Final Technical Report
Research and Development
EarthSaw™ In-Situ Containment of Pits and
Trenches

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ABSTRACT

EarthSaw™ is a proposed technology for construction of uniform high quality barriers under and around pits and trenches containing buried radioactive waste without excavating or disturbing the waste. The method works by digging a deep vertical trench around the perimeter of a site, filling that trench with high specific gravity grout sealant, and then cutting a horizontal bottom pathway at the base of the trench with a simple cable saw mechanism. The severed block of earth becomes buoyant in the grout and floats on a thick layer of grout, which then cures into an impermeable barrier.

The “Interim Report on task 1 and 2” which is incorporated into this report as appendix A, provided theoretical derivations, field validation of formulas, a detailed quantitative engineering description of the technique, engineering drawings of the hardware, and a computer model of how the process would perform in a wide variety of soil conditions common to DOE waste burial sites. The accomplishments of task 1 and 2 are also summarized herein Task 3 work product provides a comprehensive field test plan in Appendix B and a health and safety plan in Appendix C and proposal for a field-scale demonstration of the EarthSaw barrier technology. The final report on the subcontracted stress analysis is provided in Appendix D. A copy of the unified computer model is provided as individual non-functional images of each sheet of the spreadsheet and separately as a Microsoft Excel 2000 file.

Table Of Contents

Section	Title	Page
1.0	INTRODUCTION	4
2.0	EXECUTIVE SUMMARY	4
3.0	EXPERIMENTAL (SCOPE OF WORK)	5
4.0	RESULTS AND DISCUSSION: ACCOMPLISHMENTS	6
4.1	Summary Of Interim Report	8
4.2	Theoretical Proof/Derivation of Buoyancy	9
4.3	Equations Governing The Process	10
4.4	Field Test Validation of Friction Formula	10
4.5	Step-By-Step Quantitative Descriptions	11
4.6	Grout Properties	12
4.7	Equipment Design	13
	4.7.1 Operational Safety of Equipment	14
4.8	Computer models	14
	4.8.1 Buoyancy Model	15
	4.8.2 Conceptual Basis of the Model	16
	4.8.3 Data Output and Display	16
	4.8.4 Cable Force and Friction	16
	4.8.5 Relationship Between Stress and Barrier Uniformity	17
	4.8.6 Cracks, Discontinuities and Voids	18
	4.8.7 Transient Stress during the Horizontal cut	19
	4.8.8 Effect of Water Table	19
	4.8.9 Cap significance in Verification	19
	4.8.10 Modeling Deflection In Unbalanced soil Blocks	20
	4.8.11 High Density Objects	21
	4.8.12 Punching and Local Deflection	22
4.9	Applicability Limitations	23
4.10	Schedule and Cost of Phase I	25
4.11	Hazardous Waste Report	25
4.12	ASME Peer Review Presentation	25
	4.12.1 Structural Modeling	26
	4.12.2 Failure Mode Analysis	26
	4.12.3 Large Scale Voids	27
	4.12.4 Balanced Blocks	27
	4.12.5 Punching Failure Model	28
	4.12.6 Rock Cuttings and Other Excluded Data	28
	4.12.7 Model Improvements	29
	4.12.8 Positive Statements	29
4.13	Finite Element Stress Analysis	29
4.14	Engineering and Design	41
	4.14.1 Cutting the Bottom Pathway	42

4.14.2	Planes of Weakness and Structural Strength of Block	42
4.14.3	Adjusting Buoyancy in Variable Strata	42
4.14.4	Compensating for dished Bottom or Large Voids	43
4.14.5	Grout Functions	44
4.14.6	Winches	44
4.14.7	Engineering Drawings of Load Frame	45
4.14.8	Technology Development Roadmap	70
4.15	Comprehensive Test Plan	70
4.16	Frequently Asked Questions	70
4.17	DOE Comments on Draft Report	76
5.0	CONCLUSION	81
	LIST OF ACRONYMS AND ABBREVIATIONS	81
	Appendix A: INTERIM REPORT ON TASK 2 AND 3	83
	Appendix B: PHASE II FIELD-SCALE TEST PLAN	241
	Appendix C: HEALTH AND SAFETY PLAN FOR FIELD-SCALE TEST	285
	Appendix D: SCREEN SHOTS FROM THE COMPUTER MODEL	320

The computer model is designed to run in Microsoft Excel 2000, on a Pentium 4 class computer. Attached spreadsheet files in native Excel format and as static Adobe PDF format.

1.0 INTRODUCTION

The EarthSaw construction method is designed to construct a continuous and uniform bottom and side barrier under and around a waste burial site without contacting or exposing any of the waste. This process is intended for pits and trenches in the DOE complex that contain radioactive and hazardous wastes in a variety of geological and hydrological conditions. The EarthSaw Vertical Block Method seems capable of constructing a durable barrier under a multi-acre size block of earth up to 1000 feet long and 500 feet wide with the same hardware planned for the 50-foot by 50-foot by 30 foot deep field scale demonstration planned for phase II. Depths over 90 feet deep should be possible by adding extra sections to the Load frame hardware. In the EarthSaw method, these huge blocks of earth are physically severed from the ground and floated upward on a heavy grout material that subsequently cures into a seamless impermeable liner.

In the Phase I work now completed, we prepared detailed engineering plans and calculations as well as computer models of the barrier installation process to numerically demonstrate the theory, physics and engineering viability of the method.

Our next objective in Phase II is a field-scale demonstration of the method. We plan to cut a conventional vertical trench around the perimeter of the site and then fill it with high density liquid grout. A cable saw device operated from load frames sunk into two adjacent corners of the trench, will saw or slice horizontally at the base of the trench. Gravity will force the grout to flow into the horizontal cut and buoyantly lift the block of earth upward, while creating a continuous horizontal barrier layer underneath it.

If successfully developed, the EarthSaw technology will provide a powerful tool capable of isolating and containing undocumented waste burial sites, without disturbing the waste. Since the waste is not disturbed or altered, all future treatment or technologically advanced removal options remain open, but the urgency decreases significantly. The environment is protected immediately. Treatment or extraction is simpler in a contained volume and subsequent evaluation may indicate that no additional action is required.

2.0 EXECUTIVE SUMMARY

DOE landfills contain more than 3 million cubic meters of buried waste contaminating the surrounding environment. At DOE sites throughout the country, soil, groundwater, and landfills containing or contaminated with hazardous and radioactive contaminants have special cleanup needs. The EarthSaw buoyant barrier process is a patented technology that makes it feasible to construct a thick and impermeable bottom barrier under a contaminated landfill area without disturbing the buried waste or exposing personnel to its hazards.

The purpose of this project is to demonstrate an effective method to install an engineered barrier that surrounds and underlies a buried waste-storage area. The barrier is expected

to provide verifiable containment for both pits and trenches without disturbing the waste left in place, and without limiting future treatment options. The EarthSaw buoyant barrier process, developed by Carter Technologies, provides a low-permeability enclosure by mechanically cutting a horizontal pathway and emplacing a high-density grout material both around and beneath a contaminated landfill area.

The process works by first surrounding the landfill with vertical slurry trenches full of the high-density grout. Then a cable saw mechanism cuts a horizontal pathway under the landfill from the bottom of the vertical trenches. Gravity forces the high-density grout to flow into the horizontal cut as it is being made by the cable saw. The high-density grout is denser than the earth, and causes the severed block of earth to float. When additional grout is placed into the trench, it gradually raises the block of earth upward until the bottom barrier reaches the desired thickness. The waste-storage area is thus encased in low-permeability grout that forms a containment barrier to contaminant migration. A synthetic cap would be added to form a complete vault. This prevents surface water infiltration and allows accurate monitoring and continual verification of the vault integrity.

Previous Proof-Of Concept field-testing has demonstrated that the process can work. Task 1 and 2 of phase I of this project were designed to provide a more complete theoretical and engineering analysis and develop a computer model to help define the limits and applicability of the method in a wide variety of geologic and hydrologic conditions. Task 3 of phase I produced the attached comprehensive plan to demonstrate the technology in field scale. The field scale demonstration is planned for a clean site outside the fence of a DOE facility, but only a quarter mile from a uranium burial ground pit that is a candidate for application of the technology. The field scale test would form a barrier to the same depth as the candidate site and serve as a demonstration of how that site could be isolated and contained. The completed structure would be monitored for one year to gather additional data for permitting a full closure. The same equipment used in the field scale demonstration could then be re-used for the actual remediation.

3.0 EXPERIMENTAL (SCOPE OF WORK)

Phase I was designed to accomplish the following objectives.

1. Provide calculations that numerically demonstrate the viability of the theory, physics, and engineering of the EarthSaw technology.
2. Develop a computer model to simulate the installation of a containment barrier using the EarthSaw technology. Specifically simulating the conditions of: Variable host media (e.g., variable lithologies such as unconsolidated sediments and bedrock); Variable hydrologic conditions (e.g., near-surface water table); Host media with discontinuities such as complexly interbedded sediments, highly bedded strata, fractured bedrock, and others; and Waste areas with variable geometries, dimensions,

and waste material contents.

3. Demonstrate computer modeling of the installation of a containment barrier for a minimum of three different cases, defined by variable subsurface conditions and waste areas. The model must demonstrate the ability to construct a barrier with continuous, minimum bottom and side thickness.
4. Assist DOE in identification of a field site that contains representative subsurface conditions of DOE waste areas for conducting a controlled field-scale test.
5. Identification and evidence of DOE end user(s) with interest in using the EarthSaw technology.
6. Develop a comprehensive field test plan for a controlled field-scale test isolating a block of Earth 50 ft by 50 ft by 20 ft to 30 ft deep, for Phase II.

Phase I began August 16th of 2001 and is now complete. Phase II is designed to accomplish the following additional objectives.

1. Conduct a full scale In-Situ demonstration isolating a block of earth 50 ft by 50 ft by 20 to 30 ft deep.
2. Provide constructability and cost data needed to plan full-scale deployment at the site.
3. Measure the performance of both the construction process and the integrity of the barrier.

4.0 RESULTS AND DISCUSSION: ACCOMPLISHMENTS

Phase I has been highly successful in providing improved definition and detailed theoretical and engineering analysis compared to the original conceptual plans. The computer modeling has proven to be a useful tool in advancing understanding of the limiting factors that govern the technology application. This model has shown that the mechanically simple form of the technology known as the Vertical Block Method is applicable to much larger sites and a broader range of conditions than originally surmised. The model indicates that the method may be applied at sites up to 500 feet wide and 1000 feet long with depths to 90 feet or more. This maximum size can probably be extended by additional measures that reduce friction.

The modeling effort also helped us develop a safer system to power the cable saw and significantly increased confidence that the technology can be extended to tilted rock layers and sloping terrain to a limited degree. The model shows that the method can work in unconsolidated sand, clay, or silt both above and below the water table. The method may be limited in certain formations such as clean gravels that are too porous to hold drilling fluids. The method is applicable to a broad range of soil types, including soft rock such as limestone and shale. There may be practical production speed limitations in soil having an overabundance of large hard rocks. Work in competent hard rock formations seems feasible but will

require additional field-testing of cable saw and abrasive grout materials to verify durability and production rates.

In preparing this Final Topical Report, we have benefited from the critiques of several independent reviews. These reviews pointed out several areas of our initial modeling effort that were incomplete. In the final report, we have improved the computer model and added a supplemental engineering analysis of additional possible modes of failure or factors that were omitted from the initial analysis. Many of these improvements are discussed in the Computer Models (section 4.8) of this report beginning near page 14.

We have added consideration of large voids in non-uniform soil, collapse of large voids near the bottom, punching failure due to high density objects, barrier collapse due to high density objects, overcoming a friction stuck cable, use of abrasives to cut rock, the dilution of grout with rock cuttings, cuttings-handling methods, cuttings disposal, fragmentation of the earth block, maintaining fluid flow to cable, physical verification of barrier continuity, and more discussion of how to use the model for cap construction and long term verification. We have also provided a section further describing the limiting conditions and scale-up issues for the technology.

A finite element analysis of potential transient stress of the earth block due to the construction method was performed by our consultant. In this work, they calculated how much stress and strain we can place on the block by lifting it in a non-uniform manner. This was evaluated with a 3-D elastic modeling package that evaluated stress as though the block were a uniform material to determine the potential magnitude of stress. The points of greatest stress were then evaluated by a 2-D finite element computer model that evaluated the both stress and strain using non-elastic parameters designed to simulate performance of natural soil.

Some reviewers suggested that we conduct a more detailed structural evaluation of the earth block that is isolated by the EarthSaw method using a full 3-D finite element technique with specific properties of each cubic foot of a non-uniform block containing various layers of strata, random discontinuities and various types of waste and evaluating the interactions between each element. We have evaluated this issue and believe that additional modeling in this area would not provide any significant further benefit for the following three reasons:

1. One of our initial design goals was the safety benefit of containing an undocumented waste-site without any human exposure to the waste. Structural strength data, of the required quality and quantity, on the interior of a radioactive waste disposal pit is not likely to ever be available for any prospective EarthSaw site.

2. In order to construct a uniform thickness barrier, an EarthSaw project must raise every point on the earth block an equal vertical distance and all loads must be balanced. Verification of this uniformity and adjustments to achieve it would be done immediately after the horizontal cut, and prior to increasing the thickness of the horizontal barrier. Once this balanced condition is achieved, the earth block retains structural loadings identical to those prior to construction. With no change in loading compared to its starting condition, there is really nothing to model.
3. In the EarthSaw method, the earth block is not required to be a structural element. Mechanical fracture, shear, compression or deformation of the earth block does not significantly interfere with construction of a perfect EarthSaw barrier. Cracks and discontinuities in the block do not affect the construction or the final integrity of the barrier because they are automatically sealed by the construction process. The lack of a valid structural failure mode limits the usefulness of the structural analysis. A design goal of the EarthSaw technology was for containment of undocumented waste of unknown physical properties. We want the method to work equally well, regardless of the mechanical strength or condition of the waste or the soil around it. The calculation of how far we can deform a hypothetical earth block before it fractures is an academic exercise that has no end use in the current project.

The EarthSaw technology permits many variations to adapt to the potential variations in subsurface conditions believed to exist at various waste sites. This report attempts to address a wide range of applications and conditions anticipated in radioactive waste burial sites. If this technology is embraced for DOE cleanups, there will be many more reports and papers written. We believe that this Topical Report provides sufficient calculations, drawings, and computer models to demonstrate the viability of the theory, physics and engineering of the EarthSaw technology. This report also provides a robust source of engineering data suitable for the final engineering design of EarthSaw based containment projects at many sites and while providing a framework for continued development of the technology application at others.

4.1 Summary of Interim Report

The Interim Report on task 1 and 2 contains the detailed analysis, construction drawings, computer software models, and equations describing the physics of the method. The Interim report on task 1 and 2 is reproduced in Appendix A in its original form but summarized here in section 4.1 through 4.16 of this report along with the comprehensive field scale test plan and additional improvements.

We have completed detailed calculations to numerically demonstrate the viability of the theory, physics and engineering of the EarthSaw technology. We

developed equations to simulate the buoyant barrier process and the cable saw cutting process. We have developed engineering drawings to fabricate the hardware needed for the field scale demonstration. We prepared detailed design drawings describing the various engineering controls and design options preferred for safety and reliability in the process.

We developed computer models that simulate the installation of a containment barrier using the EarthSaw technology. This computer model simulates variable soil types having different densities, strength of the soil in the cutting plane, tilted subsurface layers, uneven topography, variable water tables, variable waste density, variable water table. Other portions of the model deal with friction fracture, grout flow, logistics, cable friction, and pressure monitoring. The software has been applied to evaluation of several possible DOE waste sites. The model allows analysis of sloped and curved bottom barriers as well as surcharge loadings and variable waste loadings within a disposal cell.

This document was reviewed by DOE in draft form and then revised from the original Interim report to incorporate discussion of issues raised by the reviewers that were not sufficiently addressed in the interim report and answer various technical questions posed by the ASME review. DOE's comments are reproduced in Appendix E. Improvements made as a result of these comments are discussed in the model section.

4.2 Theoretical Proof/Derivation of Buoyancy

The buoyancy of a rectangular block of earth floating in high-density grout is described as follows: The ratio of the grout density to the earth density is equal to the ratio of the total vertical thickness of the block to the thickness that is submerged in the grout. For a given density difference (between earth and grout) the greater the total thickness of the block, the further the block will rise out of the grout.

A block floating on grout in an excavation is no different except that we can now also see how high the block rises above the ground level and how close the grout fluid level is to the ground level. The distance the block rises above the ground level is the same as the thickness of the grout layer under the floating block. The distance between the grout fluid level and the ground level is called "freeboard."

If we vertically divide the block into small finite segments that are not bound together, each one will follow the above rule and rise to its own level. Large blocks of soil in the EarthSaw method tend to be much thin compared to their length and width and so tend to behave as relatively flexible materials. Density and thickness changes tend to be gradual, so each of these mathematically divided

segments will tend to seek its own buoyant level. This simplifying assumption allows us to model the behavior of a large block with very simple equations. For the derivation of the equations, see the *Interim Report on task 1 and 2*.

4.3 Equations Governing The Process

The primary equations governing the EarthSaw process are equations for buoyancy and equations for loss in cutting force due to friction on the cable saw.

The buoyancy ratio equation is: $D_g = (T_b/T_s) \times D_b$

Where;

T_b = the vertical thickness of the block of earth

T_s = the vertical thickness of the portion of the block of earth submerged in the grout

D_g = the density of the grout

D_b = the density of the block of earth

The bottom barrier thickness is: $T_{BB} = [T_b - \{(D_b / D_g) \times T_b\}] - F$

Where;

T_{BB} = the thickness of the bottom barrier or the vertical lift above grade

F = the freeboard depth of the grout fluid level below the surface grade level

Friction of the cutting cable passing around the curve of the cut increases exponentially with the total contact angle and the coefficient of friction. The friction factor is an exponential function of the angle of contact with the soil times the coefficient of friction. This factor defines the ratio of power lost to friction due to the contact angle. This friction reduces the pull of the winch by a ratio factor but can never make it zero. The drag friction is the weight of the cable laying horizontal on the ground times the coefficient of friction. This drag friction subtracts from whatever force remains after applying the friction factor and can cause it to fall below zero, indicating a stuck cable.

The Pounds Total Friction = $e^{\lambda \alpha} + W_h \times \lambda$

Where λ is the coefficient of friction

and α is the angle of contact in radians

and W_h is the weight of the cable laying on the ground surface and in the horizontal cut-

4.4 Field Test Validation of Friction Formula

Because of the complexity of friction between surfaces such as steel cable and soil are not historically well known we put these equations to the test. We placed

a one-inch diameter steel cable in an arc underground and pulled the cable with instrumented dozers to measure the force required to slide across the soil and to shear the soil. The dozers were equipped with wireless remote-reading digital load cells. We also measured the friction loss at various contact angles. We tested direct shear where both dozers pulled in unison and also tested by holding a measured resistance with one dozer while pulling with the other to generate linear sawing motion of the cable through the earth.

We built a friction sled with steel cables for runners and pulled it through three different soil types, both dry and wetted with a three different types of grout. We also ran limited tests on concrete. We recorded friction coefficient values ranging from 0.5 to 1.0

4.5 Step-By-Step Quantitative Descriptions

In the Interim Report, we provided a quantitative discussion of the step-by-step process for implementing the EarthSaw method and provided the numerical calculations applicable to each of twelve sites that illustrated hydrologic and geological differences. The different hydrologic and geologic conditions have only a limited affect on the process. The cutting process is significantly affected by the soil strength and coefficient of friction between soil and cable. The geological conditions may have a significant affect on soil strength and coefficient of friction but no generalized data is available. Therefore, we have designed the model to allow for direct entry of these factors. All of the descriptions are based on the vertical block method using two load frames with winches mounted on top of the load frames.

The EarthSaw work procedure is substantially the same regardless of the site geologic and hydrologic conditions or the type of waste deposited. The EarthSaw method begins with soil borings along the perimeter of the barrier to be formed. This provides data on the in-place bulk density of the soil. Optionally this may be broken down to reflect porosity and water table level. Cone penetrometer and other strength data is also collected at this time. Special monitor wells would then be installed within the “clean” corners of the block as well as outside the perimeter. These borings will help verify if the perimeter is clean and is substantially outside the contaminated area. The data from the borings, combined with any available information of the waste and the size and shape of barrier desired is entered into the computer buoyancy model to help design an approach that will produce a uniform barrier. This may require changes in the depth of the barrier or addition of surcharge soils to portions of the site. The model will also help plan the type of cutting action required, friction, and the size of cable needed.

A conventional vertical slurry trench is excavated around the perimeter of the site to establish the vertical boundary of the barrier to be constructed. The EarthSaw

load frames and cutting cable are lowered in the trench with a crane. The cable depth is mechanically controlled at the four corners of the soil block to be isolated. The TECT grout material is then poured through a tremie pipe to the bottom of the vertical trench, displacing the lighter excavation slurry. The light excavation slurry is pumped off the top of the trench and placed in storage tanks. A civil survey crew then installs a grid of iron survey rods flush with the surface of the soil. This enables the surveyor to monitor the original ground surface as it is raised even if soil is added.

The cable saw is activated by the remote control system to pull or “saw” the cable through the soil. After the horizontal cut has been completed, another elevation survey is performed and soil surface loadings will be adjusted to achieve a uniform vertical lift over the entire area of the soil block. After another survey verifies that the block has been adjusted to a uniform lift of about two inches, additional grout will be added to the perimeter trench to increase the bottom barrier to the desired thickness. A final thickness verification survey would then be performed.

The monitor wells would be fitted with sensors and a synthetic liner would be installed in the perimeter trench and covering the top of the block. Additional earthen cap construction would then be completed according to the specific site requirements.

4.6 Grout Properties

We provided a detailed discussion of the required properties of EarthSaw grouts in the Interim Report and discussed the uses of the main types of TECT grouts. All the grouts have special properties that make EarthSaw possible. These include:

- Density greater than the soil block
- Ability to flow into the horizontal cut
- Ability to suspend cuttings with minimal affect on fluid properties
- Controlled fluid loss properties
- Ability to remain liquid during extended operation
- Ability to seal small fractures and yet not flow into the porosity of the soil
- Suitability for mass production, low permeability
- Resistance to environmental degradation
- Natural analog to durable natural material
- Chemical resistance and stability over time
- Resistance to biological attack

TECH A grout is a cementitious grout having a low water ratio and a high inert solids ratio. The grout has a physical viscosity appearance similar to catsup and can be readily pumped through 4-inch diameter hoses by centrifugal pumps

designed for water service if the pumps are cleaned regularly. The grout is available with or without fiber reinforcement.

TECT B grout is a non-hardening clay based grout. TECT B is applied as a flowable slurry with highly lubricative properties. The grout cures to a peanut butter like condition over a period of 6 to 12 months. In this condition, it is fully self-healing and should offer a very high level of containment integrity over very long time periods. This grout actually provided three means of containment at once: The grout's high hydrostatic gradient prevents groundwater from flowing into the grout. The grout's low permeability impedes groundwater permeating the grout. Finally, the reactive zero valant metals and zeolites in the grout treat contaminants that may eventually diffuse into the grout.

Carter Technologies can also provide special midrange TECT CB grouts that harden over time to between 10 to 200 psi strength yet withstand significant elongation before fracture. These grouts can be thought of as midway between the TECT A and TECT B designs. They do harden but reach properties similar to native clay. Their permeability is higher than the other grouts and they are not able to resist prolonged dry climate as well as the TECT A grout.

TECT W is a high-density version of a molten wax grout used in jet grouting tests at the INEEL, known as WAXFIX. TECT W has a melt point of 125 to 140 degrees F and is prepared and placed at a temperature of about 160 to 180 degrees F. Clean up of equipment may be done with hot water. The molten grout has a high heat capacity and low thermal conductivity so when placed in a large mass it loses heat quite slowly. However, when the grout enters a fracture or permeates into porous soil or rock it loses heat more rapidly and solidifies. This property makes this grout ideal for work in fractured rock. The solidified material made from the preferred polymer is malleable and slightly sticky. A sample hit with a hammer will simply dent or flatten without breaking. A sample cut off with a knife will re-adhere to the original mass with a small amount of pressure. These properties make it an excellent material for a containment barrier that may be subjected to mechanical stress.

4.7 Equipment Design

Most of the equipment needed to implement the EarthSaw method is common construction equipment such as trackhoes, dozers, grout mixes, winches, and a surveyors transit. The method also requires special equipment that we call load frames. These load frames are large but simply constructed steel towers that fit down into the intersections between grout filled trenches surrounding the block of earth to be isolated. The load frame's primary function is to position a large pulley at the bottom of the trench and support a large winch at the surface that pulls the one-inch diameter wire rope cable. The winch and load frame

configuration is the same for all projected EarthSaw operations. The remote controlled units can operate in a back and forth sawing motion in rocky ground or immediately switch to pulling in unison to rapidly slice through soft ground.

The load frame has very large “wing” surfaces that bear against the vertical corner and walls of the earth block on the lower end of the load frame. The geometry of the load frame is such that the soil near the surface sees only minimal loading, but the upper portion also has an equal cross section and bearing area. This uniform cross section should make the unit easier to remove. The wing can be extended to add extra surface area but surface area of the base design is sufficient to allow use in soil as soft as 1-½ tons per square foot with full power. Optionally, the load frames may be pinned to the bottom of the trench by driving a pair of pilings through the openings in the two aft wings.

The load frames and winches used in the phase II demonstration are suitable for performing the full scale remediation of the Paducah C-749 uranium burial grounds or the Los Alamos MDA-C pits after the field-scale clean demonstration is complete. The load frames are designed to be used many times in full-scale work and have been made extra heavy and very much stronger than required to enhance durability. We have prepared final drawings on these load frames and obtained quotations for fabricators to build them. The load frames are long enough to work up to 30 feet deep and can be transported on a standard flat bed trailer. Modular sections can be added to increase operating depth to 90 feet or more. The load frames have been designed for easy decontamination and outdoor storage.

The 125,000 pound capacity winches required for the work are large, and preferably operated by remote control. Winches of this size however, are seldom available for rental in pairs. We have not found a vendor capable of guaranteeing availability of a pair of suitable winches. However, we have obtained favorable quotations from vendors to build suitable winches.

4.7.1 Operational Safety of Equipment

The EarthSaw has been called an inherently safer technology compared to baseline methods such as excavation. The EarthSaw method described herein includes conventional methods of slurry trenching and grout batching operations that are already relatively safe technologies. The new technologies of EarthSaw avoid hazards through careful engineering. The operation of cutting and raising the block of earth does not require significant manual labor and mechanical breakdowns can be repaired without workers entering a contaminated area. Fewer workers on the site also tend to reduce the potential for ordinary accidents. Workers remain above ground and are not exposed to high-energy equipment. The taunt steel cable is located deep underground and the winches are operated by

remote control. Grout materials are non-toxic. The method does not require workers or equipment to be exposed to contaminated material. EarthSaw is preferably applied from the clean perimeter around a site. In this case, contaminated earth is never contacted or disturbed. The EarthSaw can also be safely applied to a “hot spot” within a larger contaminated area by using suitable contamination control procedures.

4.8 Computer Models

Task 2 included predictive computer modeling of the upcoming field test. The modeling activity projected buoyancy and cable friction conditions for different EarthSaw vertical wall configurations. The model was designed to consider a relatively broad range of shapes, sizes, and conditions. The friction input to the modeling was based on field friction tests of steel cable against soil (both wet and dry) using a friction sled. A summary of cable-cutting behavior was prepared from the friction tests and cable-cutting tests, and the summary was factored into field-test design. The means of correcting tilt in a waste block caused by variable soils, waste loadings, variable waste density, water table, and slanting topographies were incorporated into the computer model.

4.8.1 Buoyancy Model

We derived the equations for calculating buoyancy and developed a computer based predictive model implementing these equations to model the performance of the buoyancy on a non-homogenous block of earth. The model allows for any vertical wall, 4-sided, block of earth with variable corner angles and length sides. By shortening one side to near zero length, the model can also deal with 3-sided blocks. The block may have variable depths at each corner and center and may have two distinct layer formations of material such as rock and soil that may be tilted relative to the surface and of variable density from corner to corner. The waste may be deposited in different percentages in each quadrant of the site and the waste may be of different average densities. Void spaces may be simulated by variation in average density of the waste deposited in each quadrant. In sites where the fill material is lower density than original soil, the entire fill volume in each quadrant is treated as a waste container. The model allows a water table depth to be specified also variable void space ratios in the upper and lower formations. The model will allow for an uneven bottom cut that may be tilted or curved. The model allows the user to add or remove surface soil to balance the block and achieve a uniform bottom barrier condition. The user can also vary the depth of cut separately at each corner and in the center to model a uniform bottom barrier even at sites with surface slopes, subsurface density variations, and variable density waste deposits. A barrier sloping to a sump can also be simulated.

4.8.2 Conceptual Basis Of The Model

Generating a uniform bottom barrier requires that the soil block be balanced so that it is not tilted or forced to bend. This requires measurement of the density of continuous core samples taken from the corners of the path of the vertical trench to be excavated. Waste disposal records and soils data are also used to help determine the correct depth profile and grout density required. Fine-tuning of the buoyancy of the block is performed after cutting the barrier by adding or removing surface soil, to achieve balance within the nearest inch. Buoyancy should be adjusted so that all areas of the block have an equal increase in elevation. The model is designed to assist in achieving this condition by providing estimates of how much soil to add or remove.

The mechanical strength or lack of it has little effect on a block of earth that is properly balanced to yield a uniform barrier. The model is not intended to evaluate construction of non-uniform barriers. Therefore, no variables for material heterogeneity are needed in the model. The same is true of fractures and discontinuities within the block. A balanced block made of many broken and fractured segments will exhibit the same buoyant response as a block of uniform material.

4.8.3 Data Output and Display

The model displays both a numerical and graphical representation of the bottom barrier thickness and the resulting top surface of the block relative to its surroundings. This graphic may be dynamically rotated in 3-D space by selecting a corner with the mouse and dragging it. The model incorporates automatic data input validation and pop-up instruction balloons, to minimize input of invalid data. The model runs rapidly on a standard office computer, providing a real time update of the results of each change in parameters. The model also calculates the amount of grout required and the logistics of supply. We demonstrated operation of this model using data from five hypothetical sites pre-approved by DOE.

The model was verified to work with specific conditions and block dimensions that were researched for potential treatment of the Paducah C-749 Uranium Burial Ground; the Los Alamos PRS 50-009 site; the Idaho National Engineering and Environmental Laboratory Pit 9 site; the Hanford high-level waste tanks; and the Oak Ridge National Laboratory Bear Creek Valley trenches.

4.8.4 Cable Force and Friction

The cable force and friction computer model calculates the feasibility of cutting the bottom barrier with specific inputs of cable size, power, coefficient of friction, soil strength, depth, and arc of contact. This model indicates that by using a sawing action we should be able to make bottom barriers up to 500 foot wide and 1000 feet long with the proposed load frame and winch hardware. After considering the results of Phase I friction modeling, the load frame design has been strengthened. Depending on friction, this hardware may be used to construct barriers up to 10 acres in size. Friction of the cable, due to contact angle, is a major factor in project feasibility. Various technical options to reduce friction were developed.

4.8.5 Relationship Between Stress and Barrier Uniformity

The computer model of buoyancy provides the means to control block design so that the EarthSaw process generates very little differential stress on the soil block. Under certain conditions, an unbalanced EarthSaw block may be subject to significant mechanical stresses. This stress can cause the earth block to bend and deform. The buoyancy model may be used as a pre-production tool to prevent these conditions. Conditions that could cause stress include: a non-flat bottom cut, large variations in waste density and excessive buoyancy during the horizontal cut process. The mechanism for this stress is differential buoyancy.

Assume a 400-foot square soil block 30 foot thick. If the middle of the block is lighter than the rest of the block, then that central area will rise more than the perimeter areas. The buoyancy computer model graphically shows the magnitude of this rise assuming the block is large enough to be

fully elastic. This will make the bottom barrier thicker under the middle of the block. The model assumes that no block will remain rigid but will eventually conform to the load placed on it by breaking, bending or deforming. The model helps us determine how much extra soil must be added on top of the central portion of the block to keep the barrier thickness uniform. The model contains two main graphics. One shows the thickness and surface contour of the bottom barrier and the other shows the elevation and contour of the top surface of the block. In uniform conditions, they look much the same. However, if there are major density variations or we have re-contoured the surface soil to make the barrier thickness uniform, then these two surfaces no longer match. If the earth block is made of soft soil, this effect may be noticeable in smaller blocks too.

It should be noted that if the soil within the block is sufficiently strong, the elastic response might be reduced or eliminated. In that case, the block may act as a rigid body. In smaller blocks such as the 50 foot square by 30 foot

deep field scale test, the block may be too thick to allow much deformation but variations in density and voids can cause one edge of the block to float higher than another. The computer model allows us to determine correct surcharge loadings to adjust for this and produce a uniform lift with no significant stress on the block. In order to construct a uniform thickness bottom and side barrier using buoyancy, the earth block's top surface must float parallel to the original ground surface. (See Engineering Controls section of the field work plan) This implies that the final buoyant position of the block is not listing to one side or bent by unbalanced forces. Any forces that would tend to change the original surface slope of the block must be counter balanced to achieve our objectives of a uniform barrier. The model may be used to evaluate varying the depth and slope of the bottom cut and the impact of adding or removing earth on top of the block. This inherent requirement for balanced forces limits the potential for meaningful stress analysis work to descriptions of the transient loads that can flex the block as it is being cut and balanced.

4.8.6 Cracks, Discontinuities and Voids

The TECT A and B grouts are thixotropic fluids that are designed to seal off in narrower cracks while flowing freely into large ones. Molten wax based TECT W gets the same effect through greater heat loss in the smaller cracks. If cracks form in the bottom or sides of the soil block during the horizontal cut, or the soil already contains such cracks connected to the cut barrier area, they will be automatically filled and sealed off by the barrier grout. This is a very useful feature since the undiscovered presence of such features can cause failure of competing technologies. The sealed cracks will probably have a lower permeability than the original soil. The grout can never rise higher in a discontinuity than the elevation of the grout in the trench. Fractures and cracks which do not contact the barrier will, of course not be sealed or filled with grout. Large cracks and voids crossed by the cutting cable have the potential to consume large volumes of grout. However, the volumes of grout available in the vertical perimeter trench are such that many truckloads of grout are required to make any visible difference in grout level.

4.8.8 Transient Stress during the Horizontal Cut

Stress due to excess buoyancy during a cut may occur due to errors in assumed soil density. We evaluated the probable magnitude of these stresses using an outside consultant. We evaluated stress produced with up to 12 inches of excess buoyancy at three points in the progress of the cut, in three different simulated site conditions. Results indicate that in the modeled conditions, the earth block will not crack due to 12 inches of excess buoyancy. See the consultants complete report below in section 2.4.

4.8.9 Effect of Water Table

The computer buoyancy model shows that water table and porosity of the soil prior to operations, affect density and thus buoyancy quite significantly. If data on the net wet bulk density of the entire soil interval is collected from borings in the four corners of the site then the water table variable may be overridden by setting porosity to zero. Once the barrier is constructed, water can no longer enter or leave the earth block and increases in the external water table will have no effect on the barrier because the barrier and all that is in it are much heavier than water. Removal of ground water within the block will reduce the weight of the block and thus tend to increase the thickness of the barrier if a non-hardening TECT B grout was used.

4.8.10 Cap Significance In Verification

The cap structure is an integral part of the barrier and is formed by a combination of a top synthetic liner, which is keyed into the vertical wall, a concrete or clay perimeter ring placed in the upper portion of the trench, and an earthen cap. For 1000 year durability, we suggest that a rock armor layer and nontoxic bio-intrusion-resistant materials mixed with cap soil may be more effective than traditional vegetative caps for applications where institutional control can not be maintained. For saturated sites, a monitor well within the block may be used to remove ground water from the interior, and then verify that additional ground water does not leak in through the barrier. For dry sites, the airtight cap structure allows the integrity of the vault to be monitored by air pressure differentials that occur naturally with changing weather. A computer model was prepared to simulate collecting barometric pressure data from a monitor well inside the block and comparing it to data from the soil outside the block. Statistical tests were used to infer if the data had a significant correlation.

4.8.11 Modeling Deflection In Unbalanced Soil Blocks

Modeling of shear stresses for large non-uniform blocks incorporating large voids was evaluated in the following manner. Stresses could, in theory, be created by differential buoyancy acting on block with large voids or very heavy waste deposits. If a block were to be very light or heavy in an area, that area would experience extra force urging it to rise or sink relative to the rest of the block resulting in a bending load on the block. If the block had no structural strength it might deform significantly and possibly develop fractures within the block. The buoyancy model can be used to predict the maximum deflection that could occur. Actual deflection would be less if the soil has significant structural strength.

However, for these deflections to occur, the EarthSaw block would have to be floating on a very thick layer of grout. When the bottom cut is made, the earth block has only a few inches of net positive buoyancy and so it can only deflect a few inches. In order to generate a uniform bottom barrier thickness this deflection must be eliminated. After the cut is complete, the post-cut elevation survey would show this deflection and the surface soil would be re-contoured to eliminate this stress before grout was added to raise the block to final position.

4.8.12 High Density Objects

Another aspect of non-homogeneity we considered was the effect of high-density objects within the waste deposit area. The grout can support soil because it seals the surface of the soil and acts on the bulk density of the soil. Would a sufficiently heavy object near the bottom barrier fall through the liquid grout?

During the excavation of the first field test, we noted that I could walk on a top of an 18-inch thick layer of fluid grout in areas having about 12 inches of sand still covering the grout. To support my 190-pound weight the sand must be spreading the load over a larger area. The grout weighs about 160 pounds per cubic foot. Since this wet sand had little strength, the interface between the grout and the sand would have to deflect enough to displace $190 \text{ lb} / 160 \text{ cubic feet} = 1.19 \text{ cubic foot}$ to buoyantly support me. For an observed deflection of less than 2 inches, the load must have to be spread to the equivalent of a 3-foot diameter area. If we attempted to walk on areas covered only by a 2-inch thick sand layer, this would probably result in our feet breaking through and falling through the fluid grout. The soil could shear or “punch through” around the 24-inch long perimeter outline of my boot if the sand’s shear strength was less than $(2 \text{ in} \times 190 \text{ lb} / 24 \text{ in}) = 3.9 \text{ psi}$.

We know that some rocks will be dense enough to fall through the fluid grout. However, most rocks will not fall through a significant thickness of soil. If the grout supports the soil, then the soil will hold up the rocks just as it held us up when we walked on soil above the grout. In Section 5.6 of the Interim Report, we discussed how rocks and cobbles near the cutting cable may fall into the liquid

barrier unless they are supported by soil around them or have enough soil below them to distribute their weight. This is mentioned as one reason for choosing to make the barrier thicker than the diameter of the largest rocks.

It should be noted that high-density objects, such as a 10-inch diameter steel bar, generally do not sink very far into the ground regardless of how large they are. The explanation for this is that the ground below them becomes stronger as it is compressed due to friction between the grains of soil. This effect spreads the load so that it can be supported at the grout/soil interface. Once an object sinks below the surface its net downward force is reduced due to the buoyant effect of the surrounding soil. How thick a layer of soil is required to support a heavy object? It depends on the depth, the density, to overall weight, the friction angle, and the load footprint of the object.

4.8.13 Punching and Local Deflection Due To Heavy Objects

If there were a very dense object, such as a 20 inch tall and 20 inch diameter round bar made of solid steel in a 20 foot deep pit, the soil under it would already be compressed enough to support it so it and this compressive load is not altered just because we support the soil below it with buoyancy. This compression increases the shear strength of the soil. For the bar to drop through the soil, it must punch through the soil below it. At the least, this would be a shear area equal to the circumference of the bar times the thickness of the soil below it. For a 2 foot thick soil layer this is 20 inches x 3.141 x 24" = 1508 square inches. The bar weighs 1778 pounds in air but only 1342 pounds submerged in 120 pound per cubic foot soil. For the bar to punch through to the grout, the soil would have to have a very low minimum shear strength of 1342 Lb/1508 sq in = 0.89 psi.

However, the extra concentrated weight could theoretically, cause the bottom of the block to bulge if the soil had no mechanical strength. Steel has a density of about 489 pounds per cubic foot. At a depth of 2 feet below it, assuming a friction angle of 30 degrees, the 1778 pound bar's weight is distributed over a 47.7 inch diameter circle. (12.4 square feet of area) We can use the buoyancy model to evaluate this or perform the calculations manually. If the average soil density were 120 pounds per cubic foot, the bar would add a net 1342 pounds of weight to the 12.4 square foot area at the grout interface. If the barrier is 30 feet deep, then the volume of the block in this area is 12.4 sq ft x 30 ft = 372 cu ft. The bar adds 1342 lb/372 cu ft = 3.6075 lb/cu ft of density yielding an average density of 123.6075 lb /cu ft.

The bottom barrier thickness equation is: $T_{BB} = [T_b - \{(D_b / D_g) \times T_b\}] - F$
 If the grout is 150 pounds per cubic foot and freeboard is 2 foot, this will result in a thickness of: $[30 \text{ ft} - \{(123.6075 \text{ pcf}/150 \text{ pcf}) \times 30\text{ft}\}] - 2\text{ft} = 3.2785 \text{ feet thick}$ in the heavy area compared to a nominal thickness of 4 feet in the other areas. In

typical soil conditions, the mechanical strength of the soil would spread this load even further and there would be an even smaller change in barrier thickness.

Placing these density values into the computer buoyancy model, with a waste density of 489 lb/ cu ft and a waste loading percentage of 0.977449% in one quadrant having an area equal to 12.4 square feet also yields a normal barrier thickness of 4 feet and a reduced barrier thickness of 3.28 feet in the heavy area.

This deflection would be immediately noticeable to the elevation survey team. Repair options include removing some soil from the area over the object to reduce the unit weight.

4.9 Applicability Limitations

The study indicates that the EarthSaw is applicable to both wet, dry, and water saturated sites and that the water table has little impact on construction. For EarthSaw to work, the cable saw must be able to cut through the soil and the grout must not leak out into the formation. The soil type can limit the ability to cut the bottom barrier. Sand and soft soils appear to be easy for the process to handle. Gravel mixed with sand should not present a problem but clean gravel formations (1" diameter rocks with no sand or soil between them) would not be feasible because the grout could leak away. Fractured basalt with many vertical fractures such as at the INEEL site may require use of the molten wax based TECT W grout, however even this might not work if the fractures are sufficiently large. Cutting in rubblelized hard rock or clean gravel zones may not be feasible because of grout leakage.

In our test, we found it easy to saw through a cubic foot size limestone rock with a plain steel cable. We easily cut through a sample of volcanic Tuff received from Los Alamos National Laboratory. Cutting in soft rock such as limestone and sandstone appears to be feasible. Hard soils containing many large rocks may be slow to cut with standard wire rope. If the rocks are frequent or very hard, the cable will require frequent replacement. Cutting in harder rocks will require further testing on special cable with an abrasive grout for the application.

There do not appear to be any buoyancy limitations on the method, but there may be economic limits based on the fact that the cost per gallon of grout rises significantly as we move from specific gravity of 2.5 to 3.5 which might be required for working certain solid rock formations. The Idaho RWMC area at INEEL is underlain by volcanic basalt rock that is said to have a relatively light 2.6 average specific gravity. Therefore, grout for this site would be within the medium price range. The site selected for the first field test has the potential for large earthquakes so we have focused on the use of the soft non-hardening TECT B grout for its potential to construct an earthquake resistant barrier.

Work in sites having many voids, density variations, and planes of weakness has caused initial concern to some reviewers, but as long as the engineering controls on depth of cut and surcharge loadings are correctly applied and excess buoyancy is limited the method appears applicable even to blocks having these conditions. These sites can be contained and raised without significant deformation to the soil block. One simple way to minimize variations in density is to simply increase the depth of the bottom barrier. This may be desirable when working with buried tanks that are relatively fragile. Large voids and discontinuities within the soil block will be automatically filled with grout if they are in contact with the barrier layer or so close to it that they collapse. If they are not in contact with the barrier, they will impact only the bulk density of the soil block and make the barrier slightly thicker.

The maximum size of a barrier is limited mostly by friction. Using only two load frames with a one-inch diameter cable with 100,000 pounds of winch pull and coefficient of friction of 1.0, the maximum size cut is about 500 foot wide by 1000 feet long. Reducing the friction or increasing power can make larger cuts possible. Use of the optional backhoe attachment discussed in the work plan to reduce the contact angle can increase the maximum size significantly. Reducing the contact angle from 180 degrees to 90 degrees allows sites as large as 2000 feet by 2000 feet to be cut by cable sawing action.

There are possible economic limitations regarding the minimum size of an EarthSaw containment barrier. As EarthSaw projects become larger, the cost of the grout and other factors is greatly reduced. At the size of 50 foot square and 30 foot deep the surface area to volume ratio is 0.1293 sq ft/cu ft. At the size of 200 foot square by 40 foot deep the surface area to volume ratio is 0.0475 sq ft/ cubic foot, and the cost per cubic foot is only 37 percent of the unit cost of the smaller site.

The technology appears to be limited to sites that are relatively flat. Working on a hillside with slopes greater than 10 feet from one side of the site to another is probably not feasible. This could complicate application at some of the Oak Ridge Bear Creek Valley trenches. These trenches would have to be done in two separate sections.

A with a building on it would not be a problem because the weight of the building is generally small compared to the soil block. However, the method is difficult to apply to landfills that rise like a tall hill above the surrounding landscape. The problem of attaining sufficient buoyancy may be addressed to some degree by making the barrier deeper, to increase the vertical lift. However, the vertical block method would tend to make the barrier thicker at the edges. A directional drill based version of the technology may offer a means of dealing with this type

of site but discussion of it is beyond the scope of the current work, which focuses on the vertical block method.

Another limitation concerns sites that have require the perimeter barrier to be constructed in contaminated soil. When constructing the vertical slurry trench in contaminated ground, some of the inherent safety of the method is not realized because contaminated spoils are still produced to dig the vertical trench.

4.10 Schedule and Cost of Phase I

Total cost of Phase I is expected to be the contract price of \$277,662 and duration is expected to be 13 months.

4.11 Hazardous Waste Report

No hazardous wastes were generated during this project.

4.12 ASME Peer Review

We presented the EarthSaw Interim report on task 1 and 2 to an American Society of Mechanical Engineers peer review panel on June 4th of 2002 prior to beginning task 3. The panel's report called EarthSaw an important and inherently safer design and recommended going forward with a site demonstration. Both the design and implementation of the EarthSaw project are consistent with established scientific and engineering principles and standards. They said the Project Team has the required expertise, and includes individuals qualified in their respective fields. The Project Team documented the assumptions underlying the physical model, and presented the equations used in the mathematical models, with the exception of the stress analysis model. The EarthSaw technology has the advantage of relative simplicity in that it minimizes the number of mechanical components.

However, they also said: "The modeling of the subsurface conditions is not adequate to provide an analysis of technology viability. The effects on buoyancy due to different densities and different layers are taken into account. However, vertical discontinuities, vertical lithological heterogeneities, planes of weakness, and large-scale voids are not accounted for by any one component of the modeling system."

Unfortunately, the panel did not mention how they assume these factors could affect construction, and we were refused permission to ask the panel this and other similar questions to clarify the panel's comments. It is not clear if this represents a flaw in the ASME review system or an error of the moderator in our

particular review. Our analysis indicates no mechanism for these factors to significantly affect construction other than density and permeability. It should be noted that lithological factors within the earth block are not required in the buoyancy model and that a key advantage of the EarthSaw technology is that they have little influence on the construction process.

The panel also made several puzzling comments on the “transition” between the use of the cable saw as a slicing tool versus its use as an abrasive sawing tool, apparently not understanding that the load frame hardware is designed to use both methods without interruption, according to load conditions and even to switch from sawing to slicing automatically.

4.12.1 Structural Modeling

It has been suggested that we should finite element model the stresses on the earth block as though it were a structural element, which should be protected from mechanical damage. A waste disposal block may be thought of as a collection of thousands of rocks, various layers and pockets of soil, and debris with random planes and angles of weakness and strength. Good quality data on the triaxial structural strength and discontinuities of an undocumented radioactive waste disposal pit are highly unlikely to be available or obtainable. This would require detailed continuous soil borings through every cubic foot of the entire earth block and expose workers to many hazards. Therefore, any model of the structure of a highly heterogeneous block would be based largely on guesses about properties of each element and its relationship to adjacent elements. Consequently, the design objective of the EarthSaw is to design the process so that this data is not required to achieve our objective.

4.12.2 Failure Mode Analysis

Cracks, fractures, distortions and stresses in the earth block do not prevent the construction of a perfect barrier. If a burial ground consisted of nothing but billions of shoeboxes filled with dirt and all neatly stacked together we could use EarthSaw to cut a vertical path around a selected million boxes. The grout might flow quite far into most of the spaces between the shoeboxes on both sides of the cut before sealing off. Vertical discontinuities could occur through out the entire block separating the boxes into distinct segments. However, the grout would still form a complete barrier under and around the boxes we choose to contain. The grout could fill every space between the boxes and other than changes in net density of the block, it would have no impact on our ability to create a uniform barrier. It does not matter if some of the boxes are crushed or if some pull apart from the others more or less? If they pull apart, the spaces between them will be filled with low permeability grout to seal the gap. We believe that the lack of a

valid failure mode along with the lack of structural data inherent in old waste pits renders the suggested structural analysis useless.

The objective of a properly designed EarthSaw project is to construct a uniform bottom barrier. To accomplish this, every part of the block must be lifted the same vertical distance. If a given area of the block has higher weight, it will not rise as high as the rest of the block. (and stress will be induced). We have two ways to compensate. We can change the weight by removing topsoil, or we can make the bottom barrier deeper in that area. The same factors that produce a uniform bottom barrier also result in maintaining the same stress distributions and compressive loads that existed before barrier construction. Vertical lithological heterogeneities, vertical discontinuities, and planes of weakness in the block allow each section of the block to respond more independently to buoyant conditions within an immediate area during the transition period as the block is first cut and leveled.

4.12.3 Large Scale Voids

Large-scale voids are represented in the model in the sense that if they are known they may be included in the model data as an increase in the void ratio of the soil layer or a decrease in the average density of the waste containers in any quadrant of the block. We believe that the actual size and distribution of voids will be an unknown factor in many cases. Heave collapse of large voids near the bottom of the block were mentioned by the Peer Review Panel. There is very little new or additional force available during the lifting of the earth block to cause such a collapse. Collapse of voids has no serious consequence other than a variance in the weight of an area of the block. This will become apparent when performing the elevation survey after the horizontal cut but before the extra grout is added to increase barrier thickness. At this time, additional soil will be added to the floating areas of the block and perhaps removed from the non-floating areas to balance the block before adding all the final batch of grout.

4.12.4 Balanced Blocks

In order to construct a uniform thickness bottom and side barrier using buoyancy, the earth block's original top surface must remain parallel to the original ground surface. This implies that the final buoyant position of the block is not listing to one side or bent by unbalanced forces. Any forces that would tend to change the original surface slope of the block must be counter balanced to achieve our objectives of a uniform barrier. The buoyancy model can be used to evaluate varying the depth and slope of the bottom cut and the impact of adding or removing earth on top of the block to achieve this balanced condition. This inherent requirement for balanced forces limits the application of stress analysis

to descriptions of the transient loads that can flex the block as it is being cut and balanced and punching failure caused by high density objects located very close to the bottom barrier. In order to evaluate the transient stresses, we contracted with a professor of geo-mechanics at a major university to perform a finite element modeling task however his final report was not complete until after the Peer Review. The full report is reproduced in pages 30-40.

4.12.5 Punching Failure Model

We can calculate the potential for an object “punching” through the soil into the fluid grout. Suppose we have a cylindrical drum measuring 25 inches in diameter and 48 inches tall (13.6 cubic feet) with an average density of 312 pounds per cubic foot or twice the density of the grout sitting on only 2 feet above the bottom horizontal cut. If the soil is 125 pounds per cubic foot, the drum is 187 pounds per cubic foot heavier than the soil and exerts a net downward force of 187 pounds/cu ft x 13.6 cu ft = 2543 pounds. If we assume a worst case condition where punching shear acts as a vertical shear force at the perimeter of the high density object then we have a shear area of 25” x 3.141 x 24” = 1885 square inches. So the soil must resist a shearing force of 2543 pounds / 1886 square inches = 1.35 pounds per square inch. Most soil has shear strength many times this level. It also is unlikely we would choose to make the bottom barrier so close to the bottom of the pit. While punching failure should always be considered, it is unlikely to be significant in most projects.

Most high-density waste is contained in packages that reduce the net density. Metal parts disposed in crushed Tuff behave as one large package. Drums of uranium metal dust and turnings buried at the Paducah Gaseous Diffusion Plant C-749 pit were packed with oil. According to the detailed records we obtained, the average density of the drums was about only 216 pounds per cubic foot in the quadrant having the heaviest drums.

4.12.6 Rock Cuttings and Other Excluded Data

The Peer Review panel also said that the step-by-step description provided only limited information on cable sawing in rock formations and provided no information regarding: 1) the dilution of grout with rock cuttings; 2) cuttings-handling methods; and 3) cuttings disposal.

