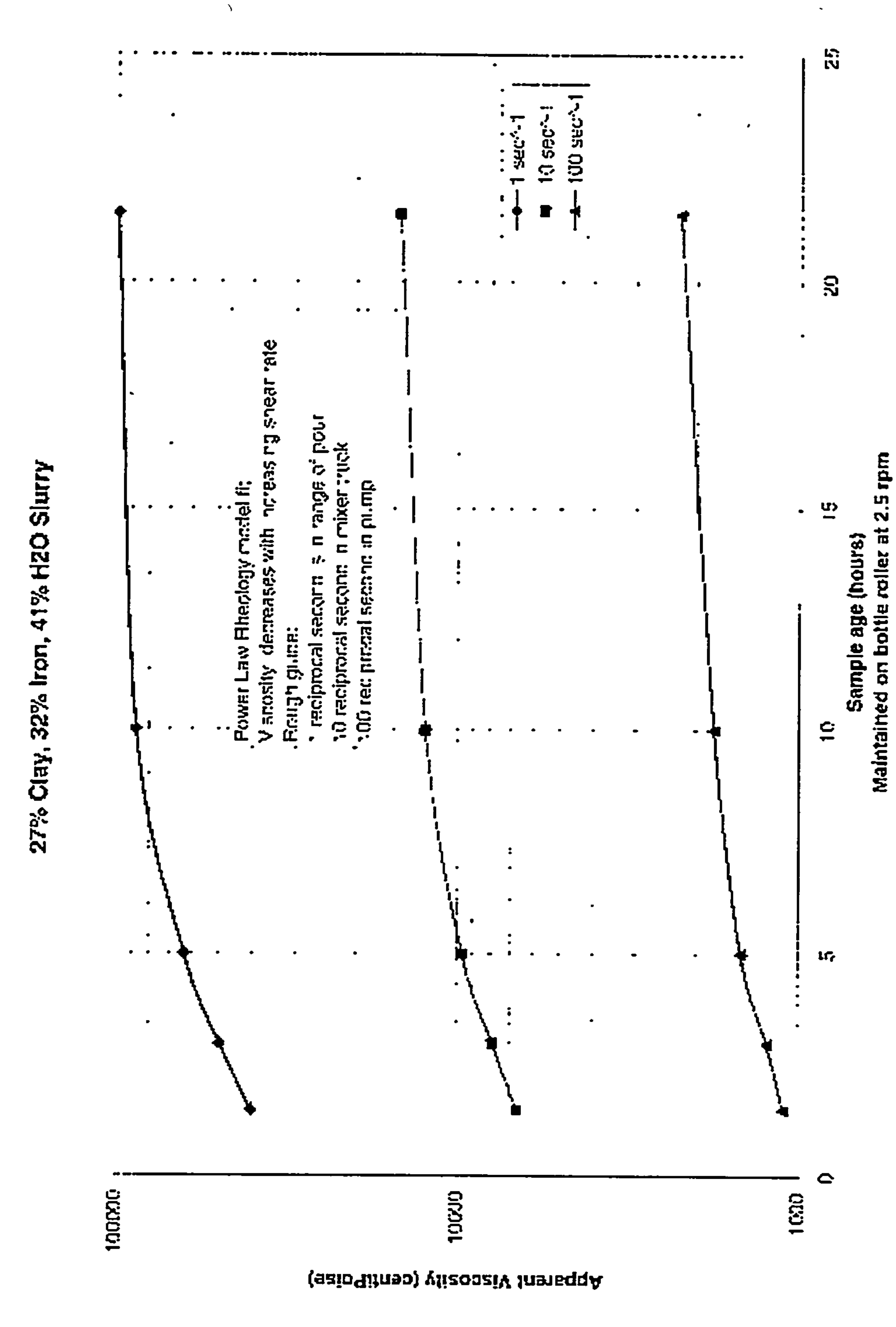


Figure 47. Photo Showing Typical Vacuum Truck that Could be Connected to Spoils Control Box Via 6-Inch or Larger Flexible Hoses


27% Clay, 32% Iron, 41% H2O Slurry
Power Law Rheology model fit
Viscosity decreases with increasing shear rate
Rough guide:
1 reciprocal second is in range of pour
10 reciprocal second in mixer truck
100 reciprocal second in pump
1 sec^-1
10 sec^-1
100 sec^-1
Apparent Viscosity (centiPoise)
100000
10000
1000
0
5
10
15
20
25
Sample age (hours)
Maintained on bottle roller at 2.5 rpm
Page 1

C: D. L. Johnson - ENGR - BEC 16/2413
J.Y. Yeung - ENGR - BEC 16/2232
G.E. Miller/S. T. Myrick BEC 16/1
IC 13 Mechanical Technologies - BEC 8/1

January 10, 1996

TO: R. C. LANDIS ENGR - BMP 27//2288

FROM: E. H. PEREZ ENGR - BEC 16/1105

GROUND REMEDIATION TECHNOLOGY - TREMIE TUBE METHOD FOR PILING NATURAL FREQUENCY AND BUCKLING ANALYSES OF TREMIE TUBE PILING

Refs.: 1) "Natural Frequencies of Cantilever Bars with Concentrated End Masses", by J. I. Weindling, Machine Design 2/3/1966

2) "Finding Natural Frequencies for Common Beam Configurations" by A. Hassoun, Machine Design,3/3/1966

We have performed natural frequency and buckling analyses of the proposed Tremie Tube shown in attached Figs. 1 and 3. The information on the proposed piledriver, American Piledriving Equipment APE Model 180, is given in Fig. 2. The suspended weight of the pile driver is 9,800 lbs, but only 6,400 lb rest on top of the piling. This mass was included in the natural frequency calculations. The piledriver normally operates at a frequency of 27.9 cps (1675 cpm).

The cross-section of the piling is shown in Fig. 3. The two 6"' x 1" end plates are added to increase the stiffness of the cross section. The calculated section properties are shown in sheets No. 1 and 2.

The piling was analyzed as a cantilever beam, fixed at the bottom and free at the top with a 6,400 lb mass attached to the top edge of the piling. The first 5 lateral (bending) natural frequencies of the beam/end mass system were calculated using Ref.[1l. The calculations were performed at 5 piling lengths (120", 240", 360", 480", and 600"), and the five calculated values were plotted to determine at what piling lengths the natural frequency coincides with the vibrator frequency (27.9 cps). The calculations are given in sheets No. 3 through 6. The results are tabulated in Table I and plotted in Fig. 4.

The first lateral natural frequency is well below the operating frequency for all piling lengths. The fifth lateral frequency (not plotted but tabulated in sheet No. 5) is **well** above the operating frequency for all piling lengths. The second, third, and fourth natural lateral frequencies coincide with the operating frequency at the following approximate piling lengths:

Lateral Mode	Resonant Piling Length
Second	160" (13.33 ft)
Third	280" (23.33 ft)
Fourth	375" (31.25 ft)

Since the damping provided by the ground is unknown, it is possible that we will find excessive vibration during the piledriving operation when the piling length is close to the calculated values. The vibration frequency of the piledriver vibrator can be lowered a little to reduce the vibration when we approach the critical vibration piling lengths.

2

January 10, 1996
R. C. Landis

The longitudinal and torsional natural frequencies were also evaluated as a function of the piling length. The first longitudinal natural frequency is well above the operating frequency. See Table I and Fig. 4. Therefore no longitudinal vibration resonance **will** exist in the 50 feet long piling.

The analysis of the torsional spring constant of the Tremie Tube is shown in sheets No. 6 through 8. The contribution of the two end plates is negligible, the torsional stiffness is provided by the 4 welded rectangular tubes. The calculation of the first torsional natural frequency is shown in sheet No. 9, and plotted in Fig. 4. The results indicate that the first torsional natural frequency is below the operating frequency at all lengths. Higher torsional modes were not calculated since they are more difficult to excite during the piledriving operation.

The buckling analysis of the piling was performed assuming a column with one end fixed and the other end free. The calculated critical buckling stress and loads as a function of piling length are given in sheet No. 10. The calculated critical loads are higher than the 6,400 lb mass attached to the top edge of the piling. In the real world, the bottom edge of the piling is not 100% fixed, in particular at the start of the piling operation when the length of the piling is close to 50 feet. Lateral support or guides would help to prevent sideway deflection if the bottom end of the piling is not well embedded into the ground at the start of the piledriving operation.

Please, let us know if you need additional information on this subject,

EHP/bas
Attachment

SUMMARY SHEET

'a' for calculating Qt: 0.900
Value for Water Table (in m): 6.000
Sand Compressibility for calc Dr: High
Method for Friction Angle: Robertson & Campanella
Method for calculating Su: Nc
Value of the constant Nc: 15.000

Soil Behavior Type Zone Numbers
For Rf Zone & Bq Zone Classification

--

Zone #1 = Sensitive fine grained Zone #7 = Silty sand to sandy silt
Zone #2 = Organic material Zone #8 = Sandy to silty sand
Zone #3 = Clay Zone #9 = Sand
Zone #4 = Silty clay to clay Zone #10 = Gravelly sand to sand
Zone #5 = Clayey silt to silty clay Zone #11 = Very stiff fine grained *
Zone #6 = Sandy silt to clayey silt Zone #12 = Sand to clayey sand *
* Overconsolidated and/or cemented

NOTE:

