Development of an Integrated, In-Situ Remediation Technology - Task 1 - Evaluation of Treatment Zone Formation Options

Topical Report

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A. Executive Summary

Development of an Integrated *In Situ* Remediation Technology

DOE Contract Number: DE-AR21-94MC31185

Topical Report for Task #1:

"Evaluation of Treatment Zone Formation Options"

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***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, 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. This topical report presents the results of evaluations by E.I. duPont de Nemours & Co., Inc. of treatment zone and electrode emplacement alternatives for use in the integrated treatment process. Specifically, the scope of this study was limited to vertical configuration emplacements. Several promising alternatives were identified ranging from approaches involving "standard" excavation techniques to relatively specialized geotechnical construction methods which could be modified for the treatment zone emplacement purpose. Information developed in this report is designed to help the user select the most promising emplacement methods(s) for a given site on the basis of (1) depth of emplacement, and (2) restrictions on handling excavated soils. Advantages, disadvantages, and estimated costs are identified for each alternative, and possible bases for improvement and cost reduction through further development are described.*

B. Acronyms and Abbreviations

DOE	Department of Energy
GE	General Electric Company
HDPE	high-density polyethylene
NA	not available
O&M	operating and maintenance
XU, XUS	Dow XUS sorbent (Dow Chemical)

C. Units

cu yd	cubic yard(s)
F, °F	Fahrenheit, degrees Fahrenheit
ft	feet
gal	gallons
hr	hours
in.	inches
K	thousand
kw	kilowatts
KW hr	kilowatt-hour
L	liters
lb, lbs	pound(s)
m	meter
mg	milligrams
MGD	million gallons/day
min	minutes
ml, mL	milliliters
MM	million
mm	millimeters
ppb	parts per billion
ppm	parts per million
ppmw	parts per million by weight
ppmv	parts per million by volume
psi	pounds per square inch
psia	pounds per square inch—absolute
psig	pounds per square inch—gauge
SCF	standard cubic feet
sf	square foot
µg	micrograms
µL	microliters
µm	micrometers

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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 in moving water uniformly through low-permeability soils with very low power consumption.

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 Consortium's activities are being facilitated by Clean Sites, Inc., under a Cooperative Agreement with EPA's Technology Innovation Office. A schematic diagram of the government/industry consortium is shown on the front page of this topical report.

Management Plan

A Management Plan for this project was prepared 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), Martin Marietta Energy Systems (MMES), and the Department of Energy. The DOE Gaseous Diffusion Plant in Paducah, Kentucky, has been chosen as the site for the initial field tests.

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.

In 1994 and 1995, technology development was carried out under the present contract by Monsanto, DuPont, and GE. These studies evaluated various degradation processes and their integration into the overall treatment scheme at bench and pilot scales.

Technical Deliverables

Tables 1 and 2 summarize the 13 technical tasks and the 8 topical reports which will be written describing the results obtained in the technical tasks. These two tables show which organization is primarily responsible for the tasks and for preparing the topical reports. The present topical report summarizes Task #1 - Evaluation of Treatment Zone Formation Options.

Table E-1. List of Tasks and Responsible Company

Task	Company
Task 1 - Evaluation of Treatment Zone Formation Options (5.1.2)	DuPont
Task 2 - Electrokinetic Model Validation and Improvement (6.5)	GE
Task 3 - Design Guidance for Field Experiments (6.6)	GE/DuPont
Task 4 - Analysis of Electrode Geometry and Soil Heterogeneity (6.7)	GE/DuPont
Task 5 - Cost Analysis (7)	Monsanto/DuPont
Task 6 - Lab-Scale Development of Microbial Degradation Process (8.1.2)	DuPont
Task 7 - Lab-Scale Electrokinetic and Microbial Degradation (8.1.6)	Monsanto
Task 8 - Lab-Scale Tests of Lasagna Process Using DOE Paducah Soil (8.1.7)	Monsanto
Task 9 - TCE Degradation Using Non-Biological Methods (8.2.1, 8.2.2.2, 8.2.3.2)	GE/Monsanto
Task 10 - Bench- and Pilot-Scale Tests (9.3)	Monsanto
Task 11 - Establish Contamination Conditions Before and After Tests (10.1.2)	DuPont/MMES
Task 12 - Design and Fabrication of Large-Scale Lasagna Process (12.1, 12.2)	Monsanto/DuPont/Nilex
Task 13 - Large-Scale Field Test of Lasagna Process (12.3, 12.4)	Monsanto/CDM

Table E-2. List of Topical Reports and Responsible Company

Topical Report	Company
Task 1 - Evaluation of Treatment Zone Formation Options	DuPont
Tasks 2 - 4 Electrokinetic Modeling	GE
Task 5 - Cost Analysis	Monsanto
Task 6 - Laboratory-Scale Microbial Degradation	DuPont
Tasks 7, 8, 10 - Bench- and Pilot-Scale Tests of Lasagna Process	Monsanto
Tasks 9 - TCE Degradation Using Non-Biological Methods	GE
Task 11 - Contamination Analysis, Before and After Treatment	Monsanto
Tasks 12 and 13 - Large-Scale Field Test of Lasagna Process	Monsanto

F. Topical Report for Task #1

1.0 INTRODUCTION AND PURPOSE

Contamination in low permeability, clayey soils poses a significant technical challenge to *in situ* remediation efforts. Poor accessibility to the contaminants and difficulty in delivering treatment reagents make traditional, cost-effective *in situ* methods, such as bioremediation and soil vapor extraction, ineffective for clayey soils.

The Lasagna™ process seeks to address these limitations. Lasagna™ is an integrated *in situ* treatment in which established geotechnical methods are used to install degradation zones directly into the contaminated soil, and electro-osmosis is used to move the contaminants to and through these zones to complete the treatment *in situ* (Brodsky and Ho, 1995). Electro-osmosis is a classical civil engineering technique well known for its effectiveness in dewatering low-permeability soils. Conceptually, the integrated technology could treat a range of contaminants, including organics and inorganics.

The general approach of Lasagna™ can be summarized as follows:

- Create treatment zones in close proximity sectioned through the contaminated soil region by emplacing appropriate materials, such as sorbents, catalytic agents, microbes, oxidants, etc., chosen to fit the given contaminant(s). Hydraulic fracturing and related technologies may provide an effective and low-cost means for creating such zones horizontally in the soil. The treatment zones also can be placed in a vertical configuration.
- Use electro-osmosis as a liquid pump for flushing contaminants from the soil into the treatment zones. Since these zones are spaced closely, the time to move contaminants from one zone to the next can be short. In the horizontal configuration, the zones above and below the contaminated soil region can be injected with graphite particles or other conductive material to form electrodes in place. Similarly, vertically oriented electrodes can be installed using standard geotechnical practices such as steel sheet pile installation.
- Reverse liquid flow by switching electrical polarity to effect multiple passes of the contaminants through the treatment zones for complete sorption/destruction. This step also can serve to minimize complications associated with the long-term application of one-directional electro-osmotic processes (e.g., development of osmotic and pH gradients, soil drying, and mineral precipitation).

In the typical application of electro-osmosis, water introduced into the soil at the anode region flows under electro-osmosis through the contaminated soil, flushing the contaminants to the cathode region for extraction and treatment aboveground.

Major advantages for electro-osmosis include (1) uniform flow distribution in a low permeability or heterogeneous soil because flow rate is independent of pore size; (2) controllable flow direction and rates by the placement of electrodes and applied voltage, and (3) relatively low power consumption (Acar et al., 1992; Shapiro, 1990).

Electro-osmotic flow velocities are slow, usually on the order of 2 cm per day or less for most soils under typical voltage gradients. The slow rate limits the practical spacing between anode and cathode, since flow must be driven all the way between electrodes to effect contaminant removal. The electrode spacing affects not only the time required to complete cleanup, but also the power requirements, ultimately, the cleanup cost. Based on an economic model for the electro-osmotic soil flushing process using planar electrode systems developed by Schultz (1996), the cost-optimized electrode spacing, which allows cleanup within a reasonable time frame (e.g., less than five years) while avoiding soil overheating, is on the order of 3 to 6 m for most soils. In addition, Schultz used the model to predict that electrode construction would constitute a significant portion of the overall application cost of the optimized electro-osmosis process, generally on the order of 20 to 40%.

As discussed above, the Lasagna™ process places treatment zones between the electrodes to reduce this electrode spacing limitation. Conceptually, cleanup time and power input are reduced, since contaminants must be transported only between treatment zones, rather than the electrodes. If one assumes that treatment zones can be installed for less cost than electrode systems, a substantial cost benefit may be realized. Whether a horizontal or vertical configuration is chosen, the ability to emplace treatment zones and electrodes in the soil in relatively close spacing and at reasonable cost is critical to the cost effectiveness of the technology.

The purpose of this report is to document DuPont's study of methods for treatment zone emplacement in the vertical Lasagna™ configuration. The focus of this work is to identify and evaluate the most promising alternatives that could be applied with minimum added development effort. Items considered in addition to emplacement method are treatment zone material selection and depth and thickness of emplacement. Costs associated with treatment zone construction are estimated considering depth of emplacement, emplacement technology used, and treatment and electrode media costs. In addition, potential ancillary costs are identified, such as waste soil management costs as an outgrowth of excavation to emplace the treatment zones or electrodes.

Results from this report are used extensively in Topical Report No. 5, which is the evaluation of the overall cost of the Lasagna™ technology. Refer to Report No. 5 for additional discussion of the impact of treatment zone and electrode cost on the overall cost basis of the technology.

2.0 SURVEY OF TREATMENT ZONE EMPLACEMENT TECHNOLOGIES

2.1 Overview

Electrode structures for electro-osmosis generally combine a highly conductive medium such as steel sheet piles, metal mesh, or granular graphite with a channel structure to allow water to flow freely in or out of the ground. For example, a common means of emplacing such electrodes is to bore a hole in the soil, construct a well with screen and casing, and insert the electrode in the well. Alternatively, the hole could be bored, an electrode rod inserted, and a porous fill such as gravel or sand backfilled into the bored hole.

Voltage gradients are established between anode and cathode electrodes by applying direct current (DC) electric voltages to create an electric field in the soil. A noncontaminating purging liquid, such as water, is supplied to the anode so as to flow into the channel and out through the perforated sections into the pores of the contaminated soil region. Contaminants are displaced and moved by the purging liquid, which is pumped through the soil under the influence of the voltage gradient. In some cases, depending on the nature of the contaminant or contaminated liquid, the contaminant may be moved through the pores directly by electromigration or electro-osmosis to the cathode where it is removed with the collected water through the cathode channel.