Cuttings are the particles of soil and rock produced by cable sawing operations. These cuttings are generally carried along by the cable and are suspended in the grout. The movement of the cable acts as a pump to move grout through the horizontal cut. Cuttings tend to make the grout viscosity rise and this increases the ability of the cable to pump grout through the cut, which in turn brings fresh lower viscosity grout back into the cut from the other side. Some cuttings may fall and stack up on the bottom of the trench,

while others will be dispersed in the grout. These cuttings become a permanent part of the grout. Some small fraction of the cuttings may be carried up to the winch by the cable, where they will fall back into the trench.

The panel noted the absence of field work plans, safety reviews and costs. These items were part of the scope of task 3 and thus were not available for the peer review but are included in the current report.

4.12.7 Model Improvements

The panel said that the buoyancy, stress analysis, and cable-friction computer models adequately implement the theoretical equations but the boundary conditions used for the buoyancy computer model limit the validity of the simulations to soil blocks experiencing small strains. However, the panel also recommended proceeding with a field scale demonstration after correcting modeling deficiencies. The subcontractor supplied, finite element portion of the computer model was not yet complete during this review, but the completed report is presented in section 2.4 herein. After the peer review, the computer model of buoyancy was upgraded to allow the block to flex in the middle due to variable density of depth at the midpoint. This will allow the model user to evaluate means to prevent deformation of the block. If the above discussion of modeling issues does not resolve all questions, we would expect to perform additional modeling at the beginning of Phase II.

4.12.8 Positive statements

The review panel also said: The design of EarthSaw appears to be “inherently safer” because:

1. It does not require working underground
2. It is designed to be implemented outside of, and below, the area of contamination (thus limiting the transport of the buried waste to surface)
3. Under normal operating conditions no personnel are expected to be within 15 to 30 meters of the operation area
4. Cable winches are expected to be remotely controlled

Considering the residual risks remaining for workers, the remedial capabilities of the EarthSaw technology appear to be sufficiently important to warrant going forward with a site demonstration. Remedial capabilities of EarthSaw include the ability to provide a low-permeability barrier on the sides and bottom of the waste disposal site. Combined with capping, this technology has the potential to: 1) isolate the waste; and 2) allow for monitoring of containment.

4.13 Finite Element Stress Analysis

Following is the proposal from Dr. Grabinski, professor of Geo-mechanics at the University of Toronto, on the stress analysis:

65 First Avenue, Toronto, ON, Canada M5S 1A4

Phone 416 462-3557 Fax 416 946-5014

Email murray@civ.utoronto.ca

FINAL REPORT

3-D Elastic Modeling of Three Hypothetical EarthSaw Sites

Submitted to

Ernie Carter, P.E.

CARTER TECHNOLOGIES CO.

Underground Engineering And Environmental

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Submitted on

July 4, 2002

July 4, 2002

Ernie Carter, P.E.
 CARTER TECHNOLOGIES CO.
 Underground Engineering And Environmental
 9702 Garden Row, Sugar Land, TX 77478
 (281) 495-2603 Voice (281) 495-0540 Fax

Re: Final Report on 3-D Elastic Modeling of Three Hypothetical EarthSaw Sites

Dear Ernie,

Enclosed are the final analysis results of three-dimensional elastic modeling of three different site conditions where the EarthSaw technology is being considered for potential application. While the modeled conditions are meant to be representative of actual sites, there is currently limited geotechnical data available for any of the actual sites and so an attempt has been made to come up with reasonable modeling parameters based on the assumed or hypothesized conditions.

As explained in the original scope of work prepared for these analyses, the intention of this work is to provide you with insights regarding the extent to which the EarthSaw process may cause distress to the isolated soil mass, and the potential mechanisms responsible for any such distress. It is important to reiterate that, under the terms of our contract, it is not possible to consider the entire range of parameter values for all possible parameters for any generic site. Based on the information you have made available to me, I have selected modeling parameters and values that are consistent with published literature and used in geotechnical engineering practice. This should be sufficient for the preliminary feasibility study stage at which the EarthSaw technology is currently being evaluated. Once the EarthSaw technology is to be attempted at an actual site, a detailed geotechnical site investigation must be carried out and the analysis results presented here must then be re-evaluated in the context of the findings of such a site investigation.

A sub-contractor, Rocscience Inc. of Toronto, Ontario, carried out the three-dimensional elastic analysis using their proprietary boundary element modeling package *Examine*^{3D}. There are three predominant forms of boundary elements viz the direct, the displacement discontinuity, and the fictitious stress formulations. A complete review of each is beyond the scope of this report, but it should be pointed out that the developers of *Examine*^{3D} have published leading works in internationally peer-reviewed journals and, as such, the *Examine*^{3D} package establishes the standard in this form of stress analysis technology.

A feature of any linear elastic analysis (whether based on boundary elements, finite elements, or analytic solutions) is that computed displacements are proportional to applied loads, and inversely proportional to material stiffness. In the case of the EarthSaw technology, the applied loads viz the grout pressures and gravitational loads are known with a high degree of certainty, whereas the material stiffness is not. As a result, computed elastic displacements must be treated with a high degree of caution. Indeed, it

is probably more appropriate to calibrate the material's elastic stiffness so as to obtain displacement magnitudes that are in the range known or expected to occur. For this reason, little use of displacement magnitudes in the following results, except for comparative purposes between elastic and plastic analyses at the end of this report.

Another important limitation of the modeling package employed is that the buoyancy effect cannot be modeled directly. As a result, we have used a "worst case scenario" of grout pressures equivalent to a final block uplift of 12" and these pressures remain constant on the base of the modeled block (as compared to the real situation, where the base pressures decrease as the block rises relative to the free surface of the grout). However, this assumption will have the effect of generally over-predicting the induced stresses and displacements in the isolated block.

As a final general note, the predicted elastic stress concentrations at the leading edge of the cut are very dependant on the assumed leading edge geometry. For example, a preliminary estimate of these stress concentrations could potentially be made based on available analytic solutions for pressurized cracks near a free surface. However, these analytic solutions assume the crack to be infinitesimally thin, whereas the actual geometry is considerably more blunt at the leading edge, and the excavated crack has a thickness that is quite finite as compared to the depth of overburden. Hence, although all reasonable attempts have been made to ensure the elastic analysis results are "convergent" and therefore accurate for the assumed geometry, it is foreseeable that other attempts to model the same problem but with different assumed leading edge crack geometries could generate nominally different induced stresses. In the end, however, these differences are probably moot, as nonlinear material response will tend to dampen these concentrations (as demonstrated by the nonlinear analysis at the end of this report).

Each of the three case studies will now be considered in turn, followed by a more generic two-dimensional nonlinear analysis.

Site #1

The conditions for Site #1 were roughly based on the available information for Paducah, Kentucky. The geometry for each of the three analysis stages is shown in Figure 1. The block is 35' deep.

Figure 1. Geometry of the three stages of analysis used for Site #1.

Perspective views of each analysis stage are shown in Figure 2.

Figure 2. Perspective view of three geometries used for Site #1.

The top of the isolated block has been removed so that the base of the cut can be seen. The black portions at the base represent the solid soil yet to be cut, the blue portions are the saw-cut areas.

The average density of the material, provided by Carter Technology Co. spreadsheet calculation tools, is 130.1 pcf. The vertical in situ stress is governed by this unit weight, and the horizontal:vertical in situ stress ratio, K_0 , is taken to be 0.8 (typical for the types of soils determined to be at this site). Grout freeboard of 4' is simulated, and the grout density is taken to be 152.0 pcf which is equivalent to 12" uplift of the block once cutting is complete.

The “minimum principal stress” is a measure of the least compressive direct stress acting within the block at a given point. Before cutting begins, the minimum principal stress is horizontal and equal to $0.8 \times (\text{overburden weight})$ at any given depth. The figure below shows cutting planes through the center of the isolated block at the three different stages of analysis, with contours of the new minimum principal stress for each respective stage shown on the cutting planes.

Figure 3. Contours of minimum principal stress (least compressive) through middle of the soil block for Site #1. ($\gamma_{\text{soil}}=130.1\text{pcf}$, $\gamma_{\text{grout}}=152.0\text{pcf}$, $E=450\text{ksf}$, $\nu=0.3$, $K_0=0.8$)

The main feature to note from these images is that the in situ stress contours (indicated by the color bands at the far left of each cutting plane) deviate very little from the induced stress contours (closest to the leading edge of the cut), suggesting that the cut is having a minimal effect on the stress distribution within the block. Indeed, similar contours of “strength factor” based on an assumed strength criterion such as Mohr-Coulomb also show minimal effect of the cut (although these have not been reproduced in the report).

Site #2

The conditions for Site #2 were roughly based on the available information for Los Alamos. The block is 40' deep and the cut geometries are given in the Figure 4.

Figure 4. Geometry of staged analysis for Site #2.

The above drawing is not to scale; the perspective view in Figure 5 provides a better sense of the relative dimensions of the isolated block.

Figure 5. Perspective view of 2nd stage of analysis for Site #2.

This block is modeled with an average density of 111.84 pcf, and an in situ stress ratio of 0.8 is again used. (Much less information is available regarding suitable in situ stress ratios for these types of materials, and so this parameter should be given particular attention in any future geotechnical site investigation.) This analysis assumed 6' of grout freeboard and a grout density of 136 pcf to once again produce an equivalent uplift of 12" upon completion of the base cut.

The last analysis stage did not produce convergent results, suggesting that horizontal fracturing sufficient to finish the base isolation of the block would be likely for this advanced stage of excavation (i.e., the stresses would enhance the cable's effectiveness in the final stage of cable cutting). Analysis results for the first two stages are presented in Figure 6. As with Site #1, the analyzed stress perturbations in proximity of the leading edge of the cut are minor.

Figure 6. Contours of minimum principal stress (least compressive) through middle of the soil block for Site #2 (the view is in the horizontal plane, directly on the vertical cutting plane). ($\gamma_{\text{soil}}=111.84\text{pcf}$, $\gamma_{\text{grout}}=136.0\text{pcf}$, $E=14,400\text{ksf}$, $\nu=0.3$, $K_o=0.8$)

Site #3

The conditions for Site #3 were roughly based on the available information for the INEEL pits and trenches. The geometry for each of the three analysis stages is shown in Figure 7. The block is 27' deep.

Figure 7. Geometry of staged analysis for Site #3.

Perspective views of each analysis stage are shown in Figure 8.

Figure 8. Perspective view of three geometries used for Site #3.

The average density of the material is given as 132.38 pcf and the in situ stress ratio is again taken as 0.8. (As with Site #2, this value needs to be confirmed through site investigation.) The grout freeboard is 4' and grout density is 163 pcf in order to model an equivalent final uplift of the isolated block of 12".

Stress results in terms of minimum principal stress are shown in Figure 9. Once again, the modeled cut appears to have no significant effect on the isolated block.

Figure 9. Contours of minimum principal stress (least compressive) through middle of the block for Site #3. ($\gamma_{\text{soil}}=132.38\text{pcf}$, $\gamma_{\text{grout}}=163.0\text{pcf}$, $E=144,000\text{ksf}$, $\nu=0.3$, $K_o=0.8$)

For all three sites considered so far, additional analysis results could be processed in a number of ways, including generating multiple cutting planes and/or isosurfaces within the soil volume to show three-dimensional effects, stress ribbons through the volume to show stress channeling, and safety factor contours to show localized regions of most significant effects on the block. These, however, do not change the general conclusion that the modeled process does not significantly disturb the block. Again, this conclusion is based on the model parameters and values assumed (which must be verified by in situ testing) and based on the assumed finite-width crack created by the cutting process.

2-D Nonlinear Analysis

In order to demonstrate the effect of a more severe crack geometry assumption (i.e., an infinitesimal width crack) and also the effects of material nonlinearity, an idealized mid-section was taken from the Site #3 geometry at the last stage of cut (i.e., as shown in the cutting plane in the far right of Figure 9) and used in a finite element analysis. With the FE analysis it is much easier to incorporate the buoyancy boundary condition on the cut surface at the bottom of the block, and so this was done for the nonlinear analysis (otherwise, the simulation becomes physically and numerically unstable). The equivalent of 12" uplift buoyancy was simulated.

The first analysis is an elastic one, and the crack geometry and pressure and displacement boundary conditions have been specifically selected to generate a "worst case" scenario (i.e., the predicted stresses from this analysis are expected to be significantly higher than those from the Site #3 analysis in the preceding section). The minimum principal stress results for the first elastic analysis are shown in Figure 10. All tensile stress are shown in gray, and it can be seen that the stresses are significantly more tensile than was the case for Site #3. The general shape of the tensile zone is similar to that arising from the analytic solution for a pressurized thin crack. At first glance one might assume that the block was undergoing severe distress, but to understand the problem more fully a nonlinear analysis is required.

Figure 10. Elastic stress distribution for “worst case scenario” (most severe geometry) 2-D analysis (gray zone is the predicted region of tension; 12” simulated buoyancy).

Because a soil mass cannot withstand such tensile stresses, a nonlinear analysis must be used to determine the consequences of stress redistribution associated with soil failure. For the nonlinear analysis a conventional Mohr-Coulomb failure criterion with cohesion nominally zero and friction angle equal to 30° is assumed. These values are typical of cohesionless sands, for example. The minimum principal stress distribution after failure is allowed to take place is shown in Figure 11.

Figure 11. Stress distribution for “worst case scenario” (most severe geometry) 2-D analysis after plastic stress redistribution (compare to Figure 10 and note how all tensile stresses have redistributed to result in a stable block).

Note how, in the region predicted by the elastic analysis to be in great distress due to the formation of tensile stresses, material failure has permitted stress redistribution such that the block falls back to a compressive stress regime. This is achieved primarily through the formation of a “plastic hinge” as shown by the plot of plastic strain in Figure 12. It should be noted that the block would not undergo tensile fracturing, even though the elastic model suggests large tensile regions. This is because the nonlinear analysis involves the gradual application of loads such that the stress path of any given point approaches the shear failure envelope first, with plastic straining and stress redistribution following. In other words, because the failure criterion does not allow the formation of any tensile stresses, the material will always fail in shear and never in tension, and so a “tension crack” simply cannot be formed. The plastic regions shown in Figure 12 therefore indicate where the material is being sheared (similar to shearing a deck of cards) and the shape of the plastic zone at the bottom should not be used to infer propagation of a tensile crack up into the block.

Figure 12. Zones of plastic shear straining, showing formation of a plastic “hinge” that dissipated tensile stresses (no tension cracking is permitted by the failure model used).

If the 3-D elastic simulations were modified to use more severe (i.e., flatter) crack geometry and higher grout pressures, the 3-D results could be made to more closely resemble the 2-D elastic results presented in Figure 10. However, based on the 2-D nonlinear simulation, we can reasonably expect that 3-D plastic straining would then follow and stresses would be redistributed to result in a stable block (as shown in Figures 11 and 12). Of course this should be verified with full 3-D nonlinear analysis, although such analyses can only be achieved at considerably greater effort and computational expense.

Conclusion

Perhaps the most useful conclusion can be drawn from the combined results of the 3-D elastic analysis for Site #3 and the 2-D plasticity finite element analysis for Site #3’s equivalent mid-section. As discussed, the predicted elastic stress distribution at the leading edge of the cut is influenced not only by the 3-D geometry of the site, but also by assumptions of crack geometry (i.e., flat vs. finite width) and boundary conditions *viz* grout pressure and flexibility of the uncut region of the block (i.e., in the 2-D analyses the base of the uncut block was restrained from any movements). The 2-D analysis therefore represents something of a “worse case scenario” in that:

- 1) at about 5H:1V, the aspect ratio is relatively high (i.e., deeper blocks will tend to have more localized and less significant stress concentrations);
- 2) the block was assumed to have no tensile strength and a frictional strength typical only of sands (i.e., more competent soils or rocks will better be able to withstand imposed tensile stresses);
- 3) the crack geometry in the 2-D analyses was a flat crack with “sharp” tip (i.e., the actual EarthSaw process will produce a comparatively rounded tip with finite crack width, which will tend to “blunt” the stress concentrations); and
- 4) all analyses assumed grout pressures equivalent to 12” of buoyant uplift, which is the maximum anticipated every being required to facilitate the operation of the EarthSaw equipment (i.e., normal operating conditions are believed to require less than 12” buoyant uplift, and so the stress concentrations will be much less than those predicted by either the elastic or plastic analyses).

Even under these conditions, the nonlinear analysis indicates that the block will respond in a stable manner through plastic deformations and stress redistributions that make the block compatible with the applied buoyant forces. If the above conditions are accepted as reasonably representing a “worse case scenario”, then it is reasonable to assume that other sites that have a lower aspect ratio (i.e., more equal side dimensions), stronger material properties, and lower grout pressures should similarly respond to the EarthSaw process in a relatively benign way.

The above conclusion is made in the context of the analysis assumptions discussed within this report and such a conclusion must be critically reviewed in light of any new geotechnical or other site information arising from site investigations in advance of actual field applications. Based on this study, however, it is reasonable to assume that three-dimensional elastic analyses (to investigate potential 3-D geometric effects) and two-dimensional nonlinear finite element analyses should be sufficient for engineering design purposes and may be readily carried out by qualified numerical analysts with geotechnical engineering backgrounds.

Respectfully submitted,

Murray W. Grabinsky, P.Eng.
July 4, 2002

4.14 Engineering And Design

The engineering design of the system in 4.14.1 through 4.14.5 is reproduced from the “Design and Engineering Controls” sections 3 through 6 of the PHASE II FIELD-SCALE TEST PLAN in Appendix B. Additional data may be found in sections 5.8 and 5.9 of the Interim Report on Task 1 and 2.

4.14.1 Cutting The Bottom Pathway

The cutting of the bottom barrier is done by a cable saw pulled by powerful winches. The winches planned for this work are remote controlled and can pull the cable with over 100,000 pounds force. In softer soil, with cut width less than 75 feet wide, this cable saw cut may take the form of a slicing action as both winches pull on the cable at the same time. In larger sites with harder soils or rock, the cutting involves reciprocating the cable back and forth repeatedly to saw through the earth. The same winch and load frame hardware can be switched back and forth to either type of cutting without any modification or work stoppage. If the cable breaks or shows wear in the middle of a cut, the cable can be replaced and the cut continued. After the horizontal cut is complete, the soil block will actually be floating on the grout. Adding more grout to the perimeter trench raises both the fluid level in the trench and the floating block an equal distance as the thickness of the bottom layer of grout increases.

4.14.2 Planes Of Weakness And Structural Strength Of Block

The magnitude of buoyant vertical lift of the block is a function of the ratio of the grout density/soil block density and the depth of the horizontal cut. The final ratio of the vertical thickness of the block to the thickness of the block submerged in the grout will be equal to the ratio of the density of the grout to the density of the soil block. The buoyant lifting process requires no structural or cohesive strength in the portion of the soil block below grade. Plastic and elastic deformation of the soil is expected to minimize the influence of variable structural strength and discontinuities within the soil block. Most soil blocks envisioned for containment with this technology are sufficiently large that they are expected to deform elastically or plastically and thus each (plan view) area of the block will tend to rise to a level determined by its own bulk density and depth of cut. This local deformation of the block may occur through slow subsidence or quickly according to the thickness and physical properties of the soil and debris in the block.

4.14.3 Adjusting Buoyancy In Variable Strata

Variable surface slope, variable density, or voids within the soil block can be compensated for by altering the depth of the cut in one area or on one side of the

block. Final adjustment of the buoyant lift (and thus the barrier thickness) of any given area of the floating block may be done by moving dirt on the surface of the floating soil block. Adjusting cut depth and soil surcharge loadings to achieve a uniform bottom barrier thickness also minimizes deformation of the soil block. A well-designed work plan can lift the block uniformly with no significant deformation, thus forming a bottom barrier of uniform thickness.

The deeper the cut, the higher the block rises. An example of this is shown below. In the bottom figure, one side of the site is 3 foot higher than the other and also contains a thicker rock layer and has a higher bulk density. By making the bottom cut deeper on that end, we can achieve a uniform bottom barrier thickness. Moving soil around on the surface changes weight distribution and provides a means of overcoming data gaps and fine-tuning the barrier thickness.

4.14.4 Compensating For Dished Bottom Or Large Voids

The bottom cut made by a tensioned steel cable is relatively planar and flat. However, if the cable tension was low and the cable weight was high, such as in a 500 foot wide barrier, the cable might sag several inches along the centerline of the cut. This effect may be balanced by the tendency of any cutting tool to deviate toward the direction of reduced stress, which in this case is upward. If sag should occur, the bottom barrier will be concave and not flat. This would cause the block to bow upward slightly along that same centerline of the cut. This condition may also be caused by unexpectedly low density of waste, or many voids. If the elevation survey indicates this has occurred we would compensate by moving several inches of surcharge soil to the centerline of the block. This would flatten the block and return

the bottom barrier to constant thickness. If we place the surcharge load before cutting the barrier, there is no deformation of the soil block and a uniform bottom barrier layer is achieved.

4.14.5 Grout Functions

The grout must have a density sufficiently greater than the soil block to make the soil block float with the desired freeboard and barrier thickness. This density can be adjusted over a wide range and is one of the primary design controls. The high density grout fluid also has special rheological properties that allow it to seal off against permeable soil formations such as sand and gravel, while still flowing and transmitting hydrostatic pressure through the thin cable saw cut. Large voids or fractures that are exposed by the cut will be automatically filled with grout. Wide vertical discontinuities or monitor wells, which extend through the bottom cut, would also become filled with the grout to the same elevation as the grout in the perimeter trench. The properties of the grout prevent it from flowing into small fractures or the porosity of the soil when the bottom barrier is cut horizontally.

4.14.6 Winches

The winches selected for the cost estimate of this work are built by TEX-A-Draulics Inc. We will need 2 winches, 2 hydraulic motors and 1 hydraulic power unit. Delivery was quoted at 14 weeks A.R.O. Specification is as follows:

LANTEC custom winch model #LW1600 with 24 inch drum diameter, 42 inch flange diameter, 24 inch long – holds 1600 feet of 1-inch cable on 8 layers – No brake is included, Prepared to accept KYB-MRH 2-135-2 motor for clutch-like action – Unit now capable of 130,000 pounds line pull at 30 feet per minute bare drum.

KYB Hydraulic Motor number MRH2-135-2

TEX-A-Draulics custom power unit with electronic control stand (50 ft long cable)
Double Hydrostatic drive, 370 HP Cat Diesel #C-12 DITA

Complete skid with Oil and Diesel tanks, separate control stand, IQAN Control module with joysticks, all necessary accessories. One power unit drives both winches.

The above winch systems were quoted at a very attractive price roughly the same as the price for the load frames (see the cost proposal.) Both the winch systems and the load frame are designed for service at the Paducah C-749 site. However, they would work just as well at the Los Alamos MDA C sites or the INEL or Oak Ridge pits and trenches. The only modification required is to add an extension piece to the top of the load frame. This hardware may be reused many times. The pulley bearings and seals are the only maintenance item to be replaced after each use.

The steel cable is used as a cutting tool in this technology and may not be reused once it has been in service. After use, the cutting cable will be rolled back on a spool and disposed in a suitable landfill. The cable will eventually decompose to rust and the wooden spool will rot.

4.14.7 Engineering Drawings of Load Frame

Following are the fabrication drawings for the load frames. The text portions of these drawings are slightly stretched due to the file import process:

4.000

14.0 Ref.

1.0 R

63

Cut steel bar to length and radius ends.
Electroless nickel
or chrome plate.

3 required for each load frame

1	3	Steel bar, 4130, Q & T, Rc 35-42 4.00 OD x 14.25 LG

Carter Technologies Co Sugar land, TX 381-495-2603	Hinge Pin	Change letter ____ Date ____ Checked By ____ Date ____	LFRAM011.gcd
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Note: the pulley may be supplied by a vendor as a unit with an alternate design as long as the dimensions are the same to fit mating parts.

- Weld the 4 pipe sections as shown, relative to the 26" hole
maintain 6.38" between 8" diameter pipe sections and 28" hole

Note:
The JU-36 power pack
may be removed or moved to the front
of the winch to create a
balanced load

Drilled Holes, 2-1/2" Dia.
Line up holes with
2-1/2" rod before welding
tubes to plate.

NO	QTY	DESCRIPTION
1	1	1" thick Steel plate, A-36 - 81" x 97"
2	8	8" OD carbon steel tube, 3/4" to 1" wall

Carter Technologies Co
Sugar Land, TX 77478 281-495-2603

JU-36
Winch base plate

Change letter _____ Date _____
Checked by _____ Date _____

LFRAM028.gcd

This drawing shows how the legs on the winch plate fit over the top of the load frame and pin it in place.

This photo of the paper model shows the geometry of the bottom opening. (The horizontal ridges on the front face have since been deleted.)

4.15 Technology Development Roadmap

The next step in the development of this technology is a field-scale test in clean soil at Paducah Kentucky. The comprehensive test plan is contained in Appendix B. This plan calls for a 50 foot square by 30 foot deep demonstration test to be performed on government property outside the security fence at the Paducah Gaseous Diffusion Plant. The clean block of soil would be isolated by 2 foot thick side walls and 3 foot thick bottom layer of a soft, non-hardening grout material. Though the material is soft, it is highly impermeable and also provides hydraulic isolation. The plan provides for detailed measurement of the thickness of the barrier, and also a means of taking samples of the bottom barrier after installation. These samples will be lab measured for hydraulic conductivity according to the ASTM method. A report on the construction and measurement will be completed as soon as practical after the demonstration. An additional long-term data collection system will be operated for one year after construction to provide additional data to aid in permitting the method on the Paducah Uranium Burial Grounds site. This system will attempt to measure the degree of long-term isolation afforded by the barrier. Following the collection and evaluation of this data, an additional report will be prepared.

Following a successful test in the wet clay and sand at Paducah, the technology should then be tested in the soft dry rock at Los Alamos. Many technologies fail to operate equally well when taken to a site with such radically different conditions. Papers would be published in peer-reviewed journals in the US and Japan describing the details of these projects. The technology will also continue to be presented in various technical trade shows by the licensees in the US and Japan. Deployment of the technology at these two sites could proceed concurrent to additional development of the technology for use in hard fractured rock such as the INEEL site. This would involve testing of rock cutting cables as well as the molten grout technology. Ultimately we would perform demonstrations forming barriers in the basalt rock under the INEEL RWMC waste pits and trenches.

4.16 Frequently Asked Questions

- Q.* Will gas generated by the waste collect under the air-tight cap?
- A.* If the waste is found to generate gas, this may prevent effective application of the monitoring technique based on barometric pressure differential. It would not prevent the use of the drying technique coupled with the humidity sensor. Use of the drying technique may also result in elimination of gas generation.
- Q.* *What if the block of soil containing the buried trench is too heavy to float?*
- A.* Debris found in trenches is typically less dense than soil due to voids. The average density of the block is determined before the work and the density of grout is roughly 10 to 15 percent greater. If the block is not buoyant after we

have cut a distance equal to the depth of the block we will simply increase the grout fluid level in the perimeter trench. If the waste has the potential to increase in density over time by compressing all voids out over many years we would suggest building in a margin of safety or using a hardening TECT A grout.

Q. What happens if the block breaks in half while you are cutting the bottom?

A. It will be similar to breaking a piece wood in half, both halves will still float buoyantly on the grout. Hydrostatic force will strongly hold the two pieces together by unbalanced force exerted from the perimeter. Separating two halves of the broken soil block would take a huge force of over 3 million pounds! (The surface area of the side of the block times the average pressure exerted by the grout.) A soil block could have several existing but unseen large fractures, which would simply fill with the thixotropic grout, and it would have no impact on the quality of the containment.

Q. How would the lift forces affect large unconsolidated areas of the block?

A. In our small-scale demo we performed the process in wet, unconsolidated sand. We observed that there is a force from the perimeter keeping the block in its original shape. In theory the wet sands of the earth were already doing this before we made the first excavation. In our field test, large football-size clumps of un-consolidated soil were noted to float to the surface of the slurry trench. Soil blocks with little strength are held together by the compressive loading on all sides. By adjusting the depth of each edge of the cut and the surface soil loading large block can be raised without any deformation.

Q. What will keep the block from floating to one side of the trench before it cures?

A. For the block to move to one side a very large volume of viscous grout has to flow from one side of the block to the other. We are able to control the position of the block simply by where we add the extra grout to raise the block. We can always lower a steel beam, rocks or other mechanical spacers in place into the trench on each end of the block. The load frame itself also provides this restraint. The installed cap also provides resistance to movement of the block.

Q. Can the organic and aqueous contaminants flow into the grout while it is still liquid and contaminate it.

A. No, because the liquid grout is of a much higher density it exerts a hydrostatic gradient that keeps this from happening.

Q. What if the block contains substantial voids? Won't the heavy grout fill those voids and make the block too heavy to lift?

A. No, the block will be equally buoyant if it is solid or as full of holes as Swiss cheese. Consider a block of wood with many holes drilled in it floats as high out of the water as one with no holes.

Q. Will large voids near the base of the block cause bottom heave into the interior of the block?

A. Large voids near the base of the block see only about a 2 percent increase in pressure during the EarthSaw cut and lift. If this causes the grout to break into the void, then the void will be filled. The perimeter trench provides a huge reservoir of grout to fill such voids.

Q. What if contaminated water inside the block leaks into the grout and contaminates it.

A. The hydrostatic head of the dense grout prevents water from entering the grout. The high specific gravity grout forms a filter cake barrier on all the exposed soil in the trench and provides a hydraulic barrier to water flow in or out from the moment it is placed in the trench.

Q. How wide and how long of a cut can the cable saw make?

A. The maximum size is dictated by the strength of the cable, its weight, and the coefficient of friction. We believe that it will be feasible to make a single cut over 10 acres in size with 1-inch diameter cable using a sawing action. This is a site 500 foot by 1000 foot long. Larger cables, with more powerful winches can make longer and wider cuts.

Q. What good is it to make a barrier at the bottom of the trench if contamination has already leaked into the rock below?

A. By shutting off the source of contamination at the bottom of the trench we are able to prevent further pollution. We think it is more prudent to contain a high percentage of the waste that has not yet escaped than to wring our hands over what has already been dispersed. If it can be established that going 10 foot deeper will capture that extra percent then we can probably make the barrier there in the rock but of course it will cost substantially more.

Q. Can you make the barrier in rock?

A. Yes, the construction method is also designed to work in rock. The idea builds on the 30-year-old diamond wire quarry saw industry and similar stone cutting methods used for hundreds of years. We see no technical barrier to making larger diamond wire saw equipment and making larger cuts in rock. We also may be able to cut in rock by using abrasive grout slurry with standard cable. Our preferred procedure would be to use a hard steel cable with abrasive grit in the grout. The grit does the cutting work. This should increase cable life. When cables break they can be pulled out from each end and a new one installed as many times as needed. We do not plan to demonstrate this method in hard rock during the current project. We plan to demonstrate it multiple times in soil before moving to hard rock.

Q. Can you make a horizontal barrier below the water table?

A. Yes, our process will work in wet, dry or saturated conditions. Due to the high density of the grout, it displaces and excludes water easily. Rising water tables outside the block cannot affect the barrier. Changing the water level inside a non-hardening barrier can of course, change the weight of the block and alter the barrier thickness of the non-hardening types of grout.

Q. What if the pit or trench is on a hill and one side is much lower than the other, won't the grout all run to one end?

A. Small variations in elevation can be compensated for by making the uphill end of the barrier deeper. This allows us to achieve a uniform barrier thickness. Most sites are on level ground but there are several ways to apply the process on hills. One is to level the surface before the work. Another is to break the project into sections using a hardening TECT A grout. Another is to use the non-buoyant molten WAXFIX grout to create permeation barriers out into the soil above and below the horizontal cut.

Q. What if you encounter large voids or fractured rocks that allow the grout to leak out of the trench?

A. Most voids will simply be filled by the grout. Generally, voids under a waste disposal site should be filled to achieve stable long term closure. The TECT B grout is especially well adapted for work in fractured shale and limestone. It is very thixotropic and may seal ¼ inch fractures within a few feet of the cut. The trench volume is sufficient to fill very large voids without a significant drop in fluid level. If we are working in volcanic rock and expect many voids due to vertical fractures, we will pre-cut the bottom pathway using our non-buoyant molten WAXFIX or the TECT W high density molten grout. This grout is ideally suited for sealing fractured rock since grout following a fracture will quickly lose heat and solidify.

Q. What if the steel cable saw breaks halfway through the horizontal cut?

A. If the cable breaks we will pull it out from one end and install a new cable at the beginning of the trench. We will be starting over but the cable will pass quickly through the area previously cut because the buoyant grout has slightly lifted the block providing clearance for the cable to return to the face of the active cut area. There is also a technique for adding a pulley in the trench on the end of the trackhoe that dramatically alters friction by changing the contact angle of the cable. This will allow us to pass through difficult areas.

Q. Can you cut through a contaminated section to isolate just a 200 foot long part of an 800 foot long trench?

A. We can do this if it is required. There are two basic methods: We would finish our side trenches and then make the cut through the waste under the heavy TECT grout. That way all waste pulled out of the ground would be neutralized and encapsulated by the grout. The hydrostatic head of the grout would prevent any contaminated fluid from entering the excavation from the buried waste. The other

more economical method is to not excavate the cut across the waste but instead to cut horizontally to that point and then cut upward with the cable saw. This minimizes contaminating the grout. After the cut is made extra grout would be introduced to move the entire block laterally away from the cut to create the desired thickness of barrier on the final side. Large solid objects in the waste may interfere with this approach if they are hard to cut.

Q. No one knows exactly what is in some of these trenches. Some of our trenches have wastes that can explode. Does your method disturb the waste?

A. No, the waste would not be disturbed. This method does not touch or press against any of the waste so it should not disturb the waste in any way, (unless you want to isolate only a portion of a burial trench as mentioned above.) We recommend doing the entire site as one piece. This way, even if the waste included a live land mine it would not be disturbed.

Q. Some of our wastes can spontaneously combust if dry air is circulated through them.

A. After a full vault barrier is constructed, the de-watering and drying part of the work is optional. We could just as easily fill it to the brim with water or inert gas. Our TECT B non-hardening grout remains water wet in equilibrium with the soil and can also provide a degree of reactive treatment of contaminants that diffuse over time.

Q. Can you treat a burial site containing chemical or germ weapons?

A. Yes, after the barrier and top cap are constructed, the entire volume of the block would be slowly filled with a 10% bleach solution or other suitable material and allowed to remain in place. When the containers deteriorate, the contents would be neutralized by the large volumes of bleach.

Q. What are the properties of the grout after it cures?

A. The high specific gravity TECT barrier material is available in many forms to address a variety of design needs. The TECT B grouts begin as a viscous fluid product. As it cures it will achieve a soft clay-like consistency and remain soft indefinitely. TECT B grouts are designed to lose water and come into water vapor pressure equilibrium with the earth. The material remains fully plastic as it shrinks under the applied load of the block and can adapt to ground movements.

The higher cost TECT W grouts, are a thermoplastic material applied as a molten liquid that solidifies to a deformable wax-like solid with ultra low permeability and chemical resistance. TECT W contains no water or volatile components and will dent and deform rather than breaking.

The TECT A grout is a cementitious grout which remains liquid for about 2 to 3 months and then hardens to a solid with very low permeability and high compressive strength. Its unique chemistry allows it to creep and deform plastically by a small amount during its early cure. It is resistant to most

chemicals except strong acids. It is formulated with internal micro fiber reinforcement to evenly distribute stresses in large structures. It is designed as a non-shrink grout with low heat of hydration.

Q. How will the- TECT A grout barrier respond to settlement and ground movement without losing integrity?

A. The basement-like structure made from TECT A grout will be have a large section thickness with high mechanical strength. It's micro reinforcement fibers increase its tensile strength and help distribute loads. During the first year of cure the grout is designed to creep under an applied load to reduce residual stresses.

Q. How will the- TECT B grout barrier respond to settlement and ground movement without losing integrity?

A. The basement-like structure made from TECT A will be very soft and will allow movement or deformation of the surrounding earth without transmitting loads to the isolated block. The barrier can tolerate large displacements and can tolerate subsidence up to the thickness of the barrier.

Q. How will the integrity of the barrier be verified year by year?

A. There are many ways to verify the integrity of the barrier. Once the cap structure is completed, the barrier becomes a full vault. Since the seasonal high water table is above the bottom of the vault, we may place monitoring wells in the vault to look for changes in water levels inside the vault compared to wells outside the vault. If we choose to remove water from a vault made with TECT B or a TECT A that has not yet hardened, this will cause the block to rise upward. This makes the bottom barrier thicker. Leachate is removed from the block by the monitor well. Dry air is circulated through the soil block for a long time to dry it. Humidity sensors placed under the cap then monitor the moisture levels of the soil gas inside the block to detect any new moisture being introduced.

Q. Some of our long trenches run perpendicular to the slope of the land. How will your installation technique work here?

A. We cannot use a continuous buoyant liquid barrier if one end of the landfill trench is twenty feet higher than the other end. There are several ways to address this problem. We can use a hardening TECT A grout and make the barrier much deeper on the uphill end. The density of the grout will be such that the fluid level flush with the surface on the downhill end is sufficient to raise the block on the uphill end. Another option is to level the site before construction. Another method is to break the landfill trench into multiple sections every 5 feet of elevation change and use a hardening grout. We can also use a soft TECT B grout combined with short dams of hardening grout.

Q. Some of our trenches are only 5 to 10 feet apart. How much space do you require between parallel trenches?

A. This depends on several factors. We can theoretically place a barrier by this technique with only 5 to 10 feet of verified clearance between trenches but if the adjacent trench also needs a barrier, it will be better to combine both trenches in a single barrier vault. This also greatly reduces the cost of the barrier. The EarthSaw should be able to construct barriers under an entire areas containing dozens of adjacent trenches.

4.17 DOE Comments on Draft Report

The comments identified below, received September 3, 2002, are based on the information presented in the Draft Phase I Topical Report - EarthSaw™ In-Situ Containment of Pits and Trenches, July 18, 2002 in support of Contract No. DE-AC26-01NT41144. The contractors response follows each of the numbered comments. Where appropriate, the current Topical Report has also been edited to address each area of concern.

1. Information presented cites, "the EarthSaw™ buoyant barrier process is a patented technology". Patents affiliated with the EarthSaw™ need to be identified and cross-referenced to specific system components.

The EarthSaw patents are lengthy and broadly cover the various methods of cutting a block of soil free from the earth with a cable saw and buoyantly supporting it and floating it on a dense grout to form a containment barrier. It is a method patent and is not limited to the specific apparatus. This patent should cover any technology that forms a bottom barrier by buoyantly supporting the earth block on a heavy grout regardless of the hardware used to make the bottom cut. It also covers the use of a cable saw, chain, or jetting device to cut a continuous pathway between trenches, or between HDD holes, or between holes and the ground surface. Other patents include the composition and methods of making a suitable high-density impermeable grout and the method of verifying containment integrity by differential measurements between the inside and outside of the vault. Various other aspects of the grout technology are held as trade secrets. After the Paducah demonstration, licenses for the EarthSaw technology and suitable TECT grouts will be available on a project-by-project basis from Federal Industrial Products, P.O. Box 42842, Houston, Texas. Call toll free 1-866-299-1464.

2. The subsurface barrier system installation verification needs to address not only those activities during installation, but also the post curing verification activities of the entire barrier system.

Post curing and post construction verification activities are described in the comprehensive test plan for Phase II. Typically, the internal barometric pressure and external barometric pressure would be measured every 4 to 6 hours and recorded on a data logger. Every year this data would be downloaded and a statistical analysis prepared to measure any leaks in the containment structure. If leaks are indicated, tracer compounds may be injected to facilitate leak detection in the cap with portable instruments. Other tracers might be designed for easy detection within the subsurface vadose zone. In sites where dry air circulation has been used to slowly dry out the interior of the vault, a humidity sensor could detect any slow return of humidity to the interior of the vault.

The verification activities vary significantly according to site characteristics so I will include a more detailed breakdown of the possible alternatives to supplement the descriptions of the method proposed and described for the Paducah site demonstration.

- In a dry arid site, the vault would have low humidity levels so the verification method of choice would be based on air pressure differentials. We would probably maintain a slightly negative pressure inside the vault and monitor it for leakage. We could also monitor the normal variation in external barometric pressure. An odorant chemical such as that used in natural gas could be added to the interior of the vault and a person with a trained dog would walk the perimeter at regular intervals to detect leaks and their location.
- In a medium dry site, having minimal rainfall, the top cap could be a transpiring cap. In order to achieve passive monitoring by air pressure differential, a synthetic liner below the cap would still be needed. If a top synthetic cap is not used, a hardening grout such as TECT A is preferred.
- In a damp site having waste that becomes more stable when dried, we could flow dry air through injection and extraction wells at the corners of the barrier to dry out the entire earth block. Humidity sensors would then be used to monitor the condition. Leaks in the barrier would result in gradual increases in interior humidity.
- In a wet site that has water table above the bottom barrier, the block may be dewatered and partially dried as above. The site would then be monitored for any increase in humidity over time. Gas generated by the waste would be vented from time to time of when pressure increased. Other types of gas or chemical treatment could be applied to help stabilize the waste to minimize gas generation.

3. Manipulation of a surface soil layer is portrayed as an engineering control to maintain a uniform barrier thickness and compensate for varying soil block densities, but no indication of the minimum and maximum soil layer thickness is given. Are there other means to achieve these results?

For hardening barrier grouts, portable water tanks may also be used to correct tilt of the earth block until the grout hardens. Adding soil to of the block is the simplest and most economical way of adjusting the weight of a given area of the block. The proposed method for redistributing soil on the surface of the block is conventional dozer work measured by conventional surveying techniques. There is no minimum or maximum thickness of this soil layer but it could range from a fraction of an inch to ten feet thick. If the survey rods are spaced on a tighter grid, the accuracy of the work may be increased. If a ton of dirt is placed on top of the earth block, it may then be spread out on top of a given area of the block. Dirt may be added or removed from any area. The soil distribution accuracy need not be more precise than normal site preparation for slab construction. We will include a more detailed discussion of this for readers not familiar with civil construction practices. Other means of achieving these results would include placing rock instead of soil. A large high-density waste object in a soft soil site could cause a visible surface depression at the top of the block. It would also be possible to remove soil from a specific area by digging a shallow hole. If this happens, a survey rod would be installed and additional soil would be removed from this depression to bring the original surface back to proper elevation. The hole could be filled with a low density flowable fill such as foam cement. Commercially, these are made available as a class C flyash slurry with a foaming additive. A dry blend of Styrofoam packaging "peanuts" mixed with dry class C flyash makes a lightweight 30 pound per cubic foot fill material that gains strength over time.

4. The barrier system encapsulation includes installation of a surface cap over the subsurface barrier. What is the anticipated duration from when the subsurface barrier is complete to initiating the surface cap installation or can these activities proceed concurrently with some initial lag time to compensate for subsurface barrier

installation? Will re-contouring of the initial surface soil layer after subsurface barrier installation cause adverse effects to grout curing and barrier thickness?

Cap construction may be completed immediately after barrier installation while grout is still fluid if the cap construction process is carefully designed and managed to avoid unbalanced loading of the block. Generally, it is preferred that the installation of the cap's synthetic liner perimeter key-in is performed immediately after barrier construction and before any hardening of the grout. Each of the major types of grout have different hardening characteristics. TECT A grout will generally be designed with a hardening time significantly greater than the worst case construction time. Hardening times are adjustable from 6 to 60 days. TECT B grouts do not harden. TECT W grouts harden after the heating systems are removed, but remain malleable to a degree determined by the designer. When constructing an earthen cap over a non-hardened barrier a uniform loading must be maintained to avoid dimensional changes in the barrier thickness. This means that the cap soil must be added and compacted in many shallow lifts distributed over the surface rather than working uniformly from one side of the block to the other. This will require close supervision but no special expertise. TECT B grouts are preferably designed to decrease in volume from 3 to 12 percent during curing to obtain lower final permeability. The net volume loss is affected by the humidity level of the soil as well as the design of the grout. This volume loss should be considered in overall cap design as it will cause some settling of the final surface and this could damage buried sensor wires and tubes. For some projects, it may be useful to plan to re-contour the surface after the settling has occurred. Re-contouring will not affect grout curing but significant changes in weight distribution will cause changes in the barrier thickness of a soft grout, just as the buoyancy model indicates. If the grout has already cured to a putty-like consistency, these movements may take several months to occur.

5. The Cap Design Factors section cites, "Through careful engineering design of the cap it is possible to dynamically change the thickness of the bottom barrier or install a cap without changing the bottom barrier at all". What are the engineering design factors that must be optimized to ensure barrier thickness is not altered?

"Ensuring the thickness is not altered" may not be the goal. The goal may be to create the most uniform and durable barrier. We may plan in advance for the cap construction to increase the bottom barrier thickness to final specifications because it simplifies construction. If we want to avoid altering the barrier thickness during cap construction, we simply add the same depth of soil (or weight per square foot) over the entire surface of the earth block that we add over the top of the perimeter trench. This maintains gravitational balance. Optional engineering factors include the use of low-density fill and high-density fill.

6. Although the test plan discusses the use of elevation surveys to determine the final barrier thickness, a method for demonstrating the continuity of the barrier is not discussed.

The primary method discussed for demonstrating continuity of the barrier is to pass the cutting cable under the floating block. This may be done a second time after increasing the bottom barrier thickness. Of course, this does not demonstrate the continuity at the full thickness. If desired this may be done with a heavy-wall 24 inch diameter pipe whose length is equal to the width of the block. The cable would be run through the pipe before it is lowered into the trench, and then drawn under the floating block by the load frames to verify that the barrier has a thickness of at least 24 inches throughout. Alternately a chain may also be passed under the floating block. The block may also be moved sideways or bobbed up and down on a corner by

heavy equipment. We think it is unlikely that physical verification of the full thickness is needed in most cases, but we agree it should be discussed and we will add the detailed procedure to the report.

7. High-density inclusions of waste in various configurations in the center of the target mass of soil have a definite probability of causing failure by punching through the underlying soil to the bottom of the saw cut.

We can calculate the potential for an object “punching” through the soil into the fluid grout. Suppose we have a cylindrical drum measuring 25 inches in diameter and 48 inches tall (13.6 cubic feet) with an average density of 312 pounds per cubic foot or twice the density of the grout sitting on only 2 feet above the bottom horizontal cut. If the soil is 125 pounds per cubic foot, the drum is 187 pounds per cubic foot heavier than the soil and exerts a net downward force of 187 pounds/cu ft x 13.6 cu ft = 2543 pounds. If we assume a worst case condition where punching shear acts as a vertical shear force at the perimeter of the high density object then we have a shear area of 25” x 3.141 x 24” = 1885 square inches. So the soil must resist a shearing force of 2543 pounds / 1886 square inches = 1.35 pounds per square inch. This is equal to 194 pounds per square foot. If the soil has shear strength greater than this, it should not fail. Most soil has shear strength many times this level.

Most high-density waste is contained in packages that reduce the net density. Metal parts disposed in crushed Tuff behave as one large package. Drums of uranium metal dust and turnings buried at the Paducah Gaseous Diffusion Plant C-749 pit were packed with oil. According to the detailed records I obtained, the average density of the drums was about only 216 pounds per cubic foot in the quadrant having the heaviest drums.

8. High-density inclusions in the soil block could potentially elastically deform the underlying soil, even without failure, to close the saw cut completely and irreversibly.

For this to happen to a significant degree we would need enough total additional mass to sink a large portion of the block. This could cause the barrier to pinch out but would also create a depression on the surface. We can recover by removing some surface soil or increasing the grout head to compensate. We would notice this depressed area at the first survey after the initial horizontal cut, before the block was significantly raised. We would adjust the topsoil weight by removing soil and adding low density fill to compensate before increasing the barrier thickness.

If we do not have a punching failure potential, then we can assume that the friction angle of the soil will spread the load from a massive object. The buoyancy model may be used to determine the consequences of this or if it affects only a fraction of the block we can calculate it as follows:

If there were a very dense object, such as a 20 inch tall and 20 inch diameter round bar made of solid steel at the bottom of the 20 foot deep pit, the soil under it would already be compressed enough to support it so it can not sink further just because we support the soil below it with buoyancy. The extra concentrated weight could theoretically, cause the bottom of the block to bulge downward. If the object were 8 feet above the bottom and we had a minimal friction angle of 25 degrees, the 1778 pound bar’s weight would be distributed over a 9.1 foot diameter circle (65.4 square feet of area) at the soil/grout interface. If the average soil density were 120 pounds per cubic foot the bar would add a net 1342 pounds of weight to the 65.4 square foot area at the grout interface. If the grout was 150 pounds per cubic foot, this extra weight would allow that 65.4 square foot area to deflect downward enough to displace 9 cubic feet of grout. This would be an average of about 1.64 inches of barrier thickness reduction spread over a shallow bowl shape.

The INEEL pit 9 site contains eight inch thick reactor shielding and other large objects. These objects would need to be located by ground probing radar and the calculations performed to evaluate these issues if the barrier was to be made in the three-foot thick layer of clay soil below the waste. We could compensate for a local heavy spot by removing surface soil and replacing it with lightweight fill. However, it is more likely we would make the barrier 8 feet deep into the basalt rock layer below pit 9. In this case, the rock layer would distribute the load to an entire quadrant of the pit. We could compensate for this known load by making the barrier deeper in that corner.

9. The upper part of the load frame that bears on the trench wall will load the near-surface soil greatly, with surface failures possible. Either the near-surface horizontal stress needs to be decreased or the near-surface soil in the vicinity of the load frames needs to be reinforced to prevent vertical deformation.

The upper part of the load frame does not experience significant lateral loads against the soil. The winch is mounted directly on top of the load frame and the cable runs straight down through the center of the load frame. The loads between the winch and the bottom pulley are carried in the steel structure. The major loads against the soil are all at the bottom wings of the load frame and are well within the bearing strength of most soil. These loads are due to the reaction of the cable tension between the bottom pulley and the soil. The bulk of this load is distributed along the bottom 10 feet of the load frame. The 2-foot wide "wings" have an area of 40 square feet. The maximum 125,000 pound load that the winch can apply would produce a load of 3125 pounds per square foot. Soil firm enough to require maximum cutting power would generally have a bearing capacity in excess of 1.5 tons per square foot. If needed another I-beam may be added to each side to increase bearing capacity. If the load frame were used in an over width trench, this would reduce the bearing area and cause the load frame to dig in to the bottom corners of the block. In some cases, the load frame might act on a fulcrum halfway between the trench bottom and the surface. The wings are just as large at the top of the load frame and would be able to resist the same loads as at the bottom.

The load frame does not contact the surface soil except as the block begins to rise to final position. Optionally, if the winch is left in place as the block rises, the corner of the block will bear on the under side of the winch base plate to help lift the load frame off the bottom.

10. Many waste sites are not well defined. Original trench boundaries and waste types are not known in many cases. This makes it difficult to define the dimensions of the soil block to be cut or to calculate the density of the block when determining the factor of safety required to assure avoidance of punching failure.

Generally, we should have some idea of the depth of a trench. Ground probing radar can help to determine this. Determining the boundaries of the waste is important but it is not really part of the EarthSaw technology. Ultimately we are dependant on the site owner/manager to discern the maximum probable depth of the original trench, plume depth, and the probability and nature of high-density objects. Any construction contract would specify the minimum depth and corner location coordinates of the barrier. The first step in an EarthSaw project is to collect continuous core samples from at least the four corners of the proposed vertical trench, for density measurement, and penetrometer shear strength data from the corners at the proposed depth of cut. This should provide us with reasonable data to calculate a factor of safety against punching failure. Unless there is a rock layer such as at INNEL, it is easy to choose to make the barrier deeper and the construction vendor will prefer to make the barrier deeper to be safe.

11. Changes in slurry density, combined with irregularities on the lower surface of the block, could cause a dam of material under the block and prohibit free flow of slurry following the cutting cable. The grout must follow the cable or the block will not float.

The grout is a highly engineered fluid manufactured by a world class drilling fluids company. The slurry density and other properties are highly uniform. However, the constancy of buoyant force is not dependent on uniform density of the grout, but rather the net average density. It is true that the grout must enter the bottom cut for the block to float, but it is not an absolute requirement for the grout to follow the cable 100 percent. If we used 4 percent excess buoyancy due to hydrostatic head in the trench, and for some reason our cutting cable left 2 percent of the horizontal cut inaccessible to the grout, the block would still float and those areas would then become accessible to the grout. In practice, the free end of the block will rise several inches thus ensuring that grout is free to flow fully into the cut.

If the block did not float due to some areas that did not get grout due to some kind of defect in the fluidity of the grout, or a dam of cuttings, we could simply run the cable saw under the block again to complete the work.