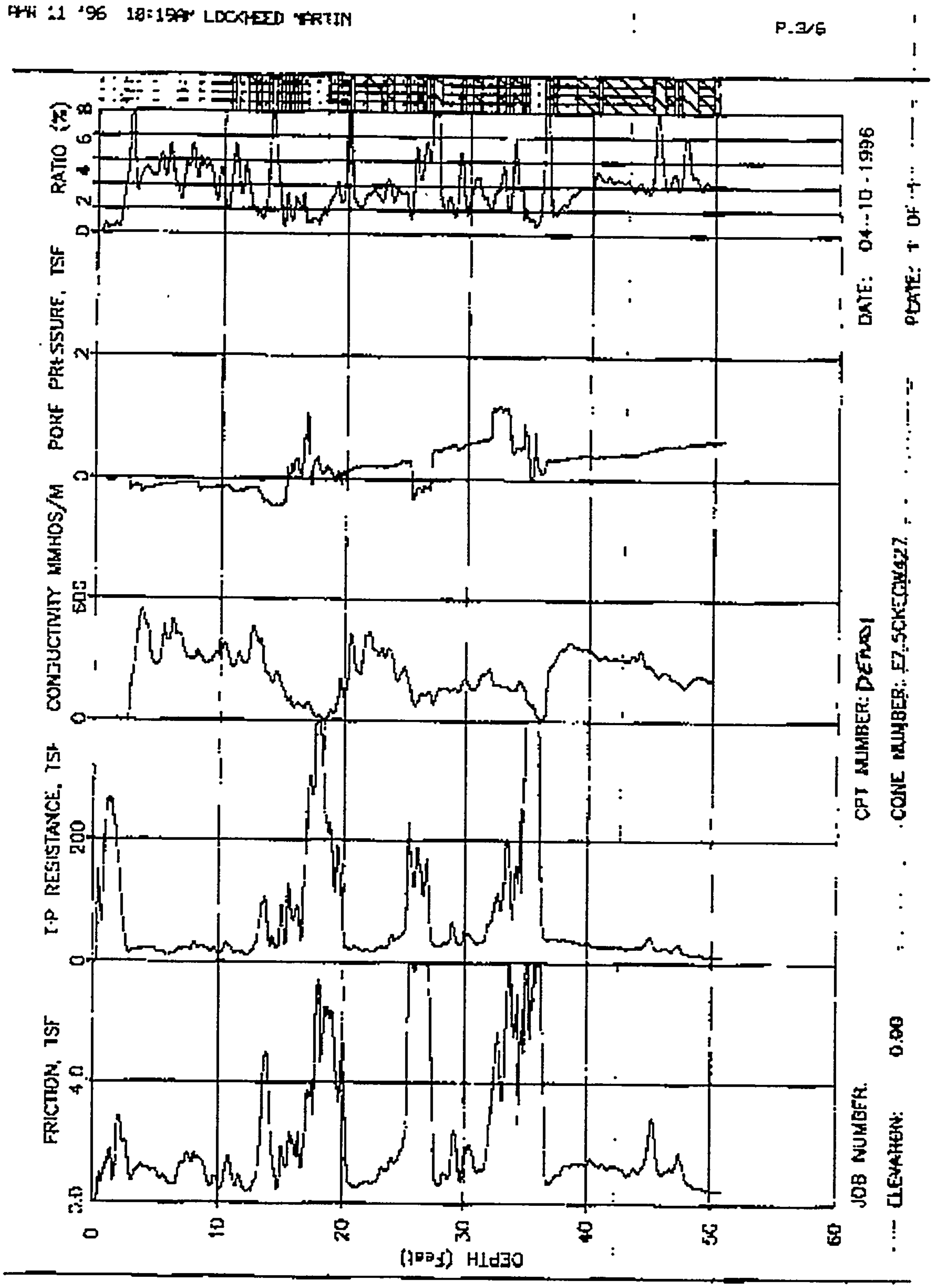
For soil classification, Rf values greater than 8 are assumed to be 8.

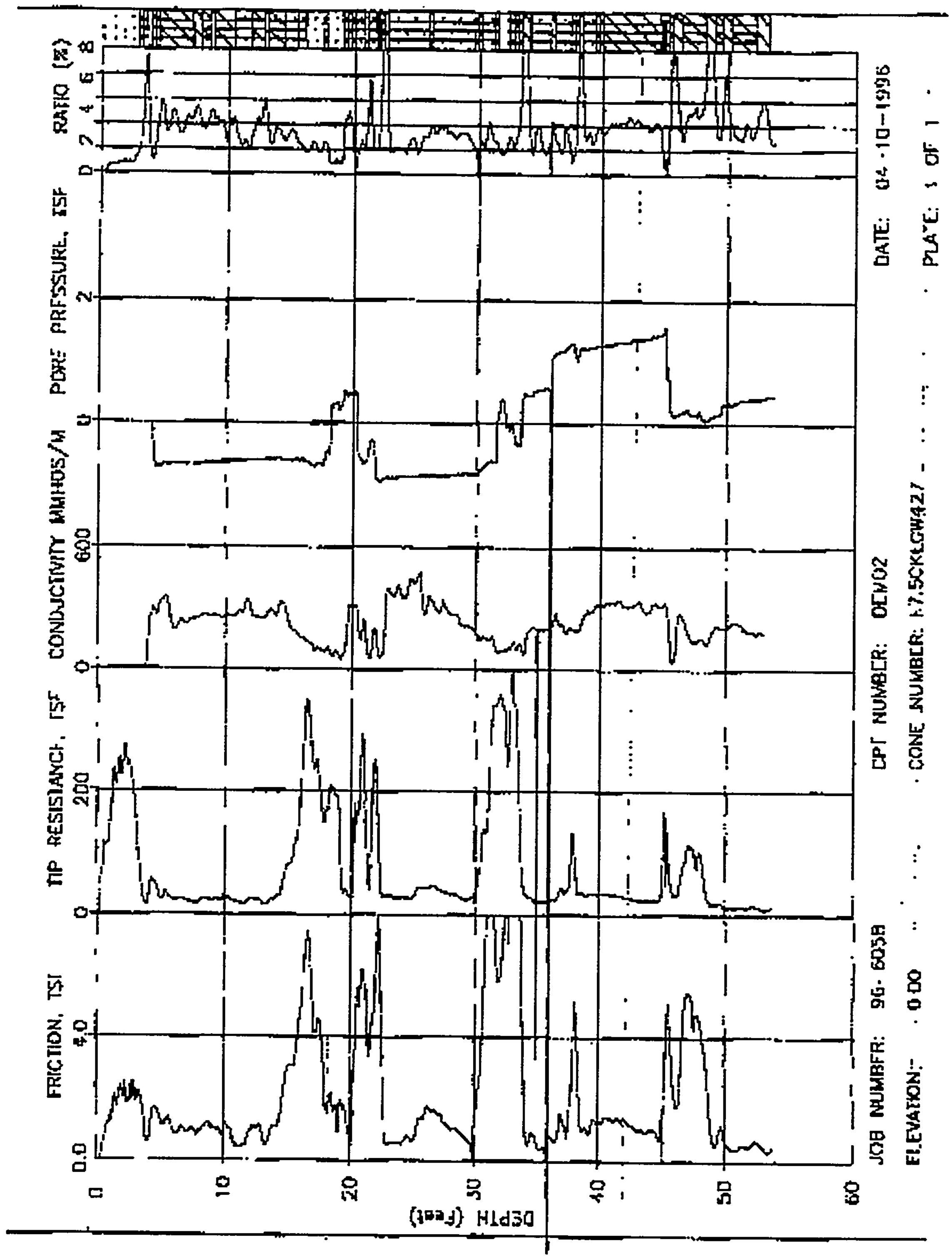
NOTE:

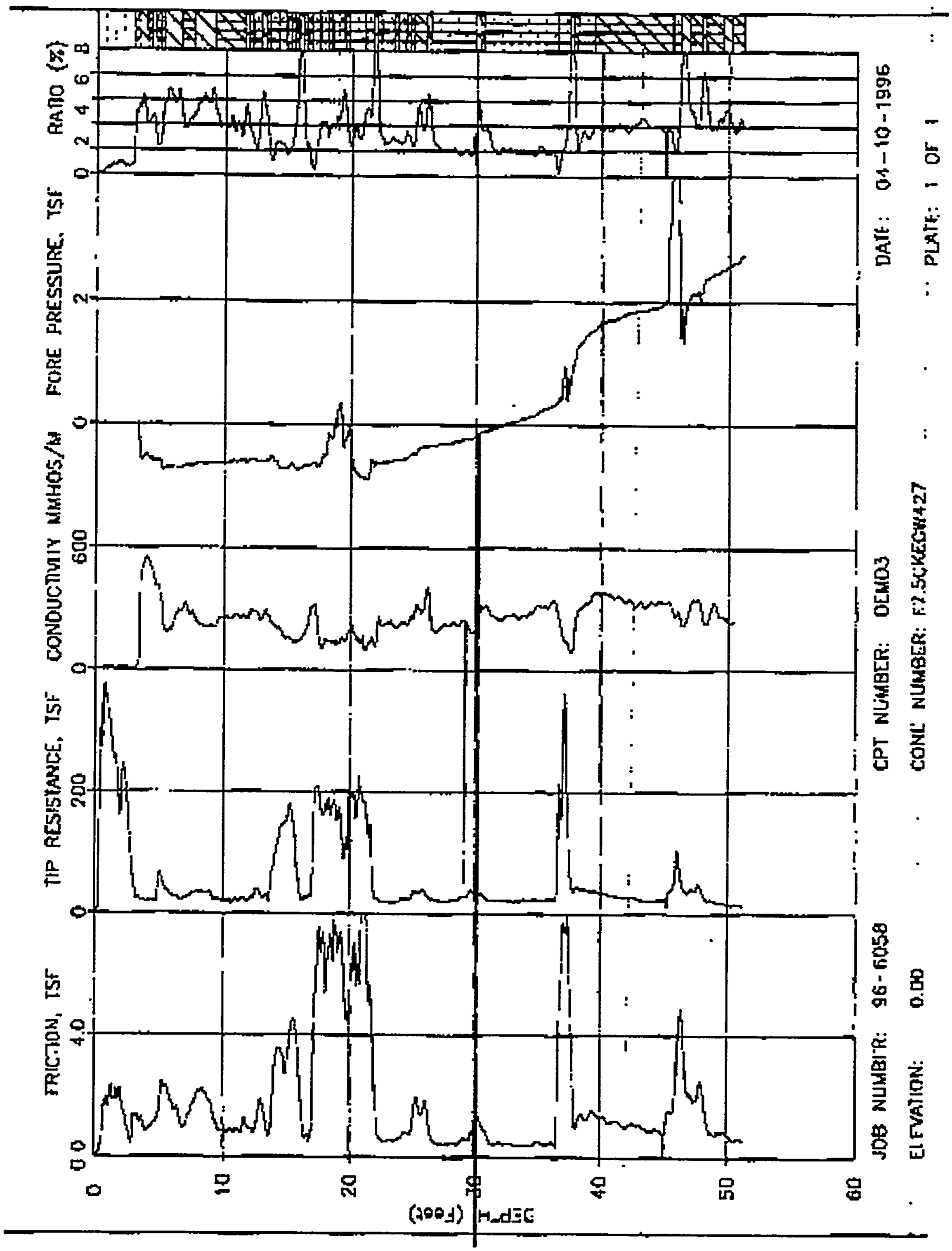
Since U2 (pore pressure) has not been defined, Qt cannot be calculated, therefore, the value of Qt has been made equal to Qc.