By controlling the applied DC voltage levels, the number of electrodes, and the depths and spacing of electrodes so as to control the directions and interactions of the voltage gradients, the system can be operated in a manner so as to effect remediation of soils having relatively low hydraulic conductivities such as silts and clays. However, there is a problem with the use of electrode wells in an array pattern of alternating anodes and cathodes. In this type of conventional array, a highly nonuniform electrical field is produced because of unequal current paths between unlike electrodes. This so-called "two-dimensional" field effect was reported by Probst (1994) following observations from laboratory experiments. In such a system, the soil must be treated for a time sufficient to remove the contaminant from the portion of soil having the longest current path. This results in great inefficiencies in electrical power consumed and in the extended time required to treat a given volume of soil. Additionally, heating the soil at less efficient, high currents tends to boil off the water, thereby creating nonconductive regions.

Figure F-1 presents conceptual designs of the horizontal and vertical Lasagna™ processes. Both of these approaches feature planar electrode and treatment zone systems, which represent a significant innovation with respect to electrodes based in wells. Use of planar electrodes provides the most uniform direct current electric field possible in soil. In turn, this provides the most efficient means for moving contaminants where remediation of a large volume of soil is to be accomplished. Similarly, as described in Section 1.0, the placement of treatment zones between the electrode panels provides a means to further reduce the power requirement, since contaminants need not be flushed all the way to the cathode, but only to the closest treatment zone.

The challenge presented in this study is to evaluate the feasibility of and identify the means for constructing vertical planar electrodes and treatment zones for the full-scale application of Lasagna™. As in any remediation technology, cost-effectiveness is the foremost consideration. Treatment zone and electrode construction is expected to be a major cost element in the technology, and could limit its widespread application if cost-effective means are not available. On the other hand, the realities of the remediation marketplace suggest that developing major new equipment trains be avoided if possible in favor of using existing, known methods and machinery. Hence this study is limited to the evaluation of known hardware and geotechnical processes that might be adapted readily to this task with limited further development.

The following section presents a survey of existing technologies that may be adapted to use in the vertical configuration Lasagna™ emplacement effort. Each technology is briefly described, its applicability to the Lasagna™ remediation method is reviewed, and conceptual advantages and along with estimated costs are discussed. It should be noted that the costs developed in this section are budgetary in nature and are appropriate for order of magnitude estimates when comparing options. Factors such as site topography, soil conditions, hydrogeology, accessibility, and site requirements could be important factors in the actual cost of a project.

2.2 Treatment Zone and Electrode Emplacement Technologies

Various methods for emplacing granular material based treatment zones and electrodes in a vertical orientation are discussed in this section. While many methods for emplacing materials in the subsurface are available, the focus herein is on approaches consistent with Lasagna's need for relatively thin, vertical planar systems. Among the various approaches evaluated are:

- o Mandrel-based technology (used to emplace wick drains),
- o High pressure jetting,
- o Vibrating beam technology,
- o Standard excavation methods, and

- o Specialized trenching methods.

For each method, the emplacement process is reviewed along with capabilities, limitations, advantages and disadvantages with respect to Lasagna applications, and experience to date. Estimated costs for typical Lasagna applications are developed. The discussion is not intended to be an exhaustive review of all possible emplacement approaches, but rather to reflect the state-of-the-art as currently applied or considered for near-term applications.

2.2.1 Mandrel-Based Technology

Mandrel-based emplacement using a static or vibratory driving technique is commonly used to install wick drains for soil consolidation. The technique is similar to standard techniques used to drive sheet piles with the exception that a tubular steel mandrel is driven into the ground in place of the sheet piling. A typical mandrel for wick drain emplacement has a small cross-sectional area (typical mandrel dimensions are two inches by five inches) which provides sufficient interior sleeve space to insert the standard 4-inch vertical wick drain. The typical rig used in this process includes a modified excavator or crane, a mast similar to that of a drill rig, a vibratory hammer, and a mandrel assembly. The size of the equipment (e.g., mast size, vibratory hammer size, etc.) is selected based on the soil conditions and depth of emplacement. Wick drains have been emplaced to depths up to 190 feet using this technique. However, the depth that can be achieved is a function of the soil density and vibratory hammer size, and cobbles, debris, or other impenetrable materials can cause the mandrel to meet refusal.

2.2.1.1 Emplacement description

Wick drains are used to facilitate soil consolidation. They are constructed by wrapping a permeable geotextile fabric around a spacer material to create a conduit for groundwater to flow to the surface (see Appendix A). A wick drain is installed by inserting it into a steel mandrel; a drive shoe/anchor is attached to the leading edge of the wick drain, and then placed over the leading edge of the mandrel. A vibratory hammer then drives the mandrel into the soil until the desired depth is reached. The drive shoe/anchor prevents soil from entering the mandrel during emplacement and securely anchors the wick drain in the soil at the desired depth. The mandrel is then extracted, leaving the wick drain in place. The wick drain is

then cut off at the ground surface, and the process is repeated at the next location (see Appendix A).

2.2.1.2 Application to Lasagna

To apply the mandrel technique to the Lasagna™ process, DuPont along with Nilex Corporation of Denver, Colorado developed a process to emplace electrode or treatment material in a controlled manner using a large, hollow, rectangular steel mandrel, a heavy-duty anchor/drive shoe, and a large vibratory hammer. The emplacement process begins by placing a heavy-duty drive shoe at the leading edge of the mandrel. The mandrel is then driven into the soil by a large vibratory hammer until the desired depth is reached. At this point, the vibratory hammer is released from the mandrel and raised several feet. The electrode or treatment zone material is then placed into the mandrel; the vibratory hammer is reconnected, and the mandrel is extracted, leaving the electrode or treatment zone material in place. The equipment is then indexed to the next location, and the emplacement process is repeated.

Electrode or treatment zone materials can be emplaced in a controlled manner or loosely to fill the void created by the mandrel. The "controlled emplacement" approach uses geotechnical materials, such as wick drains, geomembranes, and geotextiles. For example, with wick drains, the treatment zone can be created by pouring the material into a wick drain of appropriate thickness and sealing it, resulting in a treatment zone up to one inch thick. For an electrode assembly, the treatment zone is incorporated with the electrode material; if needed, a geomembrane insulating panel can be added. The entire structure can then be covered by a geotextile wrapping to hold everything together. These treatment zone or electrode assemblies can then be placed into the mandrel, and the mandrel is extracted, leaving the materials in place.

Lasagna Phase I Field Test Emplacement

This Mandrel-based "controlled emplacement" approach was used to install the treatment zones and electrodes in the Phase I field pilot test at the DOE Paducah Site. In the Phase I pilot test, two 15 foot long electrode rows were emplaced 10 feet apart to a depth of 15 feet. Four rows of treatment zones were emplaced equally spaced between the electrode panels. A specially designed mandrel was fabricated with outside dimensions of four inches by 21 inches and inside dimensions of three inches by 20 inches. The treatment zone material in

this case was granular activated carbon contained within an 18-inch wide wick drain (Appendix A). The electrode assemblies included a carbon filled wick drain treatment zone, an 18-inch wide by 1/4-inch thick steel plate, a second 18 inch wide by 1/4-inch wick drain, and a high density polyethylene geomembrane insulating barrier all wrapped with a geosynthetic filter fabric (Appendix A). The treatment zone panels were staggered and their edges overlapped a few inches so as to approximate a continuous wall treatment zone. Similarly, the electrode panels were emplaced with their edges end to end with a slight separation to form a planar electrode system. The Phase I layout plan view is shown in Appendix A.

Phase I emplacement work was performed by Nilex Corporation. The equipment used was a Caterpillar 235C excavator equipped to convert the excavator's hydraulic system for the bucket to raise and lower the mandrel by a Nilex-designed drive system. The total weight of the Caterpillar 235C with the Nilex drive system is roughly 50 tons. The mast was constructed of a conventional three sided lattice style box lead with outside dimensions of 44 inches by 52 inches, fabricated by Nilex and constructed of steel square tubing. The vibratory hammer used in this project was an American Pile-Driving Equipment, Inc. Model 150 unit sized to accommodate soils with relative density up to blow counts of 20 (as measured by the standard penetration test).

Note that the size (and relative cost) of equipment used in this work is sensitive to the depth of emplacement. For example, it is anticipated that a larger excavator such as a Caterpillar 375L would be used to operate the larger mast/mandrel/hammer system needed to achieve a 45-foot emplacement depth. A crane typically would be used for substantially greater depths.

"Tremie Tube" Approach

If a loose emplacement approach is sufficient or more cost effective, the treatment materials can simply be poured or pumped into the mandrel after it is driven into the ground. This technique has been termed the "tremie tube" method. As the mandrel is extracted, the treatment zone materials fill the void created in the soil by the mandrel. To emplace electrodes in a loose manner, electrode material (and if needed, geomembrane material) is placed into the mandrel, and the remaining volume is filled with treatment zone material or filler material. Again, as the mandrel is extracted, the

electrode, geomembrane, and treatment zone materials fill the created void in the soil.

At this stage of development, it is expected that electrode and treatment zone materials may consist of a mixture of ingredients such as granular iron, coke, and/or clay, which would be mixed on site and pumped as a slurry down the mandrel. However, materials might also be mixed in dry form and backfilled by gravity feed into the mandrel using a number of methods (e.g., conveyor belt, auger tube, or front end loader).

The "tremie tube" method has been proposed for a planned Phase II Lasagna field test at the Paducah site in 1996.

2.2.1.3 Advantages

The main advantage of mandrel-based technology is that virtually no excess soil is generated during the emplacement process. Another significant advantage is that no soil is brought to the surface and no open excavations are formed, thereby greatly reducing the potential worker exposure to contaminants. At sites where the contaminants dictate expensive disposal protocols and high levels of personal protection equipment, or at sites with an aggressive waste minimization philosophy, this technique may be highly desirable. Finally the ability to emplace relatively thin treatment zones and electrode systems to great depths under the right conditions is gained from this method.

2.2.1.4 Disadvantages

A potential disadvantage of the mandrel emplacement technique is that soil conditions must be conducive to driving the mandrel. If the target area contains cobbles, debris, or other impenetrable materials, the mandrel could be pushed off its intended path or meet refusal.