5.0 CONCLUSION

The EarthSaw theory, physics and engineering has been documented and evaluated in many different ways and no fatal flaw or operational problem has been identified. The technology appears to be a significant advance in containment technology that offers an inherently safer design than conventional approaches such as excavation. The method is substantially independent of the lithology or hydrology of the site. Probability of a successful field application in non-uniform soft soil or even soft rock is very high. The method may be applicable to harder rock, and highly fractured rock, but additional field-testing will be needed to verify that the cable saw can cut these materials efficiently. The method is applicable to sizes and depths corresponding to the majority of the pits, trenches, and underground tanks within DOE. Production drawings for field-scale hardware have been developed. Detailed plans and cost estimates have been completed for a comprehensive field demonstration in conditions closely approximating a DOE site that has potential application of the technology. The phase II portion of this project will complete this field demonstration and should be fully funded so that the technology may be deployed as soon as possible.

6.0 LIST OF ACRONYMS AND ABBREVIATIONS

Definitions:

The word “**trench**” may refer to the original burial pit or trench, our excavated slurry trench around the perimeter of the burial trench, or that same excavated slurry trench after the slurry is replaced with grout.

The word “**block**” in this proposal means the typically rectangular volume of earth that is cut free from the earth and surrounded by the barrier. The EarthSaw method can also isolate a block, which is round, oval, or of irregular shape. The bottom of a block may be made flat, sloped or curved. The words soil block and earth block are synonyms.

The word “**vault**” will refer to the bottom, sides, and top barrier surrounding the block after the cap is installed.

“**Cable saw**” is a steel wire rope

“**Cable**” is steel wire rope

“**Grout**” is a semi-liquid material, which is placed in position and then takes on a different physical property to accomplish an engineering purpose.

“**Buoyant Grout**” A fluid grout having a greater density than earth and thus able to buoyantly support a severed section of earth above a horizontal cut through the earth.

“**TECT A**” a Carter Technologies trademark name for a high-density metal oxide grout with cementitious properties that develops high strength.

“**TECT HG**” A metal oxide cementitious grout developed for jet grouting in buried radioactive waste.

“**TECT B**” A non-hardening metal oxide plastic grout with very high density that remains soft after curing.

“**Waxfix**” A soil permeating molten wax grout, which cures by cooling to form a malleable solid.

“**TECT W**” a densified version of Waxfix able to function as a buoyant grout.

“**EarthSaw**” The trademark buoyant barrier process by which an area of land containing a buried waste site is severed from the earth and isolated by a fluid grout barrier material, which buoyantly supports its weight while solidifying into a barrier vault.

“**Cold Demo**” A demonstration on a non-radioactive site.

“**Hot Demo**” A demonstration on a radioactive site.

“**Slurry Wall**” A continuous vertical trench excavated under bentonite slurry.

“**TECT grout**” A high density grout designed for the EarthSaw method.

“**PGDP**” the Paducah Gaseous Diffusion Plant

“**DOE**” - The United States Department of Energy

“**NETL**” The National Energy Technology Laboratory

Appendix A:

INTERIM REPORT ON TASK 1 AND 2

**This report is reproduced in its entirety below except for
Excel spreadsheet files which are on the enclosed CD ROM in both native format
and screen shots of the spreadsheet provided in Adobe PDF format.**

Interim Report: Task 1 and Task 2

Research and Development EarthSaw™ In-Situ Containment of Pits and Trenches

By

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Under Contract DE-AC26-01NT41144, Task 1 and 2

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ABSTRACT

EarthSaw™ is a proposed technology for construction of uniform high quality barriers under and around pits and trenches containing buried radioactive waste without excavating or disturbing the waste. The method works by digging a deep vertical trench around the perimeter of a site, filling that trench with high specific gravity grout sealant, and then cutting a horizontal bottom pathway at the base of the trench with a simple cable saw mechanism. The severed block of earth becomes buoyant in the grout and floats on a thick layer of grout, which then cures into an impermeable barrier.

Task 1 and 2 covered by this report, provide a detailed engineering description of the technique, and a computer model of how the process would perform in a wide variety of soil conditions common to DOE waste burial sites.

Table Of Contents

Section	Title	Page
1.0	Introduction-----	88
1.1	The EarthSaw™ Buoyant Barrier Method-----	88
1.2	Problem Definition-----	89
1.3	DOE Technology Requirements For Barriers-----	89
2.0	Background Of The Technology-----	91
2.1	Previous Earthsaw™ Field Test-----	92
3.0	Project Description And Goals -----	94
4.0	Technical Approach -----	94
5.0	Task 1 - Technical Work Product – Physics Of Earthsaw™-----	96
5.1	Hydraulics Of A Slurry Trench-----	96
5.2	Hydraulics Of Earthsaw™ Horizontal Cut-----	97
5.3	Required Properties Of Earthsaw™ Grout-----	98
5.3.1	Density -----	99
5.3.2	Viscosity -----	99
5.3.3	Static Gel Strength -----	100
5.3.4	Fluid Loss Control -----	100
5.3.5	Cuttings Transport -----	100
5.3.6	Stability Of The Slurry -----	101
5.3.7	Lubricity -----	101
5.3.8	Permeability -----	101
5.3.9	Properties Of Specific TECT Grouts -----	102
5.4	Step-By-Step Quantitative Process Description-----	105
5.4.1	Slurry Trench Perimeter Excavation -----	106
5.4.2	Installation Of Load Frame And Cable -----	107
5.4.3	Replacing Slurry With Grout -----	109
5.4.4	Filtration Control Significance In Buoyancy -----	112
5.4.5	Quantitative Description Of Cable Cutting Process -----	113
5.4.6	Activating Cutting Cable -----	116
5.4.7	Mechanical Restraints -----	117
5.4.8	Leveling Of The Bottom Barrier -----	118
5.4.9	Adding Additional Grout To Trench -----	118
5.4.10	Measurement Of Barrier Thickness -----	118
5.4.11	Sealing Surface And Cap Construction -----	119
5.4.12	Air-Tight Cap Allows New Ways To Monitor Performance	122
5.5	Derivation Of Buoyancy Equations-----	123
5.5.1	Equation For Calculation Of Required Grout Density ----	124
5.5.2	Equation For Calculation Of Bottom Barrier Thickness --	126
5.5.3	Sensitivity To Errors In Assumed Soil Block Density -----	129
5.5.4	Buoyancy Calculations During The Horizontal Cut -----	129
5.5.5	Soil Blocks With Non-Uniform Density -----	131

5.5.6	Soil Blocks On Sloping Ground	133
5.6	Buoyancy Calculations For Specific Soil Conditions	134
5.6.1	Variable Host Media	134
5.6.2	Host Media With Discontinuities	135
5.6.3	Variable Hydrologic Conditions	136
5.6.4	Variable Geometries, Dimensions And Waste Contents	136
5.6.5	The Vertical Block Method	137
5.6.6	HDD With Two Vertical Sides	139
5.6.7	HDD With Full Basin Shape	141
5.6.8	Vertical Wall HDD	141
5.7	Discussion And Calculations Of Issues In Specific Soils	142
5.7.1	Cohesive Clay With Rocks	142
5.7.2	Clay With Permeable Sand Lenses	143
5.7.3	Non-Cohesive Sand	145
5.7.4	Variable Hydrologic Conditions In Non-Cohesive Sand	147
5.7.5	Silty Clay With Cobbles	148
5.7.5	Glacial Till With Flat Rocks	149
5.7.6	Sandy Soil With Cobbles	150
5.7.7	Clay With Fractured Shale	151
5.7.8	Fractured Basalt Under Fine Sandy Clay	152
5.7.9	Sandy Soil, Underlain By Karst Limestone Formation	154
5.7.10	Sandy Soil, Debris Filled With Liquids.	156
5.7.11	River Sediment With Buried Tank	158
5.7.12	Silty Clay With Buried Drums And Debris	159
5.8	Design Requirements For Load Frames	160
5.9	Descriptive Drawings Of The Method	164
5.10	Equations For Cable Saw Friction And Shear	168
6.0	Technical Work Product For Task 2	172
6.1	Steps And Elements To Be Modeled	173
6.2	Selection Of Subsurface Conditions To Model	174
6.3	Software Selection	180
6.4	Bounding Conditions	180
6.5	Preparation Of Equipment Drawings And Specs	181
6.6	Hardware Structural Analysis	185
6.7	Additional Structural Modeling Of The Earth Block	186
6.8	Thermal Management System For Molten Grout	187
6.9	Air-Tight Cap Design	190
6.10	Using The Spreadsheet Model	191
6.11	Screen Shots Of Spreadsheet Model For Case 1	193
6.12	Vision 3D Computer Model Of Stress On Block	201
7.0	What We Learned	202
7.1	Buoyancy Equations	202
7.2	Real World Friction Tests	204
7.3	Load Frame And Cable Pulling System	205
7.4	Fabrication Drawings Of Load Frame	205

7.5	Computer Model Of Force And Friction	206
7.6	Computer Model Of Buoyancy / Barrier Thickness Prediction	207
7.7	Long Term Grout Properties	207
7.8	Cap Design And Integrity Measurement	208
8.0	Health And Safety Aspects Of Earthsaw™	209
9.0	Identification Of Data Gaps	210

Appendix

A.	Supplementary Data On Cases To Be Modeled	211
B.	Planned Subtask Elements	213
C.	Friction Test Report	215
D:	Excerpt From USDA Guide To Pulling Underground Cables	221
E:	Permeability And Rheology Lab Test Reports	224
F:	Questions And Comments From EPA	228
G:	Contract Scope Of Work – Tasks 1 And 2	233
H:	Comparison To Other Barrier Technologies	234
I:	Fabrication Drawings Of The Load Frame	See page 45
J:	CD ROM	See CD ROM of Topical Report

1.0 INTRODUCTION

1.1 The EarthSaw™ Buoyant Barrier Method

DOE landfills contain substantial amounts of radioactive and hazardous mixed waste that has the potential to contaminate the surrounding environment. Baseline technology is to remove these materials from the ground. However, in many cases, it is not safe or feasible to remove these wastes from the ground. Unsuccessful efforts to remove wastes from the ground at the INEEL pit 9 site have been very costly and hazardous to workers.

The EarthSaw™ buoyant barrier process is a method of constructing a thick and impermeable bottom barrier under and around a contaminated landfill area without disturbing the buried waste or exposing workers to its hazards. The purpose of this barrier is to permanently isolate and contain the waste without preventing retrieval or treatment in the future.

The method begins with a conventional slurry trench around the perimeter of the landfill area outside the contaminated area. This trench is then filled with a high specific gravity, grout material that cures to form a barrier. A cable saw device mechanically slices a cut horizontally through the earth under the landfill area while allowing the grout to gravity flow from the vertical trench into the horizontal cut. This high gravity grout is denser than the earth and causes the severed block of earth to become buoyant and float. Additional grout added to the open vertical trench flows into the horizontal cut, increasing the final thickness of the bottom barrier as the block of earth floats upward, just as a rising tide raises a boat. This grout cures to form a continuous bottom and side barrier up to a meter thick.

If successfully developed, the EarthSaw™ technology will provide a powerful tool capable of isolating and containing undocumented waste at DOE waste burial sites, without disturbing the waste! The EarthSaw™ may be applicable to a wide variety of earth conditions, in both dry and water saturated soils. Computer modeling indicates that sites up to 5 acres in size and up to 90 feet deep are feasible. Since the EarthSaw™ method does not touch or alter the buried wastes, all future treatment or technologically advanced removal options remain open, but the urgency decreases significantly. The environment is protected immediately. Treatment or extraction is often simpler in a contained volume and subsequent evaluation may indicate that no additional action is required.

Is there evidence of DOE's need for subsurface barrier technology or the functional requirements for the technology? Yes, in December of 1998 DOE issued an RFP soliciting new subsurface barrier technology. The RFP describes the problem of buried waste and DOE's requirements for a subsurface barrier construction technique. EarthSaw has been designed to meet these requirements. The topics of "problem definition" and "functional requirements" are best answered by quoting briefly from that RFP.

1.2 Problem Definition

(Quoted from DOE December 1998 RFP, DE-RP26-99FT40363)

“After years of designing, manufacturing, and testing nuclear weapons, the DOE is faced with the challenge of cleaning up the hazardous waste left behind. More than 5,700 known DOE groundwater plumes have contaminated more than 475 billion gallons of water. DOE landfills contain more than 3 million cubic meters of buried waste contaminating the surrounding environment. At DOE sites throughout the country, soil, groundwater, and landfills containing or contaminated with hazardous and radioactive contaminants have special cleanup needs.

“Landfills within the DOE Complex as of 1990 are estimated to contain 3 million cubic meters of buried waste. The DOE facilities where the waste is predominantly located are Hanford, the Savannah River Site (SRS), The Idaho National Environmental and Engineering Laboratory (INEEL), the Los Alamos National Laboratory (LANL), the Oak Ridge Reservation (ORR), the Nevada Test Site (NTS), and the Rocky Flats Plant (RFP). Landfills include buried waste, whether on pads or in trenches, sumps, ponds, pits, cribs, heaps and piles, auger holes, caissons, and sanitary landfills.

“The buried waste throughout the DOE complex is presently believed to be contaminated with both hazardous and radioactive materials. DOE buried waste typically includes transuranic-contaminated radioactive waste (TRU), low-level radioactive waste (LLW), hazardous waste, mixed TRU waste, and mixed LLW. The wastes at those various sites were disposed of directly or in containers such as steel drums, wooden boxes, and cardboard cartons. Coupled with the absence of containment barriers, some of the waste containers have breached from degradation over time resulting in contamination of large volumes of surrounding soils. The waste exist in the form of solids, liquids, or sludges, and have a diverse range of chemical constituents including radionuclides, polychlorinated biphenyls, heavy metals, organic solvents, and reactive compounds. Typical buried waste includes such items as construction and demolition materials (i.e., lumber, concrete blocks, steel plates, etc.), laboratory equipment (i.e., hoods, desks, tubing, glassware, etc.), process equipment (i.e., heat exchanger, valves, ion exchange resins, high-efficiency particulate air (HEPA) filters, etc.), maintenance equipment (i.e., handtools, cranes, oils and greases, etc.), and decontamination materials (i.e., paper, rags, plastic bags).”

1.3 DOE Technology Requirements for a Subsurface Barrier System

(Quoted from DOE December 1998 RFP, DE-RP26-99FT40363)

“The barrier installation process or system shall effectively and efficiently construct a continuous barrier without intrusion or disturbance to the waste requiring containment, and operate with a minimal perimeter so as not to disturb adjacent waste areas. The installed, containment barrier will be a continuous structure without discontinuities, that is constructed of durable, impermeable material, and serves to hydraulically isolate the waste site. Both the barrier installation process and the constructed barrier must meet required technology performance requirements, and must also meet any DOE site-specific and regulatory requirements.”

“The subsurface containment system that installs the barrier shall be designed to perform under broad operating conditions that exist at DOE waste or contaminated sites.”

“Subsurface barriers can be applied to contain contaminant migration, confine a treatment zone, and surround buried waste sites to prevent wastes from spreading. Required properties of a barrier include: provision for a continuous layer of impermeable material that forms a barrier structure that is free of cracks, tears, and other discontinuities; impermeable to the contaminant and groundwater; acceptable for environmental application; longevity to ensure the barrier’s design life expectancy; and durability to withstand site physical and chemical conditions including temperature and wetness, such as freezing and thawing cycles and wetting and drying cycles.”

“Advanced engineering design will be completed to develop a process or system that can install a bottom and perimeter containment barrier to surround a selected waste site. The primary purpose is to provide hydraulic isolation of the waste layer. The system shall be designed to operate under broad field conditions encountered at DOE sites; because the demonstration will be conducted at ORR, site and regulatory requirements specific to ORR must be met. The system shall be designed to operate without intrusion and/or disruption to the waste layer. The process shall be designed so that the perimeter of the operating area is minimized to avoid intrusion and disturbance of adjacent waste and contamination. The design of the system should ensure continuity of emplaced barrier material and structure, thereby resulting in a structure without discontinuities. The process shall be designed to operate in a variety of subsurface conditions such as unsaturated and saturated media, and residual soil and bedrock of various types. The design must accommodate and be adaptable to a variety of widths, depths and lengths of waste sites typically encountered at DOE sites. The process will be designed to operate at a range of depths that would typically be required for installation of a bottom and perimeter containment barrier at DOE waste sites. The barrier materials and resultant structure must be compatible with existing waste site chemical and physical conditions, and serve to hydraulically isolate the waste layer. A methodology to verify construction of barrier materials and structure must be provided.”

2.0 Background of the Technology

The need for a method to isolate undocumented pits and trenches containing radioactive waste has been the subject of many projects and conferences since the late 1980s.

In 1993, Ernest Carter invented the Horizontal SoilSaw, a horizontal barrier jetting system for forming bottom barriers under pits and trenches. This was a horizontal version of his vertical wall SoilSaw barrier system. Both systems used high energy jetting of cement grout to form barriers in place. These technologies used high energy jets to liquefy the soil and mixed the existing in situ soil with grout material to form an impermeable barrier. The technologies were technically successful in soft soils but, like the jet grouting technology it was based on, it also produced large volumes of spoils in hard soils.

Horizontal SoilSaw panels Dec. 1993

The SoilSaw forming a vertical barrier

Carter Technologies was formed in 1995. Carter already had many years of experience developing advanced grouting technologies for industry and designing special jet grouting and underground machinery for geotechnical modification and in situ treatment of waste. Carter Technologies soon began developing a more comprehensive solution for containment of pits and trenches and also continued the development of advanced grouting materials.

In January of 1999, Carter Technologies teamed with SAIC and proposed the EarthSaw™ technology to the Department of Energy in response to an RFP for demonstration of a bottom barrier at ORNL. This proposal was not accepted due in part to the absence of pilot scale field-testing to prove viability of the method. To correct this problem, two small proof-of-principle tests were performed in September of 1999. U.S. patents were also issued describing the EarthSaw™ method of using cable saws and buoyancy to create subsurface barriers.

Unlike the Horizontal SoilSaw which formed barrier sections by mixing grout with the in situ soil, the EarthSaw™ simply slices or saws a thin pathway and then expands this

thickness upward with an engineered buoyant grout. Therefore, the EarthSaw™ barriers are of more uniform properties and dimensions, and construction produces much less waste. In some conditions, the EarthSaw cable cuts like a giant cheese slicer without removing any soil to make the bottom cut. Due to the hydraulic control of the heavy grout, the EarthSaw then has the unique ability to slice horizontally through unexpected contamination, such as a perched water zone, without bringing the contamination to the surface, or contaminating the grout. Since the true subsurface conditions under a buried waste pit are seldom known for sure, this is a critical advantage over previous concepts.

2.1 Previous EarthSaw™ Field Test

In September of 1999, a privately funded “proof of concept” test was performed to verify that the buoyant barrier concept was valid. In this test, two 10-foot square cubes of soil were severed from the earth by a cable saw and floated upward to create a 2-foot thick bottom barrier. These tests were done in a sandy alluvial soil using a non-hardening clay based grout that we call TECT B. The grout had a 2.5 specific gravity. The highly porous soil had a specific gravity of about 1.7 specific gravity in the dry upper zone and about 1.8 in the water saturated zone. The grout was designed like a drilling fluid so that it would seal off on the highly permeable soil and seal any fractures.

The 85,000-pound block floats 24" above grout

getting a straight horizontal pull at the base of the soil block would require special hardware of great strength. The cut was made with $\frac{3}{4}$ " steel cable pulled by a small dozer. The cable was pulled straight through with no sawing action. The block of earth

*Dozer Pulls Cable Under Soil Block Surrounding By Grout Filled Trench
Dense Grout Flows Under Block Buoyantly Lifting It Upward*

Perimeter trench around 85,000-pound block

The soil was non-cohesive sand and the portion of the block elevated above the ground level by buoyancy tended to slough off because it was no longer supported by the fluid grout. We noted in this work that handling of the cable and

tipped up on the free edge during the cut and then popped up about 8 inches as it was cut free.

Additional grout was added to achieve about 2 feet of total lift. The bottom cut was not truly horizontal and it was noted that the depth of the bottom cut at each edge of the block dictated how much buoyant rise would result on that edge. It was observed that football sized clumps of loose sand sloughing off the edge of the trench or falling into the trench became floating “lumps” as the grout surrounded the mass of soil and formed a waterproof “skin”. This unusual phenomenon illustrates the unique properties of an EarthSaw™ grout. After the test was complete, the top 6 feet of the vertical wall section was treated with the hardening agent to firm up the grout to a soil-like condition so that no one could fall into the soft grout in the trench.

Six months after construction we returned to the site and excavated both of the sites layer by layer to physically observe the bottom barrier thickness and uniformity. The grout treated with the hardening agent was firmer than the surrounding soil, approximately 25 psi. As expected the un-hardened grout below this had lost some of its moisture to the ground and become substantially more dense. The excavated grout had the consistency of peanut butter and lab tests returned a 10^{-8} cm/sec permeability and a compressive strength of 3 to 5 pounds per square inch. This highly successful demonstration helped prove the soundness of the buoyant barrier method.

Excavation of solidified side wall

Excavation and sampling of bottom barrier

While the above proof-of-concept test did show that the process worked very well, it could not prove that the same method would work as well at a much larger scale. It was also not able to physically demonstrate the broad range of soil conditions applicable to the method. EarthSaw™ needed a much larger demonstration in order to be considered a real option for DOE cleanup managers. In the fall of 2000, Carter Technologies submitted an unsolicited proposal for a larger scale demonstration of the method to the U. S. Department of Energy, which was received with apparent interest. We were provided with a partial summary of some of the review comments. While none of these directly questioned the validity of the EarthSaw™ method, they indicated need for a more detailed mathematical discussion of the physics behind the process. Many reviewers wanted to see more calculations and engineering details of the equipment. Their

comments pointed out the importance of defining how EarthSaw™ could be applied to widely variable subsurface conditions within the DOE complex. The review comments also point out the need for such studies to be done in a methodical manner where both assumptions and physical laws relied on are clearly stated.

3.0 Project Description and Goals

The EarthSaw™ uses combinations of several existing technologies and industrial materials in new and creative ways. Many of the concepts are new, especially to those outside the oil well drilling industry, and initial presentations did not have the level of engineering detail and mathematical and scientific rigor which is typically required in the nuclear and environmental fields. The goal for task 1 was to provide a complete engineering description and detailed calculations supporting the method. The technology is intended to have broad application across a wide range of earth conditions and so the second task was to model the process to help define the range of conditions to which it could be applied. The objectives of task 1 and 2 of this study will be to: (1) Theoretical proof/derivation to support the buoyant barrier approach; (2) Predictive modeling with simulated waste area conditions to analyze the robustness of the technology. The EarthSaw™ method is designed to address very large sites and in order to be deployed at DOE sites it must be tested at near full scale.

4.0 Technical Approach

In order to achieve the goals and objectives set forth above we divided the work into several steps. The first step was to produce a more comprehensive and more quantitative description of the EarthSaw™ concept. This was to be followed by a detailed mathematical modeling and then detailed plans and costs for a 50-foot square by 20 to 30 foot deep demonstration at a site to be selected. We expect that the EarthSaw™ technology will not be more difficult at greater depths, so we planned around the 30 foot depth as nominal.

EarthSaw™ is designed to address the majority of wastes buried in pits and trenches at sites around the country so it has many variations and many different materials and optional features. To keep the discussion focused we decided to discuss only the Vertical Block Method. This would still allow us to prepare a computer model covering a multitude of shapes and sizes of barrier while keeping the parameters manageable.

We decided to limit discussion of grouts to the properties of the three main types of TECT grouts without getting into the science of how the proprietary grouts were made. This allowed us to avoid many issues regarding confidential information. We decided that to understand the EarthSaw™ technology, it was first necessary to understand the special physical properties of the grouts.

We planned to start with basic principles and derive suitable buoyancy equations to define the physics of buoyancy, cable saw friction, and various other factors which seemed to be significant.

We would then describe the cable saw technology and develop detailed specifications for the load frame and cable pulling system that we would use in the computer model. In order to do this we planned to complete the actual fabrication drawings we would need to prepare cost estimates for the field test. There are many ways to implement EarthSaw™ technology but we have selected the method which is most suited to the technical requirements already developed by DOE and stated in the DOE December 1998 RFP, DE-RP26-99FT40363.

These requirements direct us to operate in a minimum footprint space so that barriers can be made around sites surrounded closely by other waste areas. We believe that this indicates a vertical wall and flat bottom are desired. Choosing this “Vertical Block Method” lets us operate in close quarters but has at least one disadvantage in that creating the vertical wall will produce spoils of dirt. The full volume of soil in the vertical walls must be removed. Some other variations of the EarthSaw™ have 30 degree angled sides, in which the initial one-inch thick cut is buoyantly expanded upward to obtain the desired barrier thickness. This greatly reduces spoils but requires unobstructed workspace on two sides of the site.

To model the EarthSaw™ process, we recognized that we must have some data on the friction of the cable cutting through the soil and the forces that would be required. Based on our patent search, we believed that there was no existing body of data evaluating friction between steel cable and soil. We developed a plan to obtain this data. Recognizing the complexity of scaling factors for friction between complex surfaces such as soil and cable, we planned to test at full scale with actual proposed materials in as realistic an environment as possible.

We planned to search and find a proven theoretical basis for calculating friction of a line around the catenary curve of the horizontal cut. We view this as the most important factor in calculating EarthSaw™ performance so we also planned to obtain actual full-scale data to validate the formulas. Most mathematical information on catenary curves and friction around curved surfaces is focused on quite different tasks. We decided that we would need real world data before we could be certain that a formula was actually applicable to our approach.

Our next step was to develop a computer model of the mechanics and hydraulics of installing an EarthSaw™ barrier. We planned to search for commercial modeling software to do this but expected that we might have to make it ourselves since it is to model a process that is quite new and unique. We planned to begin with the outline of the model made in multiple Microsoft Excel spreadsheets, and then hire a programmer to complete the work and make the graphics.

We would then select a test site and prepare a complete plan and operations package with all costs and plans for that site. We planned to have DOE assistance in selecting a test site, but also made direct personal contacts with technical personnel at certain DOE sites that have a need for the technology.

A detailed list of subtasks that we planned to accomplish these goals is presented in Appendix B.

A requirement of NETL was to present posters at DOE technical conferences. Previous efforts have indicated that written descriptions, even when illustrated with pictures often fail to convey the basic concept. In order to surmount this problem we planned to include live demonstrations with a physical model in presentations at the mid-year review meeting.

5.0 Task 1 -Technical Work Product – Physics of EarthSaw™

Each of the planned subtask items is addressed in the following work product section, though many have been combined or re-sequenced for greater clarity. Some tasks were found to be less relevant or trivial upon detailed examination. For example, the question of the effects of water table changes after construction was found to have no effect at all, while calculation of wire saw wear rates was not possible without more full scale data. Descriptive topics are presented in the text below. The individual subtask items and computer model software items are supplied on the accompanying CD ROM compact disk.

5.1 Hydraulics of a Slurry Trench

Slurry trenching is a common method of geotechnical construction for creating a deep trench. Unlike solid rock, soil can often flow under the pressure of its own weight. As the depth of an open trench is increased, the earth pressure of the adjacent soil causes the sides of the excavation to fall in. This problem is more pronounced in certain soil and moisture conditions. In slurry trenching, this problem is solved by filling the trench to the brim with water slurry of highly dispersed colloidal clay while digging. The actual excavation is carried out under this slurry. The mechanism by which the walls are supported works like this: The water in the trench provides a hydrostatic head, which acts along with the strength of the soil to resist the earth sidewall pressure. However, a trench filled only with water could rapidly leak off into the soil. The bentonite mineral is composed of particles made up of many sheets that can hydrate and separate into billions of individual sheets dispersed in the water. In the lower portions of the trench, some of the water in the slurry, driven by hydrostatic gradient, permeates into the soil. However, the colloidal sheets of bentonite are too large and stack up on the surface or face of the trench. After enough of them stack up, they form a “filter cake” of impermeable

bentonite. This prevents more loss of fluid. At this point we can think of the hydrostatic pressure of the fluid in the trench, as acting against the surface formed by the filter cake. As long as the hydrostatic head plus the native soil strength is greater than the soil pressure, the trench wall will not collapse. This clay slurry also has the capacity to suspend sand particles and this increases the effective weight of the slurry, and thus the hydrostatic head it supplies. Once the slurry trench is formed, it is usually backfilled with a more dense mixture of bentonite and soil.

Slurry trenching technology is a highly developed and competitive industry with large equipment capable of excavating very deep slurry trenches. Carter technologies' subcontractor, Inquip Associates Inc. owns excavators for 90 foot deeps (at right) and clamshell devices (at left) able to excavate trenches 200 feet deep.

5.2 Hydraulics of EarthSaw™ Horizontal Cut

The EarthSaw™ vertical perimeter trench is simply a slurry trench. However, after construction, the slurry is replaced with a TECT grout. By “grout” we mean a fluid material which cures into an impermeable barrier material. A TECT grout is simply any grout that has the required properties for the EarthSaw™ process. (TECT stands for

tectonic, reminding us of the theory that all the crust of the earth is made up of plates floating on liquid material.) Like the slurry trench slurry, an EarthSaw™ grout uses hydrostatic head to support the walls of the trench. An EarthSaw™ trench is both vertical and horizontal. In order to support a horizontal cut the grout slurry must provide complete hydrostatic support because the soil strength provides no assistance. In order to do this the grout slurry must be denser than the block of earth to be supported. The grout must also not flow too freely into the micro-permeability of the soil because this could displace the lighter air and water and increase the effective density of the block of earth. Of course the grout may flow into larger cracks and fractures within the block, without any significant effect on buoyancy of the block. A familiar comparison would be a water logged (saturated) piece of wood which sinks in water, compared to a piece of dry wood filled with many drilled holes which still floats.

The EarthSaw™ horizontal cut is made with a relatively thin steel cable (Wire Rope). As the soil is cut, gravity forces the dense, yet fluid grout into this cut and provides buoyant support to the overburden material. We can manufacture the grout to a precise density of plus or minus one pound per cubic foot. If the density of the block of earth can be estimated accurately, the correct amount of buoyancy can be applied by controlling the fluid level in the perimeter trench. If the fluid level is too low to produce net positive buoyancy, the free end of the block will not rise after being cut. More grout would have to be added before continuing the cut. In many cases, it may be desirable to prepare a condition where the grout in the trench provides several inches of positive buoyancy. As the horizontal cut progresses, the grout flows into the horizontal cut. If excess positive buoyancy exists, the block will raise more. This will draw down the fluid level in the trench and reduce net positive buoyancy. Grout must be continually added during the horizontal cut. In practice, a worker will monitor the free end of the block and add grout as needed to maintain a specified lift.

5.3 Required Properties of EarthSaw™ Grout

This technology is based on the idea that a block of earth comprising a buried waste site will become buoyant in a grout of greater density. A perimeter trench full of a high-density liquid grout is established around the site to be contained and a cable saw mechanism is used to cut a thin horizontal pathway under the block from the bottom of the trench on one side to the trench on the other side. Gravity causes the grout in the trench to follow the cutting cable and establish a continuous layer of liquid grout under the severed block of earth. This continuous basin layer of grout is connected to the perimeter trench.

The grout is a fluid material having a density greater than the soil and having the property of sealing off a permeable soil material. This second property must be tempered with low viscosity such that the fluid flows readily into the narrow one-inch thick cut made by the cutting cable. The grout must transmit hydrostatic pressure from the hydrostatic head of fluid in the perimeter trench to the soil above and below the horizontal cut being made by

the cutting cable. This property must also be bounded by non-Newtonian properties that allow the fluid to develop sufficient static gel strength to permanently suspend solid particles.

This project will deal with three different grout materials for use with the EarthSaw™ buoyant barrier technology. All three of the grouts can be formulated to various high densities. The three grouts have radically different properties and achieve performance targets in different ways but they do share the following common properties that are needed to work in the EarthSaw™ technology:

5.3.1 Density

The density of the grout must be high enough, compared to the soil that the soil block will float to the desired elevation. If we were to fill the perimeter trench all the way to the surface, the relationship is quite simple. The (*grout/soil*) density ratio must be the same as the (*bottom cut depth/top of the bottom barrier depth*) ratio. In practice, we will not be filling the perimeter trench all the way to the surface, and there are other factors to consider. Formulas for calculating the correct density are described in section 7.52 but for this discussion, we will use a typical density of about 2.5 specific gravity. (156 pounds per cubic foot, 20.85 pounds per gallon). The grouts can be manufactured in densities up to 3.5 specific gravity, which may be needed for work in rock. The heavy weight additives and additives to maintain low viscosity are a major factor in the cost of the grout and thus it is desirable to use the lowest density grout which will achieve the desired buoyant lift.

5.3.2 Viscosity

The grout must be low enough viscosity that it can flow readily into a thin horizontal cut made by the cable saw while transmitting the hydrostatic pressure from the head of grout in the perimeter trench. Viscosity is defined as shear stress divided by shear rate. TECT grouts, like drilling fluids and cement slurries, have the property that the viscosity changes with the rate of shear. These are called Non-Newtonian fluids and cannot be properly evaluated by simple viscosity measuring flow cones such as the Marsh funnel. Typically, these fluids have a substantial shear stress value even at zero shear rates. (See static gel strength.) This desirable property allows them to suspend particles indefinitely when the fluid is static. At increasing shear rates, the apparent viscosity may decrease significantly.

A more accurate measure of viscosity is the Fann model 35 VG meter which measures the shearing friction in the annular space between an inner cylinder and an outer sleeve rotated at constant speed. This meter measures the actual shear strength in pounds per 100 square feet for 6 different rates of shear from 3 RPM to 600 RPM. The result is expressed by a series of 6 numbers such as: 16, 25, 46, 76, 99, 130. Here the 130

represents 130 pounds per 100 square feet when sheared at 600 RPM. The other values represent lower RPM rates of shear. The apparent viscosity in centipoise equals the 600 RPM reading divided by 2. Some of the grouts which we will use may be too viscous to measure using the Fann meter. They may have apparent viscosity similar to thick ketchup.

In applications where the cable cuts through a dry rock by abrasive sawing action the grout may be mixed with enough rock dust to increase the viscosity of the grout. In such applications, a lower viscosity grout should be used.

5.3.3 Static Gel Strength

Static Gel Strength is measured by the Fann model 35 VG meter by measuring the instantaneous peak reading when the rotation begins after the fluid has been static for a set time. This value is important in determining the pump pressure needed to begin pumping grout in a line or the friction to be encountered when starting up movement of the cable saw. It also helps predict the sand suspending properties of the grout. A static gel strength of 40 to 400 pounds per 100 square feet is anticipated.

5.3.4 Fluid Loss Control

The grout must not lose fluid into the soil formation and become dehydrated such that its viscosity or physical properties change. This property is measured by a drilling fluids test known as the “fluid loss” test. In this test, a sample of the grout is pressurized against filter paper on a permeable surface and the volume (milliliters) of water squeezed out of the sample in 30 minutes is measured. This is an important parameter for oil well drilling mud as well as for oil well cementing slurries since fluid loss could cause the mud to become too dry and plug the hole or inhibit transmission of hydrostatic pressure. In the case of TECT grouts, it helps define how thin of a crack the grout will flow into without dehydrating and packing off. For various reasons we are designing around a cut thickness of approximately one inch thick. The ideal grout will be able to flow into the cut but will tend to seal off smaller openings.

5.3.5 Cuttings Transport

In the EarthSaw™ technology the bottom barrier is mechanically cut by a circulating or reciprocating steel cable commercially known as wire rope. This cable is nominally from 3/4 to 1 inch diameter and has a rough exterior. As the cable saw is drawn across the face of the cut under tension, it removes particles of dirt and rock from the face of the cut. These particles must be transported out of the cut. The rough surface of the steel cable causes it to act as a pump and circulate fresh grout through the cut. In the preferred mode of operation these cuttings should become suspended in the grout and move out into the

perimeter trench. If the grout is not capable of suspending these cuttings the cuttings may tend to fall out of suspension and stack up in the perimeter trench. It is preferred that these solids stay suspended in the grout and uniformly distributed. We prefer that they neither sink to the bottom nor float to the top. After cutting the bottom barrier, the grout may have a significant amount of sand incorporated into it. Sand grains often have specific gravities between 2.2 and 2.7 and thus they are close to the specific gravity of the grout slurry. If the density of the sand is different than the slurry, the static gel strength of the slurry must be great enough to keep these grains from sinking or floating. Stokes Law calculations determine the required gel strength. Specially selected sand of the same specific gravity as the grout, may also be added to the grout during manufacture to improve abrasive cutting efficiency or to lower the cost of the grout.

5.3.6 Stability of the Slurry

The grout should be physically stable and solids should not settle out when the slurry is left in a static condition for several weeks. The cutting of the bottom barrier may take from a few hours to a few weeks depending on the size of the project and the toughness of the earth to be cut. The actual design of the grout slurry is specifically outside the scope of this project but we will evaluate some of the properties of grouts, which are planned for use in Phase II of the project. The art of formulating the grouts is proprietary to the grout suppliers. Carter Technologies' grout supplier, MI Drilling Fluids, is a world leader in supplying this kind of fluids technology for both oil well drilling and slurry trenching industries exporting their products worldwide. In production, the MI fluid specialist will be continuously measuring and monitoring the performance specifications of the grout during production at the on-site lab, just as would be done in drilling an oil well.

5.3.7 Lubricity

The coefficient of friction between the cutting cable and the soil helps determine the operating parameters of the EarthSaw™ and therefore what amount of energy is required. The amount of energy transfer possible is limited by the strength of the steel cable. Larger cables can transfer more energy but can become more difficult to handle. Lubricity may be improved by adding special materials to the grout. Cutting aids such as special sand may increase or decrease friction according to their shape and how they interact with the gel structure of the grout.

5.3.8 Permeability

After construction, the primary function of the grout is to make an impermeable barrier to prevent contamination from leaving the contained area. Therefore, the permeability of the cured grout should be less than 1×10^{-7} cm/sec. The required permeability depends

on the thickness of the barrier to be created. The grout must achieve this permeability reliably and retain it over the design life of the project. For our purposes, we will assume that the design life is 1000 years. One of the variations of the EarthSaw™™ method calls for drawing a synthetic liner under the floating block. After the liner is in place the grout could be used elsewhere. In this application the permeability of the grout is less important and its lubricity and ability to help seal joints become more important.

5.3.9 Properties of TECT Grouts

We define a grout that is compatible with the EarthSaw™ process as a TECT grout. This following section provides descriptions of the three main TECT grouts. TECT is a trademark name for any grout that can be used in the EarthSaw™ method. TECT grouts have also been used for jet grouting in radioactive waste burial pits at the Idaho National Engineering Laboratory. The grouts can be made in a wide variety of properties from rock hard, to putty-like and soft. Some TECT grouts are also designed to reactively bind chemical contaminants. There is no one “best” kind of grout for all sites.

5.3.9.1 TECT A

Tech A grout is a cementitious grout having a low water ratio and a high inert solids ratio. The grout has a physical viscosity appearance similar to catsup and can be readily pumped through 4 inch diameter hoses by centrifugal pumps designed for water service if the pumps are cleaned regularly. The grout is available with or without fiber reinforcement. Fiber reinforcement may be used for large structures where shrinkage or earth movement poses a risk of crack formation. (Use of fiber may make the grout more difficult to pump and mix and is not used in the jet groutable version of the material.) TECT A may be chemically and structurally similar to a cemented natural iron ore formation and this may be considered a natural analog for purposes of evaluating the durability of the grout in the environment over geologic time. Solidified TECT A grout is resistant to organic chemical and strong bases but may be degraded by strong acids. The thickness of the barrier can be a factor in the resistance of the grout to acid attack from finite volumes of acidic leachate within the confines of the barrier. The grout can be formulated with a delayed set time of over 8 weeks. Control of shrinkage is very important in design of a TECT A grout for a large structure.

Nominal properties of the TECT A grout are as follows:

Fann VG shear values exceeding range of measurement,

Pot life of 6 to 60 days.

Set time of 6 to 120 days.

Final compressive strength of 2,000 to 8,000 psi.

Elongation before fracture of .1 to 1 percent.

Tensile strength of 400 to 1000 psi

Viscosity of less than 100,000 cp

Marsh funnel viscosity exceeding 5 minutes

Shrinkage when cured underground in moist environment is .01 to 0.05 percent.

Fluid loss resistance sufficient to prevent plugging of 1" cut.

Permeability less than 1×10^{-8} cm/sec

5.3.9.2 TECT B

Tect B grout is a non-hardening clay based grout. TECT B is applied as a flowable slurry with highly lubricative properties. The grout cures to a peanut butter like condition over a period of 6 to 12 months. In this condition, it is fully self-healing and should offer a very high level of containment integrity over very long time periods. When initially placed in liquid form the hydrostatic head prevents any ground moisture or contaminants from entering the grout material. As time goes by the grout will cure by coming into vapor phase equilibrium with the earth. The grout loses water vapor to the ground and thus shrinks as it cures. This shrinkage is expected to take place more slowly if the grout is below the water table. This results in a final grout that is extrudable like peanut butter and no longer a liquid. The pressure of the floating block maintains a continual confining stress on the grout that prevents the volume shrinkage from causing cracks or gaps. The final cured grout has a nominal permeability of less than 1×10^{-8} cm/sec.

TEXT B grout is designed to remain a putty-like solid indefinitely just as natural clay remains damp in most subterranean formations. In most applications, the ground is always moist and the soil gas remains near 100 percent humidity, so excessive drying of the grout is not an issue. However in dry environments or near the ground surface drying of the grout could cause a loss of flexibility or even cracking. To solve this problem the grout uses a special chemistry which can be tailored to adjust the equilibrium moisture content so that the grout may remain soft and flexible even if exposed to a dryer soil environment. Increasing the drying resistance adds significantly to the final cost of the grout.

TECT B grouts may be formulated to reactively destroy organic liquids. This proprietary technology enhances the long term containment of the barrier by chemically destroying organic liquids which permeate through the barrier over geologic time.

Nominal properties of the TECT B grout are as follows:

Fann VG shear values of: exceeding range

Pot life of 120 days.

Cure time of 6 to 12 months.

Final compressive strength of 1 to 10 psi.

Unlimited elongation before fracture. Fully plastic flow

Tensile strength of 0 to 10 psi.

Viscosity of less than 100,000 cp

Marsh funnel viscosity of greater than 5 minutes

Shrinkage when cured underground in dry environment. 5 to 30 percent depending on design.

Fluid loss resistance sufficient to maintain plastic flow.

Permeability less than 1×10^{-8} cm/sec

5.3.9.3 TECT C-B

Carter Technologies can also provide special Midrange grouts which harden over time to 10 to 200 psi strength yet withstand significant elongation before fracture. These grouts can be thought of as midway between the TECT A and TECT B designs. They do harden but reach properties similar to native clay. Their permeability is higher than the other grouts and they are not able to resist prolonged dry climate as well as the TECT A grout. However for many sites this may be a viable choice because it is much closer to the properties used in conventional cement bentonite slurry walls and geotechnical engineers and regulators may find it more familiar.

Nominal properties of the TECT C-B grout are as follows:

Fann VG shear values of: exceeding range

Pot life of 10 days.

Cure time of 1 to 2 months.

Final compressive strength of 10 to 200 psi.

Up to 2% elongation before fracture.

Tensile strength of 0 to 30 psi.

Viscosity of less than 100,000 cp

Marsh funnel viscosity of greater than 5 minutes

Shrinkage when cured underground in dry environments depending on ambient moisture.

Fluid loss resistance sufficient to maintain plastic flow.

Permeability less than 1×10^{-6} cm/sec

5.3.9.4 TECT W

This is a high-density version of a molten wax grout used in jet grouting tests at the INEEL, known as WAXFIX. TECT W has a melt point of 125 to 140 degrees F and is prepared and placed at a temperature of about 160 to 180 degrees F. Clean up of equipment may be done with hot water. The molten grout has a high heat capacity and low thermal conductivity so when placed in a large mass it loses heat quite slowly. However, when the grout enters a fracture or permeates into porous soil or rock it loses heat more rapidly and solidifies. This property makes this grout ideal for work in fractured rock. The solidified material made from the preferred polymer is malleable and slightly sticky. A sample hit with a hammer will simply dent or flatten without breaking. A sample cut off with a knife will re-adhere to the original mass with a small amount of pressure. These properties make it an excellent material for a containment barrier that may be subjected to mechanical stress. Molten wax grouts generally shrink upon

cooling. Generally, this works somewhat like the shrinkage of a home made candle where the center of the candle shows the shrinkage. This can be minimized by maintaining a supply of molten liquid to feed the center areas of the candle or by increasing the proportion of inert solids. For the malleable wax version shrinkage is not really a troublesome issue since like TECT B grouts, this grout will flow plastically and self heal any crack under the applied stress of the overburden weight.

Nominal properties of the TECT W grout are as follows:

Fann VG shear values of: Exceeding range

Pot life is thermally determined

Cure time is thermally determined.

Final compressive strength of 20 to 100 psi.

Unlimited elongation before fracture. Fully plastic flow

Tensile strength of 20 to 100 psi.

Viscosity of less than 100,000 cp

Marsh funnel viscosity greater than 5 minutes

Fluid loss resistance. Not applicable, grout contains no water.

Permeability less than 1×10^{-10} cm/sec

Acid resistance to pH 1

Base resistance, to pH 13

Organic resistance is expected to be very good for low concentrations. Resistance to solvents is likely to be the same as base polymer. The more resistant polymers create a more rigid product.

5.3.9.5 Other Grouts

Conventional grouts generally do not have sufficient density, nor long enough set time to function well as TECT grouts. Concrete can be made commercially to sufficient density but this involves large aggregate sizes which are difficult to keep in suspension and may interfere with cable saw operation. There are many properties, described above which must be balanced by engineering judgment to achieve optimal results. Concrete of this type may be useful as filler for grout addition to reach final vertical displacement if it does not have too high a shrinkage factor.

5.4 Step-By-Step Quantitative Process Description (Subtask 1.06 - 1.14)

There are several different variations on the EarthSaw™ technology which each have their strengths and the method of application will vary according to the constraints of the site. In order to make this discussion quantitative we will assume that the barrier is a 100 foot by 300 foot area to a depth of 30 feet. Assume that the site contains contaminated construction debris, 1000 drums of contaminated clothing waste, 450 drums of air sensitive uranium turnings packed in oil. The soil strata varies randomly between sandy silt and silty clay with stringers of sand and average of 1 football size rock per cubic yard of soil. Soil penetrometer measurements show an average of 25 blows per foot above water and 15 blows per foot below water table. This discussion will help

explain why the type of waste disposed has little effect on this technology. We will also assume that a TECT B grout has been selected and that the water table is at 20 feet deep.

The following step-by-step process is for the EarthSaw™ “**Vertical Block Method**”. This method produces a containment structure that has vertical sides and a flat bottom. The nominal shape is rectangular but it can also be of irregular shape. In this method a slurry trench is first formed around the waste site in the uncontaminated perimeter. This trench is then filled with high specific gravity fluid grout and a cable saw device is installed using a mechanical load frame, which applies horizontal cutting force at the base of the trench. As the cut proceeds the high density grout flows under the block of earth and provides enough buoyant lift that the block does not subside. After the horizontal cut is complete the block floats on the heavy grout. Additional grout added to the perimeter trench causes the block to rise and produce a bottom barrier far thicker than the cutting device. Since the barrier is formed by an engineered fluid grout it will be of uniform quality and thickness. After the barrier is constructed it will be measured and tested by various means and if desired a suitable cap structure will be installed.

5.4.1 Slurry Trench Perimeter Excavation (1.07)

The first construction step in applying the vertical block version of the EarthSaw™ method is to construct a slurry trench around the perimeter of the contaminated area. This trench should be outside the contaminated perimeter and extend below the probable contaminated strata. Many types of equipment could be used. For a 30 foot deep trench, the trenches could be cut with an extended stick, Cat 235 class, trackhoe with a narrow 20 inch wide bucket. This will form a trench with an average width of 24 inches and a minimum width of 20 inches. (A 14 inch wide bucket could also be used.)

Before excavation begins a series of borings will be made along the proposed perimeter, for density measurement, contamination measurement, and cone penetrometer readings. This data will be needed to plan the project. If the site has a high water table, a dewatering well may be installed inside the perimeter to keep the slurry trench from raising the water table in the contaminated area.

In commercial practice, the subcontractor would prepare bentonite slurry in a shallow pit in a clean area. Dry bentonite clay is delivered 25 tons at a time in pneumatic bulk trucks and blown directly into the mixer system which mixes it with water and pumps it into the pit to hydrate. It is also possible to use metal tanks instead of a pit. The clay slurry is mixed at nominal ratio of 5 percent clay by weight of water. The clay will form a slurry with a Marsh funnel viscosity of 40 to 60 seconds. The fully hydrated slurry is a colloidal material having lubricating properties and the ability to form a filter cake on soil surfaces so that little water is lost to the earth. This is important since waste sites want to minimize water infiltration.

Pumps and a flexible pipeline will deliver this slurry to the trench as the trackhoe is excavating. As the excavation proceeds, the trench is kept full of the bentonite slurry. The hydrostatic pressure of the slurry will hold the walls of the excavation open. The soil removed from the trench is placed adjacent to the trench and the free slurry is allowed to drain back into the trench. The slurry may be placed on either side of the trench. Since the slurry seals the soil surfaces that it contacts, this practice should not cause water to infiltrate the surface soil.

In building a slurry trench around the perimeter of a rectangle, it is common to overlap the corners. We expect about 6 feet of overlap on each corner. This will increase the total linear feet of slurry trench from 800 feet to 848 feet. The slurry trench production rate will be about 200 feet per day. Excavation work should take 4 to 9 days. Excavation will produce about 2000 cubic yards of spoil. If the trenches are made outside the zone of contamination, this spoil will be clean soil mixed with the slurry. This material may be useful for cap construction. Working and mixing it with a dozer while stockpiling it, can make it into a uniform low permeability material. It would cover a 120 foot by 320 foot area to a depth of 16.8 inches.

The slurry trenching process has developed over the last 40 years to a state of the art method of construction for vertical barrier walls. Carter Technologies' subcontractor Inquip Associates Inc. routinely constructs slurry trenches to depths of 90 feet or more. In the last 20 years, they have installed over 100 miles of slurry trench. The slurry trenching experts at Inquip Associates recommend that two de-watering wells be installed inboard of the perimeter trench to prevent the rise of groundwater in the block. If this were to occur it could compromise the stability of the slurry trench before the grout is installed. (Slurry trench wall stability depends on a small amount of water being able permeate into the trench.) These wells are also potentially useful after the barrier is installed.

5.4.2 Installation of the Load Frame and Cutting Cable (1.08)

After the slurry trench is complete, the load frame device and cable saw will be installed in the trench. There are at least 2 load frames required for the EarthSaw™ process. The load frame is a structural steel frame designed to fit into the intersection of two trenches that cross at a right angle. The frame has a pulley which transfers winch pull on the cable at ground level to a horizontal pull at the bottom

of the trench. The current design may be shortened by torch cutting or welding additional sections on. After the design was finished, we discovered DOT regulations would require each unit to be shipped on separate trucks. We could solve this problem in the future by making the units from modular 8 foot sections.

Each load frame is a steel structure about six feet square and as tall as the depth of desired operation. For the planned work this is 30 feet. The load frame weighs about 25,000 pounds and requires a large (100,000 pound pull,) winch to power it. The winches selected for this work are about 6 foot wide and 8 feet long with the hydraulic power unit. One winch will be loaded with $\frac{3}{4}$ inch to 1 inch diameter high strength steel cable. The winch skid would be welded, to the top of a steel plate (LFRAM028.gcd) having 4 pins designed to fit onto the top of each load frame. The pins are then locked with quick release retainer pins. The retainer pins are strong enough to pick up the entire load frame.

The steel cable will be threaded through the first load frame and around the perimeter of the trench, restrained by a backhoe with a suitable hook attachment. The cable will then be treaded through the second load frame and attached to the second winch. The first load frame is lowered into the slurry trench. The first winch is then lowered down on top of it and secured as the backhoe takes up any slack. The weight of the load frame helps push it down past any imperfections in the trench. If the frame will not move down it can be lifted out and the trench cleaned with the trackhoe. If a narrow sidewall barrier is specified, the trench may be made slightly wider at this point to accept 24 inch section thickness of the load frame. (If the winch cannot be centered over the load frame, crane

mats stacked under the winch can be used to span the trench and support the weight of the winch.) The second load frame is then lifted and lowered into the trench. The second winch is lowered into place as the backhoe takes up slack. The cable is then allowed to fall into the trench all around the perimeter with measured string lines looped around it to verify that it reaches full depth. One winch may be activated to take up slack as this occurs.

A corner protection device, possibly a 180 degree section of 60-inch diameter pipe ten feet long, lowered into the corner on three chains, may be used to allow the winches to be tested under moderate load and speed before installing the grout. This tool can also be used to assure that the horizontal cut begins below a specific depth. The cable can be pre-attached to this tool to make sure that it reaches the desired depth. Lifting up in the outboard chains of the pipe section will cause the cable to slide down and off, and begin the cut at the base of the trench.

The slurry in the trench may then be replaced with grout by pumping the slurry to the bottom of the trench through a tremie pipe. This may be gravity discharge from concrete mixer trucks through a large 14 inch diameter tremie pipe. The light weight slurry will be pumped off at the surface and transferred to a holding tank or back to an earthen pit. Due to the large volume (about 1700 cubic yards of grout) this may take 2 to 3 days. The bentonite slurry in the pit can be treated to help the water evaporate, leaving only the sand and clay residual.