(Note: --- means Out Of Range)

APPENDIX D - Cone Penetrometer Test Plots




FRICTION, TSF
TIP RESISTANCE, TSF
CONDUCTIVITY MMHOS/M
PORE PRESSURE, TSF
RATIO (%)
DEPTH (Feet)
JOB NUMBER: 96-6058
ELEVATION: 0.00
CPT NUMBER: DEW02
DATE: 04-10-1996
PLATE: 1 OF 1


FRICTION, TSF
TIP RESISTANCE, TSF
CONDUCTIVITY MMHOS/M
PORE PRESSURE, TSF
RATIO (%)
DEPTH (Feet)
JOB NUMBER: 96-6058
ELEVATION: 0.00
CPT NUMBER: DEMO3
CONE NUMBER: F2.5CKEGW427
DATE: 04-10-1996
PLATE: 1 OF 1

ConeTec Inc.
Geotechnical and Environmental In Situ Testing Contractors
250 H St., Box 8110-233, Blaine, WA 98230 Tel: (604) 327-4311 • Fax (604) 327-4066 • Email: insitu@conetec.com

April 30, 1996

Mr. Rich Landis
DUPONT
Corporate Remediation
Core Resources Section
Barley Mill Plaza 27
P.O. Box 80027
Wilmington, Delaware 19880-0027

Dear Sirs:

RE: P.O. No. LEMH-40065
Paducah, Kentucky - Test Site

This letter summarizes our analysis of CPT data collected at the Lasagna site in Paducah Kentucky. CPT data was collected and analysed with a view to providing some design parameters for the construction of a new environmental remediation tool. Specifically, the analysis is to provide an assessment of the pull out capacity of a sheet pile deployment rig being designed and built by DuPont for the remediation of contaminated sites. This assessment of pull out capacity has been carried out under DuPont purchase order number LEMH-40065.

Soils on the site consist of primarily clayey silts and silty clays. At each of the three CPT locations inter beds of dense sand were encountered at depths of approximately 4-6 m and 9 - 11 metres.

The clays and silts at each location were over consolidated to depths of 11 to 13 m beyond which they became normally consolidated. Refer to coneplots in Appendix A for detailed soil stratigraphy and geotechnical parameters.

Page 2
DuPont
Report 96-501

Pile analyses were carried out using the CPT data and the LCPC method of pile design (refer to Appendix B). The results of the pile analyses indicate static pull out capacities of 80 to 95 tons. The results of the analyses are presented in Appendix C. The pull out capacities can be reduced by approximately 40 to 50% by taking into account the effects of vibration, lubrication and sheet pile geometry.

In over consolidated clayey soils, vibrations will have less of an impact with respect to reducing pull out capacity then the same vibrations would have in sandy soils. The over consolidated nature of the soils will make withdrawal of the sheet pile more difficult than in normally consolidated soils.

Lubrication of the sheet pile can only help to reduce the friction during withdrawal. A viscous slippery fluid like bentonite mud would be preferable.

Modification to the sheet pile geometry to reduce the required pull out capacity is a good idea provided the modifications are appropriate. In this regard, some trial and error may be necessary to optimize geometry for pull out capacity reduction.

Nilex reportedly have been unable to pull out their wick drain lances on a number of occasions. On one site, a 225 ton crane was used to pull out a lance (2" x 5") embedded 200'. If one scales these numbers to reflect the dimensions of a lance 2" x 20" x 50' then the static pull out capacity could realistically approach 90 tons.

ConeTec Inc.

If you should have any questions regarding the information contained in this letter please contact our office.

Yours truly,

for: David J. Woeller, M.Eng.
/jeb
Enclosures

wf\s\96-505.rpt

Proj. No.: 139089.LS.GE
SOIL BORING LOG

Project: DuPont-Parlin Plant | Drilling Contractor: Diamond Drilling Company, Inc.

Drilling Method & Equipment: 4.5" OD Solid Stem Auger, CME-55 | Logger: K. Hall

Depth Below Surface (FT)	Sample: Interval	Sample: Number and Type	Sample: Recovery (FT)	Standard Penetration Test Results 6"-6"-6" (N)	Soil Description Soil name, uscs group symbol, color, moisture content, relative density or consistency, soil structure, mineralogy	Comments Depth of casing, drilling rate, drilling fluid loss, tests and instrumentation
Elevation: 113.0' (approx.)					Location: Parlin, NJ	**Boring No. DB-1**
Start: 3/13/97					Finish: 3/13/97	Water Level: N/A
						Sheet 1 of 1
	0-	1-S	1.0	3-4-5-5	POORLY GRADED SAND(SP),fine-med.,	PP=0 TSF,5YR 4/4,10YR 6/6
	2.0			(9)	med. brown/yel. orange,dry,loose,w/trace	FILL
	2.0-	2-S	2.0	4-5-3-2	SILT,w/organics,w/wood and brick debris	
	4.0			(8)	SAME AS 1-S,except w/pebbles(<0.5")	PP=0 TSF,5YR 4/4,10YR 6/6
5.0	4.0-	3-S	2.0	3-2-2-3	SAME AS 2-S, except very loose,w/2" thick	PP=0 TSF,5YR 4/4,10YR 6/8
	6.0			(4)	zone of burned wood	FILL
	6.0-	4-S	2.0	4-4-3-2	SAME AS 2-S, except fine to coarse	PP=0 TSF,5YR 4/4,10YR 6/6
	8.0			(7)		FILL
	8.0-	5-S	0.8	4-5-3-2	SAME AS 2-S	PP=0 TSF,5YR 4/4,10YR 6/6
10.0	10.0			(8)		FILL
	10.0-	6-S	1.0	5-7-10-10	SILTY SAND(SM),fine-coarse,light brown,	PP=0 TSF, 5YR 5/8
	12.0			(17)	dry,med. dense,cohesive,w/pebbles(<1")	
	12.0-	7-S	2.0	10-7-7-7	POORLY GRADED SAND(SP),medium to	PP=0 TSF,10YR 6/6
	14.0			(14)	coarse,yel. orange and white,dry,medium	
15.0	14.0-	8-S	1.0	7-8-7-8	dense,w/trace SILT	
	16.0			(15)	SAME AS 7-S	PP=0 TSF,10YR 6/6
	16.0-	9-S	2.0	5-7-8-9	SAME AS 7-S	PP=0 TSF,10YR 6/6
	18.0			(15)		
	18.0-	10-S	0.8	7-7-7-7	SAME AS 7-S,except fine to medium,w/	PP=0 TSF,10YR 6/6,5YR 5/6
20.0	20.0			(14)	banding of SAND,fine,light brown	
					END BORING AT 20.0'	
25.0						
30.0						
35.0						

NOTES:

Begin drilling at 0950 HRS; end drilling at 1045 HRS (completion at 20.0').

Water level: at completion=N/A

Printed 3/13/97

Proj. No.: 139089.L5.GE

SOIL BORING LOG

Project: DuPont-Parlin Plant

Drilling Contractor: Diamond Drilling Company, Inc.

Drilling Method & Equipment: 4.5" OD Solid Stem Auger, CME-55

Logger: K. Hall

Elevation: 113.0' (approx.)

Location: Parlin, NJ

Boring No. DB-2

Start: 3/13/97

Finish: 3/13/97

Water Level: N/A

Sheet 1 of 1

Depth Below Surface (FT)	Sample: Interval	Sample: Number and Type	Sample: Recovery (FT)	Standard Penetration Test Results 6"-6"-6" (N)	Soil Description (Soil name, uscs group symbol, color, moisture content, relative density or consistency, soil structure, mineralogy)	Comments (Depth of casing, drilling rate, drilling fluid loss, tests and instrumentation)
	0-2.0	1-S	1.0	5-7-7-8 (14)	POORLY GRADED SAND(SP),fine-med., mod. brown/yel. orange,dry,med. dense, w/ trace SILT,w/organics,w/const. debris	PP=0 TSF,5YR 4/4,10YR 6/6 FILL
	2.0-4.0	2-S	1.5	2-4-3-3 (7)	SAME AS 1-S,except loose	PP=0 TSF,5YR 4/4,10YR 6/6
5.0	4.0-6.0	3-S	1.5	5-8-7-7 (13)	SAME AS 1-S	PP=0 TSF,5YR 4/4,10YR 6/6 FILL
	6.0-8.0	4-S	1.3	3-1-2-1 (3)	SAME AS 2-S, except light brown,w/ pebbles(<1")	PP=0 TSF,5YR 5/6 FILL
10.0	8.0-10.0	5-S	1.0	1-2-1-2 (3)	SAME AS 4-S	PP=0 TSF,5YR 5/6 FILL
	10.0-12.0	6-S	2.0	2-4-6-6 (10)	SILTY SAND(SM),fine-coarse,light brown, dry,loose,slight cohesive,w/pebbles(<1")	PP=0 TSF, 5YR 5/6
	12.0-14.0	7-S	1.8	9-7-9-9 (16)	POORLY GRADED SAND(SP),medium to coarse,yel. orange and white,dry,medium dense,w/trace SILT	PP=0 TSF,10YR 6/6
15.0	14.0-16.0	8-S	1.5	7-10-9-8 (19)	SAME AS 7-S	PP=0 TSF,10YR 6/6
	16.0-18.0	9-S	1.5	5-5-6-7 (11)	SAME AS 7-S	PP=0 TSF,10YR 6/6
20.0	18.0-20.0	10-S	1.5	7-9-9-6 (18)	SAME AS 7-S,except fine to medium,w/ bands of SAND,fine,lt. brown and dk. red END BORING AT 20.0'	PP=0 TSF,10YR 6/8,5YR 5/6, 5R 2/6
25.0						
30.0						
35.0						

NOTES:

Begin drilling at 1110 HRS; end drilling at 1205 HRS (completion at 20.0').