2.2.1.5 Economics

Mandrel-Based "Controlled Emplacement"

The unit costs for the Phase I field test using the mandrel-based emplacement equipment, including a Caterpillar 235C and labor expenses for the controlled material emplacement methodology in less than 25 blowcount soil formations (measured by the standard penetration test) without

underground or overhead obstructions or other complicating factors, are estimated as follows:

o Emplacement of materials:

- \$2.25/ft² including per diem and local rental of a Caterpillar 235C, but not including mobilization and demobilization of support equipment which is estimated at \$20,000.
- *Assuming Caterpillar rental rate of \$12,000 per month and 50 mandrel emplacements per day 15 feet deep.*
- \$3.50/ft² including per diem and local rental of a Caterpillar 375L, but not including mobilization and demobilization of support equipment which is estimated at \$20,000.
- *Assuming a Caterpillar rental rate of \$18,000 per month and 18 mandrel emplacements per day 45 feet deep.*

The unit cost of Phase I field test materials emplaced using the mandrel-based "controlled" method are estimated as follows:

o *In situ* treatment zone materials:

- \$10.14/ft² including a 1-inch wick drain filled with granular activated carbon.
- *Assumptions include using a 1-inch wick drain at \$0.60/ft² filled with granular activated carbon with a bulk density of 27 lb/ft³, a filling efficiency of 70% (the approximate percent open space within the wick drain), and a cost of granular activated carbon at \$1.17/lb resulting in a unit cost of \$1.84/ft², and \$7.70/ft² of labor to fabricate the assembly.*
- \$10.63/ft² including a 1-inch wick drain filled with 100% granular iron.
- *Assumptions include using a 1-inch wick drain at \$0.60/ft² filled with granular iron with a bulk density of 200lb/ft³, a filling efficiency of 70%, a cost for granular iron at \$400/ton resulting in a unit cost of \$2.33/ft², and \$7.70/ft² of labor for fabrication/loading.*

o Electrode zone materials:

- \$16.23/ft² including a 1-inch wick drain filled with granular activated carbon, 1/4 inch carbon steel plate electrode, a 1/4 inch wick drain, and an HDPE insulating panel.
- *Assumptions include using a 1-inch wick drain filled with activated carbon at a unit cost of \$10.14/ft², (see above) a 1/4-inch steel plate electrode at a unit cost of \$5.00/ft², a 0.060-inch HDPE geomembrane insulating panel at \$0.18/ft², a 1/4-in. wick drain at 0.42/ft², and \$0.49 additional labor.*
- \$16.72/ft² including a 1-inch wick drain filled with granular iron, 1/4 inch carbon steel plate electrode, a 1/4 inch wick drain, and an HDPE insulating panel.
- *Assumptions include using a 1-inch wick drain filled with granular iron at a unit cost of \$10.63/ft², a 1/4-in. steel plate electrode at a unit cost of \$5.00/ft², a 0.060-inch HDPE geomembrane insulating panel at \$0.18/ft², a 1/4-inch wick drain at 0.42/ft², and \$0.49 additional labor.*

Mandrel-Based "Tremie Tube" Emplacement

The unit cost for emplacement using mandrel-based equipment, including a Caterpillar 235C and labor expenses for the "tremie tube" method in less than 25 blowcount soil formations without underground or overhead obstructions or other complicating factors, are estimated as follows:

o Emplacement of materials:

- \$6.67/ft² including local rental of a Caterpillar 235C, but not including mobilization and demobilization of support equipment or the additional slurry mixing system that pump the slurries for the in-situ treatment zone and electrode materials to the mandrel which is estimated at \$45,000.
- *Assuming a Caterpillar 235C rental rate of \$12,000 per month and 50 mandrel emplacements per day 15 feet deep.*
- \$7.85/ft² including local rental of a Caterpillar 375L, but not including mobilization and demobilization of support

equipment or the additional slurry mixing system, that pump the slurries for the in-situ treatment zone and electrode materials to the mandrel which is estimated at \$45,000.

- *Assuming a Caterpillar 375L rental rate of \$18,000 per month and 18 mandrel emplacements per day 45 feet deep.*

The above estimated costs for the "tremie tube" emplacement method are relatively conservative and with further development could be reduced by an estimated unit cost of \$2/ft² to \$3/ft².

More materials are used with the "tremie tube" emplacement technique than the controlled emplacement technique since the mandrel creates a void that is roughly two inches wide versus the one inch for the "controlled" wick drain approach. However, the "tremie tube" emplacement technique eliminates the high labor cost associated with filling the wick drains and the cost of the wick drains themselves. The unit cost of materials only to fill the cavity left by the mandrel with a slurry are as follows:

o *In situ treatment zone materials:*

- \$5.45/ft² for granular activated carbon only (100% by volume).
- *Assuming a 2-inch wide treatment zone, granular activated carbon with a bulk density of 27 lb/ft³, a cost of granular activated carbon at \$1.17/lb and a maximum slurry density of 120 lb/ft³ of granular material which results in a unit cost of \$5.27/ft² for granular activated carbon, and using a guar gum carrier fluid costing \$3.50/lb and using 40lb/1000 gallons of carrier fluid which results in a unit cost of \$0.18/ft².*
- \$4.18/ft² for granular iron only (100% by volume).
- *Assuming a 2-inch wide treatment zone, granular iron with a bulk density of 200 lb/ft³, a cost of granular iron of \$400/ton, and a maximum slurry density of 120 lb/ft³ of granular material which results in a unit*

cost of \$4.00/ft² for granular iron and, with the guar gum carrier fluid unit cost of \$0.18/ft².

- \$1.56/ft² for a 20% granular iron/80% sand mixture (volume %).

- *Assuming a 2-inch wide treatment zone, granular iron with a bulk density of 200lb/ft³, a cost of granular iron of \$400/ton, sand at a bulk density of 110 lb/ft³, a cost of sand of \$20/ton, and a maximum slurry density of 120 lb/ft³ of granular material. This results in a slurry mixture of 37.5 lb/ft³ of granular iron for a unit cost \$1.25/ft² and 82.5 lb/ft³ of sand for a unit cost of \$0.14/ft² with the guar gum carrier fluid unit cost of \$0.18/ft².*

- \$1.66/ft² for a 20% granular iron/80% clay mixture (volume %).

- *Assuming a 2-inch wide treatment zone, using a unit cost for the granular iron of \$1.25/ft², clay at a bulk density of 110 lb/ft³, a cost of clay of \$60/ton, and a maximum slurry density of 120 lb/ft³ of granular material. This results in a slurry mixture of 37.5 lb/ft³ of granular iron and 82.5 lb/ft³ of clay for a unit cost of \$0.41/ft².*

o Electrode materials:

- \$4.18/ft² for granular iron only.

- *Assuming a 2-inch wide electrode, granular iron with a bulk density of 200 lb/ft³, a cost of granular iron of \$400/ton, and a maximum slurry density of 120 lb/ft³ of granular material which results in a unit cost of \$4.00/ft² along with the guar gum carrier fluid unit cost of \$0.18/ft².*

- \$9.82/ft² for a 80% granular iron/20% granular activated carbon mixture (volume %) with a 1/4-inch carbon steel plate added as a primary electrode in each mandrel run.

-Assuming a 2-inch wide electrode, granular iron with a bulk density of 200lb/ft³, a cost of granular iron of \$400/ton, granular activated carbon at a bulk density of 27.5 lb/ft³, a cost of carbon of \$1.17/lb, and a maximum slurry density of 120

lb/ft³ of granular material. This results in a slurry mixture of 116 lb/ft³ of granular iron for a unit cost \$3.87/ft² and 4 lb/ft³ of carbon for a unit cost of \$0.78/ft², a guar gum carrier fluid unit cost of \$0.18/ft², and a steel plate electrode unit cost of \$5.00/ft².

- \$4.97 for a 80% granular iron/20% granular activated carbon mixture (volume %) with a 1-inch diameter carbon steel rod added as a primary electrode in each mandrel run.
- *Assuming a 2-inch wide electrode, using a granular iron unit cost of \$3.87/ft², a granular activated carbon unit cost of \$0.78/ft², a guar gum carrier fluid unit cost of \$0.18/ft², and a 1-inch diameter carbon steel rod unit cost of \$0.15/ft².*
- \$8.07/ft² for a 80% iron/20% carbon mixture (volume %) with iridium oxide-coated titanium mesh added in each mandrel run to serve as a primary electrode.
- *Assuming a 2-inch wide electrode, using a granular iron unit cost of \$3.87/ft², a granular activated carbon unit cost of \$0.78/ft², a guar gum carrier fluid unit cost of \$0.18/ft², and an iridium oxide coated titanium mesh unit cost of \$3.25/ft².*

Refer to spreadsheets in Appendix F for further cost details.

2.2.2 High-Pressure Jetting

2.2.2.1 Emplacement description

High-pressure jetting uses a high-pressure stream of fluid to cut soil. The process begins by drilling into the soil to the desired depth. Once at depth, the jetting system is activated. The high pressure of the system causes a valve near the tip of the drill string to close. Once this valve is closed, a high-pressure stream of grouting fluid exits from the jetting nozzle above the tip of the drill string. After grouting has begun, the drill string is slowly extracted from the borehole (see Appendix B).

Various jetting nozzle orientations and quantities are commonly used in construction. The 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.

There are three types of high-pressure jetting systems: single, double, or triple fluid. Depending on which is used, the cutting fluid will be either the desired grout or water (see Appendix B). For single and double high-pressure jetting systems, the cutting fluid is the grout. The difference between the single and double system is that the double-fluid system uses a sheath of air around the grout jet stream to increase the depth of cut into the formation. A triple-fluid system is similar to a double-fluid system except water is the cutting fluid, and the grout is injected through a third low-pressure port nearer the bottom of the drill string. With the single-fluid system, depending upon the soil type, roughly 30% of the grouted volume comes to the surface as excess material. With the double- and triple-fluid systems, 70 to 90% of the grouted volume comes to the surface as excess, depending upon the soil type.

High-pressure jetting typically creates two types of emplacements. The most common is a cylindrical shape created by slowly rotating and extracting the drill string during the jetting process (see Appendix B). The other type produces thin diaphragm walls which are created by slowly extracting the drill without rotation during the jetting process.

The diameter of the cylindrical shapes and the length of the thin diaphragm walls range from three feet for the single-fluid system to 10 feet for the triple-fluid system, depending on the soil type. For typical sandy soils, the thickness of the thin diaphragm wall ranges from up to six inches near the drill string to roughly 18 inches at length, depending on soil type. The formation also impacts the depth of penetration of the particular jetting system. Clayey formations tend to reduce depth of penetration, whereas a sandy soil tends to maximize the depth of penetration. Clayey formations also tend to reduce the thickness of the thin diaphragm walls versus sandy formations, which are more easily eroded by the high-pressure jet stream, such that thickness' on the order of four inches are believed feasible for clay.

This technology can be used for emplacement to depths well over 100 ft and can be used to selectively grout specific zones in the geology. It can also be performed in a nonvertical orientation to grout beneath buildings or other obstructions. Further, high-pressure jetting can be done near underground

obstructions, thereby incorporating the obstruction into the grouted area.