5.4.3 Replacing Slurry in the Trench with Grout (1.09)

The grout slurry may be made off site or may be manufactured on site. If TECT B grout is manufactured on site we would preferably use the same kind of pit that was used for pre-hydrating the bentonite slurry. (The non-toxic grout can also be made and stored in tanks at a significant extra cost.) Oil field mixer systems designed for mixing drilling fluids would be used to perform the mixing and proportioning work of the base fluid. Bulk material deliveries would be by pneumatic truck. For construction of a 24-inch thick bottom barrier, About 260 truckloads of dry material will be required. Manufacture of the 3,900 cubic yards of grout required may take several days. The initial displacement of the bentonite slurry will require only about 1700 cubic yards of the grout and so only this amount needs to be made in advance.

Once the grout is ready, a 6 inch diameter by 31 foot long tremie pipe is installed, which will conduct the grout to the bottom of the trench at a rate of 500 to 1000 GPM. A 6 x 6 1000 GPM pump system would be installed on the opposite side of the trench perimeter to remove bentonite slurry at the surface. Displacement of the grout will take a full 8 hour day. The 2.5 specific gravity grout easily displaces the slurry, filling the trench from the bottom up. Clumps of dirt which slough off the sides of the trench will also be displaced upward to the grout/slurry interface surface. A cap of approximately 1- 2 feet of bentonite slurry may optionally be left on top of the grout and this slurry will have 1 to

2 feet of freeboard to the top of the trench. For calculation purposes, assume we remove all the bentonite slurry and fill the trench to within 3 feet of the surface. We will call this 3 feet of “freeboard”.

Plan view of work area for 50' x 50' pilot test

5.4.4 Filtration Control significance in Buoyancy

The buoyancy calculations in this document are not significantly affected by drilling vertical holes through the soil block or by the presence of evenly distributed voids within the volume of the block as long as the average density of the block can be approximated. However, for the average density calculations to remain accurate we must have grout materials that do not substantially enter the micro-permeability of the soil formation since the individual grains of soil have a higher density than the block as a whole. Fortunately, the oil well drilling industry solved this problem long ago. They use a term called “fluid loss” to measure the propensity of a fluid to seal off on the permeability of a soil or rock and thus prevent the mud in a deep oil well from losing its moisture to the formation. In an oil well this may involve soil, rock, or fractured rock.

Fluid loss for drilling fluids is tested by a device that presses a slurry against a porous surface of filter paper at 100 psi and measures how much fluid is lost in 30 minutes of testing. Fluids with low fluid loss are desirable for drilling wells because they prevent loss of the carrying fluid to the formation. This prevents changes in the physical properties of the fluid due to fluid loss.

Objects which contain air void spaces such as life jackets made of foam achieve their low density by trapped air. A low quality foam life jacket which is permeable to water, may have some of its cavities filled with water over time. This increases the net density of the life jacket and reduces its effectiveness by increasing its weight. Could the same thing happen to a floating block of earth? The answer is that it could happen...if our grout did not have the correct fluid loss resistance. Unlike water, a properly designed grout will not flow into the permeability of a soil, but form a seal on the surface of the soil. The same technology allows drilling fluids to seal the walls of a hole as it is drilled to great depth through many types of soil.

The grouts used in the EarthSaw™ process, like oil well drilling mud, must have the ability to seal off on the surface of sandy soil or small fractures and thus the grout does not penetrate into the soil enough to change its bulk density. Development of a suitable grout that has all the required properties is not trivial. As an example of this property consider our field test done in sandy soil. Football sized chunks of the trench wall and trench bottom which broke loose during the work floated up to the surface of the grout even though the sand particles themselves have a higher specific density than the grout. Some of these floating clumps were scooped out of the trench and examined and found to have no grout inside them. For any given drilling mud or grout design, there is a maximum size fracture that it can seal.

FILTRATION CONTROL

Leakage of fluid into soil causes clay platelets stack up against permeable formation and prevent fluid from escaping into the soil

Let us assume a high density grout with the properties of a drilling mud such that it is capable of sealing off against permeable surfaces with a minimal loss of its own fluid. This is referred to as filtration control or fluid loss control. The 1978 IMCO Halliburton Services Applied Mud Technology handbook states that this property is primarily achieved in drilling fluids by use of a highly dispersed sodium montmorillonite clay which separates into microscopic colloidal plates which seal porous formations and also produce a limited gel strength at zero shear to enable the slurry to keep solids in suspension indefinitely. These plates are thin and flat and form a compressible filter cake. (Figure 3) It is believed that the surface waters of hydration surrounding the bentonite platelets can provide an effective seal when the platelets are wedged between larger particles in the cake.

5.4.5 Quantitative Description of Cable Saw Cutting Process

Many of the calculations for cable cutting of soil involve friction coefficient as a critical value. The 1978 McGraw Hill Dictionary of Scientific and Technical Terms defines Coefficient of Friction as: "The ratio of the frictional force between two bodies in contact, parallel to the surface of contact, to the force, normal to the surface of contact, with which the bodies press against each other." Obtaining data on the true range of friction coefficient in various soil/grout/cable systems will be one of the tasks later in this project. For the present descriptive task, we will use 0.5 as a typical value.

Maximum site size is limited by total friction imposed by the total friction on the cable. When the total friction exceeds the strength of the cable or the power of the winch the cable will be stuck or will break. The friction factor is an exponential function of the angle of contact with the soil times the coefficient of friction. This factor defines the ratio of power lost to friction due to the contact angle. The drag friction is the weight of the cable on laying horizontal in the ground times the coefficient of friction. This drag friction subtracts from whatever force remains after applying the friction factor and can cause it to fall below zero, indicating a stuck cable.

Pounds Total Friction = $e^{\lambda\alpha} + W_h \times \lambda$ **Where λ is the coefficient of friction and α is the angle of contact in radians, and W_h is the weight of the cable laying on the ground surface and in the horizontal cut.**

Assume an EarthSaw™ cut being made using dozers to pull both ends of the cutting cable in a reciprocating motion. As the cable begins cutting in and taking a catenary shape, let us assume it is under a uniform load of 20,000 pounds on the pulling end and 10,000 pounds on the trailing end (pulling the other dozer) measured at the base of the load frame. When the stroke is reversed the cable loading is reversed. This implies a frictional loss of 10,000 pounds. The 10,000 pound tension in the cable is applied over an area 175 feet long and 1 inch wide. This is 14.58 square feet or 2,100 square inches. 10,000 pounds/20,000 pounds = 0.50 coefficient of friction. The face of the cut sees an alternating force from the cable that varies between 10,000 and 20,000 pounds. 10,000 pounds over 2,100 square inches is 4.76 psi while 20,000 pounds yields 9.52 psi.

Based on this value and the higher soil shear strength of 15 psi, the cable will not be able to slice through the ground without abrasive action. The slicing action will have stop

when the length of the cut becomes great enough to drop below a contact force of 15 psi. This will occur when the cut is about half rounded off.

If the coefficient of friction is reasonably low, the tension in the cutting cable may be significantly reduced to help assure that the cable will reciprocate rather than slice. Alternately, the tension may be increased by increasing drag on the trailing dozer to force the cable to slice through hard areas.

When the cable slices through the ground, we theorize that it does so by compressing the soil above and below the cut, by lifting the overburden upward, or by plastically flowing around the cutting cable. It seems likely that slicing will only be possible in soils that are not highly compacted. Softer clay soils which extrude around the cable make an interesting case. If the hydrostatic pressure from the grout does not exceed the local pressure of the grout extruding past the cable one wonders if the grout will follow the cable. To examine this issue we must consider the science of fracture mechanics.

In oil well drilling a large body of knowledge regarding fracture mechanics of soil and rock has been developed to aid in maximizing production surface area of a well. Every soil or rock has a “fracture gradient” which is the pressure in psi at which a fracture will propagate. Hydraulic fractures always propagate along the lines of least principle stress. In deep oil wells, the great overburden pressure causes hydraulic fractures to propagate vertically. However, in shallow soil areas the lack of significant overburden pressure generally causes all hydraulic fractures to propagate horizontally with an upward bias. In the case of the path of a cable that is being pulled through a plastic clay soil, the disturbance of the cable creates a significant weakness along a horizontal plain behind the cable. This horizontal plain is also in contact with the heavy grout that has pressure urging it into the gap. It all comes down to a question of which fluid is being pushed with the most pressure. It is possible that under some conditions, a slicing cable may not allow the grout to follow. However, even if this is so, the greater hydrostatic pressure of the grout would simply propagate a horizontal fracture along the plane of the cut. The net result would be the same in that a layer of heavy grout is formed under the block along the path of the cable.

In slicing through the soil, a steel cable is theorized to work much like a cheese slicer wire cuts through cheese. No waste or cuttings are produced. Hydraulic head of the grout will prevent any fluids in the waste from entering the grout to spread

contamination. A slicing action, when possible may be the most efficient cutting method. It should be much faster than sawing and will not bring significant volumes of contaminated cuttings into the grout.

5.4.6 Activating Cutting Cable (1.10)

The 1,000 foot long cutting cable may be pulled back and forth by a pair of large winches. Optionally the cable could be joined end to end by a “long splice” and circulated in continuous fashion like a band saw. For our discussion assume that two separate winch units are used and the cable is pulled back and forth.

There are several types of wire rope cable suitable for this work. One choice is an eight-strand, one inch diameter wire rope, 8/36 construction, crane rope having a nominal strength of 151,065 lbs pounds. This wire rope weighs 2.125 pounds per linear foot and has a very high modulus of fifteen million psi. Another useful cable is a three-strand type that is expected to be more effective in cuttings transport. (This three-strand cable is of the non-rotating kind, which means that changes in tensile loading do not cause it to twist.) The one-inch size has a strength of 125,000 pounds. Common six-strand wire rope in the one-inch size has a strength of about 100,000 pounds.

In the beginning of this study, it was thought that we would use large dozers to pull the cutting cables. After further evaluation of the power requirements and the dangers of highly stressed cables above ground, we decided not to use dozers. Large winches may offer superior safety features but for some contractors it will be more economical to use a pair of large Cat D-7 class dozers (track-type tractors) to reciprocate the cable in non-DOE projects. For this dozer technique, the load frames would require an additional pulley at the top. Due to the hazards of stretched cable and the limited pulling power of dozers, we prefer to use winches mounted directly on the load frame for DOE applications. This “winch on top of the load frame” configuration keeps all stressed cable below ground and reduces the space requirements around the perimeter. We can load the cable to tensile failure without any danger to workers. In some operational conditions, we may want to be able to pull the cable in two on purpose. In these cases, we will probably select a smaller diameter cable or a more powerful winch.

We plan to use a Conmaco JU-36 winch driven by an external hydraulic power unit. See: www.conmaco.com This unit has remote controls and can pull up to 106,000 pounds force in standard configuration at 21 feet per minute. The winch automatically adjusts speed to handle the applied load. Maximum speed is about 138 feet per minute. The winches will be manually controlled and one will provide back drag while the other pulls the cable until it reaches the end of the spooled cable. Then we will reverse direction by moving the control lever the opposite direction. The control stands for the winches may be removed from the winch skids and placed together at a central point to control the winches.

Ju-36 Performance 1" Wire Rope

Performance @ Maximum Line Pull

Layer	P.D. (in)	Single Line Pull (lbs)	Single Line Speed (fpm)
1	19.00	106494	21.1
2	20.69	97795	22.9
3	22.39	90370	24.8
4	24.08	84028	26.7
5	25.78	78487	28.6
6	27.47	73658	30.5
7	29.17	69365	32.4
8	30.86	65567	34.2
9	32.56	62143	36.1
10	34.25	59077	38.0
11	35.94	56299	39.9
12	37.64	53756	41.8
13	39.33	51446	43.6
14	41.03	49315	45.5
15	42.73	47353	47.4

5.4.7 Mechanical Restraints

After the cable saw has passed an area along the perimeter, steel I-beams may be inserted into the perimeter trench to provide mechanical restraint to prevent the block from tipping or moving substantially. These beams may be of a special torturous cross section shape if they are intended to remain in place.

If the beams are intended to come out after partial grout

curing they may be equipped with grout injection lines to allow grout filling as they are withdrawn. For very deep sites the beams may be made to function as strain gauges to measure an out-of-balance block condition while surface loads are altered to correct it.

It is also possible to use many large rocks in the grout, which is used to raise the block to final

Plan view of earth block with spacers made from I-Beams

elevation. These rocks can be dropped into the perimeter trench to lock the block in place and prevent lateral movement. Rocks, however have the potential to create leak paths through the grout and must be selected carefully.

5.4.8 Leveling of the Bottom Barrier

After the block is floating, the surface will be surveyed and compared to the initial surface. Any variation in the lift from one corner to another indicates a variation in the thickness of the subsurface barrier. The elevation difference will be used, along with the computer model, to calculate the correct amount of surface soils that much be moved to achieve uniform balance. For example, if we find corner D has risen only 4 inches while corners A, B, and C all rose 8 inches, our model could tell us how many inches of soil to remove from quadrant D, or add to the others, to make the barrier a uniform thickness at all four corners. This re-grading of the surface will produce a uniform bottom barrier but exaggerate any existing variation in the surface topography.

5.4.9 Adding Additional Grout to Trench (1.11)

As the cable reaches the end of its cut, the load frames allow the cable to turn inward and cut the final sections. Additional grout must be continually added to the perimeter trench to compensate for the bottom cut, but fluid level in the trench is controlled dynamically to keep uplift of the block limited to a few inches. Once the cut is complete, additional grout is added to the trench from the center of the end opposite the load frames until the block rises to its design elevation of 24 inches above grade. Additions of grout have the potential to move the block around in the trench like a floating barge tied at a dock. The load frames provide some bracing to prevent movement at one end but adding grout on one point too quickly could push the floating block around due to the viscosity of the grout. If the I-beam mechanical restraints are used, this will not be a problem.

The grout added in this buoyant lifting phase of the work may be of higher viscosity and may contain more large solids to reduce cost or minimize the potential for movement of the block.

5.4.10 Measurement of Barrier Thickness (1.13)

At this point in construction, a client may request proof of the thickness of the bottom barrier. This may be done in several ways.

1. The corners and perimeter of the block may be core drilled.
2. A very large chain may be lowered into the 100 foot long trench and both ends pulled along the 300 foot length.
3. A “U” bend of solid steel pipe may be passed under the floating block.
4. A “J” bend rod may be used to manually probe the depth of the bottom edge of the block at various points.
5. Ground penetrating radar may be used to verify the depth of the barrier.
6. The surface topography of the block may be surveyed before and after the initial cutting, before any re-grading is performed. The difference is the actual barrier thickness after cutting. If re-grading is then performed, it must be factored in to determine the true thickness. The grout fluid elevation is then surveyed before and after raising the block to final elevation. This ‘rising tide’ displacement added to the previous difference is the bottom barrier thickness.

5.4.11 Sealing Surface and Cap Construction (1.12-114)

Once the barrier is complete, it should be integrated with a cap. For the TECT B slurry in this example the preferred cap is based on a synthetic top liner keyed into the side walls by an 8 foot deep cuff. Fabrication of the cuff is as follows:

Any remaining bentonite slurry is first removed exposing the grout. An eight foot wide sheet of 80 mil HDPE is laid out around the perimeter of the site. A 6 foot wide cuff piece is laid on this and fusion bonded to make a bottom joint. 24 inch long vertical seams are fusion welded every 5 feet. (This helps the bottom end remain pointed.) One end of this composite sheet is held above the trench by a backhoe and the rest of the sheet is pushed down into the trench with poles inserted in the cuff as grout from the trench is pumped into the cuff. When this operation comes back to the starting point the ends are overlapped and bonded together. The joined section can then also be pushed down into the trench. This provides a continuous vertical perimeter sheet sticking out of the grout approximately flush with the top of the block on the inboard side and flush with the ground on the outboard side. The grout level in the cuff is flush with the grout in the trench, which typically would be 2 feet below ground level. A top liner may then be installed and fusion bonded to the vertical perimeter sheet. A protective concrete cap, slightly lighter than the grout, would be poured on top of the grout in the cuff, flush with ground level. Additional liner material would be fusion welded to the outboard edge of the cuff extending outward along the ground level about 10 feet.

Following are a series of simple graphics to illustrate the method of keying the liner into the grout and then installing the top cap.

Step 1: The Earth block is already floating. The perimeter liner is field fabricated as a deep V cuff. The perimeter liner is installed (see right side of drawing), and filled with grout to the level of grout in the trench to keep it from floating. (left side of drawing)

Step 2: The remaining freeboard space inside the liner is filled with concrete, optionally reinforced with synthetic fiber around the entire perimeter. The concrete floats on the grout and hardens. It may have any type of non-rusting reinforcement added.

Step 3: The Synthetic top cap is bonded to the perimeter and the earthen cap is installed.

The spoils from the original perimeter trench would then be used to form an earthen cover over the site according to best engineering practice. The de-watering wells installed during trench construction can be sealed with bulkhead connections through the liner for use in de-watering or for negative pressure verification methods. A TECT B grout is designed to lose some moisture to the soil formation over time until it comes into vapor pressure equilibrium with the soil. This effect can reduce the thickness of the bottom barrier, and thus reduce final elevation of the block by 5 to 30 percent. (note: if free water is pumped out of the contained volume that will cause the block to rise.) This is no cause for alarm but should be designed into the cap construction plans. It should also be understood that the block is still floating, even when the grout becomes as stiff as peanut butter. Additional weight placed on top of the block must be balanced by also placing equal weight on the concrete cap in the perimeter trench, or the block will eventually sink a corresponding amount. Of course, this will not be an issue if one of the hardening grouts is selected. We can make the grout harden only slightly or develop high strength. If weight is added evenly to the top of a cap over a soft grout, then the added load may cause the grout to squeeze more water out to the formation, thus making the grout less fluid. At some point the grout will become too stiff to flow and will behave like a natural clay soil.

5.4.12 Air-Tight Cap Allows New Ways to Monitor Performance

Permeability of the barrier can be measured by several techniques. In the example project where the ground water is mid way up the barrier, permeability may be directly measured by increasing or decreasing the water level within the capped structure and then measuring it regularly to note any return to outside levels.

Another way of measuring performance is to place a chemical tracer in the saturated zone inside the barrier, or identify a traceable contaminant, and look for it in monitor wells outside the barrier.

A more interesting way to monitor for leakage is to reduce the air pressure in the vadose zone of the contained area by 1 or 2 psi and then look for any leakage in of air or increase in the water level. This method should be most useful in dry sites.

If the block we have isolated was in a vadose zone above water table to start with we can install sensitive soil gas barometric pressure sensors to measure air pressure inside and outside of the sealed structure. Since the outside pressures naturally change with the weather fronts, we should be able to detect leakage over time. This method would also allow you to lower the internal pressure. Care should be taken not to allow external pressure to drop much below inside pressure since this may cause the top liner to balloon.

Over time, electronic sensors under the cap, inside the barrier may fail. Assume the barrier has not been maintained for Forty years and then we again wish to verify the performance. What things could have happened during that time? Ants or rodents could have made a home in the site. The electronic sensors may have failed. Earth movements may have caused one end of the site to settle 2 inches lower than the other end. What can be done to deal with these potential problems?

Solutions to many of these problems must be tailored to the probable future conditions. Settlement can be dealt with by use of one of the non-hardening barrier materials that can bend to adjust to earth movements. To solve the rodent and ant problem, we might place a non-toxic bio-intrusion layer consisting of an irritating mixture layer of lime, sulfur, alum, borax, and hot peppers over or under the cap. The grout may also contain some of these compounds to make it unpleasant to animals and insects. We could cover this with another layer of synthetic and large rocks as an erosion armor layer. An armor layer made of clay tiles, rocks, or concrete helps the barrier resist erosion from floods and wind. An asphalt cover may be used over the rock to help keep it in place.

Sensors may be replaced with small capillary tubes which terminate in an air or water permeable stone material at various depths within the vault. Airflow through these tubes can be monitored to measure pressure differentials without the need for electronic sensors. Various other types of fluid filled mechanical bellows pressure barometric measurement devices have been in use for hundreds of years and could likely survive.

5.5 Derivation of Buoyancy Equations

In this section, we derive the basic equations that apply to the EarthSaw™. We plan to excavate a trench around the perimeter of a block of earth and fill it with a fluid grout having a density greater than the soil. We will then use an abrasive cable saw to cut or slice horizontally under the block of soil flush with the bottom of the trench. We expect gravity to cause the fluid grout to follow the cable saw and displace the soil upward with buoyant force, making the block float. We want to know how thick the layer of grout under the block will be.

The 1978 McGraw Hill Dictionary of Scientific and Technical Terms defines Buoyancy as: **“The resultant vertical force exerted on a body by a static fluid in which it is partially submerged or floating.”** This can be restated as “An object floats in a denser fluid at a level such that it displaces a volume of fluid equal to the weight of the object”.

In the EarthSaw™ concept this means that in order to float an object, such as a block of earth, we require a fluid that is of greater net density than the block of earth.

Marks Standard Handbook for Mechanical Engineers, Eighth Edition 1978, under “Mechanics of Fluids” defines buoyant force as follows: **Archimedes’ principle states that a body immersed in a fluid is buoyed up by a force equal to the weight of the fluid displaced.** The buoyant force acts vertically through the center of buoyancy which is located at the center of gravity of the volume of fluid displaced. **Buoyant force is defined as: “The force exerted vertically upward by a fluid on a body wholly or partly immersed in it: its magnitude is equal to the weight of the fluid displaced by the body.”** The “buoyant force” is the entire upward vector of force on a submerged object due to gravity pulling down on the fluid the object is submerged in. If this force is greater than the weight of the body then the body will float in the fluid and we have a net positive buoyancy.

5.5.1 Equation for Calculation of Required Grout Density

Consider a 100-foot by 300-foot by 30-foot rectangular block of soil with a uniform density of 142 pounds per cubic foot, floating in an ocean of dense fluid grout in Figure 1. Assume that the grout properties are such that it does not flow into the permeability of the soil. Our boundary conditions are an infinite ocean of grout, and a rectangular box shaped object that is already floating with its top 4 feet out of the fluid. We also assume that the portion of the block above the fluid is solid enough to stand under its own weight and not crumble. The required fluid grout density to sustain the top of the block of earth at a specific elevation above the fluid level may be expressed by the relationship stated by Archimedes:

Weight of fluid displaced = weight of block

If the block is floating 4 feet out of the fluid the volume of the fluid displaced is equal to the volume of the block below the fluid, what is the density of the fluid? This volume of fluid displaced is $(30\text{ft} - 4\text{ft}) \times 100\text{ft} \times 300\text{ft} = 780,000\text{ cu ft}$. The total weight of the block is $30\text{ ft} \times 100\text{ ft} \times 300\text{ ft} \times 142\text{ pounds per cubic foot} = 127,800,000\text{ pounds}$.

Beginning with Archimedes' equation and substituting these values:

$$\text{Weight of fluid displaced} = \text{weight of block}$$

$$789,000\text{ cu ft} \times \text{Density of Fluid} = 127,800,000\text{ pounds}$$

$$\text{Density of Fluid} = 127,800,000\text{ pounds} / 789,000\text{ cu ft}$$

$$\text{so... Density of Fluid} = 163.846\text{ pounds per cu ft}$$

We will assume from here on that our fluid is called "grout." This grout is a fluid with non-Newtonian properties similar to an oil well drilling fluid. Such fluids use microscopic colloids to seal against porous formations and suspend solids while still transmitting hydrostatic pressure. (See the section on descriptions of grout properties for more detail.)

Continuing with the principle of Archimedes...

Weight of fluid displaced = weight of block

$$[(30\text{ft} - 4\text{ft}) \times 100\text{ft} \times 300\text{ft}] \times \text{Density of Grout} = 30\text{ ft} \times 100\text{ ft} \times 300\text{ ft} \times \text{Density of Block}$$

T_s is the submerged thickness of the block. $(30\text{ft} - 4\text{ft} = 26\text{ft})$

T_b is the total thickness = 30 ft

D_g is the Density of the Grout

D_b is the Density of the Block

$$T_s \times \text{Width} \times \text{Length} \times D_g = T_b \times \text{Width} \times \text{Length} \times D_b$$

Divide both sides by Width and Length and these terms drop out, leaving...

$$T_s \times D_g = T_b \times D_b$$

Dividing both sides of this equation by $(T_s \times D_b)$

$$D_g / D_b = T_b / T_s$$

So the length and width of the block do not enter into the calculation, it is simply the ratio of the densities being equal to the thickness ratio. Generalizing this observation to an irregular shape that still has vertical walls and a flat top and bottom, we can replace $(\text{Width} \times \text{Length})$ with the more general term (Area). Regardless of the complexity of the formula for area, since the same term appears on both sides of the equation, we can divide both sides by (Area) and the terms drop out. Therefore the block does not have to

be rectangular, in plan view, the block could be a vertical cylinder or an irregular kidney shape or “L” shape as long as the top and the bottom are flat and horizontal and the sides are vertical. These assumptions are valid when the ground surface is level and a horizontal bottom cut is to be made. In the “Vertical Block” EarthSaw™ method the perimeter trench is excavated as a slurry trench and therefore is substantially vertical. We can state this general principle as:

Density of the grout/density of the block = Thickness of block/Thickness of the submerged volume.

To directly calculate the required grout density, the equation: $D_g / D_b = T_b / T_s$ may be rearranged algebraically by multiplying both sides by D_b to directly calculate the required density of grout:

$$D_g = (T_b/T_s) \times D_b$$

T_b = the vertical thickness of the block of earth

T_s = the vertical thickness of the portion of the block of earth submerged in the grout

D_g = the density of the grout

D_b = the density of the block of earth

Using the density equation yields the same result as the volume equation.

$$(30 \text{ ft}/26 \text{ ft}) \times 142 \text{ lb/ft}^3 \text{ Soil block density} = 163.846 \text{ lb/ft}^3 \text{ grout density}$$

The density difference is a dimensionless ratio that determines the buoyancy of an object. It should be noted that if we drill a vertical hole straight down through the middle of the block that it will still float at exactly the same level. This is true regardless of the size of the hole as long as it is vertical. In fact the block does not have to be rectangular either, in plan view, it could be shaped like a French curve, but as long as the sides are still vertical it would float with its top exactly 4 feet out of the fluid.

5.5.2 Equation for Calculation of Bottom Barrier Thickness

In the above calculation, we have an ocean of grout so we did not consider the thickness of the bottom barrier or how full the grout trench was. If we put a shoreline around the ocean of grout and shrink it such that the soil block very nearly fills it, we have the same boundary conditions as a block of earth severed from the ground by the EarthSaw™ method. The block is still floating with its top 4 feet out of the fluid because the density of the block and of the fluid have not changed. The boundary conditions experienced by the block itself did not change, but we can now see the fluid level relative to the earth. Again, we assume the block is already floating with its top 4 feet above the fluid. This is

illustrated below in Fig 2. Note that if we were standing beside this floating block we would be able to observe certain distances such as the fluid level in the trench and how high the top of the block floats above the surrounding land. If we assume that the block was sliced from the native earth by a very thin knife and buoyed upward, and has not deformed, then the thickness of the grout layer below the block must be the same thickness as the height of the block above grade.

Standing at the ground surface we can not actually see the submerged thickness of the block (T_s). From this illustration we can see that the difference between the thickness of the block (T_b) and the Thickness of the submerged portion of the block (T_s) is equal to the bottom barrier thickness (T_{BB}) plus the “freeboard” (F) or depth from ground level to the fluid in the trench.

$$(T_b) - (T_s) = (T_{BB}) + (F) \quad \text{Or...} \quad (T_s) = (T_b) - (T_{BB}) - (F)$$

Rearranging the general equation... $D_g / D_b = T_b / T_s$
becomes $T_s = T_b \times D_b / D_g$

Substituting for (T_s)...provides us with a useful formula for calculating how a change in any parameters will affect the desired bottom barrier thickness.

$$T_b - T_{BB} - F = T_b \times D_b / D_g$$

$$T_{BB} = [T_b - (D_b / D_g \times T_b)] - F$$

$$T_{BB} = [T_b - \{(D_b / D_g) \times T_b\}] - F$$

The top of the 142 lb/ft³ soil block in the example is floating 4 feet above the 163.846 lb/ft³ grout fluid line. If the Freeboard (F) is 1 foot, then the thickness of the bottom barrier is:

$$T_{BB} = [30 \text{ ft} - \{(142 \text{ lb/ft}^3 / 163.846 \text{ lb/ft}^3) \times 30 \text{ ft}\}] - 1 \text{ ft} = 3 \text{ feet}$$

5.5.3 Sensitivity to Errors in Assumed Soil Block Density

Density of the block of soil may be roughly determined by core samples, and excavation of adjacent soil areas. In most trenches the volume of waste disposed represents less than a third of the volume which we will choose to contain. The waste may contain a significant fraction of void space and may even have a lower bulk density than soil. Documentation of waste containers such as drums and boxes disposed at a site may have actual weights listed which allows a simple bulk density calculation. We can adjust the fluid level in the trench so we do not really have to know the exact density of the block but it helps to be close because we can not easily adjust the density of the grout once it is made and the cost of the grout increases with increasing density.

In the above example we had designed the grout for a 142 pound per cubic foot block (pcf). If the block actually had an average density of 150 pounds per cubic foot, we would have a block weighing an extra 7,200,000 pounds or 135,000,000 total pounds. If we fill the perimeter trench to within a foot of the surface using our 163.846 pound per cubic foot grout how much will our bottom barrier thickness will be reduced?

Using the bottom barrier thickness formula above:

$$T_{BB} = [T_b - \{(D_b / D_g) \times T_b\}] - F$$

Where;

T_{BB} is the thickness of the bottom barrier or the vertical lift above grade.

F is the freeboard depth of the grout fluid level below the grade level.

$$T_{BB} = [30 \text{ ft} - \{(150 \text{ pcf} / 163.846 \text{ pcf}) \times 30 \text{ ft}\}] - 1 \text{ ft} = 1.54 \text{ ft}$$

Therefore the bottom barrier would only have a thickness of 18.5 inches instead of the desired 36 inches. We can accept this or... by increasing the fluid grout level in the trench by another 17.5 inches we will achieve the desired 36 inch thick bottom barrier. Since we only have 1 foot of freeboard in the trench we would have to build up a berm around the outer perimeter to do this. Just as a rising tide raises a boat, when we raise the fluid level (decreasing F), the block rises. As we saw above, the bottom barrier thickness is equal to the height of the block above grade level so we also increase the bottom barrier thickness by an equal amount. This concludes the basic derivation of

buoyancy equations for the idealized static condition. We will describe many specific cases in the section on buoyancy for specific soils and conditions.

5.5.4 Buoyancy Calculations during the Horizontal Cut

In this section, we will address the buoyancy issues during the bottom cut. Consider the previously described “ideal” rectangular block of earth 100 feet wide by 300 feet long by 30 feet deep which is surrounded by a 20 inch wide perimeter trench 30+ feet deep and filled with a fluid grout such as TECT B which is higher in density than the block of earth. The soil below 10 feet depth has an unconfined compressive strength of 30 psi and a shear strength of 15 psi. Above 10 foot depth is a firmer soil with a compressive strength of 50 psi and shear strength of 20 psi. Assume the grout has a suitable design which seals off on the natural permeability of the soil while still transmitting hydrostatic pressure and freely flowing through the cut made by the cable saw. Ground water depth is below the bottom of the desired horizontal cut depth of 30 feet. The average bulk density of the soil block is the same as previous examples at 142 pounds per cubic foot and the grout has a density of 163.846 pounds per cubic foot. Let us assume we want the block to rise only 0.2 feet during the cut and we plan to maintain the trench grout level so as to obtain that result. To determine the trench freeboard level (F) required to accomplish this, we rearrange the bottom barrier thickness formula:

$$T_{BB} = [T_b - \{(D_b / D_g) \times T_b\}] - F$$

$$\text{to...} \quad F = [T_b - \{(D_b / D_g) \times T_b\}] - T_{BB}$$

$$F = [30 \text{ ft} - \{(142 \text{ pcf} / 163.846 \text{ pcf}) \times 30 \text{ ft}\}] - 0.2 \text{ ft} = 3.80 \text{ feet below grade level}$$

Let us assume that a load frame for the Vertical Block method and 1 inch diameter wire rope cutting cable have been installed and we are ready to begin a cut. Also assume that the cable cuts at the 30 foot depth. As the cable begins moving, it will begin to slice like a knife into the corners of the block with the first stroke. The heavy grout will be forced by gravity to follow the cable and will provide a buoyant force to prevent the soil from settling back to close the cut. Consider the buoyant force on the corner of the block when the cable has sliced 10 feet into the corner. We have roughly a right triangle of soil 20 feet by 20 feet connected to the soil block along a 28.3 foot long side, 30 feet tall. What will be the shear stress imposed on the block?

The volume of a right triangular solid is (length x height x depth / 2) This right triangular corner block weighs $(20\text{ ft} \times 20\text{ ft} \times 30\text{ ft} / 2) \times 142\text{ pcf} = 852,000$ pounds and exerts a foot print pressure of $142\text{ pcf} \times 30\text{ ft} = 4,260.00\text{ Lb/ft}^2$. The grout under this triangle of soil is being pressed on by the $30\text{ ft} - 3.8\text{ ft} = 26.2$ feet of grout above it. Before the triangle of soil begins to rise, this 163.864 pcf grout exerts a pressure of $(163.864\text{ pcf}) \times 26.2\text{ ft} = 4,293.23\text{ Lb/ft}^2$ of upward force.

This is a net upward force of $4,293.2\text{ Lb/ft}^2 - 4,260\text{ Lb/ft}^2 = 33.23\text{ Lb/ft}^2$.
Over the 200 square foot area of the triangle the grout exerts an upward force of;
 $200\text{ ft}^2 \times 33.23\text{ Lb/ft}^2 = 5,963$ pounds net upward force before the block is lifted.

This load is applied along the hypotenuse edge of the triangular section which has an area of $30\text{ ft} \times 28.3\text{ ft} \times 144\text{ in}^2/\text{ft}^2 = 122,256\text{ in}^2$. This implies a shearing force of $5,963\text{ pounds} / 200\text{ ft}^2 = 29.814\text{ Lb/ft}^2$. This 15 psi shear strength of the soil is $15\text{ Lb/in}^2 \times 144\text{ in}^2/\text{ft}^2 = 2160\text{ Lb/ft}^2$. so the block will not break.

If we extend this analysis to a block which has been cut substantially half way along the 300 foot length we can perform the same analysis. Assume we neglect the catenary curve of the horizontal cut and we have cut 150 feet. In the previous example we assumed that the entire 200 square foot surface was exposed to the 33.23 Lb/ft^2 uplift pressure. If the block of earth were a rigid material which could not bend, the entire 100 ft by 150 ft undercut area exposed to this pressure would generate $100\text{ ft} \times 150\text{ ft} \times 33.23\text{ Lb/ft}^2 = 498,450$ pounds of force. The vertical shear strength of the soil of $100\text{ ft} \times 30\text{ ft} \times 2160\text{ Lb/ft}^2 = 6,480,000$ pounds would still exceed this so the block would not shear vertically. However tensile strength of soil is often not much greater than the overburden pressure so the soil at the face of the cut could fracture horizontally ahead of the cable. This would be reduced by elasticity in the soil. This would be similar to the behavior of the $10\text{ ft} \times 10\text{ ft} \times 8\text{ ft}$ deep block cut in the early field test. As we deal with larger

blocks of soil such as the 300 foot long x 30 ft deep one in our example the soil is expected to behave more elastically because the block is thin compared to its 300 ft length. In the phase II demo we plan to cut a 50 ft x 50 ft by 30 ft block and it is expected to have only slight elasticity. It should also be noted that the whole issue of fracturing and uplift can be avoided by using just enough buoyancy to keep the block from falling or rising.

As the cutting cable proceeds across the base of the block it removes soil and transports it to the perimeter trench. The heavy grout is in contact with the cable, being continually pumped through the cut by the reciprocation of the cable saw. The grout helps transport the cuttings to the perimeter trench on either side. We use a long stroke to maximize this effect. The grout is also forced to follow the cutting cable because the hydrostatic pressure of the grout from the perimeter trench is slightly greater than the force of gravity trying to collapse the pathway behind the cable.

This is true because both forces are based on gravity and the grout is more dense than the soil.

5.5.5 Soil Blocks with Non-Uniform Density

However, some one may ask, “What if the average density of one end of the block is 144 pounds per cubic foot and the other end is 140 pounds per cubic foot?” (Perhaps due to a heavy buried waste.) This would cause the lighter end (63,000,000 pounds) to float higher than the heavy end (64,800,000 pounds) and yield a non-uniform bottom barrier thickness. There are ways to correct this even after the barrier is constructed but before the grout sets. Removing 1,800,000 pounds (10.28 inches @140 Lb/ cu ft) of surface soil from the heavy end is one way. Moving 900,000 pounds (5.14 inches) of surface dirt from the heavy end to the light end is another way. Operating a dozer on a block of this size will not cause a significant movement since its weight is so small compared to the weight of the block. If we did not wish to move any soil on the block, we could add weight to the light end or mechanically restrain it.

Suppose we know in advance about the uneven density and want to calculate how uneven the barrier would be if we did nothing. Considering the block as two smaller blocks each 100 ft by 150 ft by 30 ft deep. We designed the 163.864 pound per cubic foot (pcf) grout for a 142 pcf soil and we fill the trench to within 1 foot of grade level. One end averages 140 pcf and the other averages 144 pcf. We intuitively expect the heavy end will sink lower into the fluid grout. Even though the block is no longer level, we can still use the derived buoyancy equations to approximate the answer if we mathematically break the surface of the block up into many smaller blocks of full 30 foot thickness. Assume that we break up the big block into fifty smaller blocks 6 foot long by 100 foot wide by 30 foot deep. Each of these blocks would be considered relatively level. Assume that the 25 blocks on one end are 140 pcf density and the 25 blocks on the other end are 144 pcf density. If we assume a relatively elastic soil, then most of the blocks toward the heavy

end and most of the blocks toward the light end will be floating with a bottom barrier thickness defined by;

$$T_{BB} = [T_b - \{(D_b / D_g) \times T_b\}] - F$$

The bottom barrier thickness for the heavy end blocks will be:

$$[30 \text{ ft} - \{(144 \text{ pcf} / 163.864 \text{ pcf}) \times 30 \text{ ft}\}] - 1 \text{ ft} = 2.637 \text{ feet or } \mathbf{31.64 \text{ inches.}}$$

The bottom barrier thickness for the light end blocks will be:

$$[30 \text{ ft} - \{(140 \text{ pcf} / 163.864 \text{ pcf}) \times 30 \text{ ft}\}] - 1 \text{ ft} = 3.369 \text{ feet or } \mathbf{40.43 \text{ inches.}}$$

The blocks nearer the middle will each deform slightly as illustrated below.

If we had assumed a uniform density gradient from the heavy end to the light end, the surface of the block would be straight and would not have the “S” bend but the ends would still be at the same calculated elevations.

Using the relationship $T_s = T_b \times D_b / D_g$ We can see that to maintain the same submerged thickness (T_s), the product of the vertical thickness of the block and the density of the block must remain constant. If you knew in advance that one end of the block was lighter, you could simply make the bottom barrier cut deeper on the heavy end, thus causing it to float higher out of the grout. The thickness of the bottom barrier (T_{BB}) is always the same as the elevation of the block above ground level. It is also the thickness of the whole block minus the thickness of the portion of the block which is submerged minus the freeboard (F) in the trench. (Freeboard is the vertical distance from the grout elevation to the ground level.) Or... $T_{BB} = T_b - T_s - F$

So to establish a uniform 3-foot bottom barrier thickness with 1 foot of freeboard on 163.864 lb/ft³ grout from the heavy 144lb/ft³ end to the light 140 lb/ft³ end we re-arrange the equation to;

$$T_b = T_{BB} + F + T_s \text{ to determine the depth of cut.}$$

$$\text{Heavy end, } T_b = 3\text{ft} + 1\text{ft} + 26.36\text{ft} = 30.36 \text{ ft}$$

Light end, $T_b = 3\text{ ft} + 1\text{ ft} + 25.63\text{ ft} = 29.63\text{ ft}$

5.5.6 Soil Blocks on Sloping Ground

Note in the previous example that making the bottom cut deeper also allows a lighter grout to achieve the same thickness of bottom barrier. This principal is also useful for making barriers along sites that are not level. Consider a block with uniform density of 130 pounds per cubic foot that has a surface slope such that it is 3 feet lower on the north end than the south end as shown in the figure. If the north end is 33 feet deep and has a 2.81 foot thick barrier and 3 foot of freeboard, what will the depth have to be on the south end to also have a 2 foot thick bottom barrier?

If the surface elevation is three feet lower on the one end than on the other, we would normally get a thinner barrier on the uphill end because the submerged thickness of the block is less. We can make the block float level by cutting the bottom deeper on the uphill end. First we calculate the density of the grout on the north end.

$$D_g = (T_b / T_s) \times D_b$$

$$D_g = (33\text{ ft} / 27.19\text{ ft}) \times 130\text{ pcf} = 157.8\text{ pcf}$$

Then to determine the depth of cut on the south end, we can use:

$$T_{BB} = [T_b - \{(D_b / D_g) \times T_b\}] - F$$

$$2.81\text{ ft} = [T_b - \{(130\text{ pcf} / 157.8\text{ pcf}) \times T_b\}] - 6\text{ ft} \quad (\text{Freeboard on the south end is 6 ft})$$

$$2.81\text{ ft} = [T_b - \{(0.8238) \times T_b\}] - 6\text{ ft}$$

$$8.81\text{ ft} = T_b - \{(0.8238) \times T_b\}$$

$$T_b - \{(0.8238) \times T_b\} = 8.81\text{ ft}$$

$$T_b - \{(0.8238) \times T_b\} = 8.81\text{ ft}$$

$$.1762 \times T_b = 8.81 \text{ ft}$$

$$T_b = 8.81 \text{ ft} / .1762 = 50 \text{ ft}$$

So we will have to make the barrier 50 feet deep on the south end to obtain a uniform bottom barrier. Note that the greater the density difference between the soil and the grout, the less depth differential will be required to keep the bottom level. Therefore if the site had a lower rock layer as shown in the drawing the south end might have to be deeper. The spreadsheet model is designed to allow the user to evaluate these types of scenarios very quickly.

5.6 Buoyancy Calculations for Specific Soil Conditions

The near surface soil of the earth varies widely in its physical properties. Construction processes that assume a particular soil condition, can fail when applied in radically different conditions. The EarthSaw™ method is thought to have broad applicability in many types of soil. In order to investigate the robustness of the method we will specify properties for 12 soil conditions that cover a broad spectrum of the types of conditions that exist in the United States. The descriptions are largely based on the observations of 20 years experience in grouting, trenching and civil construction related projects around the country. We will attempt to include soil conditions similar to actual DOE sites that may be candidates for this technology. Lastly, we will also describe how the technology would be expected to work in a zone composed of rock rather than soil and examine what limitations this would pose. In the following examples, we will attempt to quantify buoyancy and other technical issues at hypothetical sites with soil having:

7. Variable host media (e.g., variable lithologies such as unconsolidated sediments and bedrock)
8. Variable hydrologic conditions (e.g., near-surface water table)
9. Host media with discontinuities such as complexly interbedded sediments, highly bedded strata, fractured bedrock, and others
10. Waste areas with variable geometries, dimensions, and waste material contents.

First, we will briefly discuss these factors before moving to specific soil conditions.

5.6.1 Variable Host Media

There may be no such thing as typical dirt. Soil varies dramatically from site to site around the United States. This means different types of soil, rock, sand, clay, peat, and even salt deposits. Soil varies in an near endless variety. The cohesive strength may vary widely or there may be no cohesive strength at all. We can also find combinations of these materials in the same area. A site may have dry clay with rocks in one area and wet sand with no rocks a few hundred feet away.

Pits and trenches within the DOE complex were sometimes excavated to a depth where the digging became more difficult. This sometimes resulted in a pit or trench underlain by rock. Often the upper surfaces of the rock are weathered and fractured. This could result in a waste leakage pathway at the bottom of the pit or trench. Sometimes this rock was covered with then covered with 3 feet of clay to prevent leakage. Some pits and trenches had excavations extending down 5 to 20 feet below the top of rock. This can expose horizontal fractures and perched water zones. We will attempt to evaluate the effect of these variable host media on the EarthSaw™ process in a quantitative fashion.

In evaluating these various conditions and how they might impact the EarthSaw™ method we must first understand the properties of the grout. The EarthSaw™ grout is a fluid material having a density greater than the soil and also having the property of sealing off a permeable soil material. This second property must be tempered with low viscosity such that the fluid flows readily into the narrow one-inch thick cut made by the cutting cable. The grout must transmit hydrostatic pressure from the hydrostatic head of fluid in the perimeter trench to the soil above and below the horizontal cut being made by the cutting cable. This property must also be bounded by non-Newtonian properties that allow the fluid to develop sufficient static gel strength to permanently suspend solid particles.

The cutting action of the cable saw is also important. The cable saw is expected to be able to pull through rocky ground up to a point limited by the rock size and frequency and the soil bearing strength. Cutting force is limited by the tensile strength of the cable. The cutting force required also increases with the diameter of the cable. The strength of the cable increases with its cross-section area so bigger cables will be able to apply more cutting energy per square inch provided we can get a big enough winch. In the future, it may be worthwhile to make special winches for this application.

5.6.2 Host media with discontinuities

Discontinuities in the soil strata may include rock ledges, sand stringers, confining layers with artesian pressure, fractures rock, weathered shale, gravel, cobbles and areas of varying permeability. Some strata may be tilted and not horizontal. A shale layer tilted at a 20 degree angle may cause the cutting cable to preferentially follow the grain of the rock. This can result in cutting a more irregular bottom cut as the cable follows the grain for a time and then is forced back to the direction of cable pull. In such conditions, the bottom cut elevation should be made deep enough to compensate for this irregularity.

Rocks are common features in soil at some sites and come in many shapes sizes and compositions. Cutting through a rock with an abrasive cable saw may occur quickly if the rock is a sandstone the size of a duffle bag. However, if the rock is a piece of basalt or granite the size of a washing machine cutting will be very slow.

As a cutting cable encounters a rock, there are several possibilities. If the rock is small and the surrounding soils are soft, it may get pushed out of the way by deforming the

soils around it. If the rock is soft, the cable may cut through it quickly. If the rock is rounded, the cable may ride over it. If the rock is hard and in a very firm soil and of a shape that does not permit the cable to ride over it, the cable will just run back and forth until either the rock or the cable wears through. If there is only one such rock the cable, will probably cut through the adjacent soils and take on a "V" shape to concentrate most of the pulling force on the rock. At this point, the contact force and thus the friction between the rock and the cable will become very high and either the rock or the cable will wear out. The cable is made from very hard steel that is about 20 times harder than typical hard rock but it will still suffer wear. The cable will be inspected for wear often during a cut, and may be replaced several times during a horizontal cut. Cable breakage is always a possibility and the EarthSaw™ system allows broken cables to be replaced as many times as required to complete the work. The EarthSaw™ method may also be applied in solid rock conditions but could be significantly more costly since special custom-made abrasive cable and extra dense grout slurries may be required. Not all rock is hard to cut. In some sites such as the Los Alamos volcanic tuff, the entire site may be carved into the soft rock. Tests performed on samples of this material indicate that the cable saw method should be capable of cutting through this material very quickly with a standard cable.

5.6.3 Variable hydrologic conditions

In some sites the groundwater elevation may have increased after construction of the pit or trench. At some sites there are burial pits where the seasonal water table rises above the bottom of the pit. Water tables rising upward above the bottom of a containment vault may exert an additional buoyant force on a containment structure. At other sites the soil around an under a pit may be bone dry or may have soil material which can be altered by contact with water. Grout materials which contain residual water may be adversely affected by long term exposure to very dry conditions. Water table variations in a large site may result in uplift and undulation in adjoining soils. These and other factors must be analyzed and included in the design of the containment system.

5.6.4 Variable Geometries, Dimensions and Waste Contents

The EarthSaw™ can deal with a variety of geometries, dimensions and waste material contents. The EarthSaw™ barrier system was designed to deal with most types of buried low level and Transuranic (TRU) mixed waste. These wastes commonly exist in the form of containerized debris and protective clothing, metal drums of dry salt or organic sludge, uranium metal turnings packed in organic liquids, construction debris, and free phase organic liquids dispersed in soil. The barrier materials can be tailored to specific environmental conditions and waste types. Each of the three primary barrier materials has certain good points. The cementitious TECT-A grout is resistant to organic chemicals and provides high mechanical strength and very low permeability. The non-hardening clay based TECT-B grouts can adjust to ground movement without cracking

and self-seal mechanical penetrations. The molten wax based TECT W grouts are pliable, self-healing and able to tolerate dry conditions.

The full containment achievable by adding a top cap also makes it feasible to extract water and volatile organic wastes after containment is complete. This may be done by circulating dry air through the contained structure over a period of months or years. Since the EarthSaw™ construction method does not require drill penetration or physical contact with the waste it is able to deal with undocumented waste with a level of safety not previously available. The method can be adapted to install containment structures under buildings, lakes and tank farms. The following is a summary of the techniques and the geometries and dimensions, which are applicable to each:

5.6.5 The Vertical Block Method

This is the method proposed for modeling in this project. The method prepares a vertical slurry trench around the perimeter of a site to the depth of the desired bottom barrier. A mechanical load frame is lowered into the trench at one or more points and a cable saw is used to undercut the block. The cable saw may be pulled back and forth by large dozers or preferably by powerful winches attached to the tops of the load frames. In some soil and rock the cutting action will be a back and forth sawing action while other more plastic soils may use a direct pull to produce a slicing action on the soil. (This action is similar to that of a household cheese-slicing tool.) After the thin 1 inch thick cut is made, additional grout is allowed to gravity flow into the perimeter trench. This grout buoyantly lifts the free block of earth like a rising tide lifts a barge at the dock. The perimeter of the work can be rectangular or irregular in shape as long as it has at least one corner.

This method offers mechanical simplicity and can work in tight quarters. If the steel cable breaks it may be pulled out by each end and a new cable installed by lifting the load frame and threading a new cable. The new cable begins from the original trench and is quickly advanced to the face of the cut because the buoyancy of the grout causes the horizontal cut to remain thicker than the cable performing the cut.

Maximum site size is limited by total friction imposed by the total friction on the cable. When the total friction exceeds the strength of the cable or the power of the winch the cable will be stuck. The friction factor is an exponential function of the angle of contact with the soil times the coefficient of friction. This factor defines the ratio of power lost to friction due to the contact angle. The drag friction is the weight of the cable on laying horizontal in the ground times the coefficient of friction. This drag friction subtracts from whatever force remains after applying the friction factor and can cause it to fall below zero, indicating a stick cable.

Calculations indicate that sites as large as 500 foot square should be feasible even with a 1.0 coefficient of friction. With a suitable low friction grouts, or other geometries that reduce the total angle of the cut, much larger sites should be possible. Another limitation is that the right angle geometry of this method does not lend itself to installation of a bottom synthetic liner as well as the HDD EarthSaw™ method.

The method can also be applied using dozers instead of winches to pull the cable saw as shown below.

Estimated Max/Min depth - 90 feet / 5 feet
 Estimated Max/Min width - 1000 feet / 5 feet
 Estimated Max/Min length - 500 feet / 20 feet

The method can potentially be used to isolate one end of a burial trench without excavating through the waste. This would be done by cutting from the end of the site to the desired middle point and then cutting to the surface with the cable. Once the cut is made the entire block would be displaced toward the first end to increase the thickness of the vertical cable cut to match the bottom and side barrier thickness.

The Vertical Block Method can also be extended to complex shapes by the addition of additional load frame devices. So a “L” shaped site could be isolated in a single step without cutting through the waste.

Vertical Block Method for Complex Shapes

In some situations, high friction may limit the method. It should be possible to add a third load frame with a traveling block to reduce the angle of contact. The angle of contact has a large effect on friction.

Vertical Block Method for High Friction, Traveling block from third load frame reduces contact angle to reduce friction

5.6.7

HDD with Two Vertical Sides

In this method 2 or more horizontal directionally drilled (HDD) holes are installed and the cable saw is used to cut in between each HDD hole in turn. The bottom is essentially a series of curved surfaces between adjacent HDD holes. The cable saw then cuts a vertical path from the HDD holes on each end to the surface. The vertical cut at the side can also be created with a backhoe by the slurry trench method. This is desirable if a thick side barrier is desired. One advantage of this method is that it can be expanded to any desired width by adding more HDD holes. Another advantage is that a synthetic liner may be used in place of large quantities of grout. Once a pathway is cut with the fluid grout, a synthetic liner may be drawn under the floating section between HDD holes.

Pulling HPDE Liner Into Place And Bonding Top Sheet

Sliding joints intended for vertical liners, provide a means of joining multiple sections together underground. This method can be used for very large sites up to 20 acres or more. One limitation of this process is that the shape of the barrier must be defined by gentle curves suitable for HDD drilling. The barrier will taper to the surface on at least two sides and the buoyant barrier will be thinner at these edges.