Water level: at completion=N/A

APPENDIX G - Cost Basis for Electrodes and Treatment Zones and Fixed Costs

One Acre Template Site (15-foot depth)

List of Given Site and Design Parameters
- Treatment area = 210 ft x 210 ft
- Treatment depth = 15 ft
- Soil volume to be remediated = 24,500 cubic yds
- Remediation time = 1 yr or 3 yrs
- Power cost = $0.05/kW-hr
- Power conversion efficiency = 90%
- Soil conductivity = 0.3 mS/cm
- Soil electroosmotic permeability = 1.2 x 10-5 cm^2V/sec
- Soil porosity = 40%

List of Assumptions
- Number of flushed pore volumes required to achieve cleanup = 2
- Average cost of field construction labor = $40/hr
- Average cost of field operating labor = $50/hr
- Applied potential should be approximately 500 volts or less
- Voltage gradient should be 31 volts/m or less (to avoid overheating)

Equipment Cost Basis for Electrode and Treatment Zone Emplacement

Item	Daily Rate ($)	Weekly Rate ($)
Excavator (Cat 235C)	600	3,000
Lead/Mast	50	500
Cable	320	2,625
Mandrel	120	1,200
Vibrator	300	3,000
Elastomers	35	175
Trucks (2)	100	500
Hoses/Fittings	50	250
Boom Truck	250	1,250
Trailer	40	200
Backhoe	120	600
Welder	25	125
Fuel	100	500
Blender	420	2,100
Forklift	286	1,430
Cement Bin	25	125
TOTAL	**2,841**	**14,205**

Estimated Emplacement Cost (Mandrel Method)
The following assumptions were made:
- Six-person field construction crew (three local, three remote)
- Rate of emplacements of 50 per day to a depth of 15 ft
- Rate of electrode and treatment zone emplacements equal
- Each emplacement is 1.5 ft wide
- Each 210 ft wide row requires 140 emplacements
- Each row requires about 3 days to complete
- Twenty rows for estimation purposes (63,000 ft^2)

- Eight additional days for set up and tear down
- Average field construction labor rate = $40/hr x 6 = $240/hr
- Working time per day = 11 hrs/day
- Five working days per week
- Per diem lodging/subsistence = $70/day/person
- Non-local crew travel home biweekly ($500/trip)

A. Estimate of Total Emplacement Labor Cost
Total days of field construction (set up, emplacement, tear down)
= (20 rows x 3 days/row) + 8 days set up and tear down = 68 days

Labor cost = 68 days x 11 hrs/day x $240/hr = $179,520

B. Estimate of Travel and Per Diem Cost
Total days of per diem = 3 persons x 68 days x $70/day = $ 14,280
Travel cost = 3 persons x 5 trips x $500/trip = $ 7,500
Total $ 21,780

C. Estimate of Equipment Cost
Total days of field construction = 68 days (see above)

Cost of field emplacement equipment = $2,841/day (see attached itemized list)

Equipment cost = 68 days x $2,841/day = $193,200

D. Total Estimated Emplacement Cost (A + B + C) $394,500

E. Estimated Unit Emplacement Cost

Unit emplacement cost = $394,500/63,000 ft^2 = $6.26/ft^2

Estimated Electrode Material Cost
The following assumptions were made:
- Cost of Peerless granular iron delivered = $0.23/lb
- Cost of Loresco DW-1 coke delivered = $0.18/lb
- Weight basis of electrode mix = 50% iron: 50% coke
- Bulk density of electrode mix = 92 lb/ft^3
- Thickness of electrodes = 0.17 ft (2 inches)
- Place 1.25 inch diameter iron rod in every other emplacement
- Cost of 1.25 inch diam iron rod is $2.00/ft

A. Effective Unit Volume of Electrode Mix Required
Unit volume of electrode = 1 ft^2 x 0.17 ft = 0.17 ft^3/ft^2

B. Estimated Cost of Electrode Materials
Cost of iron = 0.17 ft^3/ft^2 x 92 lb/ft^3 x 0.5 x $0.23/lb = $1.80/ft^2
Cost of coke = 0.17 ft^3/ft^2 x 92 lb/ft^3 x 0.5 x $0.18/lb = $1.41/ft^2

Cost of iron rod = [1 ft/3 ft^2] x $2.00/ft = $0.67/ft^2

C. Unit Cost of Electrode Materials
Unit cost of electrode materials = $1.80/ft^2 + $1.41/ft^2 + $0.67/ft^2 = $3.88/ft^2

Estimated Treatment Zone Material Cost

Case 1—"Phase 2A" Mix
The following assumptions were made:
- Weight basis of treatment zone = 60% iron: 16% clay: 24% water
- Bulk density of treatment zones = 160 lbs/ft^3
- Cost of Peerless granular iron delivered = \$0.23/lb
- Cost of kaolinite clay delivered = \$0.04/lb
- Thickness of treatment zone = 0.17 ft (2 inches)

A. Effective Unit Volume of Treatment Zone Mix Required
Unit volume of treatment zone = 1 ft^2 x 0.17 ft = 0.17 ft^3/ft^2

B. Estimated Cost of Treatment Zone Materials
Cost of iron = 0.17 ft^3/ft^2 x 160 lbs/ft^3 x 0.60 x \$0.23/lb = \$3.75/ft^2
Cost of clay = 0.17 ft^3/ft^2 x 160 lbs/ft^3 x 0.16 x \$0.04/lb = \$0.17/ft^2

C. Unit Cost of Treatment Zone Materials
Unit cost of treatment zone materials = \$3.75/ft^2 + \$0.17/ft^2 = \$3.92/ft^2

Case 2—Alternate Treatment Zone Mix
The following assumptions were made:
- Weight basis of treatment zone = 30% iron: 22% coke: 19% clay
- Bulk density of treatment zones = 119 lbs/ft^3
- Cost of Peerless granular iron delivered = \$0.23/lb
- Cost of Loresco DW-1 coke delivered = \$0.18/lb
- Cost of kaolinite clay delivered = \$0.04/lb
- Thickness of treatment zone = 0.17 ft (2 inches)

A. Effective Unit Volume of Treatment Zone Mix Required
Unit volume of treatment zone = 1 ft^2 x 0.17 ft = 0.17 ft^3/ft^2

B. Estimated Cost of Treatment Zone Materials
Cost of iron = 0.17 ft^3/ft^2 x 119 lbs/ft^3 x 0.30 x \$0.23/lb = \$1.40/ft^2
Cost of coke = 0.17 ft^3/ft^2 x 119 lbs/ft^3 x 0.22 x \$0.18/lb = \$0.80/ft^2
Cost of clay = 0.17 ft^3/ft^2 x 119 lbs/ft^3 x 0.19 x \$0.04/lb = \$0.15/ft^2

C. Unit Cost of Treatment Zone Materials
Unit cost of treatment zone materials = \$1.40/ft^2 + \$0.80/ft^2 + \$0.15/ft^2 = \$2.35/ft^2

Electrode Unit Cost Summary

Crew Size	Emplacement	Materials	Total
Six person	\$6.26/ft^2	\$3.88/ft^2	\$10.14/ft^2

Treatment Zone Cost Summary

Crew Size	Emplacement	TZ Design Case	Materials	Total
Six person	\$6.26/ft^2	Alternate mix	\$2.35/ft^2	\$8.61/ft^2

Other Cost Components

A. Fixed Costs

Item	Estimated Cost ($)
Mobilization/Demobilization	45,000
Data Acquisition System	25,000
Electrical Hookup	15,000
Electrician Labor, 200 hrs@$50/hr	(10,000)
Materials (e.g., wiring)	(5,000)
Fluid Handling System (e.g., piping, tanks)	60,000
Miscellaneous Expendables	50,000
TOTAL	**195,000**

B. Operations and Maintenance Costs

Item	Estimated Cost ($)
Operating Labor (Field)	
Full-time field technician, 2,000 hrs/yr@$50/hr	100,000/yr
Operating Labor (Office Support)	
¼-time engineer, 500 hrs/yr@$100/hr	50,000/yr
Equipment Maintenance	$20,000/yr
TOTAL	**$170,000/yr**

Cost Basis For Electrodes And Treatment Zones
One Acre Template Site, 45 Ft Depth

List of Given Site and Design Parameters

- Treatment area = 210 ft x 210 ft
- Treatment depth = 45 ft
- Soil volume to be remediated = 73,500 cubic yds
- Remediation time = 1 yr or 3 yrs
- Power cost = $0.05/kW-hr
- Power conversion efficiency = 90%
- Soil conductivity = 0.3 mS/cm
- Soil electroosmotic permeability = 1.2 x 10-5 cm^2V/sec
- Soil porosity = 40%

List of Assumptions

- Number of flushed pore volumes required to achieve cleanup = 2
- Average cost of field construction labor = $40/hr
- Average cost of field operating labor = $50/hr
- Applied potential should be approximately 500 volts or less
- Voltage gradient should be 31 volts/m or less (to avoid overheating)

Equipment Cost Basis for Electrode and Treatment Zone Emplacement

Item	Daily Rate ($)	Weekly Rate ($)
Excavator (Cat 375L)	900	4,500
Lead/Mast	100	500
Cable	525	2,625
Mandrel	240	1,200
Vibrator	600	3,000
Elastomers	35	175
Trucks (2)	100	500
Hoses/Fittings	50	250
Boom Truck	250	1,250
Trailer	40	200
Backhoe	120	600
Welder	25	125
Fuel	100	500
Blender	420	2,100
Forklift	286	1,430
Cement Bin	25	125
TOTAL	**3,816**	**19,080**

Estimated Emplacement Cost (Mandrel Method)

The following assumptions were made:

- Six person field construction crew (three local, three remote)
- Rate of emplacements 24 per day to a depth of 45 ft
- Rate of electrode and treatment zone emplacements equal
- Each emplacement is 1.5 ft wide
- Each 210 ft wide row requires 140 emplacements
- Each row requires about six days to complete
- Twenty rows for estimation purposes (189,000 sq ft)

- Eight additional days for set up and tear down
- Average field construction labor rate = \$40/hr x 6 = \$240/hr
- Working time per day = 11 hrs/day
- Five working days per week
- Per diem lodging/subsistence = \$70/day/person
- Non-local crew travel home biweekly (\$500/trip)

A. Estimate of Total Emplacement Labor Cost
Total days of field construction (set up, emplacement, tear down)
= (20 rows x 6 days/row) + 8 days set up and tear down = 128 days