High pressure jetting has been used extensively for grouting and other soil stabilization applications throughout Europe and Asia for over 20 years. In recent years, it has become more widely recognized and used in North America.

2.2.2.2 Application to Lasagna

Applying the high-pressure jetting technique to a Lasagna process requires that the electrode or treatment zone material be incorporated into a slurry that can be pumped through the high-pressure jet grouting system. For an electrode, possibly a conductive material like graphite, coke, or iron filings could be slurried and high-pressure jetted using the cylindrical column or thin diaphragm wall technique. For a treatment zone, any reagent material like iron filings, activated carbon, or biological nutrients that can be slurried is a candidate for high-pressure jetting. The particulate material must be less than 50 mesh to pass through the jetting nozzles.

Use of this technique for the Lasagna remediation process is still in the development stage; however, high-pressure jetting is not a new technology. The petroleum industry uses high-pressure jetting of granular materials to improve production performance from a reservoir by cutting through the casing and penetrating into the formation. With some development regarding handling of the new slurry mixtures, high-pressure grouting may have great potential in the Lasagna remediation process.

2.2.2.3 Advantages

An advantage of high-pressure jetting is that it can be used in a variety of soils, including soils with obstructions such as utilities, cobbles, or debris. Obstructions will tend to be incorporated into the grouted target volume. It is regarded as the least soil type dependent of all soil improvement techniques as the high jet pressures can penetrate almost any soil.

2.2.2.4 Disadvantages

A disadvantage to the high-pressure jetting technique is that, short of conducting a pilot test, it is difficult to predict the depth of penetration of a thin diaphragm wall or the diameter of a jetted column. There are no proven analysis techniques

available to predict performance, thus a "design as you go" methodology is used currently. Further, it is difficult to predict the amount of soil and grout that may be exhausted to the surface. For estimating purposes for a clayey soil, it is assumed that 100% of the grouted zone is exhausted to the surface and may require disposal. All of these factors can greatly influence the unit cost of this emplacement technique.

2.2.2.5 Economics

The unit cost for dual fluid jetting equipment and labor expenses in less than 25 blowcount soil formations without underground or overhead obstructions or other complicating factors are estimated to range from about \$2.44/ft² to \$3.37/ft² for emplacements to a nominal depth of 45 feet. Details are as follows:

- o \$2.44/ft² including per diem, but not including mobilization and demobilization, which is estimated at \$45,000.
 - *Assuming an equipment and labor rate of \$7000/day and a productivity of 3150 ft² of grouted area per day, (70 feet long by 45 feet deep, seven grouting locations per day, 31,500 gal/zone, 50 gpm, 45 minutes/location).*
- o \$3.37/ft² including per diem, but not including mobilization and demobilization, which is estimated at \$45,000.
 - *Assuming an equipment and labor rate of \$7000/day and a productivity of 1890 ft² of grouted area per day, (42 feet long by 45 feet deep, seven grouting locations per day, 52,500 gal/zone, 50 gpm, 45 minutes/location).*

The unit cost of materials emplaced by the jetting technique assuming a flow volume of 31,500 gallons per zone (210 ft long by 45 ft deep) of a guar gum based slurry, boreholes on 10-ft centers, and an average zone thickness of four inches are estimated as follows:

- o In situ treatment zone materials:
 - \$11.13/ft² for 100% granular iron.
 - *Assuming a slurry volume of 31,500 gallons per treatment zone (210 feet long by 45 feet deep), granular iron with a bulk density of 200 lb/ft³, a cost of granular iron of \$400/ton, and a maximum slurry density of 16 lb/gal of granular material which*

results in a unit cost of \$10.67/ft² for granular iron, and a guar gum carrier fluid costing \$3.50/lb and using 40 lb/1000 gallons of carrier fluid which results in a unit cost of \$0.47/ft².

- \$4.17/ft² for a 20% granular iron/80% sand mixture (volume percent).

- *Assuming a slurry volume of 31,500 gallons per treatment zone (210 feet long by 45 feet deep), granular iron with a bulk density of 200 lb/ft³, a cost of granular iron of \$400/ton, sand at a bulk density of 110 lb/ft³, a cost of sand of \$20/ton, and a maximum slurry density of 16 lb/gal of granular material. This results in a slurry mixture of 5 lb/gal of granular iron for a unit cost of \$3.33/ft² and 11 lb/gal of sand for a unit cost of \$0.25/ft² and a guar gum carrier fluid unit cost of \$0.47/ft².*

- \$4.43/ft² for a 20% iron/80% clay mixture (volume percent).

- *Assuming a slurry volume of 31,500 gallons per treatment zone (210 feet long by 45 feet deep), a clay bulk density of 110 lb/ft³, a cost of clay of \$60/ton, and a maximum slurry density of 16 lb/gal of granular material. This results in a slurry mixture of 5 lb/gal of granular iron for a unit cost of \$3.33/ft² and 11 lb/gal of clay for a unit cost of \$1.10/ft².*

o Electrode zone materials:

- \$11.28/ft² for 100% granular iron including a 1-inch diameter carbon-steel rod electrode.

- *Assuming a granular iron unit cost of \$10.67/ft², a guar gum carrier fluid unit cost of \$0.47/ft², and a unit cost of \$0.15/ft² for a 1-inch diameter carbon steel rod electrode.*

- 12.90/ft² for a 80% granular iron/20% granular activated carbon mixture (volume %) including a 1-inch diameter carbon steel rod electrode.

- *Assuming a slurry volume of 31,500 gallons per treatment zone (210 feet long by 45 feet deep), a cost*

of granular activated carbon of \$1.17/lb, granular activated carbon with a bulk density of 27lb/ft³, and a maximum slurry density of 16 lb/gal of granular material. This results in a slurry mixture of 15.5 lb/gal of granular iron for a unit cost of \$10.33/ft² and 0.5 lb/gal of granular activated carbon for a unit cost of \$1.95/ft², a guar gum carrier fluid unit cost of \$0.47/ft², and a unit cost of \$0.15/ft² for a 1-inch diameter carbon steel rod electrode.

The above estimated emplacement and materials costs are optimized, and actual field costs could be higher. Refining these costs will require further "proof of principle" field experimentation and cost analysis. Refer to spreadsheets in Appendix F for further cost details.

2.2.3 Vibrating Beam

2.2.3.1 Emplacement description

Vibrating beam technology consists of an "I" beam type of structure with a long, slender "web" member and small "flange" members perpendicular to the web (see Appendix C). On the leading edge of the beam, a permanent drive shoe is attached that is at least as wide as the desired trench (typically less than six inch) and roughly one foot longer than the trench on the trailing edge of the beam (see Appendix C). High-pressure jetting nozzles, located along the leading edge of the drive shoe, inject an appropriate slurry (e.g., cement slurry, cement-bentonite slurry). The high-pressure jetting system is then activated, and a vibratory hammer drives the beam into the soil until the drive shoe reaches the desired depth, at which point the beam is extracted and the injected slurry stabilizes the walls of the trench. The beam is then indexed to the next location; however, the trailing edge of the drive shoe overlaps roughly one foot into the previous location to help ensure trench continuity. This is a somewhat common emplacement technique for interlocking geomembranes for lateral containment of hazardous waste sites.

2.2.3.2 Application to Lasagna

To apply the vibrating beam technique to a Lasagna process, a sufficiently long and deep trench is created by the vibrating beam and stabilized with the slurry. Either electrode or treatment zone material is then placed into the trench. As with the mandrel technique, electrode or treatment zone materials can be emplaced in a controlled manner or loosely to fill the

entire trench. The controlled emplacement approaches are similar to those used in the mandrel-based emplacement technique (see section 2.2.1.2) or material can be injected directly by the jetting nozzles while the vibrating beam is being driven and extracted.

2.2.3.3 Advantages

As with the mandrel technique, the main advantage of this technology is that little to no excess soil is created during emplacement, and worker exposure to the contaminants is minimized or eliminated. At sites where the contaminants dictate expensive disposal protocols or at sites with an aggressive waste minimization philosophy, this technique may be highly desirable.

As with standard excavations, the vibrating beam technique allows the electrode or treatment materials to be placed into the trench in a continuous manner. Panels can also be placed edge to edge, with a gap between panels, or overlapped at their edges. In addition, a relatively thin treatment zone or electrode panel can be emplaced to significant depths.

2.2.3.4 Disadvantages

As with the mandrel technique, a potential disadvantage of this technique is that soil conditions must be conducive to driving the vibrating beam. If the target area contains cobbles, debris, or other impenetrable materials, the vibrating beam could meet refusal. Further, emplacement accuracy may be of some concern since the drive shoe can encounter debris, cobbles, etc., which could push the beam off its intended path.

2.2.3.5 Economics

The vibrating beam methodology is very similar to the mandrel technique; however, an appropriate slurry must be used to hold the trench open. The unit cost for the vibrating beam and slurry handling equipment, including labor in less than 25 blowcount soil formations without underground or overhead obstructions or other complicating factors, is estimated as follows:

- o Emplacement of materials:

- \$6.67/ft² not including mobilization or demobilization costs, which are estimated at \$45,000.

- *The emplacement cost for the vibrating beam approach will be very similar in cost to the mandrel method using the "tremie tube" approach.*

The unit cost of materials emplaced for the vibrating beam "controlled" emplacement method are similar to that of the mandrel-based "controlled" technique used in the Phase I field test, (refer to section 2.2.1.5 for details). As with the mandrel-based "tremie tube" approach, more materials are used with the "loose" method since the entire trench is filled with materials. The estimated unit costs to fill the cavity left by the vibrating beam are similar to those of the tremie tube scenario; refer to section 2.2.1.5. Alternatively and more realistically, the materials could be injected directly into the trench while the vibrating beam is being driven; some excess grout would exhaust to the surface as with the high-pressure jetting technology. The estimated unit costs to "jet in" the vibrating beam and fill the void with slurry are similar to those of the high pressure jetting scenario; refer to section 2.2.2.5 or 2.2.2.5 for details.

Refer to the spreadsheets contained in Appendix F for further cost details.

2.2.4 Excavators

2.2.4.1 Emplacement description

Two types of excavators are generally found in construction: a track-based hydraulic excavator and a "front-end loader" with a backhoe (see Appendix D). These devices are common and usually readily available from local contractors or equipment rental agencies.