Estimated Max/Min depth - 200 feet / 10 feet , Maximum depth is a function of length and HDD hole minimum bend radius.
 Estimated Max/Min width - 2000 feet / 200 feet
 Estimated Max/Min length - 1000 feet / 200 feet

5.6.8 HDD with full basin shape

This is like the above method only the vertical sides are only a few feet deep and the barrier then curves down to deeper levels. The final shape is a full basin like a soup bowl or a pond. This method is also well suited for the largest sites. Synthetic liners may be installed in each section in turn and the bulk of the grout re-used from section to section. Another advantage of this method is that it produces little or no spoils from excavation. This method is more complex and is difficult to scale down to small size but it offers the lowest cost for large landfills. It also can be adapted to install interlock joined synthetic liner sheets under the entire landfill.

Estimated Max/Min depth - 200 feet / 10 feet , Maximum depth is a function of length and HDD hole minimum bend radius.

Estimated Max/Min width - 2000 feet / 200 feet

Estimated Max/Min length - 1000 feet / 200 feet

5.6.8 Vertical Wall HDD

In this method a perimeter slurry trench is first constructed all around the perimeter of a large site to the desired barrier depth. A series of parallel HDD holes is installed under the site from outside the perimeter trench. The trench is then filled with fluid grout and a horizontal cut is made with the cable saw between each of the HDD holes to form the bottom. The holes are cased down to the edge of the vertical trench.

Estimated Max/Min depth - 90 feet / 20 feet
 Estimated Max/Min width - 2000 feet / 200 feet
 Estimated Max/Min length - 1000 feet / 200 feet

5.7 Discussion and Calculations of Various Issues in Specific Soils

There are too many variations of the EarthSaw™ method to discuss each one in detail here for specific soil conditions. The Vertical Block method is the least complex and at this stage in development probably the most reliable approach since it minimizes friction contact angle. In these discussions, we will be discussing only the **Vertical Block Method** unless stated otherwise. These discussions will assume we are using 1" diameter cutting cable with 60,000 pound pull and cutting a 50 foot wide pathway 200 feet long. We are using a **non-hardening TECT B grout** unless stated otherwise. Over a period of one year this grout cures to a soft clay consistency like putty but remains soft indefinitely.

5.7.1 Cohesive clay with rocks

Consider a soil composed of a cohesive and plastic clay which has a many rocks ranging from saucer size to dinner plate size with a thickness of 1 inch to 3 inches. Let us further assume that the clay and rock together have an average density of 133 pounds per cubic foot. Let us assume a soil shear strength of 15 psi and an unconfined compressive strength of 25 psi. Also assume that the water table is below 30 feet.

We desire to fill the trench with grout to within 2 feet of the surface and have a bottom barrier 2 feet thick under a 30 foot deep block of earth. To calculate the required density, we will use one of the formulas from the **Derivation of Buoyancy** document:

$$D_g = (T_b/T_s) \times D_b$$

T_b = the vertical thickness of the block of earth

T_s = the vertical thickness of the portion of the block of earth submerged in the grout

D_g = the density of the grout

D_b = the density of the block of earth

The submerged thickness of the block will be 26 feet since the top of the block is 4 feet above the fluid level in the trench.

Required Density of Grout = (30 ft / 26 ft) x 133 pcf = 153.46 pounds per cubic foot.

For this soil the more difficult issue is not one of buoyancy but of cutting the horizontal pathway. The clay itself is quite firm and tough and may tend to stick to the cutting cable. We will possibly select a three strand type cable to increase the cutting action. We may need to add a pressure wash sprayer to clean the clay from the cable as it comes

out of the load frame. As the cutting cable cuts through the soil it will strike rocks from time to time. The rocks are hard material and do not break easily. The cable will naturally jump over most of these rocks. Suppose the cable strikes a dinner plate sized rock straight enough that it does not immediately slip over or under it. Assume the rock has an frontal area of 20 square inches and a upper and lower surface area of 144 square inches. For the 25 psi soil it will take about 500 pounds of force to push the rock laterally through the earth. It will take 3600 pounds to move the rock through vertically through the soil. Assume the cable has an available force up to 20,000 pounds, which increasingly bears on the face of the rock as the soil is cut away. The cable has over 5 times the force needed to push the rock along. Since pushing the rock is an unstable system it will quickly turn to one side and the cable will ride over it. If the rock had a frontal area of $(20,000 \text{ lb} / 25\text{psi}) = 800$ square inches, the cable would not be able to push the rock out of the way. This is a rock over 31 inches in diameter it can not be pushed aside. Of course if the soil is harder, the immovable rock size will be smaller. The immovable rock size will also be affected by the plasticity of the soil. A non-plastic formation will transfer load from the rock to the soil and allow only much smaller rocks to be pushed aside.

If the rock is rounded, the cable can still slide over or under the rock. However, if the rock is both strong and saddle shaped, then the cable may be trapped and will continue to saw through the rock until the rock breaks apart. Unless this is a soft rock, the ordinary steel cable may wear out on this large of a rock. If the cutting advance rate slows and cable wear begins to show, it may indicate this kind of rock in the path. If this occurs, a new rock cutting cable would be installed and drawn into the cut. A chain-type cable saw might be required in some conditions such as when the path of the cable becomes a sharp “V” working over a large rock. When working a cable saw in these conditions it may be desirable to be able to track the position of the cable underground. This may be done by attaching an RF generator, such as those used in pipeline location work, to the cable to allow us to monitor its cutting path with detectors on the surface.

5.7.2 Clay with Permeable Sand Lenses

In this example, we have a soil that is partly impermeable clay and partly highly permeable sand. The sand is a lens 2 feet thick and 8 feet wide that crosses into the volume of the barrier in 2 places. The block of earth to be isolated is mostly composed of

impermeable material and the grout buoyancy calculations are the same as in Condition 1. If the 133 pound per cubic foot block is 50 feet deep and we want 2 feet of freeboard in the trench and a 3 foot thick barrier:

$$D_g = (T_b/T_s) \times D_b$$

T_b = the vertical thickness of the block of earth

T_s = the vertical thickness of the portion of the block of earth submerged in the grout

D_g = the density of the grout

D_b = the density of the block of earth

The submerged thickness of the block will be 26 feet since the top of the block is 4 feet above the fluid level in the trench.

Required Density of Grout = (50 ft / 45 ft) x 133 pcf = 147.78 pounds per cubic foot.

As you can see the deeper the barrier the less density difference is required to obtain a given barrier thickness.

One issue of concern is; “Will the grout seal off on the face of the permeable sand or will the grout leak off into the sand formation?” The grout must seal well enough to exert hydrostatic pressure against the soil formation, but it also must flow into the 1" wide cut with the full hydrostatic pressure from the hydrostatic head of the fluid grout in the perimeter trench.

To answer this question we perform a test such as the API fluid loss test. In this test 250 cubic centimeters of the fluid grout is pressed against a permeable # 50 filter paper with 100 psi of pressure and the amount (in millimeters) of fluid which leaks through the paper in a fixed time (30 minutes) is measured. Excessive loss of fluid can reduce the viscosity of the grout and make it unsuitable. As the grout is pressured against the filter paper colloidal particles in the grout stack up against the filter paper and form a film or cake of particles which is impermeable. During the building of this cake some liquid initially passes through the filter leaving its solids behind. Soon the loss of liquid approaches zero as the filter cake forms. This filter cake forming property is essential to most drilling fluids and is well understood in the drilling industry. In our application with the sand we would want the fluid loss test to indicate that the grout seals off permeable zones before losing enough fluid to significantly reduce its fluidity.

But what would happen if the formation were dramatically more permeable than sand? Let us consider a more severe potential soil condition. In this case the path of our barrier passes through a formation composed of clean gravel (a very rare condition) with a average rock size of 1-1/2 inches. If these rocks have an average passageway of 1/4" or more this will likely exceed the permeability plugging capacity of the TECT A and TECT B grouts. In this case the grout would flow into the permeability of the formation and be lost. In oil well drilling this would be called a “lost circulation zone” and special plugging agents would be added to the drilling fluid to plug the leaks. These materials include sand, flakes, and fibers as well as chemical pre-flush agents which solidify when

contacted by the second fluid. We could modify our grouts to deal with a formation of this type, tailor a special grout, or switch to one of the molten TECT W grouts, which seal off by loss of heat instead of by forming a filter cake.

5.7.3 Non-Cohesive Sand

If the soil block has an average density of 120 pound per cubic foot block is 25 feet deep and we want 1 foot of freeboard in the trench and a 3 foot thick barrier:

$$D_g = (T_b/T_s) \times D_b$$

T_b = the vertical thickness of the block of earth

T_s = the vertical thickness of the portion of the block of earth submerged in the grout

D_g = the density of the grout

D_b = the density of the block of earth

The submerged thickness of the block will be 26 feet since the top of the block is 4 feet above the fluid level in the trench.

Required Density of Grout = (30 ft / 26 ft) x 120 pcf = 138.46 pounds per cubic foot.

In discussions, most reviewers had questions about how the method would work in soft sands having little or no cohesive strength. The first EarthSaw™ field experiments were tested in conditions of damp river sands so we have some experience to back up this theoretical analysis. Excavating the perimeter trench in soft sand presents the problem of keeping the walls of the vertical trench from collapsing. This may be accomplished by keeping the trench filled with a five percent bentonite, clay and water slurry. The soil has a limited strength of its own and is under a confining stress equal to the weight of the

soil above it. Next to the open trench the forces from the weight of soil above it are unbalanced and if the soils shear strength is insufficient, the soil sloughs off into the trench.

The bentonite slurry is a non-Newtonian fluid that has the ability to suspend sand grains in the slurry indefinitely. It also has the ability to seal off on permeable formations such as sand to prevent fluid loss from the trench. This sealing is performed by colloidal particles of bentonite that are like very thin flat plates that plug off the openings. (The grout has similar properties and this is also what keeps the grains of sand just above the horizontal cut from falling through the grout.) The bentonite slurry is denser than water because it also suspends grains of sand. The sand grains have a density of 2.1 to 2.6 specific gravity. This results in the slurry having a final density of perhaps 1.2 specific gravity, or 74.88 pounds per cubic foot. The hydrostatic pressure of the bentonite slurry presses against the walls of the trench with $74.88/144 = 0.520$ psi/vertical foot, replacing most of the balancing force of the excavated soil. This generally, but not always, is enough to keep the walls of the trench from sloughing off. This technique is called slurry trenching and has been in wide commercial practice for over 30 years.

In a non-cohesive soil it is best practice to keep the trench nearly full to within a foot of the surface to prevent caving of the edges. Our calculations show we only need 138.46 pound per gallon grout. (2.219 specific gravity). Since we may not want to be required to estimate the required grout density that precisely, we will use a more dense grout and leave the last few feet of the trench filled with bentonite slurry. When the slurry trench is complete, we will replace the 74.88 pound per cubic foot, 1.2 specific gravity slurry with 143.5 pcf (2.3 specific gravity) fluid grout. This grout provides more than enough balancing force against the sides of the trench and does not require any shear strength in the soil to hold the trench open. The fluid grout weighs 143.5 pounds per cubic foot and exerts a side wall force of $143.5 \text{ pounds} / 144 \text{ sq in per sq ft} = 0.9967$ psi per foot of depth. At a depth of 30 feet a trench filled to within 3 feet of grade with fluid grout and another 2 foot, (to within 1 foot of grade), with bentonite slurry will provide a balancing force of :

$0.520 \text{ psi per ft} \times 2 \text{ ft} + 0.9967 \text{ psi per ft} \times 27 \text{ ft} = 27.95 \text{ psi. at the 30 foot depth.}$

Our wet sand has a typical density of 120 pounds per cubic foot. This is 0.8233 psi per foot of depth. At a 30 foot depth the soil pressure will be 24.70 psi. The walls of the trench are therefore held in place by a force of $27.95 \text{ psi} - 24.70 \text{ psi} = 3.25 \text{ psi}$. Therefore the trench will be completely stable, even if the sand has no shear strength at all.

When the steel cable begins cutting the horizontal pathway, that pathway is automatically filled with the fluid grout due to the 3.25 psi net gravitational force exerted by the fluid grout. If the sand is soft, this may actually compress the adjacent sand some and increase the thickness of the cut. Maintaining an excessive amount of positive buoyancy should be avoided because it may cause the soil to horizontally fracture ahead of the cutting cable. If the horizontal cut covers a large area adjacent to the face of the cut, there can exist large upload forces on the block of earth. These upload forces if

sufficiently large can tear the soil apart and cause a horizontal fracture to propagate rapidly. When this occurs the cable advances rapidly into the cut and the cut will be more irregular than a normal sawed or sliced cut. Uncontrolled horizontal fracturing is generally undesirable and can occur when the positive buoyancy exceeds the shear strength of the soil. These conditions are most likely to occur in soft sand formations.

As the cable saw cuts the horizontal pathway the fluid grout presses against the roof of the cut and exerts a buoyant lift force upward. This force is the same 3.25 psi as for the side walls as long as the fluid level in the vertical trench is maintained. Some of the grout fills the horizontal pathway so fluid grout must be continually added to the vertical trench. Observation of the vertical displacement of the free end of the block provides operators with the information needed to maintain the trench fluid level. Nominally one to two inches of lift on the free end is considered ideal.

5.7.4 Variable hydrologic conditions In Non-Cohesive Sand

Consider the same 30-foot deep containment barrier above with an increase in water table to near the surface. Assuming the void space accessed by the water is 20 percent of the soil volume. This will imply a potential density increase of $0.2 \times 62.4 = 12.48$ pounds per cubic foot. The non-saturated sand weighs 120 pounds per cubic foot. Therefore, the saturated sand will weigh $120 + 12.48 = 132.48$ pounds per cubic foot. Since the fluid grout we previously selected weighs 143.5 pounds per cubic foot, we still have the potential for positive buoyancy. The pressure exerted by the soil block is $132.48/144 = 0.9200$ psi per foot of vertical depth while the pressure exerted by the grout remains $143.5/144 = 0.9967$ psi per foot of depth. At 30 foot of depth the soil pressure is 27.6 psi. The 27 feet of fluid grout plus 2 feet of bentonite slurry exerts the same balancing pressure as before of: $0.520 \text{ psi per ft} \times 2 \text{ ft} + 0.9967 \text{ psi per ft} \times 27 \text{ ft} = 27.95 \text{ psi}$ at the 30 foot depth.

We have a net positive upward force of $27.95 \text{ psi} - 27.6 \text{ psi} = 0.35 \text{ psi}$ so the block will still be supported though it will not rise significantly. So let us replace the top 2 feet of bentonite slurry with 2 feet of the fluid grout to give us 29 feet of fluid grout in the vertical trench. We can compute what barrier thickness this will yield by the simple ratio equation used in the derivation of buoyancy section.

$$T_{bb} = T_b - \{(D_b / D_g) \times T_b\} - F$$

Where;

T_b = the vertical thickness of the block of earth

T_s = the vertical thickness of the portion of the block of earth submerged in the grout

D_g = the density of the grout

D_b = the density of the block of earth

T_{bb} is the thickness of the bottom barrier or the vertical lift above grade.

F is the freeboard depth of the grout fluid level below the grade level. (This is 1 foot)

$$T_{bb} = 30 \text{ ft} - \{(143.5 \text{ pcf} / 132.48 \text{ pcf}) \times 30 \text{ ft}\} - 1 \text{ ft} = 1.304 \text{ ft}$$

This indicates that we will get a bottom barrier thickness of 1.304 feet. If we wanted to get exactly 2 feet of bottom barrier thickness, we can compute how much additional grout to add to the trench by re-arranging the equation to:

$$T_b - \{(D_b / D_g) \times T_b\} - T_{bb} = F$$

$30 \text{ ft} - \{(132.48 \text{ pcf} / 143.5 \text{ pcf}) \times 30 \text{ ft}\} - 2 \text{ ft} = 0.3 \text{ ft}$ So we must fill the trench to within 0.3 feet of the surface to achieve a 2 foot thick bottom barrier. It is also obvious that in order to obtain a 3 foot thick barrier we will have to make the grout more dense or redistribute some dirt.

If the groundwater level was below the bottom of the structure before construction and then increased in the surrounding area (outside the block) in later years after construction what would happen? Since no moisture changes occur in the sealed internal block of earth, the weight of the block and the weight of the grout do not change. This problem can be solved by considering the interface between the grout and the external earth. Since the grout has a higher density than the saturated soil there is always a positive pressure of the grout against the soil. Therefore, changes in the water table outside the block can have no effect on the block.

5.7.5 Silty Clay with Cobbles

This soil condition is similar to condition 1 except that the silt is likely to be less plastic than the cohesive clay described there. Cobbles are rounded rocks which are thought to have been tumbled by moving water. Cobbles are defined in the physical geology book, "The Earth's Dynamic Systems" Burgess Publishing, 1982, as rocks between 64 mm and 256 mm, (tennis ball to volley ball size). Such rocks are often sorted such that many rocks of similar size are found together. We have already addressed the issue of cutting past and through rocks. Another key factor in this example is the potential for the cobbles to slough out of the side wall trenches or to fall from the bottom of the floating block and land within the bottom barrier layer. If this should occur we would want the barrier thickness to be significantly greater than the diameter of the cobbles.

The average density of the block will be 150 pounds per cubic foot due to all the rocks. To make a 3 foot thick bottom barrier 30 feet deep, with 1 foot of freeboard in the trench:

$$D_g = (T_b/T_s) \times D_b$$

T_b = the vertical thickness of the block of earth

T_s = the vertical thickness of the portion of the block of earth submerged in the grout

D_g = the density of the grout

D_b = the density of the block of earth

The submerged thickness of the block will be 26 feet since the top of the block is 4 feet above the fluid level in the trench.

Required Density of Grout = (30 ft / 26 ft) x 150 pcf = 173.08 pounds per cubic foot.

The Relatively high specific gravity will keep most of the rocks in their positions.

However the rocks are still more dense than the grout and some rocks on the bottom of the floating block which are mostly exposed and have very little soil below them may fall. This is of little consequence with a barrier many times thicker than the rock. In applications where we have a thin barrier or want to draw a liner under the block this may be a problem.

5.7.5 Glacial Till with Flat Rocks

For this example we will assume that the soil is a mix of fine and coarse grain material with many flat rocks taking up about 4 percent of the volume. Note that if the concentration of rocks were very high, say 15 percent, we might not be able to cut effectively without a special cutting cable. Assume that the soil and rocks have an average bulk density of 140 pounds per cubic foot and that the bottom barrier is to be 65 feet deep. The buoyancy calculation is the same as in the other soils. If the desired

freeboard is 3 feet and the bottom barrier needs to be 3 feet, then the submerged thickness (T_s) of the floating block will be 59 feet. Density of the grout must be: $D_g = (T_b/T_s) \times D_b$

$$(65 \text{ ft} / 59 \text{ ft} \times 140 \text{ ft}) = 154.23 \text{ pounds per cubic foot.}$$

In coarse grain material it may not be possible for the cutting cable to substantially push rocks out of the way but with flat rocks the cable may be deflected over such rocks. To evaluate this consider a rock shaped like a dinner platter and about 2 inches thick as well as a rock shaped like a watermelon. Assume both rocks lay flat and “end first” to the path of the cable. As the cable reaches the rock and stops the contact stress on the rock will rise quickly. Assume that the cable is capable of applying 30,000 pounds of force after frictional losses. If the cable bears against the rock on an upward 15 degree angle it may develop up to $(\sin 15^\circ) \times 30,000 \text{ pounds} = 7,764 \text{ pounds}$ of upward force to deflect it over the rock. Random plains of weakness in a flat faced rock may also cause it to break along an angle as well. If the fracture plane of a rock at 45 degrees had a shear strength of 4,000 psi the plane of the fracture could be as large as:

$30,000 \text{ pounds} \times (\sin 45^\circ) / 4000 \text{ psi} = 5.3 \text{ square inches}$. It seems likely that at this level of stress that the rock would still be pushed to one side even in firm soil.

5.7.6 Sandy Soil with cobbles

This soil condition is similar to condition 1 except that the silt is likely to be less plastic than the cohesive clay described there. Cobbles are rounded rocks which are thought to have been tumbled by moving water. Cobbles are defined in the physical geology book, “The Earth’s Dynamic Systems” Burgess Publishing, 1982 as rocks between 64 mm and 256 mm, (tennis ball to volley ball size). Such rocks are often sorted such that many rocks of similar size are found together. I observed an excavation at a concrete manufacturers sand pit near a river in the town of Idaho Falls, Idaho. with many cobbles that were 3 to 6 inches in size. The cobbles were oblong and rounded and were distributed about 2 per cubic foot of soil over a depth range of 10 to 30 feet deep. The soil had an estimated shear strength of 50 psi.

Assume a 42 foot square basement pit buried with a bottom at 55 foot depth. Assume the pit is a basement structure highly contaminated and filled with sand and rock. Assume that at least one zone of perched water exists at 40 feet deep. Assume that the tank plus the soil around it has an average bulk density of 139 pounds per cubic foot. We will construct a containment structure by the vertical block method around an area 62 feet wide by 62 feet long at a depth of 65 feet.

We will construct a slurry trench using a clamshell crane mounted tool. The vertical trench will be 3 feet wide with 10 feet of clearance around the pit. Pipes leading to the pit will be sheared off by the digging tool. We will be using a TECT A hardening grout since the pit weight may change with future remedial operations. We also wish to fill and abandon any pipes leading to the tank. We want a freeboard of 2 feet in the perimeter

trench and a bottom barrier thickness of 3 feet. The submerged thickness of the block will be $65 \text{ ft} - 2 \text{ ft} - 3 \text{ ft} = 60 \text{ ft}$.

The required grout density is: $D_g = (T_b/T_s) \times D_b$
 $= (65 \text{ ft} / 60 \text{ ft}) \times 139 \text{ pounds per cubic foot} = 150.58 \text{ pounds per cubic foot}$

5.7.7 Clay with fractured shale

This soil type is modeled after the soils common in the Bear Creek Valley area of Oak Ridge, Tennessee. The surface soils are high in clay content and the area receives ample rainfall. Most of the strata is said to be a sandy to silty clay with many different layers. There are also many layers of shale rock. The strata contains layers of weathered shale that can be crushed easily as well as harder shale with a compressive strength of 500 to 1000 psi. There are also many hard limestone rocks. The ground water table is variable and in some cases may intrude into the bottom of pits and trenches seasonally. In some of the pits and trenches, the bottom of the pit lies in a weathered and fractured shale. In constructing debris burial trenches workers generally stop excavation when harder material is encountered. For this reason we can expect that the rock several feet below the original bottom of the trench is likely to be a hard material in many cases.

One good solution is to contain the source material by constructing the barrier at the interface between the weathered shale and the harder shale. The idea here is to capture the 99 percent that is still in the pit and not expend large efforts on the 1 percent that has already escaped. Assume that the soil has an average bulk density of 130 pounds per cubic foot, (pcf) and that the ground is level or can be leveled above the waste area. If the pit was 800 feet long and the grade sloped along that length, we might break it up into three sections to make leveling feasible. We also might want to save money by doing two trenches at a time to reduce the amount of grout required. In this case we would likely choose a TECT A hardening grout. For our purpose here, assume we want to

construct a 2 foot thick barrier in the weathered shale just above the harder rock at the 30 foot depth and that we can level the surface. If the waste has an average density of 125 pcf and covers 38.778 percent of the cross section, the average density of the block becomes;

$125 \text{ pcf} \times .38778 + 130 \times .6122 = 128.06 \text{ pcf}$. If we want a 1 foot of freeboard in the trench, the submerged thickness of the block is $30 \text{ ft} - 2 \text{ ft} - 1 \text{ ft} = 27 \text{ ft}$. The required density of the grout is given by: $D_g = (T_b/T_s) \times D_b$
 $= (30 \text{ ft} / 27 \text{ ft}) \times 128.06 \text{ pcf} = 142.29 \text{ pounds per cubic foot}$.

What if we wish to construct the barrier deep into the rock layer at 40 feet depth in the rock? Assume that the rock layers are tilted with respect to the leveled surface of the block.

As the cable saw cuts it will tend to ride up or down the tilted fault lines until the increased angle away from a straight path to the load frame pulley brings it down again.

Barrier in tilted plane rock formation

Let us assume that the density of the rock plus soil and the trenches has an average value of 150 pounds per cubic foot. Let us further assume that the ground water is within 20 feet of the surface and is contaminated with oils and solvents in a range greater than 1 percent. Due to this high percentage of contamination, we determine to use a hardening TECT A grout with a nominal set time of 8 weeks. Assume we have performed a cutting speed test on an adjacent site and found that we can cut the rock with a forward speed of 12 to 24 inches per hour. The 200 foot long bottom cut will take 100 to 200 hours to cut. We may wish to perform the actual cutting work using a continuous cable with a capstan drive winch. This system could be located on top of the area we are isolating if space is limited.

5.7.8 Fractured Basalt Flow under Fine Sandy Clay

This condition is similar to the INEEL in Idaho. The top soil layer is 10 to 18 feet deep with layers of basalt flow below this. The soil is a very fine grain material of low permeability. Undisturbed areas are quite hard, at least 70 psi and have a bulk density of

120 pounds per cubic foot. The basalt rock has an average specific density of 156 pounds per cubic foot but can run up to 170 pcf in some areas. TECT grout can be made with specific density up to 187 pcf or more. Many of the burial trenches at the INEEL site were excavated to rock and then 3 feet of clay soil was placed before waste was deposited. Some pits have little documentation on what was done. In many cases the preferred method will be to construct a barrier in this 3 foot thick layer of clay soil below the waste. This soil has been disturbed and is likely to be softer than the undisturbed soil and thus easier to cut with the cable saw. Though the site is in a desert the subsurface at the INEEL is surprisingly wet with high moisture levels. This means that a TECT B soft grout could be an option here. However, if the analysis of climate indicates that the deep soil might someday dry out we might prefer to use the hardening TECT A grout or a TECT W wax based grout which can withstand totally dry conditions. The bottom barrier would be at about 17.5 feet deep for the pit 9 area. Pit 9 is approximately 137 feet by 300 feet in size.

To create a bottom barrier 3 feet thick with a freeboard of 1 foot in the perimeter trench will imply that the submerged thickness of the block will be 13.5 feet.

Density of the grout must be: $D_g = (T_b/T_s) \times D_b$

$(17.5 \text{ ft} / 13.4) \times 120 \text{ pcf} = 155.5 \text{ pcf}$.

The grout required may be calculated based on a 2 foot thick wall and a 3 foot thick bottom. The perimeter is $137 \text{ ft} + 137 \text{ ft} + 300 \text{ ft} + 300 \text{ ft} = 847 \text{ feet}$ plus 32 feet of overlap at the corners = 906 feet of trench 17.5 feet deep less 1 foot of freeboard = 16.5 foot depth of the grout.

So the vertical walls will contain $16.5 \text{ ft deep} \times 2 \text{ ft thick} \times 906 \text{ ft long} = 29,898 \text{ cubic feet of grout}$. The bottom is $137 \text{ ft wide} \times 300 \text{ ft long} \times 3 \text{ ft thick} = 123,300 \text{ cubic feet of grout}$.

So total grout requirements are 153,198 cubic feet.

If we choose to make the barrier 10 feet deep into the rock the calculation would be different. Taking the heavier rock density, the average density would become $(17.5/27.5 \times 120 \text{ pcf}) + (10/27.5 \times 187 \text{ pcf}) = 144.36 \text{ pcf}$

The submerged thickness of the final floating block T_s will be $27.5 \text{ ft} - 3 \text{ ft} - 1 \text{ ft} = 23.5 \text{ ft}$

Density of the grout required is: $D_g = (T_b/T_s) \times D_b$

$(27.5 \text{ ft} / 23.5 \text{ ft}) \times 144.36 \text{ pcf} = 168.94 \text{ pounds per cubic foot} = 22.6 \text{ pounds per gallon}$.

Since this grout may be exposed to the vertical fractures of the basalt rock we may require special fluid loss additives such as plastic flakes and fibers to be used in the grout to prevent fluid loss.

If the fractures are severe we may need to use the TECT W molten wax grout. Since this grout cures by loss of heat it automatically seals off in fractures while remaining molten in the 2 foot wide trench. In order to keep the grout molten in the horizontal cut we will use a capstan drive to keep the cutting cable circulating through the cut at high speed. This will create a pumping action which transfers hot grout from the side trenches

through the cut. We will also use a higher level of buoyant force to deflect the block upward rapidly during the cut. After the rock has been cut completely under the block, we will repeat the cut through the cooled wax with high buoyancy conditions to fully release the block. Circulating hot pipes of molten wax will be maintained in the trench during the slow cooling process to manage shrinkage. The pipes act as a sprue does in molded plastic to prevent voids from shrinkage.

Disposal In Earthen Pits, Idaho

Basalt Rock With Vertical Fractures

5.7.9 Sandy Soil Underlain By Karst Limestone Formation

This condition will be 20 feet of sandy soil on the surface with a limestone formation below. The limestone contains many voids, cracks, and holes ranging in size from 1/8 inch to 1 inch in size. Some of the holes are connected by passages larger than the minimum size that the grout can seal off. The water table is 11 feet deep and is contaminated with explosives, and tritium plus various undocumented mixed waste. The dry sand has a density of 120 pounds per cubic foot. The wet sand has a density of 139 pounds per cubic foot. The saturated limestone is 168 pounds per cubic foot. The limestone will have holes that open to both the vertical and horizontal cuts we make and the grout will enter these holes for a limited distance before bridging the permeability. Assume that these holes are random and will have no significant effect on the average density of the block. The fluid in these holes is still transmitting hydrostatic force uniformly due to the head of the fluid in the trench. Note: the holes that become filled with grout are no longer part of the block, for the purpose of calculating the weight of the block. These hollows were filled with water or air and were lighter than the average density of the block. Therefore, when they are removed, by filling them with grout, it can result in a slight increase in block density. If the block is large compared to the volume of the holes in communication with the grout, then the net density change of the block will be small. If the holes are large and all well interconnected, then the effective density of the rock will be as though it had no holes at all.

Assume we wish to construct a barrier 30 feet deep and 2 feet thick with 1 foot of freeboard. Due to the presence of holes in the rock the standard TECT A or TECT B grout will be modified with additional bridging agents such as silica and flakes of mica. The initial slurry trenching work will be performed with a bentonite and sand slurry which is tailored to limit fluid loss to the highly permeable formation.

Average density of the block is:

$$(11\text{ft}/30\text{ft}) \times 120\text{pcf} + (9\text{ft}/30\text{ft}) \times 139\text{pcf} + (10\text{ft}/30\text{ft}) \times 168\text{pcf} = \mathbf{141.7 \text{ pcf}}$$

The submerged thickness of the block (T_s) will be $30 \text{ ft} - 2 \text{ ft} - 1 \text{ ft} = 27 \text{ ft}$

Density of the grout required is: $D_g = (T_b/T_s) \times D_b$

$$(30 \text{ ft} / 27 \text{ ft}) \times 141.7 \text{ pcf} = \mathbf{157.4 \text{ pcf}}$$

CARBONATE AQUIFERS

15

Some karst formations are much more extensive and interconnected such as the

illustration.

In using the EarthSaw™ for this type of geology it is possible to connect to fractures too large to seal which will consume all of the grout. For such conditions the TECT B molten grout may be useful because it is capable of sealing large fracture systems by loss of thermal heat.

5.7.10 Sandy Soil Containing Debris Filled With Liquids.

In some rare cases the site to be contained may contain pockets of liquid waste. What will happen if these pockets of liquid waste are squeezed by the heavy grout? Consider a block of earth having sandy soil and buried waste debris. Suppose that in the middle of the debris are several drums containing oily liquid waste with a specific density of 59 pounds per cubic foot as well as sludge with a specific density of 80 pounds per cubic foot. Let us assume that the drums have rusted away to nothing and the liquids are free phase in the debris and that the water table is deep.

If the site has been effectively containing the liquids and the liquid path does not intersect the barrier then there is no mechanism to cause the liquids to move. When a block of earth is lifted by buoyant grout the grout is simply taking the place of the forces that the soil was previously applying to the block. When the vertical slurry trench is cut around the perimeter of the site there may be a slight reduction in lateral stress. When this slurry has been replaced with grout this stress is increased back to just above normal levels. As the block is cut loose and is free to float this horizontal stress level declines back to near the original value. The stress is slightly higher because the top of the block is above the grout level and the horizontal compressive load will be distributed to the area below the fluid line. The top area of the block above the grout level remains unloaded of horizontal stress and may slough off if not protected. The vertical stress on the soil block is a function of the weight of the block itself and does not change. There is generally no net increase in vertical compressive stress at the boundaries of the soil block.

Consider a different site where the barrier actually intersects the liquid filled debris. In this case the waste liquids come into communication with the fluid grout. Will the liquid be forced to the surface?

If the bottom horizontal cut connects with the liquid filled debris only at the bottom of the block and that liquid filled debris zone extends upward to near the surface, then the heavy grout entering by gravity at the bottom can pressurize the lighter liquid in a confined headspace above. In order to pressurize the liquid the openings through the debris would have to be large enough that the grout would flow into the spaces in the debris and displace a significant amount of liquid. This pressurized liquid will first spread into the soil of the block by permeable flow and perhaps by fracture. Near the surface these fractures will likely be horizontal but if a suitable weakness plane exists, the liquid could be forced to the surface. The amount of liquid forced out would be less than the volume

of grout intruding into the liquid filled debris. TECT grouts are designed to seal off on permeable soil formations and debris so this is likely to be a small quantity.

If one of the vertical cuts connects to the liquid filled debris, as would occur if only one end of a pit were being isolated, the results would be different. Since the liquid would not be trapped in a headspace it could move to the top of the debris and then channel laterally to the vertical trench and up the permeable exterior of the soil block to the surface. This liquid would then pool on the top of the grout in the trench. The liquid filled debris will only be affected to the extent that the self-sealing grout can actually flow into the debris so the volume of such a flow would likely be small. If the grout was designed such that it did not flow into the debris then none of the above conditions would occur. If there were significant air voids in the debris this would also tend to damp this movement.

Assume a burial pit 400 feet long by 20 feet wide by 20 feet deep in dry sandy soil filled with general demolition, soil, and construction debris and having a void ratio of 40 percent. Assume that 10 percent of the debris volume (120,000 gallons) is free phase organic liquids sorbed and dispersed within the debris and soil. Assume that liquid free product organic liquid fills the bottom 3 feet of the original 20 foot depth. 30 percent of the void space is air filled. Assume that high levels of contamination exist only in one end of the pit. To construct a barrier 40 foot deep by 30 feet wide by 100 foot long we will use the vertical block method. Assume this end of the pit and the soil around it has an average density of 130 pounds per cubic foot. Using a hardening TECT A grout we want a 3 foot thick bottom barrier and 3 foot thick walls with 1 foot of freeboard in the trench. The submerged thickness T_s is $40 \text{ ft} - 3 \text{ ft} - 1 \text{ ft} = 36 \text{ ft}$.

The required grout density is: $D_g = (T_b/T_s) \times D_b$
 $(40 \text{ ft} / 36 \text{ ft}) \times 130 \text{ pcf} = 173.3 \text{ pcf}$

If we cut the vertical wall in a clean area outside the contaminated soil we will simply use the correct density grout and there will be no issues due to the free liquids. However since we are cutting through the active waste burial area the grout will be in direct contact with the debris. (Note: This is only a “what if” example. Carter Technologies does not advocate excavating in contaminated debris). In order to perform this work we would have a slurry trench only around the 100 foot long end of the site. The trench at the end would be made double the desired final width. The load frames would be installed 100 feet from the end of the pit. When the cutting cable reaches the load framed one load frame is removed and the cable is then used to cut vertically across the pit to the remaining load frame. As this is done the grout may to some extent flow into the permeability of the debris in the pit. Assume that the grout flows an average of 10 feet from the cut face into the permeability of the debris before plugging off. In the 100 foot long pit this will increase the organic fluid level to: $(100 \text{ ft} / 90 \text{ ft}) \times 3 \text{ ft} = 3.33 \text{ feet}$. Since the debris has a significant air void space above it this extra third of a foot is of little consequence. After the vertical cut through the waste is made additional grout would be added at the cut. This will cause the free block separate and to move away from the rest of the trench until the vertical barrier thickness is the same as the other walls.

5.7.11 River sediment with buried tank

Assume a 75 foot diameter circular tank buried with its bottom at 50 foot depth. Assume the tank is filled with solidified sludge. Assume that at least one thin zone of perched water exists at 40 feet deep and that one area 10 feet outside the tank perimeter and from the surface to 50 feet deep is highly contaminated from a surface leak. Assume that the tank plus the soil around it has an average bulk density of 139 pounds per cubic foot. We will construct a containment structure by the vertical block method around an area 95 feet wide by 105 feet long at a depth of 65 feet.

We will construct a slurry trench using a clamshell crane mounted tool. The vertical trench will be 3 feet wide and will be curved on the clean side of the tank with 10 feet of clearance around the tank. Pipes leading to the tank will be sheared off by the digging tool. We will be using a TECT A hardening grout since the tank weight may change with future remedial operations. We also wish to fill and abandon any pipes leading to the tank. We want a freeboard of 2 feet in the perimeter trench and a bottom barrier thickness of 3 feet. The submerged thickness of the block will be $60 \text{ ft} - 2 \text{ ft} - 3 \text{ ft} = 55 \text{ ft}$.

The required grout density is: $D_g = (T_b/T_s) \times D_b$
 $= (60 \text{ ft} / 55 \text{ ft}) \times 139 \text{ pounds per cubic foot} = 151.6 \text{ pounds per cubic foot}$

5.7.12 Silty clay with buried drums and debris

Silty clay presents no special problem in forming a buoyant barrier. The most significant factor is still to carefully define the location of the barrier in 3D space before work begins. It is also important to perform soil testing at the bottom elevation to determine what cutting energy will be required and what friction factor will apply. Generally the contents of drums will not affect the final density of a soil block significantly. However there is a site at Paducah Kentucky, which is said to contain steel drums vertically stacked 3 high over at least a 100 foot by 50 foot square area. Generally debris will make little net change in the average density of a block but here we will assume that the rest of the 100 foot by 100 foot pit has general debris that is of lower density due to voids. The drums are filled with uranium metal turnings and packed in oil. Assume that the soil is silty clay and the water table is 13 feet deep and the bottom of the pit is 18 feet deep. Assume the drums are rusty and leaking oil.

A barrier is to be constructed to a depth of 25 feet. Since the increase in density due to water saturation in clay soil is small we will neglect it here for simplicity. Assume that due to the weight of the drums the site is unbalanced with one side having a density of 130 pcf and the other side having a density of 136 pcf. In order to construct the barrier all in one piece we will use the vertical block method with a sloping bottom. Note that

for a given grout density the total buoyant force increases with depth. To achieve a uniform lift at the surface, the bottom barrier will be 20 foot deep on the low density side and deeper on the side with the heavy drums. Assume we want to achieve a nominal 3 foot thick bottom barrier with 1 foot of freeboard in the perimeter trench. The submerged thickness on the light end will be $20 \text{ ft} - 3 \text{ ft} - 1 \text{ ft} = 16 \text{ ft}$.

The grout density will be $D_g = (T_b/T_s) \times D_b$

$(20 \text{ ft} / 16 \text{ ft}) \times 130 \text{ pcf} = 162 \text{ pcf}$.

How deep will the heavy side have to be to maintain a level surface condition?

Rearranging the equation to: $D_g / D_b = T_b / T_s$

Where T_s is $= T_b - 3 \text{ ft} - 1 \text{ ft}$

$D_g / D_b = T_b / (T_b - 3 \text{ ft} - 1 \text{ ft})$

$162 \text{ pcf} / 136 \text{ pcf} = T_b / (T_b - 3 \text{ ft} - 1 \text{ ft})$

$1.19118 = T_b / (T_b - 4 \text{ ft})$

Through trial and error we test 25 feet to see how close we get

$25 / 21 = 1.19048$ This is low so we will test a slightly different value.

$24.9 / 20.9 = 1.19139$ This is close enough.

Therefore the deep end needs to be 24.9 feet deep.

If our estimate of the density variation of the block is incorrect, we may wind up with one side floating higher than the other. This can be addressed by moving dirt from the low end to the high end with a small dozer until a level surface is achieved. If one end of the block is 1 foot higher than the other end, leveling the block in this way will reduce the barrier thickness by 6 inches on the end the dirt is received. In order to allow for this we have specified a 3-foot thick barrier even though a 2-foot thickness would have been enough.

5.7 Design Requirements for Load Frames (Subtask 1.3)

The Load Frame is a mechanical apparatus for implementing the **Vertical Block EarthSaw™** method. In this method a conventional vertical slurry trench is constructed around the 4 sides of the area to be contained. This trench is then filled with dense fluid grout and a cable saw is laid in the trench to surround the block of earth to be isolated. This cable is then tensioned and reciprocated to act as a cutting saw between the trenches to undercut the soil block. In some conditions the cable may simply be tensioned to slice through the soil without any reciprocation. As the block is undercut the dense fluid grout must flow under the block, to provide buoyancy and to transport cuttings. In order to cut a flat horizontal bottom we will need to generate a horizontal pull at the base of the trench. The purpose of the load frame is to give us a horizontal pull at the base of the block of earth to be cut. A dozer can give a horizontal pull at the surface, but we need that force to be applied at depth.

One way to do this by placing a large pulley at the top and bottom of the end trench to transfer this load. A structure will be needed to support these pulleys and it will have a reaction force F_1 and F_2 which must be supported by the soil. The pulley must also be large enough to avoid fatiguing the wire rope cable. The width of the trench is normally dictated by the construction equipment and is as narrow as practical to avoid requiring excess quantities of grout.

The cutting cable may be powered by dozers as shown above or it may be powered by winches mounted on trucks or winches could be mounted on top of the load frame itself.

This would eliminate the reaction loadings, F_1 at the surface and would avoid having the stressed cable potentially exposed to a worker. A load frame with a winch on top would have to deal with the upward component of the cable force trying to lift it out of the trench. Another option is to use the winch that is in the crane. This is very attractive since we must have a crane on site to place the load frames in

the trench and to remove it or change broken cables. Potential problems in using the crane winch are that the load frame would have an unbalanced force that might tend to lift it and create excessive friction. In addition, the cable may carry contamination to the winch drum. If the entire crane boom were used, we would have the mechanical advantage of a multi-part line but the length of stroke would be very limited.

Winches mounted on top of the load frame appear to be the best option. This will also reduce the need for a large bearing area at the surface. Winches are available with enough power to do the job. It may be possible to rent or lease a diesel-powered winch that could be installed on the load frame at the work site. The most important thing is that the configuration precludes the cable being able to come off the pulley due to sudden slack in the line. The cable should be captive but able to tolerate rocks and sand of all sizes.

The load frame should also be adaptable to operating at great depth since routine slurry wall techniques allow trenches to approach 100 feet deep. Holding the bottom pulley in position cannot be easily accomplished through rigidity of a structure extending to the surface. If we use a 1" steel cable with a strength of 150,000 pounds, the maximum reaction load on the soil at F2 will be 150,000 pounds. We are operating with new wire rope with the winch mounted on top of the load frame. In a reciprocating cut, the cable reverses direction about every minute. The pulleys must be sufficiently strong to handle these loads and may require special sealed bearings or pressurized lubrication. The structure holding the pulleys must also transfer this cyclic load to the soil. Assume that the soil we need to operate in may be wet and soft and have a bearing strength of only 2000 pounds per square foot. This implies that we will require: $150,000 \text{ pounds} / 2000 \text{ pounds per square foot} = 75 \text{ square feet}$ of soil bearing surface to resist the load. The 4 "wings" of the proposed load frame are each about 2 foot wide and so the first 10 foot of the load frame will have a bearing area of 80 square feet. This is enough to resist the load. If we were to use a dozer pulling unit or a free standing winch, this bearing surface would have to exist at both the top and the bottom of the load frame to prevent the structure from leaning over. Even though we will be using a top mounted winch, our preferred cross type design provides abundant bearing area all the way from bottom to top. At the 150,000 pound rated load, the load frame will be subject to 150,000 pound of uplift force. If the load frame weighs 17,000 pounds submerged and the winch weighs 20,000 pounds then we can expect about 37,000 pounds of down force due to weight of the hardware. The 150,000 pounds of cable tension is also pulling down on the winch on top of the load frame. This balances the upward vector at the pulley so the load frame will not tend to rise out of the ground but will be held down by its weight of 37,000 pounds. The midpoint of the load frame sees an overall compressive load of 150,000 pounds due to cable tension plus half its 37,000 pound weight. The cross section of the load frame is 243 square inches so it is not highly stressed by this 769 psi load. Lifting the load frame back out of the grout filled trench may be difficult as a suction seal occurs on the base. If the base has a flat area of 12 square feet. (1,728 sq in) and a grout hydrostatic head of 30 psi, then it might require 51,840 pounds more than the 17,000 pound submerged weight of the load frame to lift it free of the bottom. To avoid this

problem we should add a small air line from the top of the load frame to the center of the flat bottom area to help it “break suction”.

If the block is moved toward the load frames by grout addition on the opposite end, or if the block tilts slightly, the load frames could become mechanically pinched with enough force that they could not be removed. Even 4 inches of hydrostatic head difference can result in side forces of a million pounds on a 50-foot by 30-foot deep block. Therefore, the load frame should be very strong in lateral loading. We plan to achieve this by making the load frame from 8 standard I-Beams welded together. The $\frac{1}{2}$ inch thick web of these beams will be braced against buckling and each pair will provide a cross section of 360 square inches for the 30 foot height of the load frame. At the rated minimum yield of 40,000 psi this provides up to 14,400,000 pounds of crush resistance. A block that tips would apply point loads, but these would be distributed by yielding of the soil or rock.

It may be possible to design a single load frame to fit in one corner of the trench if friction values are low. At the present we do not have enough friction data to be confident in this approach. Passing a cable around a third 90 degrees of arc more than doubles the total friction. If friction is too high, rounding the third corner could result in

a stuck cutting cable.

It seems more preferable at this stage to design the load frame to fit in two adjacent corners of the excavation. Slurry wall construction practice in turning a 90 degree corner is for each trench to overshoot the intersection point by 5 to 10 feet. In the vertical block method we plan to isolate a generally rectangular area, so the corners will have a cross shaped intersection. We can utilize this shape by making the load frame to fit into this opening.

The load frame must fit into the cross shaped intersection between trenches so it can resist side loads

The load frame may be made from heavy steel I beams which will be held in the hole by gravity. At the end of the cut the cable will be stretched along a line between the two load frame units. In addition to the large pulley at the bottom of the load frame, we will also need at least one additional pulley at the bottom to support the cable when it nears the end of the cut. This pulley will also need to withstand a 150,000 pound load. It may also be possible to allow the main pulley to swivel to compensate. When the load is on this side pulley the bottom of the load frame will bear against the bottom corner of the block so we will need bearing area here as well.

The load frame should be designed with the pulley holding the wire rope cable fully captive so it can not slip off once the unit is submerged in grout. The cable must also be threaded through the unit without great difficulty on the surface before it is installed. When the load frame is removed from the trench replacement of the cable should be as simple as possible.

The load frame units will be immersed in grout with specific gravity up to 3.0 and so they must be designed not to be buoyant. They should also be designed to be easy to clean and decontaminate. When lifted out of the grout they should allow all the grout to drain back to the trench. It is desirable to be able to transport both units on one truck and to be able to load, unload and install with a single crane. If possible the units should be designed to be easily modified in length to accommodate different depth requirements, though for greater than 40 foot depths the units may require multiple trucks to ship. Making the units modular may be undesirable if it increases the amount of on-site work to assemble and install. The units must be designed in such a way that they can be stress tested above ground to verify that they will not fail under the design loadings.

5.9 Descriptive Drawings of the Method

The EarthSaw™ method has 7 basic steps.

1. A standard 24 inch wide slurry trench is excavated around the entire perimeter of the “block” of earth to be isolated.
2. Steel frames with mechanical pulleys at their base are lowered into two adjacent corners of the trench with a length of 1-inch diameter abrasive cable looped around the corners of the block. Powerful winches attached to the cable are fitted onto the top of the steel frames.

3. The slurry in the trench is displaced with an engineered grout having a higher density than the block of earth.

4. The winches are activated which pull on the cable to saw or slice a horizontal pathway under the block of earth.

EarthSaw cutting bottom pathway

EarthSaw bottom cut complete

5. As the cable cuts horizontally under the block of earth, the heavy grout flows into the cut, lifting the block slightly upward by buoyant force.

EarthSaw bottom cut complete

6. After the block is completely severed from the earth, and floating free, additional grout is added to the perimeter trench, causing the buoyant block to float higher. The fluid level increase causes an equal increase in the thickness of the layer of liquid grout below the floating block.

EarthSaw bottom cut expanded to final thickness by buoyancy as trench is filled with dense grout.

7. The liquid grout cures into an impermeable barrier and an air tight cap may be installed on top to facilitate organic contaminant removal or leak monitoring.

5.10 Equations for Cable Saw Friction and Shear

The mechanical cutting process of the EarthSaw™ may be of several types. In some situations, abrasive cutting by a sawing action is possible, while in other conditions the cable may slice through the soil with little or no generation of cuttings. We also must avoid conditions where the friction rises to a point the cable is stuck.

We define a sawing mode as the rough surfaced cable moving longitudinally across the face of the cut and cutting off small particles as it does so. These “cuttings” must also be transported to the trenches on each side of the cut. This method should have the advantage of working in hard materials for very wide cuts. We define a slicing mode as what occurs when the soil is cut but the cable does not move longitudinally through the cut. This mode has the advantage of being very rapid and not leaving any cuttings to be transported out of the cut. The softer and more narrow the section width of soil being cut, the more likely we are to operate in slicing mode. In the recently completed friction tests we found that in the clay soil typical of southwest Houston provided conditions that forced the cable to slice instead of saw when operating across a 50 foot width. This limited the width of soil block we were able to cut with the available power. If the cut had been 200 feet wide, the same cable pulling force would have resulted in a sawing action. Of course, the cutting progress would be much slower. During the same test, we found that steel cable would readily saw through a piece of limestone rock with minimal

friction if the included angle was only 90 degrees. What are the factors that govern this? What changes can we make to control it?

Consider a block of earth 200 foot square to be cut to a depth of 25 feet by the vertical block method. Suppose the soil has an unconfined compressive strength of 2.75 tons per square foot per square foot as measured by a pocket penetrometer. This should correspond to a unconfined compressive strength of 38 psi. There are some issues on the correlation of pocket penetrometer tests with lab tests. For our purposes we will assume it means that a cable pressed against the soil at more than 38 psi will shear the soil.

When the cable is pulled through a 180 degree arc from one end, the actual tension in the cable declines exponentially around the arc of the cut. If a cable is pulled through the soil by both ends in a slicing mode the tension will be uniform and the actual arc will likely be a hyperbolic catenary. (A catenary is the shape taken by a chain hanging suspended by its two ends. It is also defined by the hyperbolic cosine.) Variations in soil strength and rocks will alter this catenary shape and pulling on one side will skew it. The actual shape the curve takes has no significant effect on the friction loss. It is simply a matter of the contact angle and the coefficient of friction. We have chosen to approximate the shape of the arc with circular arcs for all the following calculations.

If we are passing the cable 180 degrees around a section of earth and pulling from one end with a potential coefficient of friction of 0.70, then the ratio of the tension on the pulling cable to the drag on the trailing cable will be (T_1/T_2) . We will call this the drag factor:

$T_1/T_2 = e^{\lambda\alpha}$ where λ is the coefficient of friction and α is the angle in radians.

At 180 degrees the angle is π radians. If the coefficient of friction is 0.7 then...

$$T_1/T_2 = e^{0.7(3.141)} = 9.17 \text{ drag factor.}$$

At this value, 75,000 pounds at T_1 will pull $75000 \text{ Lb} / 9.17 = 8,317$ pounds of tension in the cable on the trailing end of the arc. This 8,317 pounds is reduced by the drag from the weight of the cable weight itself times the length of the cable times the coefficient of static friction. If this extra drag is greater than 8,317 pounds, the cable will be stuck. If the force normal to the cut exceeds the strength of the soil, slicing will occur. Slicing action will occur first on the T_1 side of the arc where tension is higher.

At the halfway point (90 degrees = 1.57 Radians) the cable will have a drag factor of $e^{0.7(1.57)} = 3.0$. Therefore at the midpoint of the cut the tension would be $75,000 \text{ Lb} / 3.0 = 25,000 \text{ Lb}$. Whether slicing will occur depends on the width of the cut and the soil strength.

For a 200 foot wide cut made with a 1" diameter cable slicing through the soil will have a contact area approximated by a half circle 200 foot wide:

$3.141 \times 200 / 2 = 314 \text{ ft} = 3,770 \text{ inches}$. To exceed 38 psi across the entire cutting face by pulling uniformly on both ends, the cable pull must be $38 \times 3,770 = \mathbf{143,260}$ pounds. Since we have only 75,000 pounds of pulling force available we might think that no slicing would occur. However due to friction, the bulk of the pulling force will be concentrated on the pulling side of the arc, decreasing exponentially around the arc. If the trailing end of the cutting cable is loaded just enough force to stop the motion, (8,317 pounds), we can calculate the cutting force on the cable at various points. At the midpoint of the cut the force normal to the face of the cut on a 1 inch long piece of (nominal) 1 inch frontal area cable can be calculated:

(Pounds cable tension) x Sin [180 degrees / (W x B/2)]

Where W is the width of the cut in inches.