Labor cost = 120 days x 11 hrs/day x \$240/hr = \$316,800

B. Estimate of Travel and Per Diem Cost
Total days of per diem = 3 persons x 120 days x \$70/day = \$ 25,200
Travel cost = 3 persons x 9 trips x \$500/trip = \$ 13,500
Total \$ 38,700

C. Estimate of Equipment Cost
Total days of field construction = 128 days (see above)
Cost of field emplacement equipment = \$3,816/day (see attached itemized list)
Equipment cost = 128 days x \$3,816/day = \$488,400

D. Total Estimated Emplacement Cost (A + B + C) \$843,900

E. Estimated Unit Emplacement Cost
Unit emplacement cost = \$843,900/189,000 ft^2 = \$4.47/ft^2

Estimated Electrode Material Cost
The following assumptions were made:

- Cost of Peerless granular iron delivered = \$0.23/lb
- Cost of Loresco DW-1 coke delivered = \$0.18/lb
- Weight basis of electrode mix = 50% iron: 50% coke
- Bulk density of electrode mix = 92 lb/ft^3
- Thickness of electrodes = 0.17 ft (2 inches)
- Place 1.25 inch diameter iron rod in every other emplacement
- Cost of 1.25 inch diameter iron rod is \$2.00/ft

A. Effective Unit Volume of Electrode Mix Required
Unit volume of electrode = 1 ft^2 x 0.17 ft = 0.17 ft^3/ft^2

B. Estimated Cost of Electrode Materials
Cost of iron = 0.17 ft^3/ft^2 x 92 lb/ft^3 x 0.5 x \$0.23/lb = \$1.80/ft^2
Cost of coke = 0.17 ft^3/ft^2 x 92 lb/ft^3 x 0.5 x \$0.18/lb = \$1.41/ft^2

Cost of iron rod = [1 ft/^{3} ft^2] x \$2.00/ft = \$0.67/ft^2

C. Unit Cost of Electrode Materials

Unit cost of electrode materials = \$1.80/ft^2 + \$1.41/ft^2 + \$0.67/ft^2 = \$3.88/ft^2

Estimated Treatment Zone Material Cost

Case 1—"Phase 2A" Mix
The following assumptions were made:
- Weight basis of treatment zone = 60% iron: 16% clay: 24% water
- Bulk density of treatment zones = 160 lbs/ft^3
- Cost of Peerless granular iron delivered = \$0.23/lb
- Cost of kaolinite clay delivered = \$0.04/lb
- Thickness of treatment zone = 0.17 ft (2 inches)

A. *Effective Unit Volume of Treatment Zone Mix Required*
Unit volume of treatment zone = 1 ft^2 x 0.17 ft = 0.17 ft^3/ft^2

B. *Estimated Cost of Treatment Zone Materials*

Cost of iron = 0.17 ft^3/ft^2 x 160 lbs/ft^3 x 0.60 x \$0.23/lb = \$3.75/ft^2
Cost of clay = 0.17 ft^3/ft^2 x 160 lbs/ft^3 x 0.16 x \$0.04/lb = \$0.17/ft^2

C. *Unit Cost of Treatment Zone Materials*
Unit cost of treatment zone materials = \$3.75/ft^2 + \$0.17/ft^2 = \$3.92/ft^2

Case 2—Alternate Treatment Zone Mix
The following assumptions were made:
- Weight basis of treatment zone = 30% iron: 22% coke: 19% clay
- Bulk density of treatment zones = 119 lbs/ft^3
- Cost of Peerless granular iron delivered = \$0.23/lb
- Cost of Loresco DW-1 coke delivered = \$0.18/lb
- Cost of kaolinite clay delivered = \$0.04/lb
- Thickness of treatment zone = 0.17 ft (2 inches)

A. *Effective Unit Volume of Treatment Zone Mix Required*
Unit volume of treatment zone = 1 ft^2 x 0.17 ft = 0.17 ft^3/ft^2

B. *Estimated Cost of Treatment Zone Materials*
Cost of iron = 0.17 ft^3/ft^2 x 119 lbs/ft^3 x 0.30 x \$0.23/lb = \$1.40/ft^2
Cost of coke = 0.17 ft^3/ft^2 x 119 lbs/ft^3 x 0.22 x \$0.18/lb = \$0.80/ft^2
Cost of clay = 0.17 ft^3/ft^2 x 119 lbs/ft^3 x 0.19 x \$0.04/lb = \$0.15/ft^2

C. *Unit Cost of Treatment Zone Materials*
Unit cost of treatment zone materials = \$1.40/ft^2 + \$0.80/ft^2 + \$0.15/ft^2 = \$2.35/ft^2

Electrode Unit Cost Summary

Crew Size	Emplacement	Materials	Total
Six person	\$4.47/ft^2	\$3.88/ft^2	\$8.35/ft^2

Treatment Zone Cost Summary

Crew Size	Emplacement	TZ Design Case	Materials	Total
Six person	\$4.47/ ft^2	Phase 2A mix	\$3.92/ ft^2	\$8.39/ ft^2
Six person	\$4.47/ft^2	Alternate mix	\$2.35/ft^2	\$6.82/ft^2

APPENDIX H - *Lasagna*™ 1- and 3-year Cases at 15 and 45 Feet Deep

INPUT PARAMETERS	LASAGNA™ Tremie Tube Installation, 15 ft. Deep, One Year Case			
Remediation Time and Site Dimensions				
Remediation Time	**1**	yr	8760	h
Treatment Depth	15	ft	4.575	m
X (tr length)	210	ft	64.05	m
Y	210	ft	64.05	m
Soil and Contaminant Properties				
No. PV req'd	**2**		2	
σ	0.3	mS cm-1	0.03	S m-1
ke	1.20E-05	cm2V-1s-1	0.00000432	m2V-1h-1
n	0.4	m3/m3	0.4	
Prices and Fixed Costs				
Rectifiers	120	$/kw		
Electricity	0.055	$/kwh	5.50E-05	$/wh
Electrode Mat'l & Install	**$10.14**	$/ft2	109.15	$/m2
TZ Mat'l & Install	**$8.61**	$/ft2	92.56	$/m2
Fixed Costs	$195,000			
O&M Costs	$170,000	per year		
Electrode & Treatment Zone (TZ) Configuration				
No. electrode rows	**5**			
No. TZ per AC	**10**			

CALCULATIONS				
Intermediate Calculations				
No. electrode regions	4			
A-C distance	52.5	ft	16.0	m
TZ distance	4.8	ft	1.5	m
Soil Amount, Total	24,500	yd3	18,768	m3
Soil per elect pair	6,125	yd3	4,692	m3
Soil per TZ	557	yd3	427	m3
Min effl vol reqd per TZ	90,157	gal	341	m3
Cross-sectional area	3,150	ft2	293	m2
Energy and Flowrate				
Flowrate per TZ	247	gal/d	0.93	m3/d
Total Flowrate req'd	9,880	gal/d	37.43	m3/d
Electric field gradient	**30.8**	volt/m		
Current	1,082	amps		
Total Charge Input	9,479,036	amp-hr		
Applied Potential	**493**	volts		
Power	533	kw		
Total E-field energy	4,670,807	kwh		
Costs				
Field Labor	$170,000			
Electricity	$256,894			
Electrodes & Installation	$159,705		Specific Cost	
Treatment zones	$1,084,860			
Rectifiers	$63,984		78.79	$/yd3
Fixed	$195,000		102.86	$/m3
TOTAL	$1,930,443			

INPUT PARAMETERS	LASAGNA™ Tremie Tube Installation, 45 ft. Deep, One Year Case			
Remediation Time and Site Dimensions				
Remediation Time	**1**	yr	8760	h
Treatment Depth	45	ft	13.725	m
X (tr length)	210	ft	64.05	m
Y	210	ft	64.05	m
Soil and Contaminant Properties				
No. PV req'd	**2**		2	
σ	0.3	mS cm-1	0.03	S m-1
ke	1.20E-05	cm2V-1s-1	0.00000432	m2V-1h-1
n	0.4	m3/m3	0.4	
Prices and Fixed Costs				
Rectifiers	120	$/kw		
Electricity	0.055	$/kwh	5.50E-05	$/wh
Electrode Mat'l & Install	**$8.35**	$/ft2	89.88	$/m2
TZ Mat'l & Install	**$6.82**	$/ft2	73.31	$/m2
Fixed Costs	$195,000			
O&M Costs	$170,000	per year		
Electrode & Treatment Zone (TZ) Configuration				
No. electrode rows	**5**			
No. TZ per AC	**10**			

CALCULATIONS				
Intermediate Calculations				
No. electrode regions	4			
A-C distance	52.5	ft	16.0	m
TZ distance	4.8	ft	1.5	m
Soil Amount, Total	73,500	yd3	56,305	m3
Soil per elect pair	18,375	yd3	14,076	m3
Soil per TZ	1,670	yd3	1,280	m3
Min effl vol reqd per TZ	270,472	gal	1,024	m3
Cross-sectional area	9,450	ft2	879	m2
Energy and Flowrate				
Flowrate per TZ	741	gal/d	2.80	m3/d
Total Flowrate req'd	29,641	gal/d	112.28	m3/d
Electric field gradient	**30.8**	volt/m		
Current	3,246	amps		
Total Charge Input	28,437,108	amp-hr		
Applied Potential	**493**	volts		
Power	1,600	kw		
Total E-field energy	14,012,421	kwh		

Costs			
Field Labor	$170,000		
Electricity	$770,683		
Electrodes & Installation	$394,538	Specific Cost	
Treatment zones	$2,577,960		
Rectifiers	$191,951	58.51	$/yd3
Fixed	$195,000	76.37	$/m3
TOTAL	$4,300,132		

INPUT PARAMETERS	LASAGNA™ Tremie Tube Installation, 15 ft. Deep, 3 Year Case			
Remediation Time and Site Dimensions				
Remediation Time	**3**	yr	26280	h
Treatment Depth	15	ft	4.575	m
X (tr length)	210	ft	64.05	m
Y	210	ft	64.05	m
Soil and Contaminant Properties				
No. PV req'd	**2**		2	
σ	0.3	mS cm-1	0.03	S m-1
ke	1.20E-05	cm2V-1s-1	0.00000432	m2V-1h-1
n	0.4	m3/m3	0.4	
Prices and Fixed Costs				
Rectifiers	120	$/kw		
Electricity	0.055	$/kwh	5.50E-05	$/wh
Electrode Mat'l & Install	**$10.14**	$/ft2	109.15	$/m2
TZ Mat'l & Install	**$8.61**	$/ft2	92.56	$/m2
Fixed Costs	$195,000			
O&M Costs	$170,000	per year		
Electrode & Treatment Zone (TZ) Configuration				
No. electrode rows	**4**			
No. TZ per AC	**7**			