Both devices have an articulate arm capable of digging pits or trenches. Standard larger excavators can dig a trench roughly 35 feet deep, with modified versions being capable of excavating to a depth of 70 feet. Trench widths range from one foot for small excavators to about three feet for the larger devices. Front-end loaders/backhoes typically excavate to shallow depths of about 12 feet and widths of about 16 inches. To stabilize the walls of the trench during excavation, a shallow trench can be physically braced (shored). If shoring is used, the area may need to be dewatered if the trench is into groundwater. Deeper excavations are typically filled with an appropriate slurry (e.g., bentonite slurry, cement slurry, or cement-bentonite slurry) to stabilize the walls. If a slurry is used, engineering controls usually are needed to manage the

overflow, and the site must be relatively level to prevent the slurry from flowing downgrade.

2.2.4.2 Application to Lasagna

To use excavation in a Lasagna remediation application, a sufficiently long trench would be excavated to the desired depth. Electrode or treatment zone material is then emplaced into the open, shored, or slurry-filled trench.

Electrode or treatment zone material can be emplaced in an excavated trench in a controlled manner or loosely to fill the entire trench. In the controlled approach, geotechnical materials, such as wick drains, geomembranes, and geotextiles, would be used. For example, with wick drains, the treatment zone could be created by pouring the material into a wickdrain of appropriate thickness and sealed, resulting in a treatment zone up to one inch thick (refer to Appendix A). For an electrode assembly, the treatment zone is incorporated with the electrode material. If needed, a geomembrane insulating panel can be added, and the entire structure covered by a geotextile wrapping to hold everything together). These treatment zone or electrode assemblies are then placed into the trench, and the trench is backfilled if necessary.

If a loose emplacement approach is sufficient or more cost effective, the treatment zone materials can simply be poured or pumped directly into the excavated trench. To emplace electrodes, the electrode assembly is lowered into the trench, and the remaining volume of the trench may be filled with treatment zone material or soil backfill.

Either the controlled or loose methodology can be used to emplace Lasagna materials into a slurry-filled trench. However, if a cementitious slurry is used, it would set up, thus eliminating the need to backfill the entire trench to stabilize the walls.

2.2.4.3 Advantages

Using an excavator has several advantages, such as availability of equipment, capability to dig in a variety of soils, and extensive experience digging with or without a slurry to stabilize the trench. Further, excavators have been used extensively to emplace slurry walls for civil and environmental applications to depths well over 45 feet. In addition, because the excavation allows the operation to be

easily controlled, electrodes and treatment zone material can be accurately positioned. The electrode materials can be placed in a continuous manner, or panels can be placed edge to edge, with a gap between panels, or lapped at the edges.

2.2.4.4 Disadvantages

A disadvantage with the excavator technique is that the minimum width of the trench is necessarily a function of the depth of the trench. If a deep trench is desired, the boom and stick must be fairly wide to withstand the digging forces. The bucket needs to be wider than the boom and stick, resulting in a fairly wide trench (bucket widths are typically around two feet to over 3 feet). For trenches less than about 10 feet deep, a trench width of roughly one foot can be excavated. For application to Lasagna remediation process, the thinnest bucket width generally would be most desirable to avoid disturbing a significant percentage of soil because of closely spaced treatment zones. However, to excavate to a depth of 45 feet, a bucket width of roughly three feet will be required.

Another disadvantage of standard excavation is that a lot of soil is brought to the surface, which may require disposal, or a special allowance may be needed to put the soil back into the trench. If the soil cannot be returned to the trench, new, clean soils must be secured for backfilling the trench, or excessive treatment zone materials may be consumed. This issue could make the cost of using an excavator prohibitive. Further, the slurry used to stabilize deeper trench excavations may require disposal, which also could increase the cost.

Worker exposure is another potential disadvantage. Excavating the soil creates a large amount of surface area, and if the contaminants are highly volatile, higher levels of personal protection equipment may be required. This may reduce productivity, which also could increase the cost.

2.2.4.5 Economics

Using an excavator is typically the quickest way to create a trench up to depths of roughly 70 feet. Beyond that depth, clamshell devices, draglines, or hydromills can be used; however, these devices are not as productive as an excavator.

Excavators are readily available around the country from equipment rental agencies, and mobilization/demobilization typically is not a big cost factor. For larger excavators, to

trench deeper than roughly 50 feet, mobilization could be a significant cost, depending on the size and mobilization distance.

Using an excavator to emplace treatment zones and electrodes to a nominal depth of 45 feet would probably require an appropriate slurry to stabilize the trench. If this was the case, emplacement of the treatment zone is estimated at \$6.00/ft², based upon the lower-end estimated costs to construct a soil-bentonite slurry wall. This estimate is also based upon formations with less than 25 blowcount soil formation without underground or overhead obstructions or other complicating factors.

With the "controlled" material emplacement technique, the excavated soil is backfilled into the trench after the materials are emplaced into the trench. At least some of the soil must be returned to the trench for this technique to be cost effective; otherwise, waste disposal could be a significant cost issue and make this technology prohibitively expensive. Further, disposal of the trench stabilizing slurry after construction activities are complete must be factored into the overall cost effectiveness.

The unit cost for the excavator technique, including labor expenses for the controlled material emplacement methodology, are estimated as follows:

o Emplacement of materials:

- \$6.00/ft² not including mobilization and demobilization, which is estimated at \$10,000.
- *This assumes that the emplacement technique is very similar to the construction of a soil-bentonite slurry wall that might be used as a groundwater control barrier for the construction arena. Further, the emplacement depth is limited to roughly 50 feet with conventional excavators.*
- \$10.00/ft² not including mobilization and demobilization, which is estimated at \$10,000.
- *Assuming an emplacement depth up to 70 feet and a similar emplacement technique to the construction of a soil-bentonite slurry wall that might be used as a*

groundwater control barrier for the construction arena.

The unit cost of materials only emplaced in the "controlled" manner is similar to that of the mandrel-based methodology; refer to section 2.2.1.5 for details.

As with the "controlled" emplacement methodology, "loose" material emplacement would require allowance to return the excavated soils to the trench to avoid significant potential waste disposal costs. For the emplacement of treatment zone materials, the materials could be distributed over the trenching spoils, mixed with the soil with a bulldozer, and then placed back into the trench in fashion similar to the construction of a soil-bentonite slurry wall. For electrodes, however, it is doubtful that an iron/soil mixture will have the desired electrokinetic properties for application to a Lasagna remediation process, and pure iron or an iron-carbon mixture would be cost prohibitive. A "controlled" emplacement methodology should be followed for the electrodes similar to the Phase I field test electrodes, (refer to section 2.2.1.5), since a "loose" emplacement methodology is technically improbable and probably is cost prohibitive.

The unit cost of materials only emplaced in the "loose" material emplacement methodology and to a depth of roughly 45 feet are estimated as follows:

o In situ treatment zone material:

- \$24.00/ft² for a 20% iron/80% native soil mixture (volume %).
- *Assuming a 36-inch wide treatment zone, granular iron with a bulk density of 200 lb/ft³ and a cost of \$400/ton, which results in a unit cost of \$24.00/ft².*
- \$6.00/ft² for a 5% iron/95% native soil mixture (volume %).
- \$31.92/ft² for a 20% granular iron/80% clay mixture (volume %).
- *Assuming a 36-inch wide treatment zone, using a unit cost for the granular iron of \$24.00/ft², and clay at a bulk density of 110 lb/ft³ and a cost of \$60/ton for a unit cost for clay of \$7.92/ft².*

- \$15.41/ft² for a 5% granular iron/95% clay mixture (volume %).

o Electrode materials:

- \$96.15/ft² for a 80% iron/20% native soil mixture (volume %) including 1-inch diameter carbon steel rods to serve as primary electrodes.
- *Assuming a 36-inch wide treatment zone, granular iron with bulk density of 200 lb/ft³, and a cost of \$400/ton, which results in a unit cost of \$96.00/ft²; and \$0.15/ft² for the 1-inch diameter carbon steel rod electrode.*
- \$99.25/ft² for a 80% iron/20% native soil mixture (volume %) including an iridium oxide-coated titanium mesh to serve as the primary electrode.
- *Assuming a 36-inch wide treatment zone, unit cost of \$96.00/ft² for the granular iron and \$3.25/ft² for an iridium oxide-coated titanium mesh electrode.*
- \$14.14/ft² for a 5% granular iron/95% sand mixture (volume %) including a 1/4-inch thick carbon steel electrode.
- *Assuming a 36-inch wide treatment zone, granular iron with a bulk density of 200 lb/ft³, and a cost of the iron at \$400/ton, which results in a unit cost for granular iron of \$6.00/ft²; sand with a bulk density of 110 lb/ft³, and cost of the sand at \$20/ton, which results in a unit cost for sand of \$3.14/ft², and a 1/4 inch thick carbon steel plate electrode at a unit cost of \$5.00/ft²*

Refer to the spreadsheets contained in Appendix F for further cost details.

2.2.5 Trenchers

2.2.5.1 Emplacement description

Trenching machines come in a wide variety of designs—from “chain saw” to “circular saw” devices, and they vary in size from small utility machines to huge machines for strip mining. The depth capability of these devices varies from several feet to over a hundred feet with trench widths of less than a foot to

over several feet (see Appendix E). The most widely available trenchers have depth capability less than 20 feet, typically discharge the soils to the side of the trench, and do not fill the trench with a slurry or incorporate any mechanism to stabilize the trench. Some less common machines have depth capability to roughly 30 feet and incorporate a mechanism to brace the trench. These machines are more commonly used to emplace French drains. The bracing mechanism typically is used to stabilize the walls of the trench so that a perforated and corrugated high-density polyethylene (HDPE) pipe can be emplaced and the trench can be filled with sand or other materials (see Appendix E). There is little experience with trenching in unconsolidated soils below a depth of 30 feet. Trenching to a depth of 45 feet should be considered developmental at this time, especially in unconsolidated soil formations. Only one trencher is known to have depth capability over 100 feet. This machine is built by Hokushin and uses an appropriate slurry (e.g., bentonite slurry, cement slurry, or cement-bentonite slurry) to stabilize the trench (see Appendix E).

2.2.5.2 Application to Lasagna

To apply the trenching technique to a layered remediation process, a sufficiently long and deep trench is created and either electrode or treatment zone material is emplaced into the open, shored, or slurry-filled trench.

As with the excavator technique, electrode or treatment zone materials can be emplaced in a controlled manner or loosely to fill the entire trench. The controlled and loose emplacement approaches are similar to the mandrel-based and standard excavation methodologies (see section 2.2.1.2).

2.2.5.3 Advantages

The primary advantage of a trenching machine is that it can productively trench in a wide variety of geologies ranging from soils to a variety of rock. As with the excavator technique, the trenching technique allows the electrode materials to be placed continuously, or panels can be placed edge to edge or lapped at their edges. Accurately emplacing electrode and treatment zone material should be less of a concern with this technique since emplacement occurs in an open, shored, or slurry-filled trench.