(25,000 pounds) x Sin [180 degrees / 3770 inches] = 20.84 pounds per square inch.

Since this is less than the 38 psi strength of the soil we should be in a sliding friction, or “Sawing mode” rather than in a slicing mode.

However at 40 degrees from the pulling end the cable tension will be much greater.

40 degrees = .69813 Radians

$e^{0.7 (.69813)} = \mathbf{1.63 \text{ drag factor.}}$

75,000 Lb / 1.63 = 46,007 Lb cable tension.

Cutting force will be $43,352 \text{ Lb} \times \text{Sin of } 0.04775 = 38.3 \text{ psi}$

So just past this point the cable will begin slicing into the soil rather than sawing.

To prevent this slicing from occurring at all we have at least five options:

1. Cut a wider total pathway.
2. Use a larger diameter cable.
3. Reduce the winch drag force, and thus the cable pull on the leading end.
4. Reduce the coefficient of friction
5. Reduce the total angle of contact

Notice that the first 3 options directly reduce the contact force, while the last 2 reduce the total friction or drag ratio. In field practice we will generally seek as high a load as possible without going into slicing mode. Reducing the drag force on the winch that is paying out cable will greatly reduce the tension on the winch pulling the cable. However if we reduce the winch force we may drop into the range where the cable will be stuck. Reducing the coefficient of friction is difficult once the grout has been placed in the trench. The total angle of contact may be reduced by adding a third load frame with a traveling pulley, which moves along the bottom of the trench. This method adds mechanical complexity but can reduce the drag ratio by 66 percent. (From 9.0 to 3.0) When working in environments where the coefficient of friction is high this may be cost effective.

It should be noted that the coefficient of friction for starting a pull, “static friction” is often up to twice as high as “sliding friction”, the force to keep it moving. In our field tests of friction we found static friction to approach 1.0 in many cases while sliding friction of 0.6 was typical. We found no significant difference between friction on concrete, gravel, or soil surfaces. This may be due to the relative roughness of the steel cable surfaces of our friction test apparatus.

If we are cutting in a soil filled with many small rocks or gravel, the average compressive strength, or bearing strength, of the soil may be effectively increased, just as gravel increases the bearing strength of a road. Regardless of whether the cable is operating in slicing or sawing mode, most of the rocks will be pushed out of the way and not cut in two. In more continuous rock formations, the progress of the cable will be limited to actual abrasive cutting of the rock. This is likely to be a very slow process with forward speeds measured in cubic inches per minute. The design of the grout for this type of cut must be such that cuttings are transported effectively and the grout retains its fluid properties even when mixed with cuttings.

6.0 6.0 Technical Work Product for Task 2

The most important questions in analyzing an EarthSaw™ project are:

1. Will the cable saw be able to cut the horizontal bottom pathway?
2. Will the block float and produce a sufficiently uniform barrier?
3. Will the barrier meet performance goals?

Task 2 focuses on the first two questions. Our objective in **Task 2** was to develop a detailed computer model to analyze the step-by-step installation of an EarthSaw™ Buoyant Barrier. This model attempts to evaluate the EarthSaw™ construction in a variety of subsurface conditions in which containment barriers may be utilized. Subsurface conditions such as the soil strength, permeability, porosity, water table, variable strata, tilted strata, surface slope, sloped bottom barriers, free liquids, existing fractures, fracture stress, variable density, hydraulics, variable waste loading, buried tanks, rocks, gravel, cable saw force, cuttings transport, and friction will be modeled in at least three sets of conditions agreed to by DOE.

Custom software was prepared which runs within Microsoft Excel and Microsoft Visual Basic for Applications. This program performs the required calculations and displays the results in both numerical and color 3-D graphical output. Small static images next to the input fields of the program guide the user in understanding the required inputs data. The program is self documented and also contains data validation and error prevention routines that monitor input data and provide context sensitive help so that others may use the program effectively. The accompanying CD ROM contains multiple copies of the program, each pre-filled with the data for the selected models. The input values shown in red text and may be changed as desired. The program will then quickly determine if the bottom cut is possible and compute the uniformity of an EarthSaw™ barrier under the specified conditions. The program will run on a standard PC with Excel installed. The three dimensional graphics output will work with Microsoft Office 2000 and later running Windows 98, ME, NT, 2000, or XP operating systems.

Additional numerically intensive structural modeling was performed in a customized version of Examine 3D, produced by Rocscience Co, in consultation with a professor of Geomechanics from the University of Toronto's school of civil engineering. This modeling is similar to finite element analysis and was used to evaluate mechanical stress on the block of earth as the bottom pathway is being cut. The output from modeling the first three sets of subterranean conditions is shown in graphical format with a text report. The source code for the three models geometries is included on the CD ROM. The "Examine 3D"

program required to run the models with new variables is not included on the CD ROM.

In order to perform the numerical computer modeling to answer question 1, we determined that actual data on friction between the steel cable under realistic conditions would be needed to validate the model. To this end, we conducted full scale friction tests to evaluate the forces and friction required to cut through the soil.

We also determined that before meaningful modeling could be performed it was necessary to fully define the load frame, pulling means for powering the cable saw, and the geometry of the system. To do this we prepared a full set of shop fabrication drawings for the load frame so that a structural analysis could be performed.

There are many possible variations of the EarthSaw™. On order to keep the project manageable, we modeled only the vertical block method. This method is also the most suitable for meeting the requirements of the December 1998 RFP for bottom barriers at ORNL since it can produce vertical sides and a flat horizontal bottom with minimal clearance to adjacent sites. See the Appendix of this report for the full text of the scope of work for the Oak Ridge request for proposal. We have taken the requirements of this RFP along with information from other DOE sites and technical conferences into account in development of this technology.

6.1 Steps and Elements To Be Modeled

The first steps in construction of barriers by the EarthSaw™ method is to prepare a slurry trench in clean soil around the perimeter of the site. Since the slurry wall technology is not new, we have not provided any modeling for this step.

Installing the load frames into the slurry trench is a potentially troublesome task since sloughing of the trench can cause interference problems in getting the load frame to the full depth of the trench. However, this also does not represent a step which is new or unique to the EarthSaw™ technology so no modeling is required.

The items to be modeled are as follows:

In our work subtask 2.44 we are to submit a model outline with selected parameters to be modeled for approval by DOE. Our model will be limited to four sided blocks with vertical walls with any length sides or corner angles. All excavation dimensions are expressed as components of a trapezium, which can define any four-sided figure. Note that three sided figures may be represented by having the fourth side very short.

Following are the parameters we have selected to model:

Buoyancy calculation of earth block with variable geometry, layers and waste distribution

Thickness of the horizontal bottom barrier.
 Minimum thickness of the vertical side barrier.
 Elevation of the earth block at the surface.
 Quantity of grout required and logistics of preparation.
 Force and friction on cable saw.
 Verification methods
 Shrinkage stress on grouts
 Cuttings transport
 Centering of the floating block
 Potential for stuck cable condition during cutting.
 Structural modeling of fracture potential during bottom cut due to stress on block due to excess buoyancy during cutting. (This will be modeled by Dr Grabinski using a special software package. Results are not yet complete but will be presented at the peer review.)

We will also provide a limited model and discussion of the following issues.

Effect of ground water level changes
 Heat transfer issues in molten grout curing
 Fracture sealing and fluid loss performance.
 Effect of perched liquids
 Effect of earthquakes
 Cable energy storage and wear prediction
 Grout supply logistics feasibility

6.2 Selection Of Subsurface Conditions To Model

The contract calls for us to submit a minimum of three different cases, defined by variable subsurface conditions and waste areas to be modeled. Following are the approved subsurface conditions to model for three cases. The selected modeling software falls into two categories. Special software created by Carter Technologies within Microsoft Excel and Visual Basic and also a customized version of a RocScience Examine 3D that incorporates “displacement Discontinuity” elements that are ideal for modeling the saw cut at the bottom of the block. The Examine 3D model will be coded by a software engineer at Rocscience Company and overseen by Dr. Murray Grabinsky, a professor of civil Engineering with extensive experience in modeling rock and soil mechanics.

Case 1

We propose to model a trapezoidal block 200 feet wide and 170 to 180 feet long and nominally 35 feet deep with a leveled surface and ground water 10 foot deep. For modeling, we will assume that the upper soil range is 123 pcf with a porosity of 10 percent. The formations are slopped with the transition occurring at 20 feet for corner A and D and at 21 feet for corner B and C. All soil below this to the bottom

cut is 110 pcf with porosity of 25 percent. At the 35 foot depth, Cone penetrometer strength is 20 psi and in the sand the friction angle is 27 degrees. Standard penetrometer is 20 blows per foot. Soil type is clayey sand (SC) reading 3 kg/cm² on pocket penetrometer in the 30 foot to 35 foot interval and poorly graded sand (SP). Sand has no cohesive strength. We will assume a level cut at 35 feet deep with about half of the horizontal cut to be formed in the “clayey sand” and half to be formed in the more permeable “poorly graded sand” due to slope of the subsurface formation. Assume the waste consists of pockets of stacked metal drums in many separate excavations. Density and quantity of drums in each location is known from records. Drums contain uranium metal dust and oil. Assume the site contains free organic liquids of 0.9 specific gravity floating on the water table and filling the void space in the bottom 2 inches of the Vadose zone Permeability of the soil is 1×10^{-4} cm/sec. Assume that a soft TECT B grout is preferred due to earthquake concerns. Assume that soil re-deposited in excavations has the same strength as the undisturbed soil.

The above elliptical arc represents the expected shape of the cut (plan view). Note the arc extends all the way back to the load frames. We will assume that the cut is elliptical and that the cut extends all the way back to the load frame before progressing substantially along the centerline length. Field experiments indicate this is approximately correct.

Note: for the initial finite element fracture modeling, assume that the surcharge loading will be adjusted to make the block float level as per the 2.29 spreadsheet 1. This will make the average density of the entire block 130.1 pounds per cubic foot. The finite element model will assume a grout density of 152 pounds per gallon with 4 feet of freeboard to generate a 1 foot positive buoyancy for the initial portion of the cut. We will also model the same grout density at 4.5 feet of freeboard. Young's modulus will be 450,000 psi and poisson's ratio will be 0.3

Three cable positions will be modeled, for each of the two freeboard depths, with elliptical semi-arcs of 145 ft, 115 ft, and 75 feet.

Case 2

This model would be for a site created in soft rock. The block would be rectangular, 50 feet wide by 40 feet deep and 620 feet long. The soil is composed of 2 layers. The top layer is a fine grain soil with compressive strength of 50 psi. This soil is flat at the surface and 6 feet deep along one of the 620 foot long sides of the block and 5-1/2 feet deep along the other. The upper soil has a density of 123 pounds per cubic foot. The deeper earth is a soft rock with a density of 111 pounds per cubic foot. Compressive strength of 500 psi. All soil is dry with moisture content less than 10 percent. The waste is evenly distributed with soil in an excavation 5 feet inside of the boundaries of the block from 15 to 30 feet elevation. This excavation is the “waste container”, as the solid waste is placed in a crushed tuff fill material. The interior of this 15 foot thick x 40 foot wide by 610 foot long excavation has no strength but has the same overall 102 pcf bulk density as the rock. The site contains no free or containerized liquids.

Case 3

This would be similar to conditions at one of the INEEL sites. The case 3 site has dimensions of 150 feet by 350 feet. The site has about 17 feet of topsoil

underlain by several hundred feet of lava flows. The rock has an average density of 156 pounds per cubic foot. Soil has a density of 122 pounds per cubic foot. The surface is a desert with very fine grain waterproof soils. The subsurface is damp with moisture in the 30 percent range. Undisturbed soils can be loose and sandy or very hard in excess of 20 tons per square foot. The pit was excavated with a dragline and dozers down to rock. Three feet of soil was placed on top of the rock to make a level bottom before waste was placed in the excavations. This may allow the barrier to be placed in this interval.

The basalt rock below is very hard and will likely require custom engineered abrasive cable as well as patience to make the cut. We will assume that a research program has been performed to manufacture a suitable diamond abrasive one-inch diameter cutting cable. For the purposes of this model we will assume that we wish to make the horizontal cut at 27 feet, 10 feet into the rock. Assume the rock along the horizontal cut is fractured with 20 vertical fractures having a width of 1/2 inch, a length of 20 inches and a depth extending 88 inches above and 88 inches below the horizontal cut. Further assume that the fractures do not connect to any void or chamber with more than a cubic yard of volume. Due to the large fractures we have selected a molten TECT W grout.

Case 4

This case is a rectangular block 300 feet by 400 feet and 75 feet deep. The two leading corners where the cut begins would have a 100 foot radius rather than a sharp corner. It contains 12 gunnite (steel pre-stressed concrete) tanks with a bottom concrete foundation at 43 feet deep. The tanks are located on 100 foot centers. The tanks are short vertical cylinders 75 foot in diameter with 18 foot tall sides, and a domed top rising 10 feet. The bottom of the tanks are dished 12 inches. The tank walls are 16 inches thick. The tanks sit on a soil layer 43 feet below ground level described as a sandy fine to very fine pebble. Bearing value of soil is 8,000 pounds per square foot. The soil has no cohesive strength. The site is dry with no water table in the work zone. The hardening TECT A grout would be selected for this site. Soil fill is 100 pounds per cubic foot silty sandy gravel. Tanks currently average 60 percent full but are vary significantly. We could also assume that the tanks have been emptied and partially re-filled with sand or foamed grout.

This would be similar to the Hanford tank farms 241T area. A medium grain sandy soil with rounded cobbles. (Cobbles range from baseball to volleyball size) If the process were used on a tank, the dimensions would be about 100 feet square and 75 feet deep. The side excavations would have to cut through numerous pipes, and excavation spoils could be contaminated if the soil we excavate is already contaminated. It may be far more economical to do an entire group of 12 tanks, forming a block 300 feet by 400 feet in size and 75 feet deep on 100 foot centers.

Soil moisture levels are low, perhaps in the 15 – 19 percent range. Tanks may be empty when barriers are constructed for final containment. Tanks may be quite fragile and a top cap may not be permitted due to collapse concerns.

The first three cases are the ones recommended by Carter Technologies and accepted by DOE for modeling with the outside finite element analysis. The fourth and fifth case are provided as an alternates but will still be modeled with the Carter in-house Excel model.

Case 5 Case 5 is characterized by burial trenches 800 feet long by 30 feet wide by 30 feet deep with the upper areas made of sandy clay and the bottom zone in a fractured and weathered shale. Water table is high and significant oil permeates the site.

This is typical of sites at the Oak Ridge National Laboratory, Bear Creek Valley site shown at right.

The wastes were disposed by end dumping from trucks and then covered with soil. Large amounts of free oil were also disposed in the trenches.

See the table below for other details of case 1 thru 5.

<p>Table of C</p> <p>Carter Technologies Co</p> <p>Data comparison of sites to be modeled for EarthSaw™</p> <p>Modeling for any 4 sided irregular block</p> <p>Prepared April 19, 2002</p>					
Model simulation of...	Site 1	Site 2	Site 3	Site 4	Site 5
Dimensions	Paducah c-749	Los Alamos Tuff	INEEL pits & trenches	Hanford Tanks	ORNL Bear Creek valley

Length a	0	0 ft	30 ft	0 ft	0 ft
Length b	180 ft	620 ft	300 ft	400 ft	800 ft
Length c	20	0 ft	20 ft	0 ft	0 ft
Length "h1"	180	50 ft	150 ft	300 ft	30 ft
Length "h2"	170	50 ft	150 ft	300 ft	30 ft
Plan view
Graphic of actual shape and orientation of cut					
Surface elevation at corner A	0 ft	0 ft	0 ft	0 ft	0 ft
Surface elevation at corner B	0 ft	0 ft	0 ft	0 ft	3 ft
Surface elevation at corner C	0 ft	0 ft	0 ft	0 ft	3 ft
Surface elevation at corner D	0 ft	0 ft	0 ft	1 ft	1 ft
Depth of cut at corner A	35 ft	40 ft	27 ft	75 ft	27 ft
Depth of cut at corner B	35 ft	40 ft	27 ft	75 ft	30 ft
Depth of cut at corner C	35 ft	40 ft	27 ft	75 ft	30 ft
Depth of cut at corner D	35 ft	40 ft	27 ft	78 ft	28 ft
Depth to water table	10 ft	> 50 ft	>50 ft	>100 ft	17 ft
Upper soil type	SC clayey sand	sandy clay	Fine grain clayey silt	silty sandy gravel	SC clayey silt
unconfined strength	20 psi	50 psi	277 psi	0	40 psi
Cone penetrometer strength	20 psi	50 psi	277 psi	100 psi	50 psi
porosity	10%	10%	20%	25%	18%
Permeability of soil	1x10 ⁻⁵ cm/sec	1x10 ⁻⁵ cm/sec	1x10 ⁻⁷ cm/sec	1x10 ⁻³ cm/sec	1x10 ⁻⁵ cm/sec
Upper soil density at corner A	123 pcf	123 pcf	122 pcf	100 pcf	125 pcf
Upper soil density at corner B	123 pcf	123 pcf	122 pcf	100 pcf	123 pcf
Upper soil density at corner C	123 pcf	123 pcf	122 pcf	100 pcf	123 pcf
Upper soil density at corner D	123 pcf	123 pcf	122 pcf	100 pcf	125 pcf
Waste description	uranium metal & oil	classified	sludge and debris	Tank sludge	General debris and oil
Waste packaging description	stacked metal drums	loose objects	drums, crates, loose	gunnite tanks	none
Are there free liquids?	yes	no	no	no	yes
Waste content of quadrant A	2%	29%	10.00%	14.70%	15%
Waste content of quadrant B	2%	29%	14.70%	14.70%	20%
Waste content of quadrant C	4%	29%	12.00%	14.70%	20%
Waste content of quadrant D	4%	29%	14.70%	14.70%	15%
	(Waste is all of fill)				
Density of waste quadrant A	165 pcf	102 pcf	100 pcf	78 pcf	110 pcf
Density of waste quadrant B	180 pcf	102 pcf	100 pcf	78 pcf	110 pcf
Density of waste quadrant C	216 pcf	102 pcf	120 pcf	72 pcf	110 pcf
Density of waste quadrant D	180 pcf	102 pcf	100 pcf	89 pcf	110 pcf
Depth of density transition at A	20 ft	5.5 ft	17.5 ft	43 ft	27 ft
Depth of density transition at B	21 ft	5.5 ft	17 ft	43 ft	27 ft

Depth of density transition at C	21 ft	6 ft	19 ft	43 ft	29 ft
Depth of density transition at D	20 ft	6 ft	17 ft	43 ft	29 ft

Lower zone soil type	SP, poorly graded sand	Volcanic Tuff	Basalt rock	sandy fine to pebble	Weathered shale
unconfined strength	0 psi	500 psi	7,000 psi	0	300 psi
Friction angle	27 degrees			27 degrees	
Cone penetrometer strength	20 psi			100 psi	1000 psi
porosity	25%	10%	3%	25%	20%
Permeability of soil	1x10 ⁻⁴ cm/sec	1x10 ⁻⁴ cm/sec	1x10 ⁻¹ cm/sec	1x10 ⁻⁴ cm/sec	1x10 ⁻¹ cm/sec
Probable fracture width	none	0.1 inches	0.5 inches	none	.5 inches
Probable fracture length	none	6 inches	20 inches	none	3 inches
Probable fracture depth	none	20 inches	88 inches	none	6 inches
Lower density at corner A	110 pcf	111 pcf	156 pcf	111 pcf	150 pcf
Lower density at corner B	110 pcf	111 pcf	156 pcf	111 pcf	150 pcf
Lower density at corner C	110 pcf	111 pcf	156 pcf	111 pcf	150 pcf
Lower density at corner D	110 pcf	111 pcf	156 pcf	111 pcf	150 pcf
Grout type selected	TECT B	TECT A	TECT W	TECT A	TECT B
Coefficient of friction	1	1	1	1	1

6.3 Software Selection

We performed a literature and Internet based search of modeling software and found no suitable software for modeling the EarthSaw™. We found dozens of programs for modeling groundwater flow and contaminant transport, and many for modeling structural load bearing capacity in soils as well as programs for heat transfer and mechanical strength. We were unable to think of any other potential application which might require the same kind of analysis as the EarthSaw™. We found lots of software on Naval Architecture stability and buoyancy but because it addressed many shapes, it was needlessly complex for this application. One Naval Architecture website suggested that for general buoyancy a spreadsheet was a suitable software tool. Since most of the calculations are simple, we decided to perform as much of the work as possible in an Excel spreadsheet with Visual Basic for Applications used as needed to enhance graphics.

6.4 Bounding Conditions for the Spreadsheet Model

In any modeling task it is important to define the conditions and external bounding conditions that are to be assumed by the model. In the EarthSaw™ model we assume

- A burial site situated on relatively level ground or the ground can be leveled by earthmoving.
- The plan view boundaries of the waste are known.

- c. Excavation of a slurry trench in a clean soil perimeter to below limits of contamination is possible.
- d. A fluid grout that is denser than the soil, may be formulated that will flow into the cable saw cut, while sealing permeability of the soil.
- e. Density of the soil block may be estimated within 3 percent.
- f. Density of the soil block varies less than 5 percent from one quadrant to another.
- g. The block may be balanced to float level by adding or moving soil and/or altering the depth of the bottom cut.
- h. Regulatory authorities will accept containment as a least an interim solution.
- i. The site is accessible to large crane and slurry wall construction equipment.
- j. Blocking subsurface ground water flow will cause no harm.
- k. No waste or hard objects (such as steel pipes) extend below the depth of the horizontal cut.
- l. Soil strength can be measured by cone penetrometer, for work in “slicing mode”.
- m. If working in “sawing mode”, a cable saw can abrasively saw through the soil or rock.
- n. Coefficient of friction of cable on soil/rock while submerged in grout, is no more than 1.0
- o. Minimum grain size of soil, over 20 percent passing #8 sieve.

6.5 Preparation of Equipment Drawings And Specifications

As previously stated, the modeling task required definition of the structural and mechanical layout of the system hardware. The most complete way to do this was to to prepare the actual fabrication drawings. Fabrication drawings for the load frame were prepared using Generic CADD 6.1 using 21 drawing sheets. Drawings are presented in Generic CADD 6.1 format and AutoCAD format on the CD ROM. The hard copy drawings are located in appendix D. Following is an imported copy of the final assembly drawing. The load frames for left and right hand sides are the same. Following is a copy of the assembly drawing and a thumbnail of the rest of the drawings.

The main pulley sheave and bearing set has been quoted from vendors but no drawings were supplied. We found a wide range of seals and bearings available with a wide range of prices. We plan to wait until a test site is selected to finalize the bearing and seal selection since cutting in soft rock at Los Alamos will take several days to cut and will justify a better bearing and seal than the one hour slicing application we expect at the Paducah site. We do no plan to reuse cutting cable or bearings from one project to the next.

To view the thumbnail copies in Microsoft Word, select View, and Zoom and set percent to 500% and the image will be large enough to see. Note that due to the file import process the text may be shifted to the right and curves may be broken into line segments.

Load Frame assembly drawing

LFRAM001

LFRAM002

LFRAM003

LFRAM004

LFRAM005

LFRAM006

LFRAM007

LFRAM008

LFRAM009

LFRAM010

LFRAM011

LFRAM012

LFRAM013

LFRAM014

LFRAM015

LFRAM016

LFRAM017

LFRAM018

LFRAM019

LFRAM020

LFRAM022

LFRAM023

LFRAM028

6.6 Hardware Structural Analysis

The structural analysis of the load frame system begins by defining the maximum load condition. This occurs at 100,000 pounds of line pull. The reaction forces on the load frame were previously discussed in section 7.7. Recapping, we can see that when the cable is under 100,000 pounds of tension, the load frame requires a bearing area capable of supporting that load. If we assume a minimum soil strength of 2000 pounds per square foot, we will need $100,000 \text{ pounds} / 2000 \text{ pounds per square foot} = 50 \text{ square feet}$ of bearing area. During the beginning and end of the cut, the load frame has approximately 4 square feet of bearing area per foot of height. So the soil at the face will deform until the load is spread over the bottom $50 \text{ sq ft} / 4 \text{ sq ft} = 12.5 \text{ vertical feet}$ of the load frame. At a midpoint in the cut where the cable is at a 45 degree angle the load frame has twice as much bearing area per vertical foot. The structural strength of the load frame members themselves are very strong compared to

the soil bearing loads.

The Pulley wheel at the bottom of the load frame carries a maximum load of 100,000 pounds / $\sin 45 \text{ degrees} = 141,421 \text{ pounds}$

If we assume the bottom pin carries the full shear load in its 4" diameter pin:

The pin is made from steel which is in excess of 100,000 psi strength. It has a minimum cross section of 12.56 square inches and so is loaded at :

$141,421 \text{ pounds} / 100,000 \text{ psi} \times 12.56 \text{ sq in} = 11.25\% \text{ of yield.}$

The top pin carries a much smaller load. The pin is made in three sections to keep the weight manageable for a worker during installation. The housing for the bottom pin is made from a sleeve with a 1 inch wall thickness which is welded into a reinforced box section with

3/4 inch thick HSLA , 100,000 psi yield steel plate on top and 1/2 inch thick A-36 plate on the bottom.

The pulley itself is made with a bronze sleeve bearing with over 40 square inches of surface area. The seal and bearing assembly is of a custom engineered, pressurized design, also used in rotary oil well drilling bits. The pre-assembled unit will be supplied by a vendor. The pulley has guards so that the cable is always captive on the pulley and cannot jump off the track. The clearance allows for cable up to 1.5 inch diameter to pass. Guides along the entry point help a worker thread the cable through the hole from one of the many large holes in the structure. The holes also aid in decontamination and reduce weight.

6.7 Additional Structural Modeling Of The Earth Block

We have contracted with Dr. Murray Grabinski of the University of Toronto to model the structural stress on the earth block during cutting. The block will be modeled using 6 inches and 12 inches of excess buoyancy at three points during the horizontal cut. The analysis will help determine if the block is prone to fracturing during the cut due to

excess buoyancy. He will evaluate three different sets of data representing three very different sites.

Our non-quantitative graphical analysis of the problem indicates that fracture stress will occur at the center of the arc of the cut when excess buoyancy beyond that needed to support the earth block at the original elevation. This excess buoyancy would tend to cause stress to be concentrated at this point. It seems likely that either horizontal or vertical cracks will form in the center of the arc tangent to the cable. The formation of a horizontal crack first could relieve stress and prevent a vertical crack. We hope that this further analysis will answer the question of how much excess buoyancy we can tolerate and what direction the crack would go in the first three sets of soil conditions.

6.8 Thermal Management System for Molten Grout (1.34)

The molten grout represents a new and unique material for earth modification projects. Unlike conventional grouts that set by chemical reaction or drying, the molten grout may remain fluid indefinitely until it loses enough heat to solidify. This grout was developed primarily to address the fractured basalt rock common to the INEEL site in Idaho. Wastes at this site are disposed just above what appear to be lava flows of basalt rock. The rock has many vertical fractures and could be difficult to seal with conventional grout materials.

Consider a system using the EarthSaw™ vertical block method with the molten TECT W grout to construct a 3 foot thick barrier under and around a block of earth 25 feet deep 60 feet wide and 120 feet long. If the conditions are like that of the INEEL in Idaho with 15 feet of fine grain soil underlain by fractured basalt rock. The TECT W grout is a molten wax composite having a density greater than soil and rock. The nominal melt point of the material is 130 degrees Fahrenheit. The non-toxic grout has a viscosity similar to 50 weight motor oil or ketchup.

In the vertical block EarthSaw™ method we begin by cutting a vertical perimeter trench around the site. Let us assume that the excavation is performed by a long reach backhoe with a rock bucket. If the soil is sufficiently stable for trenches to stand open we will excavate the trench in the dry. If the soil is not stable, trenches will be excavated under fluid slurry. The slurry can be conventional bentonite clay or it may be the TECT W grout itself. In the case of bentonite slurry, we would use very high (7 to 10 percent) concentration of bentonite in the slurry, and oil well type bridging agents that are useful for plugging the voids and fractures as we come to them. This slurry would be quite high in viscosity and would tend to plug any fractures. After the vertical slurry trench is complete we would install heaters and heat the bentonite slurry to at least 180 degrees F. The heavy molten wax TECT W grout would then be pumped to the bottom of the trench as the lighter bentonite slurry is pumped out at the surface.

It should also be possible to excavate under the grout itself if large fractures make it difficult to seal with bentonite. This will waste some of the more expensive grout, which will coat the spoils but will also avoid disposal of the bentonite slurry and the taboo of placing water based fluids in the ground. As the soil is excavated in the first portion of the trench the trench will be filled with the molten grout at a temperature of 200 degrees F. At this point the three-foot wide trench will be about 17 feet deep. We will place about 32 cubic yards of grout in the hole. The thermal mass of this grout will keep it molten for several days. The molten grout will flow into the fractures and fissures in the rock and will quickly cool, sealing the hole several inches away from the trench. The rock below it will be excavated under the grout and the spoils placed on a screen to recover grout back to the trench. Steam pipes will be placed into the trench. These pipes will be “U Bend” loops extending from the top of the trench to the bottom. The steam pipes will be sized according to the BTU needs of the site. A steam generator unit on the surface will feed steam to these units. Alternately the pipes may circulate hot water or be electrically heated according to availability.

Regardless of the trench construction technique, after the molten wax grout is in the trench we will need to keep it hot during the work and have the ability to re-heat it if a site shutdown were to occur during our operations. We will install 1 steam pipe “U bend” for every 5 linear feet of trench. The pipes will be installed in series with 20 “U bends feeding off of one steam unit. The molten grout has a low thermal conductivity and a high heat capacity. In order to heat the grout it may be necessary to use a flat strip electric heating element. These flexible strip heaters may be encapsulated in silicone rubber, much like the clip-on industrial drum heaters. These strip heaters would be lowered from the surface and replace the “U bends”.

For a rectangular block site, a crossing of two perpendicular trenches forms the corners. A load frame device with a large pulley on its base is inserted into two adjacent corners. A winch mounted on top of one load frame feeds a steel cable to the bottom of the trench and around the perimeter to a second load frame that has a winch taking up cable. The cable cuts through the rock by abrasive action of the cable itself and the abrasive materials in the grout. The cable is of the 2 or 3 strand twisted strand design. The strands are coated with a polyurethane coating and imbedded silicon carbide chips. As the coating wears away the chips are exposed. The abrasives in the grout are swept along by the twisted cable and perform the bulk of the cutting task. The cable circulates in one direction for 1000 feet or more and then reverses direction.

The bottom cut will take several days. At 2 linear feet per hour the cut will take 60 hours, running round the clock. Since the cut of the cable is only about an inch thick, the rock on both sides of the cut may pull enough heat from the grout to solidify it. Due to it's twisted strand construction, the cable acts as a pump moving fresh molten grout through the cut. This will bring enough heat into the cut to heat up the rock within a few inches of the cut for a brief time while the cable is close by. The area several feet behind the cut will no longer benefit from this heating and will rapidly lose enough heat for the grout to solidify. This could allow the grout in this area to solidify when the barrier is

only one or two inches thick. In order to achieve a full three-foot thick barrier we must either maintain a molten condition in the bottom cut or re-melt it for the final lift.

To maintain a molten condition we can cause grout to flow horizontally through the cut by changing the grout fluid level on one side of the earth block. This will require pumps that pull grout from the trench on one side and pump it to the trench on the other side. This would normally just create a flow from one side to the other through the trench. Thermal barriers would be placed in the two corners where the cut begins shortly after the cables have cut into the corners of the block. These barriers are hollow steel members inserted into the trench near these corners. Ambient temperature water is circulated through these steel members to cool the adjacent wax. A similar structure could be made on the inboard wing of each of the load frames. This results in a vertical seal at each of the four corners of the perimeter trench.

The majority of the surface of the perimeter trench would be covered with sheets of $\frac{3}{4}$ " plywood. This will help reduce heat loss to the surface but more significantly would protect against persons falling into the open trench. The sheets of plywood could cover the trench. Conventional expanded steel gratings would be placed over the trench as walkways where needed.

In our example, say that the east side was the 120-foot long side and that it was kept at a 2 feet higher elevation. This is 1-foot freeboard on east side, and 3-foot of freeboard on the west side. This will cause a substantial flow of grout from east to west under the block. If this flow is maintained the bottom layer should remain molten. We begin the cut at the north end of the block. As we cut to the south, the length of the cut increases the volume of grout pumped back from the top of the west trench back to the east trench will increase significantly. The higher head in the east trench will also cause a twisting moment on the block, as the northeast corner will rise more than the northwest corner. This deflection should be within the elastic range of the rock.

Once the barrier is complete, the load frames and thermal barriers would be filled with hot water to release the barrier and then removed from the trench. Freeboard would equalize in all trenches and would then be brought up to the final level to create the desired bottom barrier thickness. The flow under the block would stop and the grout under the block would begin to cool and solidify from the center outward. After the bottom barrier was completely solidified, the vertical strip heaters would be turned down gradually. The lower elevation heaters would be gradually raised upward. This would allow the heater to keep the upper area molten as the remainder of the grout cools. The area immediately around the heaters would remain molten and this pathway would serve as a "sprue" does for casting molten metal. The grout will shrink as it solidifies. The "sprue" provides a continual supply of liquid grout to make up for the shrinkage as the solidification is taking place. The TECT W grout remains plastic and deformable even after cooling.

6.9 Air-Tight Cap Design

Once a barrier has been constructed by the EarthSaw™ method, it will generally be desirable to construct a protective cap over the site to produce a sealed vault.. The cap has several functions. The cap prevents water from entering the containment structure formed by the bottom barrier. If the cap is designed to be air tight this also makes it possible to perform various measurements to validate the integrity of the barrier that are more accurate than traditional monitor well methods.

If the barrier is free of leaks and has an air-tight top cap, then we can measure chemical or pressure differentials across the barrier to verify integrity. We can lower the air pressure inside the barrier and monitor pressure inside. If the barrier has no leaks, the pressure inside should remain lower. Of course, we will have to compensate for temperature variation. If the wastes themselves produce gas, or bacterial in the ground produce gas, then this may not be possible and we may need to install automatic vents to prevent pressure buildup. It may be possible to reduce the concentration of some component of the air, such as oxygen or water vapor, in the vault. By monitoring the internal vault soil gas pressure and the external soil gas pressure with a data logger over a long period of time we can determine if there are any leaks. The external pressure will vary with the weather on a daily basis. The internal pressure should not change significantly except due to temperature. If we reduce the air pressure inside the vault by 2 psi, over a 30 day period, and then seal the vault, we would expect the pressure to remain reduced if the vault is free of leaks. If we are using a TECT A or TECT B grout that can withstand drying, it may be possible to circulate dry air through the vault from well points. Over a period of years, we should be able to dry out the entire vault contents and reduce humidity inside the vault to a low level. This reduced humidity could be monitored to continually verify vault integrity.

Removing the moisture would not be feasible if we used the clay based TECT B grout but it should work fine for the hard TECT A or the wax based TECT W grout. For a barrier made with non-hardening TECT B measurement is complicated by the fact that the barrier must remain damp. If the barrier is below the water table the barrier may be validated by pumping part or all liquid water out of the vault and monitoring for and build up of water coming into the vault not due to condensation. If the water table is below the barrier, then a negative air pressure technique is an option.

If the barrier is made from one of the soft grouts such as TECT B or TECT W the cap provides an armor barrier at the ground level. We have assumed that an earthen cap above this having anti-bio-intrusion layers would be preferred. Transpiring covers could be used above the primary impermeable synthetic barrier if desired.

EarthSaw containment vault with air-tight cap

6.10 Using the Spreadsheet Model

The Buoyancy Model spreadsheet is broken into several “sheets”, which are selected by the tabs at the bottom of the screen. The left most tab is called Sheet 1. This is where we enter most of the physical parameters of the soil and the size and shape of the soil block. The user input values are shown in red. The user may enter any value into these spaces within the limits set by the programmer. When you select any red cell, a popup window will provide information and suggest proper ranges for the variable.

The first data we would enter are the dimensions of the block. Real waste pits may not be rectangular and we want the model to apply to many different shapes. However for

A trapezium defined by lengths a, b, c, h1 & h2

data input so we must have a uniform way to describe the shape of the perimeter. We have selected a trapezium, which is a four sided object in which the sides may be uneven lengths and the angles may also be uneven. We have defined the dimensions in terms of lengths a,b,c,h1 and h2 as shown in the figure. For a rectangle the lengths a and c would be zero and h1 and h2 would be equal. For a triangular site, the length b would be zero and h1 and h2 equal. Trapezoidal shapes are also easily

defined. Angles are calculated automatically by the spreadsheet.

Prior to starting a project, borings should be made at several points along the perimeter of the barrier and at the corners. Measurement of the soil conditions by depth should be taken at each hole.

Many DOE sites have the waste disposed in surface soil layers which are right above a rock layer or a soil of a different kind. The model assumes the possibility there may be two distinct soil layers and that the waste is disposed in one of them. (You can also make both layers the same density.) The next data input is the soil density in the upper layer and in the lower layer at each of the four corners of the site. If water table conditions are dynamic you can express soil density in terms of drained density and include information on the volume percentage porosity of each soil layer and the depth of the water table measured from an arbitrary corner A. If you do not need to take variable water table conditions into account you can simply enter wet bulk density for the soil and enter porosity of zero or set water table to below the bottom cut.

Next, you enter the depth of the bottom cut and the depth of the density change for each corner. This allows the model to consider tilted subsurface rock layers and non-horizontal bottom barriers. If the ground surface is not level, you can enter the elevation of each corner relative to corner A.

The block is divided into four quadrants of equal area. The program calculates the area and volume of each quadrant. In some cases, additional soil may be added to the top of the block. This is called surcharge. We measure it in terms of tons added or taken away. We assume that this soil will have the same average density as the upper layers of soil at the four corners and that added soil will be uniformly distributed and compacted to this density. In most cases the soil may be simply moved around by a dozer, so the spreadsheet also calculates the equivalent thickness.

The next entry is for the percentage of the total volume of each quadrant filled by waste packages and the average bulk density of those packages. (Waste in drums and boxes is sometimes documented by weight of each container.) The program assumes even distribution of waste within each quadrant. Waste typically represents only a very small portion of the weight of the soil block.

The next data entries are for ground water density, grout cost, freeboard, trench width, trench overlap, ground water depth, percent porosity and percent of vertical interval saturated for each layer. Finally grout density is entered.

The program will display a dynamic 3-D graphic of the bottom barrier thickness and a detailed numerical grid. The input parameters may then be varied to achieve a uniform bottom barrier. There are two displays of bottom barrier thickness with different visual angles and different grid density, however they utilize the same data and are redundant.

The program also calculates the volume and cost of the grout needed to perform the work and what the minimum side and bottom barriers will be.

Sheet 2 of the spreadsheet shows a graphic of the NETL logo surrounded by a grid with numbers indicating the elevation relative to grad level at corner A. Clicking on the NETL logo will activate a macro that will draw a 3D graphic of the final surface elevation of the floating block. This image is only updated when the NETL Logo is clicked. This Macro was developed with Excel 2000, and may not work properly on some earlier versions.

The Cable force and friction sheet calculates the winch force and friction to determine the operational modes possible and if you have enough power to cut the horizontal barrier.

6.11 Screen Shots of Model for Case 1

Following is a screen shot image from the spreadsheet with the data for case 1. See the CD ROM for the actual Excel spreadsheets with the data per-loaded for each of the 5 cases above.

The EarthSaw barrier does not have to be rectangular, It could take many shapes. Assume a 4 sided shape with vertical walls. This is known as a Trapezium.

Cells in red require user input.

Cells in green are calculated values

The area of a Trapezium is

$$(b(h1+h2)+a*h1+c*h2)/2$$

Input dimensions in feet below.

Where h1 is equal or greater than H2

a or c may be positive, zero, or negative

0	a	Length of side a
180	b	Length of side b
20	c	Length of side c
180	h1	Height h1
170	h2	Height h2
	side 1	200.0
	side2	171.2
	side3	180.3
	side4	180.0

If we divide the Trapezium into 4 equal area quadrants, the area of each quadrant is 1/4 the total area.

Assume the average depth interpolated from corner to center point E

	sq ft area	Avg. depth	cu ft volume
Entire Block	33,200	35.000	1,162,000
Quadrant A	8,300	35.000	290,500
Quadrant B	8,300	35.000	290,500
Quadrant C	8,300	35.000	290,500
Quadrant D	8,300	35.000	290,500

90.00 calculated Angle of corner A

83.29 Calculated Angle of corner B

99.89 Calculated angle of corner C

86.82 Calculated angle of corner D

86.82 calculated angle of rectangular portion of corner D

93.18 calculated angle of rectangular portion of corner C

6.71 Calculated Angle of triangle portion of corner C

0.00 Calculated Angle of triangle portion of corner D

The following input data describe a block that may have tilted rock layers, variable water table, and variable density soil.

Note: Soil density is expressed as drained density

Note: If the yellow instruction box gets in your way while entering data, drag it away or activate the microsoft office assistant and it will move.

123 Drained Soil Density near surface at corner A

123 Soil Density near surface at corner B

123 Soil Density near surface at corner C

123 Soil Density near surface at corner D

123 Soil density near surface at E

110 Drained Soil Density near bottom at corner A

110 Soil Density near bottom at corner B

110 Soil Density near bottom at corner C

110 Soil Density near bottom at corner D

110 Interpolated Soil Density near Bottom at E

20 Depth of density change at corner A

21 Depth of density change at corner B

21 Depth of density change at corner C

20 Depth of density change at corner D

20.5 Interpolated Depth of density change at point E

35 Depth of corner A from surface

35 Depth of corner B from surface

35 Depth of corner C from surface

35 Depth of corner D from surface

35 Interpolated Depth of cut at center point E

57.14% Percent of total depth having this density

60.00% Percent of total depth having this density

60.00% Percent of total depth having this density

57.14% Percent of total depth having this density

58.57% Percent of total depth having this density

42.86% Percent of total depth having this density

40.00% Percent of total depth having this density

40.00% Percent of total depth having this density

42.86% Percent of total depth having this density

41.43% Percent of total depth having this density

The effective depth, freeboard, and block thickness are altered by the initial elevation differences

0 Surface elevation at corner A relative to corner A

0 Surface elevation of corner B relative to corner A

0 Surface elevation of corner C relative to corner A

0 Surface elevation of corner D relative to corner A

0 Surface elevation at E relative to corner A

3.20 Effective freeboard at A adjusted for surface and surch

3.15 Effective freeboard at B adjusted for surface and surch

2.79 Effective freeboard at C adjusted for surface and surch

3.01 Effective freeboard at D adjusted for surface and surch

3.04 Effective freeboard at E adjusted for surface and surch

Assume surcharge is uniformly distributed over each quadrant

- 100 Tons of surcharge weight added in quadrant A
- 75 Tons of surcharge weight added in quadrant B
- 105 Tons of surcharge weight added in quadrant C
- 7 Tons of surcharge weight added in quadrant D
- 77 Total surcharge weight added to whole block

- 0.1959 Equivalent feet thickness in Quadrant A
- 0.1469 Equivalent feet thickness in Quadrant B
- 0.2057 Equivalent feet thickness in Quadrant C
- 0.0137 Equivalent feet thickness in Quadrant D
- 0.0377 Equivalent feet thickness at E

Note: these determine "effective freeboard" above

Assuming all waste is in the upper layer

- 2.00% Percentage of upper quadrant A containing waste
- 2.00% Percentage of upper quadrant B containing waste
- 4.00% Percentage of upper quadrant C containing waste
- 4.00% Percentage of upper quadrant D containing waste
- 3.00% Interpolated Percentage of upper point E containing waste

- 165 Bulk density of waste in quadrant A
- 180 Bulk density of waste in quadrant B
- 216 Bulk density of waste in quadrant C
- 180 Bulk density of waste in quadrant D
- 185.25 Interpolated Bulk density of waste at point E

62.4 Water Density

\$4.89 Grout cost, dollars per gallon, Grout cost can vary significantly according to location, quantity, and required properties

3 Freeboard in perimeter trench at corner A after cutting is complete (feet) After cut is complete fluid level is increased

24 Vertical Trench width, (inches)

32 Total feet of overlap at corners

10.00 Water table depth below Corner A

10.00% Percent effective porosity of upper zone

50.00% Vertical Percent of upper zone saturated

25.00% Percent effective porosity of lower zone

100.00% Vertical Percent of lower zone saturated

154.00 Grout density used (pounds per cubic foot)

Blue is corner A, White is corner B

To see a more detailed 3-D graphic please go to sheet 2 and click on the blue button or the NETL logo

Note: the barrier thickness is equal to the rise above ground minus any surcharge soil added

Table of bottom barrier thickness

D	3.03	3.078412898	3.078412898	3.079021496	3.0796	3.08023869	3.080847	3.08145589	3.08	C
		3.077798301	3.078318889	3.078839478	3.079360066	3.0798807	3.08040124	3.080922	3.081442419	3.08196
		3.078400902	3.07883348	3.079266058	3.079698636	3.0801312	3.08056379	3.080996	3.081428948	3.08186153
		3.079003502	3.07934807	3.079692638	3.080037206	3.0803818	3.08072634	3.081071	3.081415477	3.08176004
		3.079606103	3.07986266	3.080119218	3.080375775	3.08	3.08088889	3.081145	3.081402006	3.08165856
		3.080208703	3.08037725	3.080545798	3.080714345	3.0808829	3.08105144	3.08122	3.081388535	3.08155708
		3.080811303	3.080891841	3.080972378	3.081052915	3.0811335	3.08121399	3.081295	3.081375064	3.08145556
		3.081413904	3.081406431	3.081398958	3.081391485	3.081384	3.08137654	3.081369	3.081361592	3.08135412
A	3.03	3.081921021	3.081825538	3.081730055	3.0816	3.08153909	3.081444	3.081348121	3.08	B

Our approach to this model is to divide the area into 4 or more quadrants and to evaluate the buoyancy of each quadrant as a finite element.

We will assume that the block varies uniformly from edge to edge in all respects.

First we interpolate from the known corners to obtain an estimate of the specifications of the center point "E"

Then we compute the average density of the entire block at each corner and center point.

Density = ((upper density x 1-percent waste fill) + (waste density x percent waste fill)) x percent upper depth + (lower density x percent depth) + (water density x upper zone Porosity x percent depth) + (water density x lower zone porosity x percent depth)

126.38 Average density of block at corner A (pounds per cubic foot)

126.60 Average density of block at corner B

128.14 Average density of block at corner C

127.20 Average density of block at corner D

127.00 Average density of block at center point E

128.14 Maximum known density at any point

Output Data computed by model

$$T_{bb} = T_b - \left\{ (D_b / D_g) \times T_b \right\} - F$$

Where;

T_b = the vertical thickness of the block of earth

T_s = the vertical thickness of the portion of the block of earth submerged in the grout

D_g = the density of the grout

D_b = the density of the block of earth

T_{bb} is the thickness of the bottom barrier or the vertical lift above grade.

F is the freeboard depth of the grout fluid level below the grade level.

2.5 Minimum desired bottom thickness, feet

Screen Shot From Page “3-D” of Spreadsheet

File: EarthSaw In-Situ Containment of Pits and Trenches, contract DE-AC26-01NT41144

Developed by Carter Technologies Co, Sugar land, Texas Ernie Carter, P.E. 281-495-203
Revision 5 dated 2/06/02

Subtask 2.25, Numerical predictive model, Cable force and friction.

This Spreadsheet is intended to define relationships and provide data for development of a detailed computer model. The calculation is based on the vertical block method with vertical sides using the following input data:

Force displayed in pounds, Distance in feet, Cable diameter in inches

Required User input cells shown in red

Input Data		Calculated values shown in green
		Load frames located at corners B and C as on sheet 1
	180	Width of the cut (in feet) from sheet 1
	173.29	Contact Angle (in degrees) from sheet 1
	190	Length of the cut from sheet 1
20		Soil in situ horizontal bearing strength (in pounds per square inch)
0.875		Cable Diameter (in inches)
1		Coefficient of friction between cable and soil, (Macro scale)
90,000		Winch pull capacity (in pounds) at T1 Yellow background indicates insufficient pull for slicing mode
2.03		Cable weight per foot, Pounds
0		Length of cable dragging above ground on T2 side
300		Pounds friction loss in sheaves and fluid drag
80,000		Minimum breaking strength of cable
	560	Maximum length of cable dragging on soil in cut and on ground surface when first arc is formed.
	1137	Pounds of drag due to cable weight on horizontal surface
	2935	Cable force available for sawing action at T2
	38,937	Pounds winch pull required at both winches to slice through soil

Computation indicates that Cable Sawing Motion is Possible !

Computation indicates this soil block may be sliced by direct pull on both winches at once !

EarthSaw cutting bottom pathway

Basis of the calculations:

If we are passing the cable around a section of earth and pulling from one end with a coefficient of friction of (λ) then the ratio of the tension on the pulling cable to the drag on the trailing cable will be (T_1/T_2).

We will call this the drag factor. (If drag weight+ winch drag equals) x (drag factor) = T_1 then sawing stops!

In our field experiments with 1 inch diameter cable the weight of the cable provides significant friction just laying on the ground.

We will call this the "drag weight" and it also includes all friction in the straight part of the cable path on the trailing side.

The winch drag on the trailing side includes all the back tension drag from the winch and any pulleys.

$T_1/T_2 = e^{\lambda\alpha}$ where λ is the coefficient of friction and α is the angle of contact in radians.

At 180 degrees the angle is π radians. Note that the formula applies to any shape arc.

If we pull uniformly from both ends to slice through the soil the shape would be a catenary.

If we use a reciprocating cable motion the cut will approximate the shape shown with the side being pulled straightening out.

If we use a continuous cable, and pull in one direction only, the curve will be skewed strongly to one side.

Field experience indicates that the cable cuts mostly on the side being pulled so the shape of the arc is non-uniform.

If the cable saw cuts by slicing mode rather than sawing mode the maximum width of cut will be limited by the available cable tension.

If the cable cuts by sawing against the face of the soil, cuts several hundred feet wide may be possible.

In order to saw rather than slice in a given 1 inch long segment of the arc of contact, the cable tension times the sine of that 1" contact angle must be less than the bearing strength of the soil.

Due to friction with the soil, the bulk of the pulling force will be concentrated on the pulling side of the arc decreasing exponentially relative to the contact angle. This allows us to calculate the tension in the cable at any point.

For a given set of input data we can calculate the cable tension which will exceed the soil strength.

During the initial cutting of the corners of the rectangular block, we will of course be slicing through the soil, but as the arc of the cut becomes a full 173.2901632 degree arc, we can approximate the contact force as follows:

The length of a circular arc is 272.1522013 feet Frontal area of 1 degree arc of cable = 16.49025 sq inches

The included angle for a 1 square inch face of cable = (contact angle / inches total arc length) / inches Cable thickness
 So 1 sq inch frontal area of cable extends an arc of: **0.0530617** degrees or 0.000926101 Radians

Note; Excel uses Radians for all trig functions.

The contact force between the soil and the cable is given by the sine of the angle times the tension force.

To achieve sawing motion with no slicing of the soil...

Soil psi must be less than the sine of 0.0009261 times the Maximum Cable Tension

Soil strength / sine of the angle = Cable tension for soil slicing to occur.

50 psi / Sine 0.0009261 radians

53,990 Pounds = Max cable tension at any point along circular curve to avoid slicing

formula is soil strength x sin{1/(length/angle)}

For 180 degree arcs, the arc of the cut will not stay circular for long and will quickly become a catenary

(A catenary is the curve made by a cord of uniform weight suspended freely between two points.)

Calculating a catenary length is complex but assume for a cut whose length is twice the width, it is about 4 x the width

Since arc length is longer than a circular arc the contact surface area is greater and thus the contact pressure would be lower.

when the 180 degree cut is about the same length as width, the arc length is about 2 x the cut width.

This would still be longer than the circular arc so the contact pressure is still lower.

For a 180 degree starting arc:

As we approach the end of the cut the length of the arc will approach the width of the cut but the contact angle also decreases.

Assume that at half the original contact angle (180/2) the arc length will be width times 1.15

The catenary arc length would be **207 feet** Frontal area of 1 degree arc of cable = 27.6 sq in

a one square inch section of cable extends an arc of **0.0725 degrees** or 0.001264731 Radians

39,534 Pounds = Max cable tension at any point along the curve near end of cut, to avoid slicing.

This is still higher than for the circular arc so the risk of slicing decreases as we approach the end of the cut.

The Drag factor increases as we move around the curve from T1 to T2

Drag factor $T1/T2 = e^{\lambda\alpha} =$ **111.32** **23.14** **10.55** **4.81** **2.85** **1.69** **1.30**
 270 degrees 180 degrees 135 degrees 90 degrees 60 degrees 30 degrees 15 degrees

For a given Pull force at T1, the maximum cable tension at any point along the arc = T1 / Drag factor

For the data values keyed into the red space above, the cable tension at T2 is:

2,915 Pounds

For the same conditions the actual cable tension at 15 degrees from T1 is:

46,180 Pounds

If this is less than the maximum allowable cable tension calculated above then the cable will not slice in at this point.