CALCULATIONS				
Intermediate Calculations				
No. electrode regions	3			
A-C distance	70.0	ft	21.4	m
TZ distance	8.8	ft	2.7	m
Soil Amount, Total	24,500	yd3	18,768	m3
Soil per elect pair	8,167	yd3	6,256	m3
Soil per TZ	1,021	yd3	782	m3
Min effl vol reqd per TZ	165,288	gal	626	m3
Cross-sectional area	3,150	ft2	293	m2
Energy and Flowrate				
Flowrate per TZ	151	gal/d	0.57	m3/d
Total Flowrate req'd	3,170	gal/d	12.01	m3/d
Electric field gradient	**18.8**	volt/m		
Current	496	amps		
Total Charge Input	13,033,675	amp-hr		
Applied Potential	**402**	volts		
Power	199	kw		
Total E-field energy	5,233,034	kwh		
Costs				
Field Labor	$457,309			
Electricity	$258,081			
Electrodes & Installation	$127,764		Specific Cost	
Treatment zones	$569,552			
Rectifiers	$23,895		66.60	$/yd3
Fixed	$195,000		86.93	$/m3
TOTAL	$1,631,600			

INPUT PARAMETERS	LASAGNA™ Tremie Tube Installation, 45 ft. Deep, 3 Year Case			
Remediation Time and Site Dimensions				
Remediation Time	**3**	yr	26280	h
Treatment Depth	45	ft	13.725	m
X (tr length)	210	ft	64.05	m
Y	210	ft	64.05	m
Soil and Contaminant Properties				
No. PV req'd	**2**		2	
σ	0.3	mS cm-1	0.03	S m-1
ke	1.20E-05	cm2V-1s-1	0.00000432	m2V-1h-1
n	0.4	m3/m3	0.4	
Prices and Fixed Costs				
Rectifiers	120	$/kw		
Electricity	0.055	$/kwh	5.50E-05	$/wh
Electrode Mat'l & Install	**$8.35**	$/ft2	89.88	$/m2
TZ Mat'l & Install	**$6.82**	$/ft2	73.31	$/m2
Fixed Costs	$195,000			
O&M Costs	$170,000	per year		
Electrode & Treatment Zone (TZ) Configuration				
No. electrode rows	**4**			
No. TZ per AC	**7**			

CALCULATIONS				
Intermediate Calculations				
No. electrode regions	3			
A-C distance	70.0	ft	21.4	m
TZ distance	8.8	ft	2.7	m
Soil Amount, Total	73,500	yd3	56,305	m3
Soil per elect pair	24,500	yd3	18,768	m3
Soil per TZ	3,063	yd3	2,346	m3
Min effl vol reqd per TZ	495,865	gal	1,877	m3
Cross-sectional area	9,450	ft2	879	m2
Energy and Flowrate				
Flowrate per TZ	453	gal/d	1.71	m3/d
Total Flowrate req'd	9,510	gal/d	36.02	m3/d
Electric field gradient	**18.8**	volt/m		
Current	1,488	amps		
Total Charge Input	39,101,024	amp-hr		
Applied Potential	**402**	volts		
Power	597	kw		
Total E-field energy	15,699,101	kwh		
Costs				
Field Labor	$457,309			
Electricity	$774,242			
Electrodes & Installation	$315,630		Specific Cost	
Treatment zones	$1,353,429			
Rectifiers	$71,685		43.09	$/yd3
Fixed	$195,000		56.25	$/m3
TOTAL	$3,167,295			

INPUT PARAMETERS	LASAGNA™ DNAPL 2 yr., 4 PV, 15 foot Case			
Remediation Time and Site Dimensions				
Remediation Time	**2**	yr	17520	h
Treatment Depth	15	ft	4.575	m
X (tr length)	210	ft	64.05	m
Y	210	ft	64.05	m
Soil and Contaminant Properties				
No. PV req'd	**4**		4	
σ	0.3	mS cm-1	0.03	S m-1
ke	1.20E-05	cm2V-1s-1	0.00000432	m2V-1h-1
n	0.4	m3/m3	0.4	
Prices and Fixed Costs				
Rectifiers	120	$/kw		
Electricity	0.055	$/kwh	5.50E-05	$/wh
Electrode Mat'l & Install	**$10.14**	$/ft2	109.15	$/m2
TZ Mat'l & Install	**$8.61**	$/ft2	92.56	$/m2
Fixed Costs	$195,000			
Field Labor Cost	$170,000	per year		
Electrode & Treatment Zone (TZ) Configuration				
No. electrode rows	**5**			
No. TZ per AC	**10**			
CALCULATIONS				
Intermediate Calculations				
No. electrode regions	4			
A-C distance	52.5	ft	16.0	m
TZ distance	4.8	ft	1.5	m
Soil Amount, Total	24,500	yd3	18,768	m3
Soil per elect pair	6,125	yd3	4,692	m3
Soil per TZ	557	yd3	427	m3
Min effl vol reqd per TZ	180,315	gal	682	m3
Cross-sectional area	3,150	ft2	293	m2
Energy and Flowrate				
Flowrate per TZ	247	gal/d	0.93	m3/d
Total Flowrate req'd	9,880	gal/d	37.43	m3/d
Electric field gradient	**30.8**	volt/m		
Current	1,082	amps		
Total Charge Input	18,958,072	amp-hr		
Applied Potential	**493**	volts		
Power	533	kw		
Total E-field energy	9,341,614	kwh		
Costs				
Field Labor	$321,786			
Electricity	$486,264			
Electrodes & Installation	$159,705		Specific Cost	
Treatment zones	$1,084,860			
Rectifiers	$63,984		94.35	$/yd3
Fixed	$195,000		123.16	$/m3
TOTAL	$2,311,599			

INPUT PARAMETERS	LASAGNA™ DNAPL 2 yr., 4 PV, 45 foot Case			
Remediation Time and Site Dimensions				
Remediation Time	**2**	yr	17520	h
Treatment Depth	45	ft	13.725	m
X (tr length)	210	ft	64.05	m
Y	210	ft	64.05	m
Soil and Contaminant Properties				
No. PV req'd	**4**		4	
σ	0.3	mS cm-1	0.03	S m-1
ke	1.20E-05	cm2V-1s-1	0.00000432	m2V-1h-1
n	0.4	m3/m3	0.4	
Prices and Fixed Costs				
Rectifiers	120	$/kw		
Electricity	0.055	$/kwh	5.50E-05	$/wh
Electrode Mat'l & Install	**$8.35**	$/ft2	89.88	$/m2
TZ Mat'l & Install	**$6.82**	$/ft2	73.31	$/m2
Fixed Costs	$195,000			
Field Labor Cost	$170,000	per year		
Electrode & Treatment Zone (TZ) Configuration				
No. electrode rows	**5**			
No. TZ per AC	**12**			

CALCULATIONS

Intermediate Calculations				
No. electrode regions	4			
A-C distance	52.5	ft	16.0	m
TZ distance	4.0	ft	1.2	m
Soil Amount, Total	73,500	yd3	56,305	m3
Soil per elect pair	18,375	yd3	14,076	m3
Soil per TZ	1,413	yd3	1,083	m3
Min effl vol reqd per TZ	457,722	gal	1,732	m3
Cross-sectional area	9,450	ft2	879	m2
Energy and Flowrate				
Flowrate per TZ	627	gal/d	2.37	m3/d
Total Flowrate req'd	30,097	gal/d	114.00	m3/d
Electric field gradient	**26.0**	volt/m		
Current	2,747	amps		
Total Charge Input	48,124,337	amp-hr		
Applied Potential	**417**	volts		
Power	1,145	kw		
Total E-field energy	20,065,123	kwh		

Costs		
Field Labor	$321,786	
Electricity	$1,044,461	
Electrodes & Installation	$394,538	Specific Cost
Treatment zones	$3,093,552	
Rectifiers	$137,432	70.57 $/yd3
Fixed	$195,000	92.12 $/m3
TOTAL	$5,186,769	

INPUT PARAMETERS	LASAGNA™ DNAPL 3 yr., 6 PV, 15 foot Case	
Remediation Time and Site Dimensions		
Remediation Time	**3** yr	26280 h
Treatment Depth	15 ft	4.575 m
X (tr length)	210 ft	64.05 m
Y	210 ft	64.05 m
Soil and Contaminant Properties		
No. PV req'd	**6**	6
σ	0.3 mS cm-1	0.03 S m-1
ke	1.20E-05 cm2V-1s-1	0.00000432 m2V-1h-1
n	0.4 m3/m3	0.4
Prices and Fixed Costs		
Rectifiers	120 $/kw	
Electricity	0.055 $/kwh	5.50E-05 $/wh
Electrode Mat'l & Install	**$10.14** $/ft2	109.15 $/m2
TZ Mat'l & Install	**$8.61** $/ft2	92.56 $/m2
Fixed Costs	$195,000	
Field Labor Cost	$170,000 per year	
Electrode & Treatment Zone (TZ) Configuration		
No. electrode rows	**5**	
No. TZ per AC	**11**	

CALCULATIONS		
Intermediate Calculations		
No. electrode regions	4	
A-C distance	52.5 ft	16.0 m
TZ distance	4.4 ft	1.3 m
Soil Amount, Total	24,500 yd3	18,768 m3
Soil per elect pair	6,125 yd3	4,692 m3
Soil per TZ	510 yd3	391 m3
Min effl vol reqd per TZ	247,933 gal	938 m3
Cross-sectional area	3,150 ft2	293 m2
Energy and Flowrate		
Flowrate per TZ	226 gal/d	0.86 m3/d
Total Flowrate req'd	9,963 gal/d	37.74 m3/d
Electric field gradient	**28.2** volt/m	
Current	992 amps	
Total Charge Input	26,067,349 amp-hr	
Applied Potential	**452** volts	
Power	448 kw	
Total E-field energy	11,774,326 kwh	