2.2.5.4 Disadvantages

As with the excavation technique, one of the disadvantages of trenchers is that the minimum trench width is a function of the desired depth and the cutting mechanism of the trencher. For deeper excavations, the cutting mechanism becomes fairly wide in order to withstand the cutting forces. As a general rule of thumb, a 4 inch wide trench is feasible to a depth of five feet, a 6-inch wide trench is feasible to a depth of 10 feet, a 12-inch wide trench is feasible to a depth of 20, an 18-inch wide to a depth of 30 feet, and a 24-inch wide to a depth of 50 feet. Further, for deeper excavations, (i.e., greater than 30 feet) a slurry may need to be used to stabilize the trench, and trenching machines have not often been used in a slurry.

2.2.5.5 Economics

Small trenching machines are readily available from local equipment rental agencies and mobilization/demobilization typically is not a big cost factor. For application to a Lasagna remediation process, the thinnest cutter mechanism width would be most desirable to avoid disturbing a significant percentage of the soil due to the potential relatively close spacing of the treatment zones. Larger machines with depth capability over 10 feet are not widely available in all regions of the country, and mobilization/demobilization could cost as much as \$50,000, depending upon the machine and transport distance. Using a trenching machine is typically the quickest way to create a trench in tough soils or rock formations up to depths of roughly 30 feet.

Based upon information from one of the leading contractors with large trenching machines, the unit cost of trenching to a depth of about 30 feet is estimated at \$12.50/ft² for short run lengths of about 200 feet. For application to layered remediation, the thinnest cutter width would be desirable in order to avoid disturbing a significant percentage of the soil. To trench to a depth of 45 feet, it is estimated that the cutter mechanism would be roughly two feet wide.

The unit cost of materials emplaced with a "controlled" material emplacement technique would be very similar to the unit costs for the standard excavation technique; refer to section 2.2.4.5 for details. As with the excavation technique and using a "controlled" material emplacement methodology, at least some of the soil must be returned to the trench for this technique to be cost effective; otherwise, waste disposal could

be a significant cost issue and result in this technology being cost prohibitive.

The unit costs for the trencher technique, including labor expenses for the controlled material emplacement methodology, are estimated as follows:

o Emplacement of materials:

- \$12.50/ft², not including mobilization and demobilization, which is estimated at \$50,000.

The unit costs of materials emplaced in the "controlled" method are similar to those for the mandrel case; refer to section 2.2.1.5 for details.

For the "loose" emplacement of treatment zone materials, the trenched soils could be deposited next to the trench, materials distributed over the trenched soils, mixed with a bulldozer, and then placed back into the trench. Alternatively, the treatment zone materials and the soils could be mixed in situ if the trenching equipment is appropriately designed. It is doubtful for electrodes, however, that an iron/soil mixture will have the desired electrokinetic properties for application to a Lasagna type of remediation effort. A controlled emplacement methodology should be followed for the electrodes similar to the Phase I field test electrodes, refer to section 2.2.1.5, since a "loose" emplacement methodology is technically improbable and probably is cost prohibitive.

The unit cost of materials only emplaced in the uncontrolled material emplacement methodology are estimated as follows:

o In situ treatment zone material:

- \$16.00/ft² for a 20% iron/80% native soil mixture (volume %).
- *Assuming a 24-inch wide treatment zone, granular iron with a bulk density of 200 lb/ft³ and a cost of \$400/ton, which results in a unit cost of \$16.00/ft².*
- \$4.00/ft² for a 5% iron/95% native soil mixture (volume %).
- \$21.28/ft² for a 20% granular iron/80% clay mixture (volume %).

- *Assuming a 24-inch wide treatment zone, using a unit cost for the granular iron of \$16.00/ft²; and clay at a bulk density of 110lb/ft³, and cost of clay of \$60/ton for a unit cost for clay of \$5.28/ft².*
- \$10.27/ft² for a 5% granular iron/95% clay mixture (volume %).
- o Electrode materials:
 - \$64.15/ft² for a 20% iron/80% native soil mixture (volume %), including a 1-inch diameter carbon steel rod electrode.
 - *Assuming a 24-inch wide treatment zone, granular iron with a bulk density of 200 lb/ft³ and cost of \$400/ton, which results in a unit cost of \$64.00/ft², and \$0.15/ft² for a 1-inch diameter carbon steel rod electrodes.*
 - \$67.25/ft² for a 80% iron/20% native soil mixture (volume %), including an iridium oxide-coated titanium mesh.
 - Assuming a 24-inch wide treatment zone, unit cost of \$64.00/ft² for granular iron and \$3.25/ft² for an iridium oxide-coated titanium mesh electrode.
 - \$11.09/ft² for a 5% granular iron /95% sand mixture (volume %) including a 1/4-inch thick carbon steel plate electrode.
 - *Assuming a 24-inch wide treatment zone, granular iron with a bulk density of 200 lb./ft³ and a cost of \$400/ton, which results in a unit cost for granular iron of \$4.00/ft²; sand with a bulk density of 110 lb/ft³ and a cost of \$20/ton, which results in a unit cost of \$2.09/ft² and a 1/4-inch thick carbon steel plate electrode at a unit cost of \$5.00/ft².*

Refer to the spreadsheets contained in Appendix F for further cost details and comparison between technologies.

3.0 EMPLACEMENT COST ANALYSIS

Section 2.0 presented an overview of various candidate emplacement technologies, including advantages, limitations, and estimated costs for

application. Section 3.0 provides a direct comparison of the technologies on the basis of estimated cost for a range of emplacement depths. For sake of simplicity, the study is focused primarily on emplacement of granular materials, with granular iron treatment zones as the standard. However, the results may be generalized to evaluate emplacement of virtually any granular-based treatment zone or electrode media if the material cost is known.

3.1 Treatment Zone Cost Components

The unit cost (e.g., cost per square foot transverse to flow direction) of emplaced treatment zones or electrodes is comprised of two basic components: (1) the cost of the material to be emplaced, and (2) the cost of putting that material into the subsurface. Selection of an emplacement technology affects both of these components.

Obviously, the various technologies will differ in their respective costs for the second component, putting the material into place. This cost may be considered as a function of depth.

The fact that emplacement technology affects the first cost component, the material cost, is less obvious. However, consider that each technology has a different capacity for creating and filling voids in the subsurface. The mandrel-based technologies, for example, can create and fill a thin, standard-width void more or less independent of depth. On the other hand, trenching and excavation technologies generally are governed by increasingly larger void dimensions with increasing depth. Since the resulting void must be subsequently filled, the thickness of the void affects the total cost of materials used in the treatment zone.

A designer would want to match the treatment zone thickness and amount (i.e., mass) of treatment medium to meet the degree of treatment needed. Anything more would incur a cost penalty. Alternatively, inert material may be used to balance the void volume vs. the amount of treatment medium needed in the system. This is an approach taken with the granular iron treatment zones where the iron is mixed with inert material such as sand, clay, or native soil to provide the optimized amount of treatment medium. However, even inert materials such as clay or sand have an associated cost.

A third cost component which must be considered relates to the handling and possible need for disposal or treatment of waste soil generated in the emplacement process. This cost is a technology-specific and site-specific concern. However, at sites where excess soil must be handled as a waste, the cost could be significant. In general, for technologies with potential to generate waste soil, such as trenching and excavation, the volume of soil and the subsequent unit cost for handling will be a function of the treatment zone width (which in turn may be related to depth).

In summary, treatment zone cost can be estimated based on these primary relationships:

- (1) emplacement depth vs. treatment zone thickness,
- (2) cost per unit volume of treatment zone medium,
- (3) emplacement depth vs. emplacement unit cost (excluding material).

The following sections discuss these relationships generalizing from results of the assessment of each technology as presented in Section 2.0.

3.1.1 Emplacement Depth vs. Treatment Zone Thickness

Figure F-2 shows emplacement depth vs. estimated minimum treatment zone thickness for each of the technologies in the depth range of 0 to 50 feet. Sufficient experience is lacking for most of the technologies to allow extrapolation below this depth. Note that the mandrel-based, jetting, and vibrating beam technologies have potential for creating treatment zones with thickness independent of depth (at least to 50 feet). Excavation and trenching, on the other hand, require progressively larger equipment at increasing depth resulting in increasing minimum treatment zone thickness. This is depicted as a "step function" in Figure F-2. Note the apparent advantage of the mandrel-based approach for creating very thin electrodes and treatment zones.

Figure F-2 considers minimum treatment zone thickness as the primary factor to be considered. This is based on the presumption that the low flow rates inherent in the LasagnaTM process (e.g., 1 cm per day) will allow long retention and adequate treatment within very thin treatment zones. This presumption appears to be true for the granular iron TCE dechlorination technology where 1 cm thick treatment zones have been tested with success in the laboratory (see Topical Report for Task No. 9). This presumption may not be valid for other treatment technologies where very long treatment zone retention might be needed.

3.1.2 Cost Per Unit Volume of Treatment Zone Medium

The unit material cost for treatment zones (cost per unit area transverse to flow) is in direct relationship to the treatment zone thickness and obviously is specific to the treatment zone material being emplaced. In addition, depending on the emplacement technology selected, there may be costs associated with granular material carrier fluids used in the emplacement process (e.g., muds used to slurry the granular material) or to contain the treatment medium (e.g., the wick drain used in the mandrel-based "controlled" emplacement process).

All things being equal, those emplacement methods which minimize the volume of the treatment zone and the need for added materials to facilitate emplacement have a potential cost advantage. However, as discussed above, the advantage of thin treatment zones from a material cost standpoint is balanced by the fact that unneeded treatment zone volume can be filled with cheap inert materials such as sand or clay.

Figure F-3 compares estimated material cost involved in forming granular iron treatment zones for application in LasagnaTM using various emplacement methods. Costs are developed per inch of thickness for a one square foot treatment zone section. The use of inert bulking material is considered in each case. For example, the mandrel "tremie tube", jetting, and vibrating beam cases assume use of a 20% (by volume) granular iron - 80% purchased clay mixture. The trenching and excavation cases assume use of less iron (5% by volume) mixed with site soil, assuming the excavated soil may be mixed with iron and returned in the backfill. These chosen mixture ratios were set somewhat arbitrarily but reflect the large cost differences which can result from material selection.

Figure F-3 shows the estimated cost of the 20%-80% iron-clay mix increasing from \$0.83 per ft² per inch for the mandrel "tremie tube" method to \$1.48 per ft² per inch for the vibrating beam and jetting methods. This increasing cost reflects the added cost of carrier fluids and the fact that some material waste is expected in the relatively uncontrolled jetting and vibrating beam methods. By comparison, the mandrel approach more or less ensures the emplacement of all materials into the proper location in the process. All of these estimates are based on a cost of \$0.20 per lb (\$400 per ton) for granular iron and \$0.03 per lb (\$60 per ton) for purchased clay.