The chart below shows the cable tension for six different positions along the curve with various T1 pull force in pounds.

The chart indicates the cable tension at which the cable will begin slicing into the soil.

You may enter new values (pounds) for the pull force in the **blue T1** column.

Arc of Contact	Pull force, (T1)	Drag to stop, (T2) =						Cable tension at various degrees from T1	
	0 degrees	270 degrees	180 degrees	135 degrees	90 degrees	60 degrees	30 degrees	15 degrees	
Note: You may change the pull force values shown in blue to get more precise answers	10,000	90	432	948	2079	3509	5924	7697	
	15,000	135	648	1422	3118	5264	8886	11545	
	20,000	180	864	1896	4158	7018	11848	15393	
	25,000	225	1080	2370	5197	8773	14810	19242	
	30,000	269	1296	2843	6236	10528	17772	23090	
	40,000	359	1729	3791	8315	14037	23695	30787	
	50,000	449	2161	4739	10394	17546	29619	38483	
	60,000	539	2593	5687	12473	21055	35543	46180	
	70,000	629	3025	6635	14552	24564	41467	53877	
	80,000	719	3457	7582	16630	28074	47391	61573	
	90,000	808	3889	8530	18709	31583	53315	69270	
	100,000	898	4321	9478	20788	35092	59238	76967	
	110,000	988	4754	10426	22867	38601	65162	84663	
	120,000	1078	5186	11374	24946	42110	71086	92360	
	130,000	1168	5618	12321	27024	45620	77010	100057	
	140,000	1258	6050	13269	29103	49129	82934	107753	
	150,000	1347	6482	14217	31182	52638	88858	115450	

Conditions highlighted in orange will be in slicing mode.

— Conditions with a stuck cable shown in a strike-through font

The 15 degree column indicates the maximum pulling force to avoid significant slicing action.

Note that if the "drag to stop" at 180 degrees is less than the friction due to weight of the cable it will be stuck!

Friction due to weight of cable around a pathway 560.27756 foot long = 1417.5022 Pounds

If we operate in slicing mode we must calculate how much pull force T1 and T2 will be required to slice through the full

180 foot width of the cut with uniform pull at both T1 and T2 winches.

File: EarthSaw In-Situ Containment of Pits and Trenches, contract DE-AC26-01NT41144

Developed by Carter Technologies Co, Sugar land, Texas Ernie Carter, P.E. 281-495-203

Graphic Model of Earth block fracture during undercutting, Version 1.0 dated March 15, 2002

Note: This is only a preliminary graphic model for planning purposes.

See the detailed finite element model for actual stress calculations.

Stress is in force/ area =psi, Strain = change in length/original length
Stress/strain - elastic modulus

Plan View

- Horizontal fracture
- Uncut soil
- Cut bottom exposed to pressure
- Cable Saw
- End of fracture

- 180 Feet Length of block
- 200 Feet Width of block
- 35 Feet Thickness or depth of block
- 20 psi tensile strength of block
- 3,000,000 psi elastic modulus of block
- 127.00 Density of block, pounds per cubic foot
- 154.00 Density of grout, pounds per cubic foot
- 0.50 Feet of uplift buoyancy
- 0.04456 PSI of net upward force
- 110 Feet of cut progress at apex of cable
- 180 feet of cut progress at edges of block.
- Linear feet of block required to rise to equilibrium
- 25,004 sq ft Area exposed to uplift buoyancy
- 80222.45 pounds Uplift force
- 144000 sq in Area of applied stress
- 0.5571 PSI net upward Stress along horizontal fracture point

- 180 Length of block
- 200 Width of block
- 36,000 Total area of block
- 70 Length along center line remaining to be cut
- 10,996 Area of block not yet cut
- 25,004 Area of block already cut and exposed to buoyant force

fractures in soil and rock form along the lines of least principal stress. This is why deep oil well fractures are vertical and near surface fractures are horizontal. As we lift the block on one end, the forces along the sides are still compressing the block with about the same force as when the block is in undisturbed soil. If the soil has any cohesive strength, this will add to its resistance to vertical fracture. If it has no cohesive strength, it will deform to adjust to a new shape. In order to fracture vertically it must first overcome the preload placed on it by the grout. If the apex of the cut is 100 feet from the edge of the block and we raise it 6 inches, then we have a "beam" bending equation with one end of the beam free and the other end fixed. It seems the beam would be a sort of S bend according to the modulus of the soil or rock and the total strength of the beam.

A true catenary shape is complex and the actual shape will be skewed according to operating conditions so...

Assume that the catenary cut is shaped like half an ellipse. The area for half an ellipse is $0.5 \times 0.7854 (2 \times h \times w)$ where h is height and w is width. Assume that the half ellipse begins at the load frames and that w is the distance between the load frames and h is the the cable apex must travel along the centerline to complete the cut.

The uplift force on the apex of the cut is very large because it comes from the entire area cut so far and it is concentrated at the point just ahead of the apex of the cutting cable. This point is likely to experience horizontal fracturing ahead of the cutting cable as shown in the above sketch. If any vertical fractures develop they will extend tangent to this same point.

File: EarthSaw In-Situ Containment of Pits and Trenches, contract DE-AC26-01NT41144

Developed by Carter Technologies Co, Sugar land, Texas Ernie Carter, P.E. 281-495-203

Predictive model of grout preparation logistics. Task 2.33 version 1 January 28, 2002

151,226 cubic feet of grout required for task
 48,826 cubic feet of slurry trench excavation slurry
 1.20 Expansion factor for spoils
 1.50 Approximate tons of dry materials per cubic yard of final grout.
 5.00 Approximate gallons of liquid additives per cubic yard of grout
 12.0 trucks per day, bulk dry material, received and unloaded to silo
 200.0 tons of storage capacity on site

5,601 Cubic yards volume of grout required
 15.00 gallons of water required per cubic yard of grout
 8,401 tons of dry materials required
 28,005 gallons of liquid additives required.
 84,014 gallons of water required
 336.1 number of 25 ton truckloads of dry material required
 11.3 Days time required to make grout
 93.3 Number of 300 gallon tote tanks required
 5.5 Number of trucks to deliver tote tanks
 2170 cubic yards of spoils produced by excavation
 137.56 Number of truck loads to remove spoils off site
 24.00 Number of spoils disposal trucks loaded per day
 5.73 Time to remove spoils

Pereparation of the required quantity of grout to make the thick and homogenous barriers installed by the EarthSaw method requires making Large volumes of grout in a relatively short period of time. The quantity of grout required is simply the volume of the vertical trench plus the volume of the desired bottom barrier.

When excavating the vertical slurry wall we will need a volume of bentonite slurry smilar to the vertical trench volume.

Slurry for excavating the vertical wall sections would be made from a 5 to 6 percent bentonite slurry. This could be stored in oil field style "frac" tanks, which hold 2,800 cubic feet each, or more economically held in a small pond if site conditions permit.

The grout materials will be brought to the area by rail cars and transferred by trucks to large silos. The grout will be mixed in rotary mixer trucks of the kind used to deliver ready mixed concrete. The mixer trucks will first receive the liquid components of the grout and then will pull under the silo to receive the dry ingrediants. The materials will then be mixed while being taken to the site. A tremmi pipe will be installed on at least two opposite sides of the trench. This tremmi pipe will have a large funnel-like opening at the top and a 16 inch diameter pipe extending down to very near the bottom of the vertical trench. The concrete trucks will discharge directly into these pipes. If access is restricted the concrete trucks will discharge into concrete pumps which will transfer the grout to the tremmi pipes.

Production rates are limited by the dry material storage capacity in site,

The bentonite slurry displaced by the heavy grout will be pumped into tanks for disposal. In some cases it may be possible to reuse the slurry in the manufacture of the grout or other cap materials.

6.17 Vision 3D Computer Model Of Stress On Block

The Finite element analysis is not yet complete. Below is one of the initial model images.

Initial model generation in finite element analysis

7.0 What We Learned

- **Non-Rotating Cable Is Needed.**
- **Coefficient Of Friction Not Greatly Reduced By Grout.**
- **Friction Increases Exponentially with Angle of Contact**
- **Friction Is Not A Greater Problem on Larger Sites**
- **More Power and Stronger Load Frame Is Better**
- **Synthetic Liners May Be Pulled Uniformly By Cables**
- **Sawing Friction is very different from Slicing Shear**
- **Directional Drilling Friction Is Higher due to increased angle of contact**
- **Excel Visual Basic Program More Capable than Expected**
- **Buoyancy Can Be Predicted and Adjusted by Altering Depth, Surface Surcharge and Grout Density**
- **Soft Rock Can Be Cut By Standard Wire Rope Cable**
- **Limiting Buoyancy Minimizes Stress on the Block During A Cut**
- **Side Wall Spacer Restraints in the Vertical Wall Are Desirable**

7.1 Buoyancy Equations

In task 1 we started from basic principals and derived the formulas for buoyancy and showed that for the special case of “shapes with vertical sides and flat tops that float level”, the length and width of dimensions are not required. The vertical block method starts from a slurry wall that is always vertical even though the sides may be of various lengths and angles. In good practice, to obtain a uniform bottom barrier thickness, the top of the block would need to float level so the assumed “special case” would be typical of most projects. In the spreadsheet model the surcharge loading and depth of each corner of the barrier should be adjusted until the barrier is of uniform thickness. Note that if soil is added or removed from the top of the block, the top elevation on sheet “3-D” may no longer be the same profile as the barrier thickness shown on sheet 1.

Applying buoyancy equations to a large section of earth is complicated by the fact that the block may not have uniform density or depth. In some cases we may desire to make one corner lower to create a sump for liquids collection. In many cases, the soil strata at a waste site may not be of uniform density. Rock layers below the waste disposal zone would need to be included within the barrier and the interface between rock and soil may be tilted or irregular. In the case of the Los Alamos site the block of earth is very different in that the outer portion of the block is solid rock and the interior is made of crushed rock of a lesser density with various radioactive metal objects scattered randomly through it. The model addresses this by treating the volume of crushed rock as a waste container of specific density. The model assumes that waste is buried in the upper soil layer so we simply reverse them and enter the lower layer information into the spreadsheet as if it were the upper layer.

Calculating the proper design of a ship is made complex by many factors including the need to keep the center of buoyancy above the center of gravity to achieve roll stability. In most cases an EarthSaw™ block’s width and length are much greater than the depth, so roll stability is seldom an issue. A more significant issue is adjusting the dimensions of a block to keep it balanced. An unbalanced block may tip, and thus reduce the barrier thickness on one side. We can also reduce this risk by adding structural spacers in the form of a double I-beam to maintain barrier thickness from top to bottom.

Water table and soil type have a significant affect on many conventional excavation and grouting technologies. In task 1 we showed mathematically why the water table and soil type have minimal effect on EarthSaw™ buoyancy.

Some versions of the EarthSaw™ made with directional drilling, are intended to make a very large basin shaped barrier. The buoyancy formula shows that for a given density difference, the barrier thickness is directly proportional to the depth of the horizontal cut. The buoyancy formulas clearly show that as a basin shaped barrier slopes up to the surface, it would become thinner and thinner. This approach is improved by having at least a shallow vertical perimeter trench, so that the barrier has some minimum thickness at the edges. It should also be noted that the un-even buoyancy of these large basin structures could generate shear forces on large buried tanks. For this reason, the vertical

block method is preferred since it generates little if any internal stress on large multi-acre blocks.

7.2 Real World Friction Tests

Task 2 called for computer modeling of the EarthSaw™ method in a wide variety of conditions. An Internet search had failed to locate any data on coefficient of friction between earth materials and wire rope, so we planned to run some tests to develop this information. We investigated having research performed at a university lab but determined that too many factors had the potential to deliver questionable data. Data on friction between tires and pavement was typically generated by a “friction sled” being pulled along a road surface. We determined that the most accurate way to obtain data would be to build a friction sled using the nominal size of steel cable as the friction surface running against various soil types while immersed in various grouts.

A suitable sled was fabricated and friction tests performed. We found that friction values ranged from .5 to 1.0 of the normal load and remained steady through the load range. Surprisingly we found no proof that the grout functioned as a lubricant. We believe that this was because the contact loads on the rough cable surfaces were high and a portion of the friction was generated by moving soil particles. We found almost the same friction on concrete as in sand or clay. We also found almost the same friction wet or dry. Starting friction never exceeded 1.0 and sliding friction was never less than 0.5 in the tests. The molten grout held the most promise for reducing friction. However our test method for the molten grout was unsuccessful due to limitations of keeping the wax molten in small batches. We also learned that a significant component of friction can come not just from surface contact, but from the shear strength of the soil which must be sheared to move the cable forward.

We also tested large-scale direct shear with 1 inch diameter cable, pulled by dozers. We had expected that friction would be a function of the total curve angle but we were surprised that it was in fact an exponential function of the angle. We were unable to direct shear a 50 foot wide block of earth, due to lack of power, but we were able to direct shear a 25 foot wide area with ease. We also found that when hooking dozers to both ends of the cable and pulling, less force was required than when trying to saw back

and forth. We found that we were unable to stroke the cable in many situations. The mathematical model developed after this provided an explanation of this behavior.

We also learned that operating in directionally drilled holes can be difficult because the friction angle of the holes going down and then up, must be added to the 180 degree plan view friction angle. We also found that we need more pump pressure and perhaps a cementing plug to help displace drilling mud out of the hole. Our driller used a type of polymer mud that gelled on contact with our grout.

We learned that we should use a non-rotating type of wire rope to prevent the cable from twisting due to tensile load.

7.3 Load frame and Cable Pulling System

The analysis showed that placing the winch on top of the load frame provided the best and safest system. This change reduced system footprint and allowed us to safely use the full strength of the wire rope. Keeping all the stressed cable underground eliminated the need to have a safety factor in the strength of the wire rope cable.

As we looked at the data provided by the friction tests we determined that the load frame and pulling system needed to be more powerful. We beefed up the load frame design so that it would withstand a 150,000 pound pull with a safety factor of 4 to 5. We also realized that it might be desirable to be able to intentionally break the cable, if it were to become stuck on a sharp rock. The broken cable could be more easily pulled out by the winches and then the load frames could be removed, a new cable installed and the load frames re-inserted so that the cut could continue where it left off.

7.4 Fabrication Drawings of Load Frame

The design of the load frame was based on use of standard steel I-Beams as the main structural element. Eight I-Beams are welded edge to edge to form a cross-like cross section that can fit down into the intersection between two trenches. By adding many reinforcement plates, this shape is made very stiff and structurally rigid. We prepared all of the shop drawings needed to fabricate the load frames. This provided us with a way to perform a meaningful stress analysis on the structure. The Load frame is a very large steel structure. Development of the full shop drawings also allowed us to make an accurate model to help locate any flaws in the design.

A 3-D model of the load frame was fabricated by printing the load frame drawings from CADD at 1/12 scale on heavy paper as though the paper were steel plate and assembling the parts with scotch tape to simulate welded joints. The model helped verify that all the parts actually fit and that the design was structural stiff. Of particular importance is that

the pulley wheel be accessible for maintenance and that the grout would drain out of the unit as it is removed from the trench.

Paper model of load frame, 1/12 scale

7.5 Computer Model of Force and Friction

We discovered the mathematical relationship to describe the cable friction in an EarthSaw™ application and verified it with field data. The friction rises exponentially as the contact friction angle and the coefficient of friction increase. We were able to build a spreadsheet which displays a table showing how changing parameters results in stuck cables, or slicing on either side of optimal sawing conditions.

Our numerical analysis indicates that very large size barriers may be formed with this method. Maximum site size with 100,000 pound winches is limited to about 500 feet by 500 feet by total friction imposed by the friction due to the weight of the cable itself. It is of course possible to use winches that are more powerful and larger cable. This size limitation can also be avoided by reducing the coefficient of friction between the cable and the soil. The length of the cable running horizontally is the limiting factor. When the total friction exceeds the strength of the cable or the power of the winch the cable will be stuck. The friction factor is an exponential function of the angle of contact with the soil times the coefficient of friction. This factor defines the ratio of power lost to friction

due to the contact angle. The drag friction is the weight of the cable on laying horizontal in the ground times the coefficient of friction. This drag friction subtracts from whatever force remains after applying the friction factor and can cause it to fall below zero, indicating a stick cable.

Pounds Total Friction = $e^{\lambda\alpha} + W_h \times \lambda$ Where λ is the coefficient of friction and α is the angle of contact in radians, and W_h is the weight of the cable laying on the ground surface and in the horizontal cut.

300,000 pound capacity winch - Proposed 100,000 pound capacity winch

7.6 Computer Model of Buoyancy / Barrier Thickness Prediction

We developed a graphical spreadsheet model of describing almost any site by parameters and depth of strata change at each corner of a site. This model produces a three-dimensional graphic of the bottom barrier thickness and the final elevations that responds dynamically to user input. This model allows us to quickly determine the parameters needed to construct the desired barrier and then tells us how much material will be required. The model also calculates a host of other factors.

The finite element modeling of potential fracturing of the earth block is not yet completed but the preliminary analysis in the spreadsheet indicates that horizontal fractures are far more likely than vertical fractures and horizontal fractures would tend to relieve stress that before a vertical fracture can occur. Horizontal fractures ahead of the cable are a potential concern when working in rock. We want to avoid drawing the cable into a fracture area that could pinch and grab the cable, causing a stuck cable condition. Excess buoyancy is the factor creating this fracture stress. It is important to accurately predict the density of the earth block before cutting and to monitor the uplift of the block while adding grout, so that excess buoyancy is not produced.

7.7 Long Term Grout properties

We provide lab data to validate the performance of examples of the three main classes of grouts. We also describe in some detail how these properties interact with the design of the system. We learned that grouts, which appear to be lubricants in lab tests, might not actually reduce friction between a wire rope cable and soil under load. Further testing should be done to verify this relationship.

Lab testing of the TECT B grouts performed by Fugro indicates that permeability is approximately 1.9×10^{-8} cm/sec for field-cured grout excavated from the 1999 field test. Previous permeability tests on this same sample two years ago gave the same results. This data helps to verify that the permeability of a soft TECT B grout does not degrade over time.

TECT B grout recently made and tested had a permeability of 8.9×10^{-9} cm/sec. We expect that after curing in the ground that this permeability would be even lower.

TECT A grout and TECT W grout permeability is too low to measure in the ASTM test.

7.8 Cap Design and Integrity Measurement

The cap is the final step in barrier construction and allows for a great number of choices according to the specific environment and waste types contained. For DOE it is not enough that we can put in a barrier of verified quality, we must also be able to verify the continued integrity of the barrier year by year upon request. This verification capability must continue even if the maintenance were to be neglected for 20 years. We want to be able to come back and be able to verify that leaks have not occurred. In our analysis of the EarthSaw™ caps we discovered that is very difficult for electronic sensors to be reliable enough to achieve this goal. We will propose methods that do not rely on batteries or electronic components under the cap.

Another thing we learned in this study is that the best design for a cap is a matter subject to considerable speculation and disagreement. We believe that caps should be designed to last over 500 years under current conditions and that yearly maintenance should not be assumed.

One of the potential test sites which is very interested in the EarthSaw™ technology has the somewhat special condition of having water table levels above the bottom barrier. They have an actual site a block away with the same condition. This is a problem in that it makes it more difficult to evaluate some of the special air pressure based techniques made possible by an air-tight cap. However, it does allow us a highly effective way of evaluating the test site. We can simply lower the water level in the contained area and note if any water leaks back into the interior. Since the grout is much heavier than water, a rise in the water table level outside the barrier cannot affect the buoyant condition of the isolated block. Reduction of the water level inside the barrier however will reduce the

weight of the block and increase barrier thickness. This effect can be modeled easily by changing the water table value in sheet 1 of the spreadsheet model.

8.0 Health and Safety Aspects of EarthSaw™

EarthSaw™ Provides a means to contain legacy radioactive buried waste without exposing personnel to the hazards of excavating through the waste contaminated areas. Conventional “baseline” excavation methods and even high tech excavation methods such as those attempted at the INEEL Pit 9 are enormously complex projects requiring hundreds of workers to build and maintain special infrastructure. EarthSaw™ is designed for work at large sites up to 5 acres in size contained within a single continuous barrier. The probability of construction accidents is greatly reduced in EarthSaw™ because only a few people are required and most of the work is performed by standard construction machinery used in the slurry trenching industry. The number of on site man-hours to perform the work is a fraction of that required for other methods. In most cases, almost all of the work can be performed in a level D environment.

The technology does not utilize any high-pressure grout systems or dangerous chemicals. In well planned project where the extents of contamination are known in advance, none of the equipment or even the grout will contact contaminated material. If contamination is encountered it is buffered and coated by the viscous fluid grout material and is unlikely to be released as an airborne contaminant. Even if the barrier should unintentionally cut across soil filled with contaminated liquid, the hydrostatic gradient will prevent the fluids from contaminating the grout. Contaminated soil cuttings, which cling to the cable saw, may be detected quickly by periodic swabs of the cable. Most contaminated cuttings would become encapsulated within the grout at the bottom of the trench where the cable exits the horizontal cut.

During the vertical side excavation and the bottom horizontal barrier cutting process, it is not necessary to have any personnel near the work area except those operating the backhoe or the winch. The backhoe has an air-conditioned cab, and the hydraulic winches may be operated from a remote stand inside an air-conditioned trailer. However when the cutting cable must be replaced, or when the cut is completed, workers must again enter the work area to connect the crane hook to lift the winches and load frames back out of the trenches. The load frames are designed to allow easy decontamination while hanging from the crane to allow excess grout and wash water to fall back into the trench or onto a prepared wash pad. They are also made to rinse clean and drain while lying down with equal ease.

The cable saw cutting technology is performed by remote operators and all of the stressed cable is below ground. The grout materials are non-toxic by ingestion and present only a minimal hazards common to concrete mixing and delivery.

At no time could a worker ever enter a trench at the EarthSaw™ job site because the trenches are always filled with slurry or grout. If a worker should fall into a trench filled with 2.5 specific gravity grout, they would float with 60 percent of their body above the fluid level. In the special case of using the molten TECT W wax based grout, there is an additional thermal hazard. We plan to use the expanded metal covers over the trench at all times, as in standard slurry wall construction practice.

Slurry wall construction 30 feet deep on a levee. Spoils piled up along sides of levee.

Spoils produced from excavating the vertical wall in the clean perimeter may be evaluated for use in the top cap. For large volume barriers, the volume of material from the walls is small compared to the soil needed to build the cap.

9.0 Identification of Data Gaps

This investigation recognizes that there may still exist some gaps in data for a full understanding of this technology. One of these is Friction. In the beginning, we recognized the absence of field friction data as a modeling limitation. Friction tests performed in task 2 provided much needed data as well as demonstrating the importance of friction data. The coefficient of friction literally makes the difference between being able to make an EarthSaw™ cut and having a cable stuck in the ground. Many variables affect the friction of a cable. We were unable to experimentally verify that the qualities of the grout can in fact alter the friction. We were also unable to verify any difference between friction in “slicing” versus “sawing” modes of operation. We had expected to data to indicate the lubricity of the grout would reduce friction, but our results were inconclusive. We did determine that the coefficient of Friction probably be 1.0 or less in most cases. This data is sufficient to design site remediation.

There are still some longer term questions that we expect will can not answer with authority until the technology has been used several times. These would include:

1. **Can we reduce friction below 0.5?**
2. **What Is The Best Cap Design?**
3. **Can A Better Cable Be Built For Cutting Hard Rock?**
4. **Can The Coefficient Of Friction Be Reduced Through Grout Design?**
5. **How Can We Design Internal Sensors To Last 1000 years?**
6. **What Issues Will Be Of Concern To Regulators?**
6. **What Issues Will Be Of Concern To End Users?**

Appendix A - Supplementary Data On Cases To Be Modeled

Case 1 conditions are similar to the uranium burial ground at Paducah, Kentucky described below. We have obtained extensive data on the C-749 Uranium Burial Ground site at Paducah. Soil types and strengths above are based on a 3/6/91 boring log H221 at the northwest corner of C-749 - WMU2. and SWMU 2-17 in the center of C-749. Available data indicates a site approximately 200 feet square requiring a barrier at least 30 feet deep. The surface is described as flat, but drawings show a foot or two of contour for runoff. This can be pre-leveled. There are no rock layers and few large rocks. There are at least three wells which may be inside the interior of the site and go below the depth of the barrier. These would have their casings pulled back to a maximum depth of 30 feet and the area below 40 feet plugged with a cement plug. The soil at this depth is said to be relatively soft and well below the water table. Water table was 26 feet deep in August of 1979 and 6 to 11 feet below top of casing in August of 1996 and varies seasonally. We will use 10 foot as the water depth for the model. Standard penetrometer data indicate a range of 40 blows per foot with full core recovery, to 20 blows per foot with poor recovery. (Driving 1.375" ID x 2" OD split spoon sampler with 140 pound hammer dropped 30 inches) Description is Silty sand, poorly graded, no gravel. Pocket penetrometer strength is from 1 to 3 kilograms per square centimeter. The soil contains very few rocks but layers above this one have gravel and we may encounter gravel. We understand the burial area contains stacked steel drums of uranium turnings packed in various oils and solvents, including PCB oils. The drums have a bulk density of 114 to 226 pounds per cubic foot. The drums represent only 2 to 3 percent of the total volume to be contained so their higher density will not hinder the design. A detailed inventory of waste barrels with net weights is available to allow calculation of waste density. For modeling we will assume that two quadrants contain 2 per cent waste and the other 2 contain 4 percent waste by volume. The soil density is not precisely known yet, but is expected to be about 125 pounds per cubic foot. The disposed uranium represents less than ½ percent of the total mass of the soil volume to be contained. Density is not expected to vary in any predictable way by depth. The site is potentially subject to high magnitude earthquakes. The site contains mostly uranium turnings, and dust packed in metal drums. Some drums also contain some organic solvents such as TCE which could difficult to contain indefinitely. We could use a non-hardening TECT B grout with zero valiant metal exchange capacity to neutralize any TCE which reaches the barrier.

Following is a description from the ROD for the Paducah C-749 site:

The C-749 Uranium Burial Ground is located in the west-central portion of the plant north of Virginia Avenue and on the western edge of the C-404 Low-Level Radioactive/Hazardous Burial Ground. It encompasses an area of approximately 2,970 square meters. The C-749 Uranium Burial Ground was used from approximately 1951 to 197 for the disposal of uranium and uranium containing wastes. The exact depth of the buried waste is not known. Wastes were reportedly placed in trenches and then covered with soil. Occasionally, fires were reported as a result of oxidation of pyrophoric uranium metal, but no subsidence was observed resulting from potential volume reductions due to the fires. In 1982, the C-749 Uranium Burial Ground was covered with a clay layer and a vegetative cover. It has been estimated that 270 tons of uranium, 59,000 gallons of various oils, and 350 gallons of trichloroethene (TCE) were buried in this area. Most of the waste (which consisted of pyrophoric uranium metal in the form of machine shop turnings, shavings, and sawdust. Pyrophoric uranium metal was usually placed in 20,30 or 55 gallon drums and petroleum-based or synthetic oils were used to stabilize the waste. It is possible these oils may have included some polychlorinated biphenyl-(PCB) contaminated oils. Other forms of uranium, including oxides of uranium, uranyl fluoride solutions, uranium-zirconium alloy, slag, and uranium tetrafluoride were buried in smaller quantities.

CASE 2 is based on sites at Los Alamos, NM which are disposed in a soft but continuous rock known as volcanic tuff. Tuff is actually compressed volcanic ash and the samples from Los Alamos are soft enough they can be carved with a pocket knife and abrasively ground up by a steel cable moving across the surface. (about 500 psi) The sites are 600 feet long by 40 feet wide and the bottom would be set 25 to 30 feet below surface. The rock is quite permeable and bone dry at less than 10 percent moisture. The tuff is of low specific gravity and is said not to have many large cracks or fractures. Bulk density is 111 pounds per cubic foot. The ground surface is level and has only a few feet of soil above the tuff. One issue to consider is that the tuff breaks up into a very fine and very dry dust. This may have an effect on the viscosity of the grout in the cut, since we will be operating in a sawing mode. The site is subject to micro-earthquakes of magnitude 2, which are seldom felt by humans.

PRS 50-009 is an inactive waste site MDA at TA-50 that was used to dispose of un-contaminated classified wastes, inorganic chemicals, hazardous chemicals, and radionuclides from 1948 to 1974. Some pits contain large numbers of drums of depleted uranium waste. The majority of the waste is in a solid and inert an immobile form. Most of the pits and shafts are unlined, but some are lined with concrete. After each pit was

filled it was backfilled to ground level with crushed tuff. In 1984 the area was covered with 1.5 feet of tuff and then .5 to 3 feet of topsoil. Because of variable cover depth, some pit depths could be as much as 30 feet deeper than the stated depths. Due to this, we propose to model the site as 50 feet wide by 40 feet deep by 610 feet long. We propose to use a fiber reinforced TECT A hardening grout. The grout will have a nominal compressive strength of 2,000 psi.

Case 3 is modeled after the Pit 9 site at the INEEL site in Idaho. This site contains a large variety of unusual hazardous and radioactive materials including thousands drums of plutonium contaminated sludge and two prototype nuclear aircraft engines. Previous attempts to excavate and remove the contents of the pit were costly and unsuccessful.

Case 4 is modeled after one of the Hanford tank farms. These tanks contain highly radioactive sludge. There are ongoing plans to remove the sludge from the tanks some day. A barrier could be useful both before and after such a removal action.

Case 5 is based on the Oak Ridge Bear Creek Valley pits and trenches. ORNL has a large number of similar trenches which are a large and difficult problem.

Appendix B: Planned Subtask Elements

Following are the subtask elements originally planned for task 1 and task 2, the individual text documents as originally completed are reproduced in **Appendix** but are summarized and updated in this report.

TASK 1, Theoretical Proof/Derivation of Technical Approach

<i>Theoretical required Properties of Grout 1</i>	<i>1.03</i>
<i>Describe required Properties of Grout 2</i>	<i>1.04</i>
<i>Describe required Properties of grout 3</i>	<i>1.05</i>
<i>Quantitative derivation of the step-by-step process</i>	<i>1.06</i>
<i>Slurry trench perimeter excavation</i>	<i>1.07</i>
<i>Installation of load frame and cutting cable</i>	<i>1.08</i>
<i>Replacing slurry in trench with grout</i>	<i>1.09</i>
<i>Activating cutting cable</i>	<i>1.10</i>
<i>Adding additional grout to trench</i>	<i>1.11</i>
<i>Sealing surface of trench</i>	<i>1.12</i>
<i>Measurement of barrier thickness</i>	<i>1.13</i>

<i>Measurement of permeability of the barrier</i>	1.14
<i>Basic proof theorem on ideal soil/Derivation of buoyancy</i>	1.15
<i>Coil Condition 1 Cohesive clay soil with rocks</i>	1.16
<i>Condition 2 Clay with un-cohesive and permeable sand lenses</i>	1.17
<i>Condition 3 Non-cohesive sand</i>	1.18
<i>Condition 4 Silty clay with cobbles</i>	1.19
<i>Condition 5 Glacial till with flat rocks</i>	1.20
<i>Condition 6 Sandy soil with cobbles</i>	1.21
<i>Condition 7 clay with fractured shale</i>	1.22
<i>Condition 8 Volcanic fractured basalt flow under fine sandy clay.</i>	1.23
<i>Condition 9 Sandy soil underlain by karst limestone formation</i>	1.24
<i>Condition 10 Sandy soil containing debris filled with liquids.</i>	1.25
<i>Condition 11 River sediment with buried tank</i>	1.26
<i>Condition 12 Silty clay with buried drums and debris</i>	1.27
<i>Cutting in rock vs cutting in soil</i>	1.28
<i>Description of mechanical cutting process</i>	1.29
<i>Description of design requirements for Load frame</i>	1.30
<i>Selection of cable properties for modeling purposes</i>	1.31
<i>Description of base design requirements for cable Pulling means</i>	1.32
<i>Selection of pulling means for modeling purposes</i>	1.33
<i>Description of thermal management system for molten grout</i>	1.34

TASK 2

Computer Modeling

<i>Review existing computer modeling software for compatibility</i>	2.01
<i>Measurement of friction between wire rope cable and 3 soils and 3 grouts</i>	2.02
<i>Measure friction on 50 width cut in 1 soil with 1 grout</i>	2.03
<i>Lab test of fracture sealing properties of grout</i>	2.04
<i>Complete Detail drawings for load frame</i>	2.05
<i>Structural load modeling of load frame</i>	2.06
<i>Verifying final formulation of grouts</i>	2.07
<i>Carter Lab testing grouts to verify physical and rheological properties</i>	2.08
<i>Detail drawings for full cable path with pulling means</i>	2.09
<i>Independent Safety review of cable pulling and load frame system</i>	2.10
<i>3D model of System</i>	2.11
<i>Numerical predictive model development</i>	2.21
<i>Numerical Predictive Model Development</i>	2.22
<i>Selection of modeling software and personnel resources</i>	2.23
<i>Numerical predictive Modeling of grout quantity requirements</i>	2.24
<i>Numerical predictive Modeling of cable force and friction</i>	2.25
<i>Numerical predictive Modeling of cuttings transport</i>	2.26
<i>Numerical predictive Modeling of Thermal heat transfer in molten grouts</i>	2.27
<i>Numerical predictive Modeling of fracture sealing properties of grouts</i>	2.28

<i>Numerical predictive Modeling of buoyancy in 12 subterranean conditions</i>	2.29
<i>Numerical predictive Modeling of behavior with liquid filled voids</i>	2.30
<i>Numerical predictive Modeling of centering and stability forces</i>	2.31
<i>Numerical predictive Modeling of cable energy storage and wear.</i>	2.32
<i>Numerical predictive Modeling of grout preparation logistics.</i>	2.33
<i>Numerical predictive Modeling of earthquake response</i>	2.34
<i>Numerical predictive Modeling of grout shrinkage stresses</i>	2.35
<i>Numerical predictive Modeling of passive verification methods</i>	2.36
<i>Numerical predictive Modeling of plastic flow of soft grouts</i>	2.37
<i>Numerical predictive Modeling of groundwater buoyancy on barrier</i>	2.38
<i>Design drawings of basic airtight cap system</i>	2.39
<i>Numerical predictive Modeling of air-drying system</i>	2.40
<i>Numerical predictive Modeling of forces to move floating block</i>	2.41
<i>Numerical predictive Modeling of cutting speeds</i>	2.42
<i>Numerical predictive Modeling of Cutting cables running in HDD hole</i>	2.43
Submission of model outline with selected variables for DOE approval	2.44
Contracted computer modeling to develop integrated predictive model	2.45

See **Appendix J** located on the CD ROM for the text of each subtask report. Some items in this report will be identified as portions of the subtasks by presence of subtask numbers in parentheses after the heading.

Appendix C: Friction Test report

Document Title: Friction Tests (Subtask 2.02 and 2.03)

During the month of October 2001, we completed the friction tests called for in Subtask 2.02 and 2.03. The objective of the tests was to measure the coefficient of friction of a steel cable against the soil and also to measure the cutting force required to cut an actual 50 foot wide pathway through the soil and to obtain some field experience in cutting soil with the cable by the proposed methods. The tests were observed by representatives of Inquip Associates and MI Drilling Fluids.

The tests were originally planned to be at the Shell Westhollow research facility near the Carter Technologies Offices. To keep on our schedule we were forced to move the tests to the back lot of a building adjacent to the Shell facility. The building manager agreed

to allow the tests to be done and solidified grout left in the ground on site if we restored the level surface and covered the disturbed areas with clean sand. The site soils were a heavy waterproof clay having a 2.0 specific density.

We began the work by performing some basic drag tests with the friction sled on the

Friction Sled and Sandbags

ground surface. The friction sled is platform which rests on two five foot lengths of 1" diameter steel cable. The cables are turned up slightly on each end like runners on a sled and welded to the bottom of ¼ inch thick vertical plate which is much thinner than the cable and so does not touch the soil. This work done without any grout and used a mechanical scale rated at 5,000 pounds to measure the pull required to move the sled.

We tested the sled with loads of sandbags creating loadings of 200, 500, 800, 1100, 1500, and 1800 pounds. Reading the mechanical scale involved some judgment calls but the trend of the data made it clear that the coefficient of friction was at least 0.5 for sliding friction. We were not really surprised by this value for soil with no grout to lubricate it. The sled created 2" to 4" deep grooves in the ground surface at the higher loadings as expected. the 1800 pound loading over the 120 square inches of cable runner is equivalent to 15 psi contact load on the cable which is thought to be roughly comparable to about 9000 pounds of pull on a 50 foot wide cut in the ground.

Due to schedule pressures and limitations on the volume of grout available, we decided to install the directionally drilled holes and their pipes and cable assemblies first before performing the open trench test. Pulling the pipe/cable

Pipe and cable assembly being pulled into hole

Directional drilling

assemblies into the hole resulted in a 400 degree rotation of the assembly which concerned us very greatly since this could cause the carefully aligned cables to wrap around the pipe or each other. We attempted to untwist the pipe by reverse rotation but friction in the hole prevented this. We began pumping grout into both pipes, which were perforated midway, and waited to see flow of mud out of the holes. The grout was pumped by a vacuum truck which also delivered the grout ready to use. Surprisingly we noted little if any returns of drilling mud or grout at the ends of the hole. We later determined that we did not in fact displace the mud with the grout. This may have been due to the mud in

the holes being too solidified or the vacuum truck displacement pressure being too low. In the future all holes should be drilled with bentonite drilling mud instead of synthetic mud.

A curved trench 14 inches deep was made between the HDD hole positions and the 1" cutting cable pulled into position in it. The HDD holes were 50 feet apart. The trench was filled

with grout to the surface. We tested the density of the grout and found it to be 20 pounds per gallon. We also verified that chunks of the clay soil and limestone rocks would float in the open trench. We set up the wireless digital scales on each dozer and began to pull on the primary horizontal cutting cable. At first cutting was easy with friction values of 7,000 to 10,000 pounds. After three strokes the friction had risen to 16,000 pounds.

The dozers were unable to pull more than about 12,000 pounds consistently due to the relatively wet

surface soil. At this time we decided that we would need to have significantly more pulling

force to complete the tests. We ordered two larger D-6 dozers for the following day, which were said to be capable of over 25,000 pound pull. We also use the backhoe to cut a curved trench approximately 5 foot deep and 50 foot wide and fill it with the remaining grout so that we can release the trucks. We also decide that it is possible that the cables have twisted around the pipe or the other cables so we pull out everything but the primary cable for the horizontal cut to eliminate these variables.

Limestone rocks float on Tect B grout

Curved trench for direct shear friction test

The following day we began stroking the cable with the larger dozers. The first pull on the south side takes 24,000 pounds to begin and drops to 14,000 pounds sliding friction. Pulling the other side starts at 14,000 pounds and rises to 16,000 pounds. The south end the takes 25,000 pounds to reverse and drops to 20,000 pounds. This is repeated several times until we are not able to pull any longer due to lack of traction for the dozers.

We fabricated a section of cable into a sling and ganged both dozers together. This allowed us to pull with about over 30,000 pounds of force. This was capable of pulling the cable with zero load on the trailing end for about 6 strokes with no problem. Force ranged from 20,000 pounds to 30,000 pounds. We can tell from the variations in loading that the grout is not getting to the cable anymore and we are essentially cutting dry. Because of the increased load on the cables and our lack of a suitable swivel on each end the cable undergoes a twisting motion as it is stressed. When the dozer backs up to release the cable it twists into a kink and when it is pulled on the next time it breaks. In the future we should use the non-rotating type cable and or a suitable swivel between the dozer and the cable.

We have a three quarter inch cable in the open curved ditch. The ditch is filled with grout and the dozers and load cells are hooked up. The dozers begin stroking and have similar difficulties. The dozers pull at up to 25,000 pound loads but are able to cut only a few meters before the cutting plane rises above the grout and friction exceeds the dozer traction. The following day we divide the trench in half so that we are only cutting a 25 foot wide pathway. This cut begins with minimal friction and slices a wedge shaped section of earth loose from the

Dozers pulling in direct shear test

ground. The cut was made with a continuous pull by both one d-6 dozer and one small John deer 450 dozer pulling less than 10,000 pounds. This cut involved a slicing motion rather than a sawing action. The dozer tracked out onto this cut section and reversed, causing the floating section of earth to move several feet sideways. The 300 inch long width by $\frac{3}{4}$ " thickness of the curve in the cable implies a slicing force of (10,000 pounds)/ (0.75 x 300 inches) = 44.4 psi I ran a penetrometer test on the soil using a 0.25 inch diameter (.049 sq in) pocket penetrometer and found that it was well off the scale but estimated that 40 pounds provided enough weight to push it in 1/4 inch. The pocket penetrometer reads 4.5 tons per square foot at 18 pounds of load on a hard surface. This implies an unconfined compressive strength of 10 tons per square foot or 138 psi. My previous experience indicated that pocket penetrometer values may vary by a factor of 3 or 4 from that of true unconfined compressive tests.

The next day the other 25-foot-wide half-section of the trench was then tested using a sawing action with only the backhoe and the small dozer.

The friction values of leading and trailing cable tension for this work were as follows:

670/320 Pounds

1000/100

700/50

800/50

2300/40

2400/30

4700/200

3100/200

1200/60

2540/60

2540/40

2000/70

4000/100

1520/100

450/100

630/100

2370/300

3100/100

3450/100

6700/680

4370/100

Tect B grout delivery into curved trench

The cut was then modified to be a 270 degree loop instead of a 180 degree U bend. This was expected to increase friction by over 50%. After only a few strokes the dozer pull rises to 8,000 pounds. Unfortunately the backhoe could not pull more than 4,000 pounds so the test was ended. This tends to confirm the idea that the total friction will be a function of the total degrees of curve in the cutting line. The force in the wire rope perpendicular to the face of the cut is a function of the total angle of contact.

Calculations indicate that with a coefficient of friction of 0.5 the tension in the pulling line should be 4.81 times as high as the trailing line for a 180 degree arc and 10.55 times greater for a 270 degree arc. This can be expressed as:

$T_1/T_2 = e^{\lambda\alpha}$ where λ is the coefficient of friction and α is the angle in radians.

For cable cutting without lubricating grout it seems that the coefficient of friction may be higher than 0.5

I also performed many more friction tests with the friction sled in a trench. These tests did not indicate a significantly different frictional value for the grout filled groves. I believe this was due to the weight of the sled being able to fully displace the grout and then bite into the soil such that no grout was actually between the sled and the cable runner. We achieved some values from 0.3 to 0.8 but the majority of the tests gave a value between 0.5 and 0.6

Liner attached to catenary arc of cable

Based on this information we can see the importance of maintaining a supply of grout to

the cutting face. It is also important that the cable not pass around more than 180 degrees. In some applications such as soft soil we may not be able to achieve a reciprocation of the cable around a full 180 degrees. For example in our 50 foot wide cut test with a coefficient of friction of 0.5 the required load on the pulling end must be 4.81 times higher than the drag on the trailing end. For our 25,000 pounds of pull from the dozer we can tolerate a drag of no more than 5,197 pounds. The 500 foot cable itself weighs 2000 pounds and has an estimated drag on the trailing end of 800 pounds so the cable should be able to move. However if the coefficient of friction rises to 1.1 because of lack of grout in a fully plastic soil, the drag factor (T_1/T_2) will rise to: $T_1/T_2 = e^{\lambda\alpha}$ where λ is the coefficient of friction and α is the angle in radians. $31.6 = e^{1.1(3.141)}$ At this value 25,000 pounds will pull only $25000 \text{ Lb} / 31.6 = 789$ pounds of drag and motion will stop.

1" Steel cable used in the test

It is useful to note that even if we were in fact stuck with the higher coefficient of friction we could still make the EarthSaw™ process work by adding a third load frame with a pulley which reduces the cutting cable's total radians of contact with the soil. At 0.5 radians (90 degrees) and a coefficient of friction of 1.1, the drag factor drops to 5.6 and the 25,000 pounds of force would be able to pull 4,441 pounds.

If the directionally drilled portion of the test had been more successful, we were prepared to evaluate pulling a synthetic liner through the grout. A local liner manufacturer, SLT, provided a roll of liner material and a crew to assemble it at no cost to the project. They seamed two sections of liner making a 44 foot wide sheet and cut it into tabs to fold over and fit a catenary arc of $\frac{3}{4}$ inch steel cable. Test pulls were then made with the dozer to verify that the liner could be uniformly pulled by cables along the edges. This work indicated that it may be feasible to drag a liner sheet under a floating block, using the same cable arrangement used to cut the soil. The catenary arc evenly distributes the pulling loads along the leading edge of the liner material, allowing it to be pulled uniformly.

Appendix D:

Excerpt from USDA guide to pulling underground cables
See the CD ROM for full copy of report

UNITED STATES DEPARTMENT OF AGRICULTURE

Rural Utilities Service

BULLETIN 1751F-643

SUBJECT: Underground Plant Design

TO: All Telecommunications Borrowers

RUS Telecommunications Staff

EFFECTIVE DATE: Date of Approval

EXPIRATION DATE: Seven years from effective date

OFFICE OF PRIMARY INTEREST: Outside Plant Branch, Telecommunications
Standards Division

PURPOSE: This bulletin provides RUS borrowers, consulting engineers, contractors and other interested parties with information on the design and construction of underground plant facilities. CFR Part 1753.6, Standards, Specifications, and General Requirements.

11.3 The factors that should be used in determining the lengths of copper cables that may be safely installed in conduit systems are as follows:

- a. Cable size and conductor gauge;
- b. Maximum pulling strain allowed on conductors;
- c. Cable pulling method (pulling eye or basket weave grip);
- d. Number of bends in conduit system;
- e. Bend radii;
- e. Bend radii;

- e. Bend radii;
- e. Bend radii;
- f. Bend angles;
- g. Coefficient of friction; and
- h. Cables pulled dry or lubricated.

11.4 Equation #1 listed below should be used for calculating maximum pulling tensions of copper cables equipped with factory installed pulling eyes:

$$T = ANK \text{ (Equation \#1)}$$

Where:

T = Maximum allowable pulling tension in pounds (lbs) [kilograms (kgs)].

A = Cross-sectional area of copper conductors in circular mils [square millimeters (mm²)].

N = Number of conductors terminated in factory installed pulling eyes. Typical all conductors in cables are terminated in factory installed pulling eyes.

K = 0.008 lbs/circular mils (7.2 kgs/mm²) for copper.

11.5 After calculating maximum pulling tensions of copper cables, maximum allowable pulling lengths of cables should be calculated using equation #2 listed below:

$$L = T/Wf \text{ (Equation \#2)}$$

Where:

L = Maximum allowable pulling length in ft (m).

T = Maximum allowable pulling tension in lbs (kgs).

W = Cable weight in lbs/ft (kgs/m).

f = Coefficient of friction for type of conduit used in installation.

11.6 Another factor that should be considered in calculating cable pulling tensions is the number and effects of bends in conduit systems. For conduit systems containing bends, pulling tensions of copper cables should be calculated on cumulative basis using equations #3 and #4 listed below:

$$T = LWf \text{ (Equation \#3)}$$

$$T = T_1 e^{fa} \text{ (Equation \#4)}$$

Where:

T = Pulling tension in lbs (kgs).

L = Cable length in ft (m).

W = Cable weight in lbs/ft (kgs/m).

T₁ = Accumulated tension to start of bend in lbs (kgs).

e = Naperian logarithm equal to 2.718.

f = Coefficient of friction for type of conduit used in installation.

a = Bend angle in radians (1 radian = 57.3 degrees).

11.7 Another factor that should be considered is the maximum allowable sidewall pressure. Sidewall pressures are radial forces exerted on cable sheaths at bend points when cables are under tension. Sidewall pressures at bend points should be calculated using equation #5 listed below:

$$P = T/R \text{ (Equation \#5)}$$

Where:

P = Sidewall Pressure in lbs/ft (kgs/m).

T = Pulling tension in lbs (kgs).

R = Bend radius in ft (m).

The maximum allowable sidewall pressure for copper cables should not exceed 100 lbs/ft (149 kgs/m). In conduit systems containing multiple bends, the last

bend in the system would develop the greatest sidewall pressure on the cable. Therefore, during the design of conduit systems, bends with the severest radii

Permeability Lab Test Reports

Sample 008 was for the TECT B grout made during this year. Sample 009 was an archived sample collected during the excavation of the bottom barrier formed in the 1999 field test. The samples of TECT A were also tested but were of too low a permeability to measure in the ASTM test.

Appendix E Permeability and Rheology Lab Test Reports

Report No.:	0401-1440	April 30, 2002
Material:	Soil Samples	
Client:	Carter Technologies Company	
Project:	Carter Technologies Company	
Sampled By:	Client	
Attention:	Mr. Ernie Carter	

HYDRAULIC CONDUCTIVITY

ASTM D 5084

Sample Identification

	1008	1009
Hydraulic Conductivity (cm/sec)	8.9E-09	1.9E-08
Initial Water Content (%)	13.4	18.1
Final Water Content (%)	12.6	16.0
Initial Dry Density (g/cm ³)	2.459	2.669
Final Dry Density (g/cm ³)	2.526	2.762
Final Degree Saturation (%)	100	100
Total Back Pressure (psi)	46	46
Maximum Effective Stress (psi)	4	4
Hydraulic Gradient	28	29
Intrinsic Permeability (cm ²)	9.1E-14	
Volumetric Water Content (cm ³ /cm ³)	0.331	0.483
Inc.	Fugro South,	
Manager	Bill DeGroff Laboratory	

Rheology results from TECT B Grouts, supplied by MI Drilling Fluids

Rheology

Lab Number	20020740	20020741	20020739
Type	Tect B	Tect A	Tect B
Other	White Cap	Black Cap	Green Cap
Data	Silver Cont	Sand	Gallon
Brookfield	1,302,000	Complete solid	528,000
API	6 not done		9
			9 cc out of 400 cc

Rheology results from TECT B Grouts, supplied by MI Drilling Fluids

Lab Number	20020738	20020737	20020742
Type	Tect B	Tect B	Tect B
Other	Blue Cap	Quart	Field
Data	Gallon	Tackle	Aged Blk cap
Brookfield	320,000	No Measure as could not be reconstituted	1,150,000 Note that unstirrable added 17 cc water before testing
API	10	0	11

Rheology results from TECT B Grouts, supplied by MI Drilling Fluids

Rheology

	600
	300
	200
	100
	6
	3
Brookfield	
PV	
YP	
Gel 10"	
Ge; 10 '	
API	

Appendix F: Questions and Comments from EPA

Following are questions and answers about EarthSaw™ from a recent e-mail discussion with and EPA representative. We solicited questions that regulators might ask.

Thank you for your responses. I will try to answer your questions one by one. Your question will be in smaller italic font:

In the video, you claim only 1×10^{-6} cm/sec permeability for the grouts. This was the permeability of the liquid TECT B test grout used in the first proof of concept test. It was not intended to be a low permeability material but was formulated to be cheap and easy to work with. After six months of curing however, even this test grout was 10^{-8} cm/sec permeability. Typically a TECT B grout would be less than 10^{-7} permeability during installation and cure to 10^{-8} or lower. One great virtue of TECT B grouts is that they remain deformable and flexible after curing.

Is it the same for all three grouts?

TECT A grouts on the other hand have not ever been measured for permeability before hardening. After hardening, they vary from 10^{-8} to 10^{-11} permeability according to application. The molten wax based TECT W grouts are too impermeable to be measured by ASTM methods but are estimated to have a value of about 10^{-12} to 10^{-14} cm/sec. These wax grouts are malleable down to 50 degree F temperatures and will only dent when struck with a hammer.

How was the value determined? The value was determined by the Fugro South Inc. soils lab using the ASTM test for soil permeability.

Are the grouts customizable on a site-specific basis? Yes they are. We can tailor the grouts to have specific properties of strength, plasticity, permeability, density, and chemical resistance.

Is a less-permeable grout available for critical applications? Yes, as stated above we can provide grouts with very low permeability. The molten grout is also available in a polyethylene version which is less malleable but equal more chemically resistant. In some applications we may be able to install a synthetic bottom barrier liner in addition to the grout.

Why is it necessary to install such a thick layer of grout? Would a thinner amount provide adequate containment (and minimize damage to the sides of the buoyant block)?

The thickness of the bottom barrier is at the customers option. We think thicker is better because the barrier should be thicker than any gravel or cobble which is in the plane of the cut. Cobbles that are on this cutting plane and wind up in the barrier thickness may not be as impermeable as the grout and thus may create a leak path. A thick barrier also makes it easy to verify the barrier thickness as the rise in the block is visually apparent. The vertical side walls need to be at least the minimum thickness required for the slurry trenching equipment. This is nominally 24 inches for depths from 30 to 50 feet. For 20 to 30 foot depths they can be as narrow as 14 to 18 inches.

How long is the grout expected to maintain its engineering properties? All grouts are designed to maintain their properties for 1000 years in underground conditions. This is based on natural analogs theory but the thickness of the grout layer is also a factor.