Costs		
Field Labor	$457,309	
Electricity	$580,682	
Electrodes & Installation	$159,705	Specific Cost
Treatment zones	$1,193,346	
Rectifiers	$53,764	107.75 $/yd3
Fixed	$195,000	140.65 $/m3
TOTAL	$2,639,805	

INPUT PARAMETERS	LASAGNA™ DNAPL 3 yr., 6 PV, 45 foot Case			
Remediation Time and Site Dimensions				
Remediation Time	**3**	yr	26280	h
Treatment Depth	45	ft	13.725	m
X (tr length)	210	ft	64.05	m
Y	210	ft	64.05	m
Soil and Contaminant Properties				
No. PV req'd	**6**		6	
σ	0.3	mS cm-1	0.03	S m-1
ke	1.20E-05	cm2V-1s-1	0.00000432	m2V-1h-1
n	0.4	m3/m3	0.4	
Prices and Fixed Costs				
Rectifiers	120	$/kw		
Electricity	0.055	$/kwh	5.50E-05	$/wh
Electrode Mat'l & Install	**$8.35**	$/ft2	89.88	$/m2
TZ Mat'l & Install	**$6.82**	$/ft2	73.31	$/m2
Fixed Costs	$195,000			
Field Labor Cost	$170,000	per year		
Electrode & Treatment Zone (TZ) Configuration				
No. electrode rows	**5**			
No. TZ per AC	**12**			
CALCULATIONS				
Intermediate Calculations				
No. electrode regions	4			
A-C distance	52.5	ft	16.0	m
TZ distance	4.0	ft	1.2	m
Soil Amount, Total	73,500	yd3	56,305	m3
Soil per elect pair	18,375	yd3	14,076	m3
Soil per TZ	1,413	yd3	1,083	m3
Min effl vol reqd per TZ	686,582	gal	2,599	m3
Cross-sectional area	9,450	ft2	879	m2
Energy and Flowrate				
Flowrate per TZ	627	gal/d	2.37	m3/d
Total Flowrate req'd	30,097	gal/d	114.00	m3/d
Electric field gradient	**26.0**	volt/m		
Current	2,747	amps		
Total Charge Input	72,186,506	amp-hr		
Applied Potential	**417**	volts		
Power	1,145	kw		
Total E-field energy	30,097,685	kwh		
Costs				
Field Labor	$457,309			
Electricity	$1,484,346			
Electrodes & Installation	$394,538		Specific Cost	
Treatment zones	$3,093,552			
Rectifiers	$137,432		78.40	$/yd3
Fixed	$195,000		102.34	$/m3
TOTAL	$5,762,176			

INPUT PARAMETERS	LASAGNA™ DNAPL 6 yr., 12 PV, 15 foot Case			
Remediation Time and Site Dimensions				
Remediation Time	**6**	yr	52560	h
Treatment Depth	15	ft	4.575	m
X (tr length)	210	ft	64.05	m
Y	210	ft	64.05	m
Soil and Contaminant Properties				
No. PV req'd	**12**		12	
σ	0.3	mS cm-1	0.03	S m-1
ke	1.20E-05	cm2V-1s-1	0.00000432	m2V-1h-1
n	0.4	m3/m3	0.4	
Prices and Fixed Costs				
Rectifiers	120	$/kw		
Electricity	0.055	$/kwh	5.50E-05	$/wh
Electrode Mat'l & Install	**$10.14**	$/ft2	109.15	$/m2
TZ Mat'l & Install	**$8.61**	$/ft2	92.56	$/m2
Fixed Costs	$195,000			
Field Labor Cost	$170,000	per year		
Electrode & Treatment Zone (TZ) Configuration				
No. electrode rows	**5**			
No. TZ per AC	**13**			

CALCULATIONS				
Intermediate Calculations				
No. electrode regions	4			
A-C distance	52.5	ft	16.0	m
TZ distance	3.8	ft	1.1	m
Soil Amount, Total	24,500	yd3	18,768	m3
Soil per elect pair	6,125	yd3	4,692	m3
Soil per TZ	438	yd3	335	m3
Min effl vol reqd per TZ	425,027	gal	1,609	m3
Cross-sectional area	3,150	ft2	293	m2
Energy and Flowrate				
Flowrate per TZ	194	gal/d	0.73	m3/d
Total Flowrate req'd	10,092	gal/d	38.23	m3/d
Electric field gradient	**24.2**	volt/m		
Current	850	amps		
Total Charge Input	44,686,884	amp-hr		
Applied Potential	**387**	volts		
Power	329	kw		
Total E-field energy	17,301,050	kwh		
Costs				
Field Labor	$782,812			
Electricity	$730,285		Specific Cost	
Electrodes & Installation	$159,705			
Treatment zones	$1,410,318			
Rectifiers	$39,500		135.41	$/yd3
Fixed	$195,000		176.77	$/m3
TOTAL	$3,317,620			

INPUT PARAMETERS	LASAGNA™ DNAPL 6 yr., 12 PV, 45 foot Case			
Remediation Time and Site Dimensions				
Remediation Time	**6**	yr	52560	h
Treatment Depth	45	ft	13.725	m
X (tr length)	210	ft	64.05	m
Y	210	ft	64.05	m
Soil and Contaminant Properties				
No. PV req'd	**12**		12	
σ	0.3	mS cm-1	0.03	S m-1
ke	1.20E-05	cm2V-1s-1	0.00000432	m2V-1h-1
n	0.4	m3/m3	0.4	
Prices and Fixed Costs				
Rectifiers	120	$/kw		
Electricity	0.055	$/kwh	5.50E-05	$/wh
Electrode Mat'l & Install	**$8.35**	$/ft2	89.88	$/m2
TZ Mat'l & Install	**$6.82**	$/ft2	73.31	$/m2
Fixed Costs	$195,000			
Field Labor Cost	$170,000	per year		
Electrode & Treatment Zone (TZ) Configuration				
No. electrode rows	**5**			
No. TZ per AC	**13**			

CALCULATIONS				
Intermediate Calculations				
No. electrode regions	4			
A-C distance	52.5	ft	16.0	m
TZ distance	3.8	ft	1.1	m
Soil Amount, Total	73,500	yd3	56,305	m3
Soil per elect pair	18,375	yd3	14,076	m3
Soil per TZ	1,313	yd3	1,005	m3
Min effl vol reqd per TZ	1,275,082	gal	4,826	m3
Cross-sectional area	9,450	ft2	879	m2
Energy and Flowrate				
Flowrate per TZ	582	gal/d	2.20	m3/d
Total Flowrate req'd	30,276	gal/d	114.68	m3/d
Electric field gradient	**24.2**	volt/m		
Current	2,551	amps		
Total Charge Input	134,060,653	amp-hr		
Applied Potential	**387**	volts		
Power	988	kw		
Total E-field energy	51,903,150	kwh		

Costs			
Field Labor	$782,812		
Electricity	$2,190,855		
Electrodes & Installation	$394,538	Specific Cost	
Treatment zones	$3,351,348		
Rectifiers	$118,500	95.69	$/yd3
Fixed	$195,000	124.91	$/m3
TOTAL	$7,033,053		

INPUT PARAMETERS	LASAGNA™ DNAPL 12 yr., 24 PV, 15 foot Case			
Remediation Time and Site Dimensions				
Remediation Time	**12**	yr	105120	h
Treatment Depth	15	ft	4.575	m
X (tr length)	210	ft	64.05	m
Y	210	ft	64.05	m
Soil and Contaminant Properties				
No. PV req'd	**24**		24	
σ	0.3	mS cm-1	0.03	S m-1
ke	1.20E-05	cm2V-1s-1	0.00000432	m2V-1h-1
n	0.4	m3/m3	0.4	
Prices and Fixed Costs				
Rectifiers	120	$/kw		
Electricity	0.055	$/kwh	5.50E-05	$/wh
Electrode Mat'l & Install	**$10.14**	$/ft2	109.15	$/m2
TZ Mat'l & Install	**$8.61**	$/ft2	92.56	$/m2
Fixed Costs	$195,000			
Field Labor Cost	$170,000	per year		
Electrode & Treatment Zone (TZ) Configuration				
No. electrode rows	**6**			
No. TZ per AC	**12**			

CALCULATIONS				
Intermediate Calculations				
No. electrode regions	5			
A-C distance	42.0	ft	12.8	m
TZ distance	3.2	ft	1.0	m
Soil Amount, Total	24,500	yd3	18,768	m3
Soil per elect pair	4,900	yd3	3,754	m3
Soil per TZ	377	yd3	289	m3
Min effl vol reqd per TZ	732,355	gal	2,772	m3
Cross-sectional area	3,150	ft2	293	m2
Energy and Flowrate				
Flowrate per TZ	167	gal/d	0.63	m3/d
Total Flowrate req'd	10,032	gal/d	38.00	m3/d
Electric field gradient	**20.8**	volt/m		
Current	916	amps		
Total Charge Input	96,248,674	amp-hr		
Applied Potential	**267**	volts		
Power	244	kw		
Total E-field energy	25,683,357	kwh		
Costs				
Field Labor	$1,179,409			
Electricity	$816,674			
Electrodes & Installation	$191,646		Specific Cost	
Treatment zones	$1,627,290			
Rectifiers	$29,319		164.87	$/yd3
Fixed	$195,000		215.22	$/m3
TOTAL	$4,039,338			

INPUT PARAMETERS	LASAGNA™ DNAPL 12 yr., 24 PV, 45 foot Case			
Remediation Time and Site Dimensions				
Remediation Time	**12**	yr	105120	h
Treatment Depth	45	ft	13.725	m
X (tr length)	210	ft	64.05	m
Y	210	ft	64.05	m
Soil and Contaminant Properties				
No. PV req'd	**24**		24	
σ	0.3	mS cm-1	0.03	S m-1
ke	1.20E-05	cm2V-1s-1	0.00000432	m2V-1h-1
n	0.4	m3/m3	0.4	
Prices and Fixed Costs				
Rectifiers	120	$/kw		
Electricity	0.055	$/kwh	5.50E-05	$/wh
Electrode Mat'l & Install	**$8.35**	$/ft2	89.88	$/m2
TZ Mat'l & Install	**$6.82**	$/ft2	73.31	$/m2
Fixed Costs	$195,000			
Field Labor Cost	$170,000	per year		
Electrode & Treatment Zone (TZ) Configuration				
No. electrode rows	**6**			
No. TZ per AC	**12**			