Referencing Figure F-3, the typical treatment zone thickness for the mandrel "tremie tube" method would be about two inches, for total material cost of about \$1.66 per square foot. Assuming effective treatment zone thickness of three inches for jetting and vibratory beam results in a projected material cost of about \$4.40 per square foot. At \$0.17 per inch of thickness, the trenching and excavation methods could range in cost for material from about \$2 per square foot (one foot wide excavation) up to \$6 per square foot (three foot wide excavation).

As shown on the figure, the mandrel "controlled" emplacement method used in the Phase I pilot is projected to cost about \$10.60 per ft² per inch should 100% iron be substituted for the activated carbon used at Paducah. This relatively high material cost reflects the added cost of the wick drain material and the labor involved in loading and securing the materials. Note that the total thickness of these zones were about one inch.

Refer to Appendix F for details concerning cost factors used in developing Figure F-3.

3.1.3 Emplacement Unit Cost vs. Emplacement Depth

Figures F-4 and F-5 present estimated cost for emplacement (excluding materials) vs. depth of emplacement for the various technologies based on findings documented in Section 2.0. Figure F-4 presents the case where excess soils may be graded in place, while Figure F-5 considers the generation of waste soils requiring treatment or disposal. For purposes of estimation, the cost of waste soil handling and disposition is assumed to be \$250 per cubic yard, a typical cost for off-site secure landfill disposal.

None of the estimated costs shown in Figures F-4 and F-5 include mobilization/demobilization of equipment to the site. Those costs are independent of the size of the project and therefore become less significant with increasing project size.

It should be noted that since full-scale construction cost data are lacking for treatment zone emplacement, estimated costs are based on best engineering judgment extrapolating from similar projects or applications. Certain estimates of productivity were made based on discussions with vendors and the authors' experience. Note also that other cost factors can come into play. For example, the cost of excavation is shown on Figure F-4 to be sensitive to depth of emplacement. It is assumed that excavation below a depth of about 10 feet (a somewhat arbitrary figure which in fact will vary with soil conditions) may require over excavation or use of slurry wall construction techniques to maintain trench integrity through completion of material placement. This would incur added cost compared with cost of excavation at shallower depths. However, excavation cost should be relatively insensitive to the length of treatment zones since excavators are easily moved and deployed.

On the other hand, cost for use of trenchers is highly sensitive to length of the trench, a fact which is not illustrated on Figure F-4. Longer trenches are substantially less expensive to construct on a unit area basis. Much of the cost of deep trenching is related to setting up the equipment at the beginning of the trenching run and pulling the equipment out at the end. The unit cost of about

\$12.50 per square foot shown on Figure F-4 is based on a maximum treatment zone length of roughly 200 feet, assuming typical LasagnaTM applications of one acre or less. Trenching runs of around 1000 ft length can be expected to cost substantially less than \$10 per square foot, excluding waste soil costs.

Estimated cost for trenching is provided only for the depth interval between 10 feet and 30 feet in depth. Data for depths less than 10 feet could not be located and in any event is not likely to be competitive with backhoe excavation. While trenching equipment is available commercially for depths up to 30 feet, commercial offerings for greater depths could not be located in North America.

3.2 Combined Cost Estimates

Figures F-6 and F-7 present the estimated costs of emplacement and total emplacement plus material costs for treatment zones and electrodes projected for each of the emplacement methods for depths of 15 feet and 45 feet, respectively. The combined treatment zone cost is specific to granular iron treatment zones and uses the material cost estimates developed in Figure F-3 combined with minimum emplacement thickness from Figure F-2. The estimated emplacement costs are taken from Figure F-4 (which assumes no added cost for waste soil generation). Again, it should be noted that none of these costs include equipment mobilization/demobilization which can be significant depending on the technology and project size. Spreadsheets showing details of the cost development are provided in Appendix F.

Comparative electrode cost has not been considered up to this stage. The assumed electrode design varies somewhat between the different emplacement methods in this cost comparison. In each case, the electrode design also incorporates a granular iron treatment zone. For example, the mandrel "controlled" case is based on use of a one inch wick drain filled with granular iron and backed with an iridium-coated titanium mesh. The mandrel "tremie tube", jetting, and vibrating beam cases all consider use of an 80% iron/20% activated carbon (by volume) mixture in combination with the iridium-coated titanium mesh. Jetting and vibrating beam assume three inch thick electrodes while the mandrel "tremie tube" electrodes are two inches thick. Finally, both the trencher and excavator concepts use a 1/4-inch steel plate electrode placed in a backfill of a 5% iron/95% native soil mixture.

3.3 Conclusions

A number of patterns emerge from study of Figures F-6 and F-7. The following is a summary of generalizations which can be derived from the cost data:

Mandrel "controlled" emplacement has potential for offering inexpensive emplacement at all depths. However, treatment zone and electrode material cost penalties may result from the use of wick drain materials, and particularly from labor-intensive fabrication. This method could be competitive if cheaper materials could be fabricated inexpensively.

1. The mandrel-based "tremie tube" approach offers the potential for optimum use of materials in the LasagnaTM process. The currently identified drawbacks are related to a current lack of (1) an efficient, rapid method of delivering the materials through the mandrel, and (2) field experience from which to estimate emplacement cycle time. The current vision requires mixing and delivering materials in a slurry. Considering lack of experience, a conservative production estimate is built into the emplacement cost. This method could benefit from further development and optimization of the mixing and delivery systems.
2. The vibrating beam technology is quite similar to the mandrel "tremie tube" approach as reflected in identical estimated emplacement costs. However, the vibrating beam method is considered less attractive due to the wider treatment zone dimension and less optimized use of materials. Furthermore, wastage of material can be expected in this process, and waste soil will be produced which could require management.
3. At face value, jetting appears to offer potentially the cheapest treatment zone emplacement alternative across most of the depth range considered in this analysis. Factors contributing to jetting's attractiveness for treatment zone formation includes the low projected emplacement cost, and relatively efficient use of material. The potential for further cost optimization is limited, but it may be possible to further optimize the granular iron/clay ratio to reduce the material cost of treatment zones. (This also is true of the vibrating beam method). However, jetting appears to have limitations for electrode emplacement. Since granular iron is envisioned as the primary electrode in a jetting-based design, a relatively pure iron core must be emplaced. This may not be conducive to efficient material usage in jetting-based electrodes. An alternative may be to increase the proportion of less-dense carbon materials (such as coke) in the electrodes.
4. Use of trenching machines does not appear attractive for use in LasagnaTM under most circumstances. Trenching technology may be more appropriate for emplacing longer treatment zones, for example continuous permeable reactive barriers, within a certain depth range. (i.e., less than 30 feet).
5. Excavation is perhaps the most straightforward technology but carries the penalties associated with overexcavation, particularly at the greater depths, and the requirement for slurry stabilization at greater depths. Overexcavation could be balanced by mixing treatment material with the excavated soil for use in backfilling the trench, as discussed herein. As well, a number of other

techniques not considered in this report may be available to counter the downside of overexcavation. For example, a number of geosynthetics have been developed for application in trenches which might be used to help separate materials in the trench and allow more efficient use of treatment zone and electrode materials. As an outgrowth of further development along these lines, excavation may be a viable, cost-effective option at some sites where waste soil management is not an issue and excavated soils may be backfilled in place. It should be noted that excavation appears to be the low cost alternative in the depth range of 0 to 10 feet when excavated soil may be backfilled.

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Figure F-1. Schematic Diagram of the Lasagna™ Technology

TREATMENT ZONE THICKNESS VS. EMPLACEMENT DEPTH

Lasagna Emplacement Cost Analysis

FIGURE F-2

ESTIMATED UNIT COST OF TREATMENT ZONE MATERIALS

FIGURE F-3

EMPLACEMENT COST VS. DEPTH (NO WASTE SOIL GENERATION)

FIGURE F-4

EMPLACEMENT COST VS. DEPTH (WITH WASTE SOIL GENERATION)

FIGURE F-5

ESTIMATED TOTAL TREATMENT ZONE AND ELECTRODE COSTS, 15-FOOT DEPTH

Lasagna Emplacement Analysis (Emplacement Depth Is 15 Feet)

FIGURE F-6

ESTIMATED TOTAL TREATMENT ZONE AND ELECTRODE COSTS, 45-FOOT DEPTH

Lasagna Emplacement Analysis (Emplacement Depth Is 45 Feet)

FIGURE F-7

APPENDIX A

MANDREL-BASED EMPLACEMENT BACKGROUND MATERIAL

Cutaway Section of the Nilex Mebra Drain™ Wick System

Installation
equipment

Driving
mandrel

Extracting
mandrel

Cutting
drain

WICK DRAIN EMPLACEMENT PROCESS

LP-2B

Lasagna Anode or Cathode Zone

R. J. Griffith 8/31/94

DESIGN OF ELECTRODES USED IN THE PHASE I FIELD TEST (DUPONT)

LP-3

Lasagna Treatment Zone

Granular Activated Carbon Filled

Sampling Tube
LP-24

18.6" Ref.