CALCULATIONS				
Intermediate Calculations				
No. electrode regions	5			
A-C distance	42.0	ft	12.8	m
TZ distance	3.2	ft	1.0	m
Soil Amount, Total	73,500	yd3	56,305	m3
Soil per elect pair	14,700	yd3	11,261	m3
Soil per TZ	1,131	yd3	866	m3
Min effl vol reqd per TZ	2,197,064	gal	8,316	m3
Cross-sectional area	9,450	ft2	879	m2
Energy and Flowrate				
Flowrate per TZ	502	gal/d	1.90	m3/d
Total Flowrate req'd	30,097	gal/d	114.00	m3/d
Electric field gradient	**20.8**	volt/m		
Current	2,747	amps		
Total Charge Input	288,746,022	amp-hr		
Applied Potential	**267**	volts		
Power	733	kw		
Total E-field energy	77,050,072	kwh		
Costs				
Field Labor	$1,179,409			
Electricity	$2,450,022			
Electrodes & Installation	$473,445		Specific Cost	
Treatment zones	$3,866,940			
Rectifiers	$87,957		112.28	$/yd3
Fixed	$195,000		146.57	$/m3
TOTAL	$8,252,772			

INPUT PARAMETERS	LASAGNA™ Tremie Tube Installation, 15 ft. Deep, One Year Case			
Remediation Time and Site Dimensions				
Remediation Time	**1**	yr	8760	h
Treatment Depth	15	ft	4.575	m
X (tr length)	210	ft	64.05	m
Y	210	ft	64.05	m
Soil and Contaminant Properties				
No. PV req'd	**2**		2	
σ	0.3	mS cm-1	0.03	S m-1
ke	1.20E-05	cm2V-1s-1	0.00000432	m2V-1h-1
n	0.4	m3/m3	0.4	
Prices and Fixed Costs				
Rectifiers	120	$/kw		
Electricity	0.055	$/kwh	5.50E-05	$/wh
Electrode Mat'l & Install	**$10.14**	$/ft2	109.15	$/m2
TZ Mat'l & Install	**$8.61**	$/ft2	92.56	$/m2
Fixed Costs	$195,000			
O&M Costs	$170,000	per year		
Electrode & Treatment Zone (TZ) Configuration				
No. electrode rows	**5**			
No. TZ per AC	**10**			

CALCULATIONS				
Intermediate Calculations				
No. electrode regions	4			
A-C distance	52.5	ft	16.0	m
TZ distance	4.8	ft	1.5	m
Soil Amount, Total	24,500	yd3	18,768	m3
Soil per elect pair	6,125	yd3	4,692	m3
Soil per TZ	557	yd3	427	m3
Min effl vol reqd per TZ	90,157	gal	341	m3
Cross-sectional area	3,150	ft2	293	m2
Energy and Flowrate				
Flowrate per TZ	247	gal/d	0.93	m3/d
Total Flowrate req'd	9,880	gal/d	37.43	m3/d
Electric field gradient	**30.8**	volt/m		
Current	1,082	amps		
Total Charge Input	9,479,036	amp-hr		
Applied Potential	**493**	volts		
Power	533	kw		
Total E-field energy	4,670,807	kwh		

Costs		Specific Cost	
Field Labor	$170,000		
Electricity	$256,894		
Electrodes & Installation	$159,705		
Treatment zones	$1,084,860		
Rectifiers	$63,984	78.79	$/yd3
Fixed	$195,000	102.86	$/m3
TOTAL	$1,930,443		

INPUT PARAMETERS	LASAGNA™ Tremie Tube Installation, 45 ft. Deep, One Year Case			
Remediation Time and Site Dimensions				
Remediation Time	**1**	yr	8760	h
Treatment Depth	45	ft	13.725	m
X (tr length)	210	ft	64.05	m
Y	210	ft	64.05	m
Soil and Contaminant Properties				
No. PV req'd	**2**		2	
σ	0.3	mS cm-1	0.03	S m-1
ke	1.20E-05	cm2V-1s-1	0.00000432	m2V-1h-1
n	0.4	m3/m3	0.4	
Prices and Fixed Costs				
Rectifiers	120	$/kw		
Electricity	0.055	$/kwh	5.50E-05	$/wh
Electrode Mat'l & Install	**$8.35**	$/ft2	89.88	$/m2
TZ Mat'l & Install	**$6.82**	$/ft2	73.31	$/m2
Fixed Costs	$195,000			
O&M Costs	$170,000	per year		
Electrode & Treatment Zone (TZ) Configuration				
No. electrode rows	**5**			
No. TZ per AC	**10**			
CALCULATIONS				
Intermediate Calculations				
No. electrode regions	4			
A-C distance	52.5	ft	16.0	m
TZ distance	4.8	ft	1.5	m
Soil Amount, Total	73,500	yd3	56,305	m3
Soil per elect pair	18,375	yd3	14,076	m3
Soil per TZ	1,670	yd3	1,280	m3
Min effl vol reqd per TZ	270,472	gal	1,024	m3
Cross-sectional area	9,450	ft2	879	m2
Energy and Flowrate				
Flowrate per TZ	741	gal/d	2.80	m3/d
Total Flowrate req'd	29,641	gal/d	112.28	m3/d
Electric field gradient	**30.8**	volt/m		
Current	3,246	amps		
Total Charge Input	28,437,108	amp-hr		
Applied Potential	**493**	volts		
Power	1,600	kw		
Total E-field energy	14,012,421	kwh		
Costs				
Field Labor	$170,000			
Electricity	$770,683			
Electrodes & Installation	$394,538		Specific Cost	
Treatment zones	$2,577,960			
Rectifiers	$191,951		58.51	$/yd3
Fixed	$195,000		76.37	$/m3
TOTAL	$4,300,132			

INPUT PARAMETERS	LASAGNA™ Tremie Tube Installation, 15 ft. Deep, 3 Year Case			
Remediation Time and Site Dimensions				
Remediation Time	**3**	yr	26280	h
Treatment Depth	15	ft	4.575	m
X (tr length)	210	ft	64.05	m
Y	210	ft	64.05	m
Soil and Contaminant Properties				
No. PV req'd	**2**		2	
σ	0.3	mS cm-1	0.03	S m-1
ke	1.20E-05	cm2V-1s-1	0.00000432	m2V-1h-1
n	0.4	m3/m3	0.4	
Prices and Fixed Costs				
Rectifiers	120	$/kw		
Electricity	0.055	$/kwh	5.50E-05	$/wh
Electrode Mat'l & Install	**$10.14**	$/ft2	109.15	$/m2
TZ Mat'l & Install	**$8.61**	$/ft2	92.56	$/m2
Fixed Costs	$195,000			
O&M Costs	$170,000	per year		
Electrode & Treatment Zone (TZ) Configuration				
No. electrode rows	**4**			
No. TZ per AC	**7**			

CALCULATIONS				
Intermediate Calculations				
No. electrode regions	3			
A-C distance	70.0	ft	21.4	m
TZ distance	8.8	ft	2.7	m
Soil Amount, Total	24,500	yd3	18,768	m3
Soil per elect pair	8,167	yd3	6,256	m3
Soil per TZ	1,021	yd3	782	m3
Min effl vol reqd per TZ	165,288	gal	626	m3
Cross-sectional area	3,150	ft2	293	m2
Energy and Flowrate				
Flowrate per TZ	151	gal/d	0.57	m3/d
Total Flowrate req'd	3,170	gal/d	12.01	m3/d
Electric field gradient	**18.8**	volt/m		
Current	496	amps		
Total Charge Input	13,033,675	amp-hr		
Applied Potential	**402**	volts		
Power	199	kw		
Total E-field energy	5,233,034	kwh		

Costs		Specific Cost	
Field Labor	$457,309		
Electricity	$258,081		
Electrodes & Installation	$127,764		
Treatment zones	$569,552		
Rectifiers	$23,895	66.60	$/yd3
Fixed	$195,000	86.93	$/m3
TOTAL	$1,631,600		

INPUT PARAMETERS	LASAGNA™ Tremie Tube Installation, 45 ft. Deep, 3 Year Case			
Remediation Time and Site Dimensions				
Remediation Time	**3**	yr	26280	h
Treatment Depth	45	ft	13.725	m
X (tr length)	210	ft	64.05	m
Y	210	ft	64.05	m
Soil and Contaminant Properties				
No. PV req'd	**2**		2	
σ	0.3	mS cm-1	0.03	S m-1
ke	1.20E-05	cm2V-1s-1	0.00000432	m2V-1h-1
n	0.4	m3/m3	0.4	
Prices and Fixed Costs				
Rectifiers	120	$/kw		
Electricity	0.055	$/kwh	5.50E-05	$/wh
Electrode Mat'l & Install	**$8.35**	$/ft2	89.88	$/m2
TZ Mat'l & Install	**$6.82**	$/ft2	73.31	$/m2
Fixed Costs	$195,000			
O&M Costs	$170,000	per year		
Electrode & Treatment Zone (TZ) Configuration				
No. electrode rows	**4**			
No. TZ per AC	**7**			
CALCULATIONS				
Intermediate Calculations				
No. electrode regions	3			
A-C distance	70.0	ft	21.4	m
TZ distance	8.8	ft	2.7	m
Soil Amount, Total	73,500	yd3	56,305	m3
Soil per elect pair	24,500	yd3	18,768	m3
Soil per TZ	3,063	yd3	2,346	m3
Min effl vol reqd per TZ	495,865	gal	1,877	m3
Cross-sectional area	9,450	ft2	879	m2
Energy and Flowrate				
Flowrate per TZ	453	gal/d	1.71	m3/d
Total Flowrate req'd	9,510	gal/d	36.02	m3/d
Electric field gradient	**18.8**	volt/m		
Current	1,488	amps		
Total Charge Input	39,101,024	amp-hr		
Applied Potential	**402**	volts		
Power	597	kw		
Total E-field energy	15,699,101	kwh		
Costs				
Field Labor	$457,309			
Electricity	$774,242			
Electrodes & Installation	$315,630		Specific Cost	
Treatment zones	$1,353,429			
Rectifiers	$71,685		43.09	$/yd3
Fixed	$195,000		56.25	$/m3
TOTAL	$3,167,295			