Monsanto Hydaway 2000 Product
LP-23

R. J. Griffith 8/24/94

**DESIGN OF TREATMENT ZONES USED IN PHASE I FIELD
TEST (DUPONT)**

APPENDIX B

HIGH PRESSURE JETTING BACKGROUND MATERIAL

Vertical Columnar
Barrier Construction

Repetition of
the process

COLUMNAR JET GROUTING PROCESS

Jet Grouting Systems

Single Rod

Double Rod

Triple Rod

PHOTO OF EXCAVATED JET GROUT COLUMN

Vertical Thin Diaphragm Walls

**TYPICAL LAYOUT OF SUBSURFACE BARRIER WALL
COMPOSED OF INTERSECTION JETTED THIN DIAPHRAGM
WALLS**

APPENDIX C

VIBRATING BEAM BACKGROUND MATERIAL

**PHOTO OF VIBRATING BEAM CUTOFF WALL CONSTRUCTION
(VIBRATING BEAM SHOWN TO RIGHT)**

PHOTO OF GEOMEMBRANE INSERTION INTO VIBRATING
BEAM CUTOFF WALL

VIBRATING BEAM TECHNOLOGY (FROM RUMER AND RYAN, 1995)

APPENDIX D

EXCAVATION BACKGROUND MATERIAL

**TYPICAL RUBBER -TIRED BACKHOE FOR SHALLOW
EXCAVATION**

TYPICAL TRACK-HOE FOR DEEP TRENCH EXCAVATION

APPENDIX E
TRENCHING BACKGROUND MATERIAL

PHOTO OF TYPICAL SHALLOW TRENCHING MACHINE

TYPICAL MEDIUM-SIZED TRENCHING MACHINE

MEDIUM-SIZED "CHAIN SAW" TYPE TRENCHING MACHINE

PHOTO OF HOKUSHIN (JAPAN) TRENCHING MACHINE

PHOTO OF HOKUSHIN TRENCHING MACHINE OPERATING IN
SLURRY-FILLED TRENCH

APPENDIX F

COST ANALYSIS SPREADSHEETS

Phase One Materials			Unit Cost	Cost per Ft^2				
Original Tremie Tube Emplacement								
Electrode - Mat'ls Only				100% Carbon	100% Gran. Fe			
Steel Plate With 1" Wickdrain				\$16.23	16.72			
ITZ - Mat'ls Only								
1" Wickdrain Filled With Carbon				\$10.14	10.63			
Emplacement				\$2.24	\$3.50			
Mob/Demob.			\$20,000.00					
Phase Two Potential Materials								
Tremie Tube Emplacement								
Basls		Width	Length	Depth				
		(Ft)	(Ft)	(Ft)				
Site Dimensions		210	210	45				
Emplacement Thickness		0.17						
		Percentage	Volume	Area	Mixture	Unit Cost	Sub Cost	Total Cost
		(vol %)	(Ft^3)	(Ft^2)	(Lb / Ft^3)	(\$/Lb)	(\$/Ft^2)	(\$/Ft^2)
Electrodes - Mat'ls Only								
Iron Only	Iron	100.00%	1575.00	9450	120	\$0.20	\$4.00	\$4.18
	Guar Gum	100.00%			0.30	\$3.50	\$0.18	
Iron/Carbon								
	Iron	80.00%			116	\$0.20	\$3.87	\$4.82
	Carbon	20.00%			4	\$1.17	\$0.78	
	Guar Gum	100.00%			0.30	\$3.50	\$0.18	
Iron/Carbon/Mesh								
	Iron	80.00%			116	\$0.20	\$3.87	\$8.07
	Carbon	20.00%			4	\$1.17	\$0.78	
	Guar Gum	100.00%			0.30	\$3.50	\$0.18	
	Mesh						\$3.25	
Iron/Carbon/Rod								
	Iron	80.00%			116	\$0.20	\$3.87	\$4.97
	Carbon	20.00%			4	\$1.17	\$0.78	
	Guar Gum	100.00%			0.30	\$3.50	\$0.18	
	1" Dia. Rod						\$0.15	
Iron/Carbon/Mesh/Hydroway								
	Iron	80.00%			116	\$0.20	\$3.87	\$9.07
	Carbon	20.00%			4	\$1.17	\$0.78	

	Guar Gum	100.00%			0.30	\$3.50	\$0.18	
	Mesh						\$3.25	
	1" Hydroway						\$1.00	
		Percentage	Volume	Area	Mixture	Unit Cost	Cost per Ft^2	Total Cost
			(Ft^3)	(Ft^2)	(Lb / Ft^3)	(\$/Lb)	(\$/Ft^2)	(\$/Ft^2)
ITZs - Mat'ls Only								
Iron Only	Iron	100.00%	1575.00	9450	120	\$0.20	\$4.00	\$4.18
	Guar Gum	100.00%			0.30	\$3.50	\$0.18	
Iron/Sand	Iron	20.00%	315.00		37.5	\$0.20	\$1.25	\$1.56
	Sand	80.00%	1260.00		82.5	\$0.01	\$0.14	
	Guar Gum	100.00%			0.30	\$3.50	\$0.18	
Iron/Soil	Iron	20.00%	315.00		37.5	\$0.20	\$1.25	\$1.70
	Soil	80.00%	1260.00		82.5	\$0.02	\$0.28	
	Guar Gum	100.00%			0.30	\$3.50	\$0.18	
Iron/Clay	Iron	20.00%	315.00		37.5	\$0.20	\$1.25	
	Clay	80.00%	1260.00		82.5	\$0.03	\$0.41	\$1.66
			Unit Cost	Cost per Ft^2				
Emplacement				\$6.67				
Mob/Demob			\$30,000.00					
Jet Grouting Emplacement								
Basis								
			Length	Gallons Used				
Thin Diaphragm Wall Dimensions			10	31500				
			6	52500				
Electrodes - Mat'ls Only								
		Percentage	Volume	Area	Mixture	Unit Cost	Sub Cost	Total Cost
		(vol %)	(Gallons)	(Ft^2)	(Lb / Gal)	(\$/Lb)	(\$/Ft^2)	(\$/Ft^2)
Iron Only	Iron	100.00%	52500	9450	16	\$0.20	\$17.78	\$18.56
52500	Guar Gum	100.00%			0.04	\$3.50	\$0.78	
	1" Dia. Rod						\$0.00	
31500	Iron	100.00%	31500		16	\$0.20	\$10.67	\$11.28
	Guar Gum	100.00%			0.04	\$3.50	\$0.47	
	1" Dia. Rod						\$0.15	
Iron/Carbon								
52500	Iron	80.00%			15.5	\$0.20	\$17.22	\$21.40
	Carbon	20.00%			0.5	\$1.17	\$3.25	
	Guar Gum				0.04	\$3.50	\$0.78	
	1" Dia. Rod						\$0.15	

31500	Iron	80.00%			15.5	\$0.20	\$10.33	\$12.90
	Carbon	20.00%			0.5	\$1.17	\$1.95	
	Guar Gum				0.04	\$3.50	\$0.47	
	1" Dia. Rod						\$0.15	
ITZs - Mat'ls Only								
Iron Only	Iron	100.00%			16	\$0.20	\$17.78	\$18.56
52500	Guar Gum	100.00%			0.04	\$3.50	\$0.78	
31500	Iron	100.00%			16	\$0.20	\$10.67	\$11.13
	Guar Gum	100.00%			0.04	\$3.50	\$0.47	
Iron/Sand	Iron	20.00%			5	\$0.20	\$5.56	\$6.94
52500	Sand	80.00%			11	\$0.01	\$0.61	
	Guar Gum	100.00%			0.04	\$3.50	\$0.78	
31500	Iron	20.00%			5	\$0.20	\$3.33	\$4.17
	Sand	80.00%			11	\$0.01	\$0.37	
	Guar Gum	100.00%			0.04	\$3.50	\$0.47	
Iron/Soil ?	Iron	20.00%			14.74	\$0.20	\$16.38	\$17.31
52500	Soil	80.00%			1.37	\$0.02	\$0.15	
	Guar Gum	100.00%			0.04	\$3.50	\$0.78	
31500	Iron	20.00%			5	\$0.20	\$3.33	\$4.53
	Soil	80.00%			11	\$0.02	\$0.73	
	Guar Gum	100.00%			0.04	\$3.50	\$0.47	
Iron/Clay	Iron	20.00%			5	\$0.20	\$5.56	\$5.56
52500	Clay	80.00%			11	\$0.03	\$0.00	
31500	Iron	20.00%			5	\$0.20	\$3.33	\$4.43
	Clay	80.00%			11	\$0.03	\$1.10	
			Unit Cost	Cost per Ft^2	Gallons Used			
Emplacement				\$5.28	52500			
				\$3.17	31500			
Mob/Demob			\$30,000					

Zone Construction	Method	Emplacement (\$/Ft^2)	Electrodes (\$/Ft^2)	Treatment Zone (\$/Ft^2)	Sub-Total (\$/Ft^2)	Zone (Yd^3)	Excess Soils (Yd^3/zone)	Disposal / Yd^3 \$250	Sub Cost (\$/Ft^2)
1" Wickdrains	Mandrel	\$3.50		\$10.63	\$14.13	0	0	\$0	\$3.50
1" Wickdrains	Mandrel	\$3.50	\$16.72		\$20.22	0	0	\$0	\$3.50
2" Iron Only	Tremie Tube	\$7.85		\$4.18	\$12.03	0	0	\$0	\$7.85
2" Iron/Clay	Tremie Tube	\$7.85		\$1.66	\$9.51	0	0	\$0	\$7.85
2" Iron/Carbon/Rod	Tremie Tube	\$7.85	\$4.97		\$12.82	0	0	\$0	\$7.85
2" Iron/Carbon/Mesh	Tremie Tube	\$7.85	\$8.07		\$15.92	0	0	\$0	\$7.85
4" Iron Only	Jet Grouting	\$3.37		\$11.13	\$14.50	117	117	\$29,167	\$6.46
4" Iron/Clay	Jet Grouting	\$3.37		\$4.43	\$7.80	117	117	\$29,167	\$6.46
4" Iron/Carbon/Rod	Jet Grouting	\$3.37	\$12.90		\$16.27	117	117	\$29,167	\$6.46
3" Iron Only	Vibrating Beam	\$7.85		\$11.13	\$18.98	88	88	\$21,875	\$10.16
3" Iron/Clay	Vibrating Beam	\$7.85		\$4.43	\$12.28	88	88	\$21,875	\$10.16
3" Iron/Carbon/Rod	Vibrating Beam	\$7.85	\$12.90		\$20.75	88	88	\$21,875	\$10.16
1" Wickdrains	Vibrating Beam	\$7.85	\$16.72		\$24.57	88	88	\$21,875	\$10.16
1" Wickdrains	Vibrating Beam	\$7.85		\$10.64	\$18.49	88	88	\$21,875	\$10.16
36" Iron/Clay	Excavator	\$6.00		\$31.92	\$37.92	1050	315	\$78,750	\$14.33
36" Iron/Carbon/Rod	Excavator	\$6.00	\$96.15		\$102.15	1050	315	\$78,750	\$14.33
36" Iron/Carbon/Mesh	Excavator	\$6.00	\$99.25		\$105.25	1050	315	\$78,750	\$14.33
1" Wickdrains	Excavator	\$6.00	\$16.72		\$22.72	1050	315	\$78,750	\$14.33
1" Wickdrains	Excavator	\$6.00		\$10.64	\$16.64	1050	315	\$78,750	\$14.33
24" Iron/Clay	Trencher	\$12.50		\$21.28	\$33.78	700	210	\$52,500	\$18.06
24" Iron/Carbon/Rod	Trencher	\$12.50	\$37.25		\$49.75	700	210	\$52,500	\$18.06
24" Iron/Carbon/Mesh	Trencher	\$12.50	\$40.35		\$52.85	700	210	\$52,500	\$18.06
1" Wickdrains	Trencher	\$12.50	\$16.72		\$29.22	700	210	\$52,500	\$18.06
1" Wickdrains	Trencher	\$12.50		\$10.64	\$23.14	700	210	\$52,500	\$18.06

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