How is the grout made to cure? Is an additive required, or is it simply a passage of time? If it is time-dependent, what is the amount of time needed? In the EarthSaw™ process the grout must remain liquid during the process of cutting the bottom pathway. This can take hours or weeks depending on conditions. The TECT A grout is cementitious chemical formation of silicates and has a special retarder additive to delay setting up to 8 weeks. The molten Wax based TECT W grout cures by cooling below 125 degrees F. When the cut is complete, we will stop adding heat and the grout will solidify within 2 weeks. We stop heating the bottom layers first to make it solidify from the bottom up. The non-hardening TECT B grout is more complex. The "curing"

process is the clay in the grout reaching a more complete state of hydration and partly a result of the water in the grout coming into vapor phase equilibrium with the surrounding soil. This process can take several months to occur. The grout is tailored for a given set of ambient soil humidity conditions by adjusting the vapor pressure of the water within it. This allows us to design a grout which will remain soft and moldable even if the soil is somewhat dry. We can also add cementitious hardening agents to the TECT B grout to make them harden faster or develop significant strength, but this will increase permeability slightly.

Has this technique been applied at a site with contaminated soil? (other than the test plots you describe)? No, It has only been applied at the two blocks of clean soil on the test site in Liberty, Texas.

What is the largest application to date? It has only been applied at the two blocks of clean soil on the test site in Liberty, one was 8' by 14' and the other was 10 foot square. A friction test was performed cutting a pathway 25 feet wide, but it was not intended as a demonstration. In phase 2 of the NETL project we plan to do a block 50 foot square and 30 feet deep.

What is the amount of time necessary to drag a cable through rocky soil? This of course depends on many factors, such as the frequency and size of the rocks, the bearing strength of the soil, the winch power available and the width of the cut. If the soil contains an average of one bowling ball size rock per cubic foot we would not attempt the project without a diamond cable saw. We are also not ready to work in hard rock at this time. One of the slower cutting sites we have contemplated is in the compacted volcanic tuff at Los Alamos, NM. This rock is similar to sandstone and the cut will be 625 feet long and 50 feet wide. With the 100,000 pound pull winches and 1" cable we expect that it will take between 125 and 250 hours to complete the cut. We might have to replace the cable during the cut if it breaks or begins to wear. The cutting work would probably continue round the clock. Other sites such as a 200 foot by 200 foot square wet saturated sand could be cut using the slicing mode in less than an hour.

What maintenance is required of the finished project? Is the grout protected with any covering? The grout must be protected by a covering. This design depends on the type of grout used and the hydrologic conditions and waste forms present. Generally we believe that the cap should consist of a synthetic liner keyed deeply into the vertical perimeter wall and an cover of earth. An concrete armor layer over this with irritant type bio-intrusion materials (such as a proprietary composition containing sulfur, alum, pepper, soda ash, and Fullers earth) and a second synthetic liner would be covered with an earthen cap doped with the same bio-intrusion materials. The cap may optionally have a type of built in passive pressure sensing to monitor vault integrity.

During a multi-segment application, do you anticipate two directionally drilled holes at the interface of each segment, or can the first one be reused? The multi-segment HDD approach shown is an artists conception and varies from our actual plan. Actually the

same hole is used for cuts on both adjacent panels so the adjacent panels are inherently joined to each other. After the HDD hole is drilled a pipe with several non-crossed cables strapped to it is pulled into the hole. One of these cables is used to pull the first cutting cable into position. This HDD method is not the method proposed for the NETL work.

What are the size limitations of the technique? Generally the bottom cut will preferably be located below the depth of contamination and the perimeter trench will be outside the limits of contamination so that no contamination is ever exposed. The Vertical block method appears to be suitable for sites up to 300 feet wide and perhaps 600 feet long depending on soil conditions and cable saw hardware power. Depth may be up to 80 feet with common slurry trenching equipment. The block of earth can be rectangular but may also be irregular 3, 4, or 5 sided figures. The HDD method is intended for much larger sites but is not as fully developed as the vertical block method.

What is the thickness (or thinness) limitations of the soil layer involved in the technique? The actual horizontal bottom cut is made by a one inch diameter steel cable. If the cable is operating in sawing mode it removes one inch of soil, if it operates in slicing mode, no soil is removed. The buoyancy of the grout expands this thin cut to any desired final thickness, such as 3 feet. The bottom cut may pass through bedded layers of soil and shale or over and through some rocks. The bottom cut may optionally be made to be deeper on one end or corner to create a sump.

How are the sides of the elevated block sealed? Do they spall and fall into the grout while curing? How can this be prevented? Many soil types will slough off after prolonged exposure. Soil which falls in the grout before the cap liner is installed will float on top of the grout and is not a problem. As soon as the block is in final position, the sides of the elevated block are covered with the HDPE liner which covers the entire block and is keyed deep into the perimeter trench. A concrete cap layer may be placed in the top of the perimeter trench above the liner. In some cases spacer I-beams may be inserted into the trenches below the cap to prevent tipping movement of the block due to differential surface loading while constructing the cap. See the discussion of caps above.

What ambient conditions are required to implement the technique (weather, etc?) Personally, I prefer no rain, sleet or snow as this hampers general operations. Freezing weather makes any outdoor construction work more complicated. Wet weather makes earthmoving difficult but there are no special issues. The molten wax method is preferably done in hot weather.

What are the effects of encountering the water table with the technique? The presence or absence, or the rise and fall of the water table makes no difference at all other than its obvious part in calculating the total initial weight (density) of the soil block that you plan to float. The grout is always significantly more dense than the soil. The grout seals the surface of the soil and exerts hydrostatic gradient force against it so the ground water can never enter the dense grout. A rise in external water table can have no effect on the

buoyant condition of the block once it is floating in the grout.

What soil types are poor candidates for this technique? Can overconsolidated soils be treated this way? Poor candidates would include rock that is too hard to cut with steel cable, hard clay soil filled with boulders or cobbles so densely that the cable cannot pass around them. If by overconsolidated you mean hard dirt, the answer is yes if the friction calculation indicates sawing mode to be possible. Use of special friction reducing grout may be needed in sites less than 60 feet wide. Wider sites are easier to saw.

Are some soils (like glacial till) impossible to pass a cable (or directionally drill) through?

As previously stated if the rocks are large compared to the cable diameter and there are lots of them and the soil holds them firmly this can make it too difficult to cut. Some areas described as “glacial till” such as the area surrounding the Fernald site in Ohio look to me like silty clay with a lots of dinner plate sized flat hard rocks. We excavated a 14 foot deep by 2 foot wide and 14 foot long hole and found about a hundred rocks. I believe we could operate the vertical block method without a problem because the rocks are laying horizontal and there is plenty of space between them.

What are some typical costs of the installation and maintenance of the system? The cost for DOE sites is probably 2 to 3 times that of industrial sites. We estimate that a 2 acre DOE site 40 feet deep will be on the order of 40 million dollars. Once the cap is complete it maintenance would consist of collecting pressure data on a regular basis from the passive monitoring system, caring for any vegetation planted there, and preventing deep rooted plants and trees from growing there.

<http://www.epa.gov/ORD/SITE/>

We find your idea intriguing, and will keep all of the information you shared with us confidential.

Please reply with any questions.

David Carson
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National Risk Management Research Laboratory
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Appendix G: Contract Scope of Work – Tasks 1 and 2

The following is an excerpt from the contract defining the Scope of Work:

The objectives of this study will be conducted under a phased approach as follows: Phase 1, complete theoretical proof/derivation to support the buoyant barrier approach, and complete predictive modeling with simulated waste area conditions to analyze the robustness of the technology; and Phase 2, conduct controlled field-scale testing. This latter objective will permit field-validation of the technical approach of the EarthSaw™ barrier technology; enable an engineering analysis of the constructability and functional performance of the barrier; and gather data to complete a life cycle cost and performance analyses of the EarthSaw™ barrier technology.

Phase 1 - Task 1.0 -- Theoretical Proof/Derivation of Technical Approach

The objective of this task is to provide the physics and engineering derivation/computations for proof to support the buoyant barrier technical approach. The Contractor shall conduct quantitative derivation of the step-by-step barrier installation process to support the theoretical basis and proof using the EarthSaw™ approach to contain waste areas. The derivation must be robust enough to accommodate variable subsurface conditions in which containment barriers may be utilized; these may include, but may not necessarily be limited to, the following conditions: variable host media (e.g., variable lithologies such as unconsolidated sediments and bedrock); variable hydrologic conditions; host media with discontinuities such as complexly interbedded sediments, highly bedded strata, fractured bedrock, and others; and waste areas with variable geometries, dimensions, and waste materials. Results shall be used for Task 2, and also included in an Interim Report that is to be submitted to the DOE COR for review and comment within 10 days after completion of Task 2.

Phase 1 - Task 2.0 -- Predictive Modeling of Installation of Containment Barriers in Simulated Conditions

The Contractor shall perform predictive modeling with computer modeling software to simulate installation operations required to construct the containment barrier using the EarthSaw™ technology. The model must be robust enough to simulate a variety of subsurface conditions in which containment barriers may be utilized, as well as the step-by-step process for installation of the buoyant barrier with the EarthSaw™ technology. A minimum of three different cases, defined by variable subsurface conditions and waste areas, shall be modeled. The modeling must be robust enough to simulate the following conditions: variable host media (e.g., variable lithologies such as unconsolidated sediments and bedrock); variable hydrologic conditions (e.g., near-surface water table); host media with discontinuities such as complexly interbedded sediments, highly bedded strata, fractured bedrock, and others; and waste areas with variable geometries, dimensions, and waste material contents. The selected model, as well as the variable subsurface parameters for the three different cases, shall be submitted to the DOE COR for approval prior to initiation of the modeling. Results shall be documented in an Interim Report that is to be submitted to the DOE COR for review and comment within 10 days after completion of Task 2.

Appendix H: Comparison to Other Barrier Technologies

Deep Vertical Wall to Natural Clay

One traditional method of getting a bottom barrier is to make a perimeter barrier as deep as need be to find a natural barrier layer. The problem with this is that there may be layers of fractured rock between the surface and that barrier. Another problem is that vertical barriers tend to be more imperfect as they go deeper and the volume of contaminated soil becomes ever greater with depth.

Horizontal SoilSaw

The Horizontal SoilSaw uses high pressure jetting to carve a horizontal pathway through the ground. Adjacent horizontal panels are inherently connected and large multi acre basins can be constructed. Barrier panels can be up to 12 inches thick. The method requires a great deal of energy (1500 horsepower) to operate, highly skilled oil field workers, and million-dollar high-pressure equipment. The method creates large volumes of spoils equal to twice the volume of the barrier in soft soil and more in hard soil. The method can work above or below the water table. Ability to deal with rocks is limited to widely spaced 6 inch cobble and cutting in solid rock is not possible. The method requires lots of room on at least two opposite ends of the site.

Block Displacement Method

This method was developed for coal mining and uses injected pressure to create horizontal fractures and to force a block of earth upward. Cutting and sealing the perimeter is difficult. The thickness of the barriers formed is erratic and limited to a few inches unless the perimeter is sealed. Unlike the EarthSaw™ this method does use pressurized grout so random fractures up into the soil block can occur. The pattern made by the fractures is uncertain and may overlap in a way to leave a pathway through the barrier. Geological features such as sand lenses and layers of harder material can defeat the method. Hydro-fracturing is a subset of this method, which suffers from the same problems of lack of control and lack of monitoring means. Hydro-fracture barriers are typically less than a half-inch thick.

Jet Grouting

Jet grouting has been used extensively to make side and bottom barriers around areas to be excavated. The method often leaves small pinholes that must be manually plugged as they are uncovered during excavation. The defects are due not only to mechanical positioning but to hard spots in the dirt that resist disintegration by the jet blast. The most effective method is a circular ring of vertical columns with short vertical overlapping columns at depth making up the bottom. Another approach is to use angled columns to make a V shaped floor but this is much more difficult to maintain accuracy on. This method also makes a very large volume of waste spoils perhaps twice the volume of the barrier.

Horizontal Jet Grouting

In this method horizontal directionally drilled holes are pre-drilled and logged before jet grouting to bridge the distance between holes. This method can also be defeated by the occasional lump of hard dirt or a rock that produces a “shadow” to protect an area from the jet blast. This method is very useful for subway construction and normally requires lots of room around the perimeter of the site to dig access pits. This method also leaves some holes on occasion that cannot be detected except by excavation.

Freeze Barriers

Freeze barriers work by drilling many holes on a precise pattern to create a V shaped framework. Refrigeration lines inserted into these holes freeze the water in the ground to form a barrier made of frozen soil up to ten feet thick. The method can form barriers that can stay frozen for months after the power is off. Complex systems are needed to verify that all of the chilling tubes remain functional all the time. The method should work well in homogenous soil conditions. The system can potentially be defeated by lenses of dry waterproof soil or by certain natural structures that have the character of a pipe through the barrier zone. The method provides no permanent protection without regular maintenance.

Dry Air Barriers

Dry air barriers require that a grid of horizontally drilled holes of uniform spacing pass under the waste site. The holes are completed as vacuum point wells and are used to draw all the moisture out of the soil within the grid. The method is limited to relatively tight and dry formations. Lenses and stringers of permeable and non-permeable soils can cause difficulties, but the system may be made robust enough to cover gaps. Pipe shaped structures can defeat the system.

Permeation Grouted Barriers

Permeation barriers made with low viscosity grouts such as colloidal silica or polyacrylamides can be used to bridge the gaps between injection points. To get the materials to the area below the waste, directional drilling or slant hole drilling methods must be used. One problem is that the injection pipes must still be quite close to one another and variations in soil permeability can make the grout flow where it is not needed. Verification of the barrier is difficult. Success can be often achieved by using three layers of horizontal injection patterns to flood an area three times as thick as the spacing between pipes.

RAHCO Method

The RAHCO Subsurface Barrier Containment System is a remote controlled mechanical excavating system. The system requires large excavations on all four sides of the site making the site into a large mound. Elaborate mechanical equipment is placed in the excavation that operates a powerful rock cutter to carve a foot thick pathway under the mound. After advancing a few feet, the machine pushes a series of concrete blocks into the cavity it has hollowed out. Another mechanism cuts off a narrow strip of bentonite-backed polyliner and lays it very precisely on top of the blocks. When the next strip is

laid down, it overlaps the first one by several inches. After the machine passes, the earth is allowed to subside down on the polyliner strips pressing them together. After the machine has passed under the entire mound, it is removed and the sides of the mound are wrapped with polyliner. The trenches are backfilled with concrete.

It seems that these trenches must remain dry so this limits application, as does the requirement to dig the trenches in the first place. If the machine encounters contamination or perched fluids in the middle of the crossing, it is unclear how to recover. If the cutter head machinery hangs up while it is under the waste site in a contaminated environment recovery could also be very costly and expose workers to waste or require them to go below ground level. Relying on a 40 mil layer of bentonite clay to seal polyliner strips also seems to be a weakness in the design. Organic liquids can degrade bentonite. Controlling the precise positioning of these loose strips could be a problem. Gravel or sand or mud may fall in between layers. It is not clear if the system could work in sticky or saturated soils.

Micro Tunneling

Micro tunneling is a large-scale version of directional drilling that allows large tunnels lined with pipe to be placed accurately under a site. The idea here is to place the tunnels so close together and precisely parallel that a secondary group of tunnels can go in-between them and create a continuous floor. This method has merit for sites where we can be sure that we are working below contamination depth. This method also has a problem when it encounters contamination under the site. The volume of spoils produced by this process would be quite large and the access pits on either side would have to be large.

Jacked Microtubes

Small tubes or large rectangular cross section tubes can be jacked horizontally from a pit on each side of the site, to pass under the site. The issue here is keeping the pipes parallel and sealing between them. A jet grouting lance is passed along the length of the intersection to seal the leaks. Control and measurement of performance is again the issue here. This method makes an imperfect barrier and then attempts to seal the joints. There is no obvious way to tell where the leaks are and verify they are sealed. The long term performance of steel as a barrier material is also open to questions. If the pipe hits a big rock or hard soil, it may push away from its intended path.

EarthSaw™ Buoyant Barrier

EarthSaw™ addresses the problems of hitting unexpected contamination more gracefully than the above methods. Contaminated liquids are kept in check by hydrostatic force of the grout so that they cannot contaminate the grout. Particles of the soil removed may get into the grout but the grout itself is able to encapsulate the particles, and in some cases it may also have treatment properties. In addition, EarthSaw™ recovers from mechanical breakage by allowing all hardware to be removed and re-installed quickly without any . The installation process does not require personnel go below ground level. The

EarthSaw™ perimeter trench may be as narrow as the excavation equipment can make it and no dewatering of the soil is required.

The EarthSaw™ is a positive mechanical cut and passage of the cutting cable physically verifies the continuity of the barrier. Forgotten pipelines and conduits are physically cut by the abrasive cable and are automatically filled with grout. EarthSaw™ requires very little perimeter space around the site to be contained. EarthSaw™ barriers are of measurably uniform thickness up to 3 feet thick. EarthSaw™ barrier materials made of deformable soft grouts adjust to earth movements from earthquakes and subsidence. A wide range of grout formulations is available for diverse applications. Barriers in a wide range of shapes and sizes up to 5 acres and 90 feet deep may be formed in a single cut. EarthSaw™ is expected to perform best in soft soil and soft rock. Eight-inch cobbles may be tolerated if not too densely spaced. EarthSaw™ can tolerate only a limited 3 to 5 foot elevation change from one end of the pit to the other. EarthSaw™ has the potential to work in hard rock but only after development of new abrasive cutting cables.

EarthSaw™ Benefits Summary

- Reliable technology, mechanically simple and low tech, easy to understand
- Reduced costs, perimeter barrier costs less than treating entire volume
- Accelerated closure, construction is fast and less characterization required
- Assured closure, airtight enclosed vault facilitates continual verification
- Reduced worker exposure, waste is never uncovered, exposed, or touched
- Prevents the spread of contamination, continuous side and bottom barrier
- Flexible barrier, “TECT B” grouts deform with earth movement, remain flexible
- Chemical treatment, long-term chemical treatments can be applied inside the vault

End of Interim Report on Task 1 and 2

Appendix B: PHASE II FIELD-SCALE TEST PLAN

CARTER TECHNOLOGIES CO.

EarthSaw Controlled Field-Scale Test Plan

Draft Revision 4

DOE Contract No. DE-AC26-01NT41144

National Energy Technology Laboratory

United States Department of Energy

Research and Development Test of
EarthSaw Containment of Pits and Trenches
at
Paducah Gaseous Diffusion Plant
Paducah, Kentucky

Prepared By:

Carter Technologies Co., 9702 Garden Row Dr, Sugar land, TX 77478

July 12, 2002

Ernest E. Carter, P.E. , Principle Investigator

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Gary Bodenstein, P.G. DOE Ground Water Program Manager

Table of Contents

1.0	INTRODUCTION
1.1	Technology Description
2.0	OBJECTIVES
2.1	Success Criteria
3.0	DESIGN AND ENGINEERING CONTROLS
3.1	Cable Saw Cutting
3.2	Planes Of Weakness And Structural Strength Of Block
3.3	Adjusting Buoyancy In Variable Strata
3.4	Compensating For Dished Bottom Or Large Voids
3.5	Grout Functions
3.6	Grout Material Selection
3.7	Functional Requirements Of The Cap
3.8	Cap Design Factors
4.0	TEST SITE
4.1	DOE Site Interest And Final Selection
4.2	Conditions at selected site
4.3	Proposed Grout
4.4	Disposal Of Excess Soil And Water
5.0	ONSITE CONSTRUCTION OPERATIONS
5.1	Contract Negotiation with PGDP
5.2	Pre-mobilization Work
5.3	Subcontractors
5.4	Mobilization
5.5	Preparation of Block Defects
5.6	Monitor Well Installation
6.0	BUILDING PERIMETER SLURRY TRENCH
6.1	Excavation Spoils
6.2	Wire Rope
6.3	Making Bentonite Slurry
6.4	Installing the Load Frames and Winches
6.5	Making Grout
6.6	Replacement of Slurry with Grout
6.7	Survey of Initial Elevations
8.0	CUTTING THE BLOCK AND CONTROLLING UPLIFT
8.1	Contamination Control
8.2	Documentation and Data Collection During Bottom Cut
8.3	Winch Removal
8.4	Load Frame Operations
8.5	Survey Elevations after Cut
8.6	Leveling the Earth Block
8.7	Increasing Barrier Thickness
8.8	Third Elevation Survey

9.0 ENGINEERED TOP CAP

- 9.1 Liner Cuff
- 9.2 Approach To Hydraulic Measurement
- 9.3 Barometric Pressure Testing
- 9.4 Top Cap And Experimental Plan

10.0 DATA AND EVALUATION

- 10.1 Sample QA/QC And Data Collection
- 10.2 Data to be collected and sample technique
- 10.3 Experimental Procedures
- 10.4 Data Management
- 10.5 Data Analysis and Interpretation

11.0 EQUIPMENT**12.0 ADDITIONAL PLANS**

- 12.1 Environmental Impact
- 12.2 Environmental Safety and Health
- 12.3 Waste Management Plan
- 12.4 Erosion Control Plan
- 12.5 Public Participation Plan
- 12.6 Schedule Plan
- 12.7 Regulatory compliance Plan
- 12.8 Project Organization Plan
- 12.9 Independent Sampling, measurement and control Plan
- 12.10 Equipment Clean Up / Decontamination Plan
- 12.11 Final Report
- 12.12 Long Term Permeation Test Methodology
- 12.13 Site Restoration Plan

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July 11, 2002

EarthSaw Controlled Field-Scale Test Plan

1.0 INTRODUCTION

The EarthSaw construction method is designed to construct a continuous and uniform bottom and side barrier under and around a waste burial site without contacting or exposing any of the waste. This process is intended for pits and trenches in the DOE complex that contain radioactive and hazardous wastes in a variety of geological and hydrological conditions. In this work plan, we will demonstrate the EarthSaw method on a block of earth 50 feet long, 50 foot wide and 30 foot deep. The process will physically sever this soil block from the earth and float it upward on a heavy grout material. The thickness of the vertical grout sidewalls will be 2 feet but the thickness of the bottom layer of grout will be increased to over 3 feet thick. The grout will be a non-hardening clay-based material forming a seamless impermeable liner under and around the entire soil block.

1.1 Technology Description

The EarthSaw is a mechanical construction method. It begins with the excavation of a conventional slurry trench around the four sides; (the perimeter) of soil block to be isolated. At the two corners of one side of the soil block, the crane will lower in hollow steel load frame structures that have large pulleys at their base. A steel wire rope cable extends from a powerful winch at ground level down through the load frame to the pulley at the bottom of the load frame. The cable runs around the pulley and then horizontally around the other three sides of the soil block, and back up the second load frame to the second winch. The pulley at the bottom of the trench directs the pull on the cable so that we can control the inclination of the bottom cut precisely. The lightweight slurry used to excavate the perimeter trench is replaced with special grout that is denser than soil. When the winches are activated, the cable cuts horizontally under the soil block and gravity forces the fluid grout to flow into the cut and buoyantly float the soil block.

2.0 OBJECTIVES

The basic principles of the EarthSaw have previously been field demonstrated on a small scale but the scope of that test was too limited to provide all the data and hard evidence needed to permit using the technology on a radioactive site. The previous demonstration was less than full scale and did not have the hardware means to assure a flat horizontal bottom cut. The object of the field test is to demonstrate that EarthSaw can produce a thick and uniform bottom barrier in-situ at full scale. The EarthSaw construction method will be demonstrated at a clean site and we will measure the uniformity and impermeability of the barrier produced. A further goal of the test is to gather data to help demonstrate the safety, constructability and contamination control features of the method that would have to be addressed in obtaining a permit for use of the technology on a radioactive site. In order to provide a credible demonstration suitable to persuade regulators of the merit of the technology it will be necessary to perform the work in full scale. The test will isolate a 50-foot square area to a depth of 30 feet. This field-scale test will be specifically designed to serve as a demonstration of a method for remediation of the SWMU 2 site at the Paducah Gaseous Diffusion Plant known as C-749, which is about 1100 feet away. The C-749 site is a CERCLA site in need of corrective action. The field-scale test will cover only a fraction of the land area of C-749 but it will be performed at the same depth, in similar soil types, and similar groundwater levels.

2.1 Success Criteria

1. The cutting cable should pass completely under a 50 foot by 50 foot block of earth at a the depth of the load frame. This should be visually apparent.
2. The 50 foot by 50 foot by 30 foot deep block of earth must float on the grout. This criterion will be verified by the survey of elevations at various times during the work.
3. The grout must form a continuous bottom and perimeter layer, defined as the floating block not physically contacting either the bottom or the sides of the grout filled excavation. The elevation survey will provide data that allows this to be verified by calculation.
4. The bottom grout layer is to be at least 24 inches thick and within plus or minus 20 percent of uniform thickness. If the layer is nominally 36 inches thick, permissible variation is plus or minus 7.2 inches. This will be determined by calculations based on the elevation survey and confirmed to a lesser accuracy by drilling holes through the block to directly measure the barrier thickness.
5. The side grout layers are to be at least 18 inches thick and within plus or minus 20 percent of uniform thickness. If the walls are nominally 24 inches thick, then permissible variation is plus or minus 4.8 inches. This will be determined by calculations based on the elevation survey and mechanically confirmed to a lesser accuracy by the load frame and spacer I-beams in the vertical trench.
6. The barrier permeability shall be less than 1×10^{-7} cm/sec. This will be measured by obtaining samples of the grout from deep within in the vertical

trench, (outside the corners), and from the holes drilled in the block. These will be tested for hydraulic conductivity by ASTM D-5084. We will attempt to verify these results through pumped removal of water from the interior of the barrier followed by measurement of water level change within the interior of the barrier.

7. The artificial discontinuity in the block should not significantly affect the final thickness or shape of the barrier. This criteria will be evaluated by survey of elevations at 6 points bounding the discontinuity both before and after the horizontal cut. A lack of relative movement at the discontinuity will indicate success.

3.0 DESIGN AND ENGINEERING CONTROLS

The EarthSaw barrier to be constructed here is square but many shapes are possible. The rectangular box shape proposed here provides the clearest demonstration of the buoyant lift method.

3.1 Cable Saw Cutting

The cutting of the bottom barrier is done by a cable saw pulled by powerful winches. The winches planned for this work are remote controlled and can pull the cable with over 100,000 pounds force. In softer soil, with cut width less than 75 feet wide, this cable saw cut may take the form of a slicing action as both winches pull on the cable at the same time. In larger sites with harder soils or rock, the cutting involves reciprocating the cable back and forth repeatedly to saw through the earth. The same winch and load frame hardware can be switch back and forth to either type of cutting without any modification or work stoppage. If the cable breaks or shows wear in the middle of a cut, the cable can be replaced and the cut continued. After the horizontal cut is complete, the soil block will actually be floating on the grout. Adding more grout to the perimeter trench raises both the fluid level in the trench and the floating block an equal distance as the thickness of the bottom layer of grout increases.

3.2 Planes Of Weakness And Structural Strength Of Block

The earth block is generally not considered as a structural element in the process and cracks and discontinuities pre-existing in the block or created during the work do not prevent construction of a perfect barrier. However, if we are creating a secondary containment under an existing underground tank we may wish to avoid inducing stress in the tank wall.

To construct a uniform bottom barrier we must cause every area of the block to rise the same vertical distance. If we achieve this the final stress conditions on the block will be

identical to those of the ground before the barrier was cut. Small transient stresses may be created by improper operating procedures such as excess buoyancy during the cut. Stress on a buried tank may be minimized by forming the barrier at a greater depth.

The magnitude of buoyant vertical lift of the block is a function of the ratio of the grout density/soil block density and the depth of the horizontal cut. The final ratio of the vertical thickness of the block to the thickness of the block submerged in the grout will be equal to the ratio of the density of the grout to the density of the soil block. The buoyant lifting process requires no structural or cohesive strength in the portion of the soil block below grade. Plastic and elastic deformation of the soil is expected to minimize the influence of variable structural strength and discontinuities within the soil block. Most soil blocks envisioned for containment with this technology are sufficiently large that they are expected to deform elastically or plastically and thus each (plan view) area of the block will tend to rise to a level determined by its own bulk density and depth of cut. This local deformation of the block may occur through according to the thickness and physical properties of the soil and debris in the block.

3.3 Adjusting Buoyancy In Variable Strata

Variable surface slope, variable density, and voids within the soil block can be compensated for by altering the depth of the cut in one area or on one side of the block. Final adjustment of the buoyant lift (and thus the barrier thickness) of any given area of the floating block may be done by moving dirt on the surface of the floating soil block like moving ballast on a ship. Adjusting cut depth and soil surcharge loadings to achieve a uniform bottom barrier thickness also minimizes deformation of the soil block. A well-designed work plan can lift the block uniformly with no significant deformation, thus forming a bottom barrier of uniform thickness.

The deeper the cut, the higher the block rises. An example of this is shown below. In the bottom figure, one side of the site is 3 foot higher than the other and also contains a thicker rock layer and has a higher bulk density. By making the bottom cut deeper on that end, we can achieve a uniform bottom barrier thickness. Moving soil around on the surface changes weight distribution and provides a means of overcoming data gaps and fine-tuning the barrier thickness.

3.4 Compensating For Dished Bottom Or Large Voids

The bottom cut made by a tensioned steel cable is relatively planar and flat. However, if the cable tension was low and the cable weight was high, such as in a 500-foot wide by 1000 foot long barrier, the cable might sag several inches along the centerline of the cut. If this should occur, the bottom barrier would be concave and not flat. This would cause the block to bow upward slightly along that same centerline of the cut. This condition may also be caused by unexpectedly low density of waste, or many voids. If the elevation survey indicates this has occurred we would compensate by moving several inches of surcharge soil to the centerline of the block. This would flatten the block and return the bottom barrier to constant thickness. If we place the surcharge load before cutting the barrier, there is no deformation of the soil block and a uniform bottom barrier layer is achieved.

In practice, we will seldom know how much surcharge is needed in advance. Therefore, we will install standard iron survey rods (perhaps on 50 foot centers) in the cover soil and take careful survey measurements of the elevation of all areas of the block both before

and immediately after the horizontal cut while the block is only a few inches higher. Since little lift has occurred, little deformation is possible. Soil would then be moved around on top of the block to balance the floating block precisely within the accuracy of standard survey measurements. The balancing task is complete when a survey indicates that all portions of the block have risen the same vertical distance. In certain cases, rock or lightweight aggregate may also be used to balance the block. Additional grout would then be added to the top of the perimeter trench to lift the balanced block to final elevation. This technique effectively limits the significance of the structural properties of the block.

3.5 Grout Functions

The grout must have a density sufficiently greater than the soil block to make the soil block float with the desired freeboard and barrier thickness. This density can be adjusted over a wide range and is one of the primary design controls. The high density grout fluid also has special rheological properties that allow it to seal off against permeable soil formations such as sand and gravel, while still flowing and transmitting hydrostatic pressure through the thin cable saw cut. Large voids or fractures that are exposed by the cut will be automatically filled with grout. Wide vertical discontinuities or monitor wells, which extend through the bottom cut, would also become filled with the grout to the same elevation as the grout in the perimeter trench. The properties of the grout prevent it from flowing into small fractures or the porosity of the soil. ~~When the~~ When the bottom barrier is cut horizontally

3.6 Grout Material Selection

The Paducah site has the potential for strong earthquakes. Many of the wastes buried at C-749 have solvents and oils that may leak out over time and contaminate groundwater.

TECT B grout is a clay based grout material that is available in completely non-hardening versions and versions which cure to a consistency like peanut butter. Since this type of grout does not harden and set like concrete, there is no time constraint on the speed of operations. This can prevent problems when doing complex work or when the threat of work stoppage exists. The work crew could evacuate the site at any point during construction and return weeks later with no consequence on the quality of the project. The TECT B grout remains very soft and plastic after construction and can deform and adjust to earthquake subsidence. In order to compensate for possible subsidence from an earthquake the grout barrier should be made quite thick. We plan to make the side barriers 2 feet thick and the bottom barrier about 3 feet thick.

The grout is installed as a liquid and tends to become thicker and more viscous over time. The grout has self-healing properties. We can also add hardening additives to make this occur faster. If a fault line intersects the barrier and an earthquake displacement does not

actually cross the 3-foot thickness of the barrier, then containment would be maintained because the grout would flow to adjust to the movement. If earthquake vibrations were to cause a liquefaction effect and temporarily increase fluidity of the grout, this would produce no detrimental effect since the containment does not rely on any structural property of the grout. The barrier is fully functional even when it is in a fully liquid state. The permeability of the TECT B grout has been measured at 1×10^{-8} cm/sec in both lab mixed and field mixed samples.

The grout selected for this work can optionally contain the same reactive iron additives that are being commonly used in current research for in-situ treatment of many types of organic contamination, such as TCE, in ground water flow. Conventional permeable reactive walls lose effectiveness over time as the wall becomes less permeable and the flow goes around it. However, in the EarthSaw method, the barrier completely surrounds the source material and water cannot go around or under it, so the remedial benefits continue indefinitely. A barrier vault with these materials is expected to have the ability to reactively destroy many contaminants that might permeate through the barrier over very long periods of time.

The C-749 site may contain free solvents and oils. If we were performing a project there, we might choose this reactive version of the TECT B grout. Therefore, even though we have no need of the reactive properties in our test plan, it seems reasonable to offer to include the reactive additives in the grout formulation of this test to gather constructability data for permitting real projects. Including these additives may also increase the value of the vault as a controlled release site for other DOE experiments if DOE decides to keep it substantially intact after our demonstration is complete. The optional additional cost of adding the reactive component will be specified in the cost proposal.

3.7 Functional Requirements Of The Cap

EarthSaw is more than just a means of constructing a bottom barrier. It is also an integrated means to verify the performance of the barrier year by year as long as desired. A complete demonstration of EarthSaw barriers will include an air tight and durable cap structure to measure the performance of the barrier and to demonstrate how the cap and measurement technology are integrated into the barrier. A top cap of some kind is generally needed to complete a barrier and prevent rainfall from pooling in the barrier. The top cap also completes a closed container so that various absolute monitoring means can be performed. The top cap for an EarthSaw barrier consists of seven main components:

1. A liner cuff extending down into the trench
2. A concrete or clay cap over the liner cuff
3. Monitor wells, micro tubes, or buried sensors
4. A liner over the top of the block sealed to the liner cuff

5. A perimeter liner covering both the top of the block and the perimeter slope
6. An earthen cover, with bio-intrusion preventatives
7. An armor layer

Since this is a demonstration and is not a permanent installation, we do not plan to use the item 6 and 7 bio-intrusion materials and armor layer, but will instead use a traditional vegetative cover like that used in the PGDP SWMU 3 closure.

3.8 Cap Design Factors

A TECT B grout has the virtue of remaining plastic and thus is not prone to cracking due to earth movement. This feature helps make the barrier earthquake proof but also makes the design of a top cap for a non-hardening TECT B grout more complex than for hardening TECT grouts. Adding weight on the block or above the perimeter trench can result in up or down movement of the block, thus affecting the bottom barrier thickness. The TECT B grout is designed to lose some volume during the curing process. This may cause the initial bottom barrier thickness to decrease about 10 percent during the first month of curing. The thickness reduction causes a net improvement in the properties of the barrier because the grout becomes firmer and less permeable. Saturated ground water conditions may slow the cure process.

Without a top cap, rainfall could enter the vault and increase the weight of the block. With a TECT B soft grout this could also result in a progressive subsidence as the barrier basin fills with water year by year. Without a cap, we would have no positive means of measuring groundwater leakage into or out of the barrier since water could enter and leave through the open top. The cap also isolates the near-surface portions of the barrier from excessive seasonal drying to maintain optimal plasticity of the barrier.

Building up soil along the side of the elevated block over the perimeter trench will cause the block to move upward. Adding soil on top of the floating soil block will cause the block to subside to a new buoyant elevation. Through careful engineering design of the cap it is possible to dynamically change the thickness of the bottom barrier or install a cap without changing the bottom barrier at all by simply adding the same weight above the block that is added above the perimeter trench.

4.0 TEST SITE

4.1 DOE Site Interest And Final Selection

We talked with two different DOE sites that expressed a desire to host the demonstration of the EarthSaw and had potential applications on their sites. Los Alamos National Lab has several large sites in a volcanic Tuff formation. Most of their sites needing the

barriers would be 600 feet long and 40 feet wide and the entire bottom barrier would be in the Tuff. Los Alamos provided a sample of this rock and we found that it cut very easily with a sawing action of the cable saw. Therefore, we could do the test at Los Alamos since its rock is not too hard for a standard cable. Los Alamos is very dry and would provide a good example of an arid site.

The Paducah Site has at least one landfill that could use the technology. The C-749 landfill contains uranium turnings and uranium dust in oil filled drums. The soil is relatively soft and not rocky. The Paducah site would appear to be an ideal candidate for future use of the technology. C-749 would require a barrier about 200 foot square and 30 foot deep. There are perched water zones within the depth of the barrier. Paducah is a good example of a wet soil site.

Both DOE sites have provided official letters describing their interest and desire to host the test. We have also made inquiries about a privately owned farm site 5 miles away from the PGDP, as a backup site if the Paducah site becomes problematic. We have also received expressions of interest from the Shell Oil Company, to host the test at their West Hollow Research Center, in Houston, Texas. Carter Technologies finds all of these sites acceptable.

DOE and NETL have selected the test site at the Paducah Gaseous Diffusion Plant, (PGDP) for this test plan. This test plan will require minor modification, revised NEPA documents, and perhaps a change in type of grout characteristics to be converted to a plan for another site. Transportation cost for the grout may also vary by location and size of the job. DOE site managers know that technologies suitable for dry western sites sometimes do not work well at wet eastern sites. We anticipate that to achieve full acceptance in DOE the technology will have to be tested in both a wet and then a dry site. We will propose that a successful test be followed by a test at the other kind of site.

4.2 Conditions at selected site

The proposed EarthSaw test site at Paducah is outside the fence but on DOE property. This site is about 1100 feet from the SMWU 2 disposal area known as the uranium burial grounds that is a good candidate for remediation with this technology. The Paducah Gaseous Diffusion Plant has provided Carter Technologies with an extensive book of data regarding the conditions at the SMWU 2 and SMWU 3 sites, C-749 and C-404. They have also included detailed historical, ecological, geological, and hydrological data for the waste site. It is believed that the test site will have the same subsurface conditions as C-749 and that the EarthSaw demonstration will provide enough evidence and data to qualify it for use at the C-749 burial grounds. The soil at this site is relatively soft and often wet. Our computer model indicates it may be cut by either slicing mode or sawing mode.

The DOE Paducah Groundwater manager has told us he believes that the soil and water within the depth range of our operation will be clean. Since the site was once used as a munitions plant it is possible that there will be unknown burial sites from past industrial activities.

The site is subject to earthquakes and the barrier design should be able to tolerate earthquakes.

4.3 Proposed Grout

We propose to use a non-hardening TECT B grout for the first half of the project making the bottom horizontal cut. Additional grout added to buoyantly lift the earth block will have a slightly greater amount of hardener and will cure to the “peanut butter” like consistency within a few weeks. The grout will be made on site from custom mixed components stored in cubic yard size “super sacks”.

24,000 cubic feet of grout will be required. Federal Industrial Products of Houston, TX will provide pre-measured grout component materials for the work. The grout will be mixed, and placed by our subcontractor, Inquip and Associates. The grout is custom blended and is non-returnable.

4.4 Disposal Of Excess Soil And Water

Disposal of generated wastes is technically feasible since the PGDP has an on-site landfill and a water treatment plant. However, since the soil is expected to be clean, we prefer to be as self sufficient as possible. We plan to work from natural grade level to avoid any need for clearing and grubbing. Excavation of the slurry trench will produce 600 cubic yards of soil spoils.

We would like to re-use all soil excavated from the vertical walls to form the cap over the completed barrier. However, this material will be very wet as it is removed from the trench and may not compact well for forming the cap. Due to the relatively small size of the project there may not be enough time for it to dry naturally. This might not be a problem if the weather is dry, but in wet weather, it would delay completion. To solve this problem we have a backup plan to use a dozer to excavate soil four feet deep in a nominal 50 foot by 100 foot square borrow area adjacent to the test block to build the cap. The wet soil from digging the slurry trench will then be backfilled into the borrow pit to dry naturally. Extra cost alternatives include mixing the soil with up to 100 tons of Portland cement to solidify it to a damp compactable condition. The mixing would be done with a dozer. The soil could be re-used or taken to the PGDP landfill.

Water from the slurry trenching process can be recycled in making the grout but we do not plan to do this because it adds variables to the quality control of the grout. This

slurry begins as clean potable water trucked to the site by a commercial water hauler and mixed with bentonite clay. It will pick up a significant volume of soil particles during the slurry trench work but the hydraulic gradient tends to keep groundwater from intermixing with the slurry. For estimating purposes, we plan to dispose of this slurry by discharging it on four acres of adjacent land at a thickness of one inch. This will require a state permit and may require testing of the slurry for contaminants. The slurry will be held in the slurry trench until any required testing is complete. For an extra cost, we can treat the slurry to remove most of the solids and make the resulting water suitable for disposal at the PDGP water treatment plant.

In order to conduct hydraulic testing of the barrier we plan to pump as much water as possible out of the contained soil block. This is anticipated to be on the order of 100,000 gallons. This water, extracted from the monitor wells after construction of the barrier, is expected to be clean and suitable for irrigation discharge on the surface of the property. This will require a State permit and may require testing. If testing is required, the water will be left in the ground until testing is complete. For an additional cost, the water may also be taken to the PGDP water treatment plant, or other disposal facilities.

Details of soil, slurry and water disposal would have to be worked out in discussions with DOE, state, and PGDP site personnel before completion of the final plan. We do not anticipate any other generation of waste materials in the project except for the empty sacks from our grout materials. These sacks and miscellaneous office trash will be disposed as non-hazardous solid waste with a local trash service or taken to the PGDP landfill.

In the waste site work anticipated for EarthSaw, there is always the possibility of unknown hazards that the land owner is unaware of. EarthSaw methods are designed to provide a considerable margin of inherent safety from chemical and radiological hazards for workers. Our excavation machine will be large enough that the operator will be a significant distance away from any buried material in the trench pathway. One issue to be addressed in planning work in potential contaminated areas concerns contamination control and proper disposal of contaminated soil and water. If the 200 foot square by 30 foot deep C-749 site the spoils from excavating the vertical trenches could be placed on top of the floating block, they would be only 15.3 inches thick. This method avoids many disposal issues. By placing an equal thickness of soil above the perimeter trench as part of a comprehensive cap design the final barrier thickness will be unaffected.

5.0 ONSITE CONSTRUCTION OPERATIONS

5.1 Measurement Of Soil Properties

Before undertaking a containment project, the location of the waste must be determined and the boundaries of the area to be contained must be decided. We must also determine the soil density profile and the mechanical strength of the soil. Since one goal of this

demonstration is to show how the C-749 site could be contained we want to work at full scale depth and a significant size area as close as possible to the C-749 site. This plan will demonstrate EarthSaw on a soil block 50 foot square and about 30 feet deep. The test area is about a quarter mile away from the C-749 site.

For the demonstration, we are conducting a test at a clean site with no known contamination so the corner points of the barrier may be selected for convenience within the general area provided. Even though we may not be concerned about perimeter contamination at the test site, we still have to perform mechanical testing on the soil to gather data. We want to know the strength of the soil along the path of the cable saw and we need to know the density of the soil at many points so that we can accurately calculate the buoyancy.

Cone penetrometer readings will be taken from 27 feet to 33 feet of depth at each of the 4 corners and in the center of the block. The cone penetrometer reading is expected to be a good predictor of the mechanical force required for the cable to shear or slice through soil. We will also core drill and recover core for the entire interval from surface to 30 feet deep. As the cores are removed from the hole, they will be cut into convenient and uniformly precise lengths (preferably 6 to 12 inches) and weighed to determine actual in-place density. We need to determine the average density of the soil and the tilt of any strata that represents a density difference. This data is used to calculate the buoyancy of the soil block. This measurement is to be performed within 15 minutes of bringing the core to the surface to minimize evaporation. After density testing, cores will be checked for pocket penetrometer reading, sealed in plastic bags, labeled, and stored for the duration of the project. This work will be done by a local specialty contractor. The final work plan includes an engineering drawing showing the planned location of the vertical trenches to be constructed and the placement of the residual spoils from excavation of the trenches. The drawing will also show the location of the equipment to be mobilized and the location of silt fences for erosion control.

The DOE ground water program manager and the site management contractor have developed a plan to perform a preliminary contamination survey that would also gather the soil strength and density data. For cost estimate purposes we will assume that we will have to gather the soil strength and density data ourselves.

5.2 Pre-mobilization Work

After receiving contract notice to proceed, Key personnel would attend a NETTL kickoff meeting and we would work with DOE to finalize approval of the test plan and health and safety plan. We would meet with DOE site personnel and coordinate completion of the many plans and documents needed to comply with regulatory authorities. We would also contract for delivery of the grout. We would mark the work area and subcontract subsurface investigations of the proposed test site, in cooperation with site management.

We would release purchase orders for construction of the load frames and the procurement of the winch systems needed for the work. The load frames are fully load tested before being shipped to the job site.

The winches shall have a capacity in excess of 100,000 pounds on a hydraulic drive. The control stand will be remote mounted 50 feet away from the winch so that both winches may be controlled by one person. See the proposal section for details.

5.3 Subcontractors

We plan to subcontract the construction work to a specialty subcontractor that has assisted in the development of the technology. All work physically performed at the site during construction will be under the direct control and supervision of Inquip Associates Inc. Inquip will provide a standard letter of insurance similar to that used for slurry wall construction. Carter Technologies Co. will be named as an additional insured party on the Inquip certificate of insurance. Carter can optionally provide separate contractors liability insurance for a significant extra cost, but requests that the Government provide indemnification according to public law 8504.

5.4 Mobilization

The following tasks will be performed in the mobilization period.

Tasks:

1. Complete emergency training class if required by Paducah site. (Estimate 5 days)
2. Present Paducah site personnel with a list of all equipment, safety inspections, and operator certifications that they may require.
3. Obtain final approval of Site Specific Health and Safety Plan and complete site safety meetings with PGDP outlining hazards, plan for route to medical emergency facilities, required PPE and security issues.
4. Prepare site access with gravel as needed.
5. Deliver portable sanitary facilities with eye and hand washing station.
6. Mobilize dust control equipment. Dust control equipment will consist of a large hopper approximately 4 feet in diameter and 4 feet high. The hopper will have flexible overlapping strips (like those on a garbage disposal) or other suitable device to narrow the opening to less than the diameter of the super sacks. A 500 CFM exhaust fan attached to the hopper will suck air through the top opening and discharge it into a large fabric dust bag. A powered sack cutter in the hopper will cut sacks as they are lowered into the hopper by the cherry picker. An auxiliary water mist system can also be manually activated if needed.
7. Set up portable site office trailer with 2 desks, generator for electric outlets, and air conditioning, chairs and folding tables suitable for an eight person meeting. Provide one dedicated cellular phone for official site office use.

8. Provide roped off observation area for visitors to have a clear view of the work.
9. Mobilize four large 21,000 gallon water tanks, (Frac tanks), to the site.
10. Mobilize a bentonite mixing plant and connect it to the tanks.
11. Fill tanks with up to 100,000 gallons of clean potable water by a water hauling company or obtain hookup to adjacent fire hydrant. (non-potable fire water will not be used.)
12. Receive and unload about 1000 to 1100 super sacks weighing 1 ton to 2 ton each, 6 pallets of dry sack material, and 23 pallet tanks (totes) of liquid additive.
13. Provide and assemble an OSHA compatible batching stand made from scaffolding complete with all safety rails, stairs and an automatic sack cutting hopper able to receive at least one full super sack at a time and funnel contents into a mixer truck below.
14. Mobilize small crane and rough terrain fork lift to handle super sacks and lift them to the hopper.
15. Survey elevation of work area and place survey marker flags along the 50 foot by 50 foot perimeter every 5 feet and install survey iron rods in 4 corners and center of block and at least one point external to the block.
16. Pass equipment inspection of Paducah site safety officer.
17. The site is relatively flat. No leveling or grading will be performed. Just as if the site were contaminated, no soil or vegetation is to be removed from the site. We plan to leave as much of the surface native grass as possible. If the survey indicates significant slope, we will modify the depths of the corners of the trench to compensate.
18. Mobilize excavator suitable for digging 24 inch wide trench 30 feet deep.
19. Mobilize a 75 ton or larger crawler crane suitable for lifting load frames out of trench. (load frame weighs 28,000 pounds and may encompass 75,000 pounds of grout during removal.)
20. Mobilize winches, load frames and cable.
21. Weld winch to load frame base plate. (LFRAM028.gcd) (Welding permit required) This may also be done off site.
22. Determine PGDP safe fuel storage procedures, or contract with refueling service.

5.5 Preparation of Block Defects

The 50' x 50' x 30' deep soil block will be modified to simulate a defect such as may exist at some waste sites. This defect will help verify the performance of the technology in sites having voids, vertical discontinuities and planes of weakness within the soil block. The defect will be prepared as follows:

1. Obtain Excavation permit, from site office.
2. Excavate a nominal 2-foot wide ditch from 3 feet inside the trench perimeter approximately 30 feet across the 50 foot block, (parallel to and 20 feet from the load frame side.) The excavation should extend 30 feet deep and 30 feet long. No person will be allowed to come within 15 feet of the open trench

except in the trackhoe operators cab. Excavated soil will be placed directly into a dump truck and piled outside the perimeter of the soil block.

3. The bottom 5 feet of the ditch will be back filled with un-compacted sand and gravel mixture from local sources, spread and leveled with the excavator. This mixture should be half sand and half one inch minus gravel. If the trench will not stay open to full depth, it will be excavated to the depth it will remain open. (A local excavating contractor expressed the opinion that the trench would likely stay open to 30 feet in this area long enough to place materials in the trench.) If the trench will not stay open to 30 feet we will start at whatever depth it will stay open. No shoring will be used in the trench because no personnel will be permitted to come within 15 feet of the trench.
4. Obtain sixty empty 30 to 50 gallon fiber drums and cut one 8-inch hole in each end. Randomly dump the drums into the trench to simulate voids. (Trucks, dozers, and people on foot are not to come within 15 feet of the trench.) Prepare two 40-foot long sections of 2 inch PVC pipe. Use the trackhoe to place them into the trench with the bottom extending to the voids created by the fiber drums, and the top reaching flush to the surface. Then add 12 cubic yards of 1.5 inch to 2-inch gravel attempting to cover the drums.
5. Place 12 cubic yards of 4 inch to 8-inch riprap rocks into the trench.
6. Backfill the remaining areas with native soil. Place marker flags every 5 feet along the path of the ditch.
7. The entire process of constructing the trench defects should take place in one day so the trench will not be left open at night.
8. Significant portions of the construction of the trench defect will be video taped from the trackhoe operators cab.
9. Excess remaining soil will be used to prepare a one-foot tall diversion berm around the 50 by 50 soil block area to minimize rainfall runoff entering the Work area.

The actual design of any defect trench, will no doubt be subject to much further discussion and approval but the above plan may be considered as a preliminary plan.

5.6 Monitor Well Installation

A pair of 3 inch diameter monitor well/extraction wells will be installed 10 feet inboard from two opposite corners of the 50' x 50' block to reduce the water table within the block as needed. The wells will be drilled by an 8 to 12 inch auger to 29 feet of depth and back filled with at least 1 foot of fine sand before installing a screen. The remainder of the screen will be packed with coarse sand. Optionally a pre-packed assembly type screen may be used. The casing and screen assembly must not extend below 28 feet. (We do not want to hit them with the cutting cable.) The well completion will be suitable for dewatering or vacuum extraction. These wells will be fitted with a suitable pump for extracting ground water. The top 5 feet of the well annulus will be filled with native clay. The top of the casing is to be 30 inches above grade and have an NPT threaded cap

or other airtight closure. This well will be left in place and used again after all work is completed so it must be protected from damage. A similar shallow monitor well 35 feet deep would be installed outside the barrier to provide control data. The well installation will be performed by a state licensed contractor.

6.0 BUILDING THE PERIMETER SLURRY TRENCH

The vertical perimeter trench will be excavated by Inquip using a standard slurry trenching process. Nominal trench depth will be 30 feet and should be accurate within a range from 30 feet to 31 feet inches over the majority of the trench so that the cable will lie at the correct elevation to begin the horizontal cut. We will cut the trench somewhat deeper than nominal and prepare a positive mechanical means of holding the cable at just the right depth until the cut begins.

The anticipated control method is that the spacer I-beams will be fitted with a cross bar which limits their insertion into the trench to a specific depth. The spacer I-Beams are simply a tack-welded pair of W24-104 inch I-beams like those used in the load frame. The cable will be tied to the bottom of the spacer I-beam with a loop of bailing wire such that it is free to slide through the loop but not free to drop any lower vertically. The I-beam and cable will be lowered into the trench. As the cable is tensioned, it will slice into the corners of the soil block at the correct depth and then as the cut proceeds, the bailing wire will break off.

Final cable depths will be provided by the engineer after the initial elevation survey. The cable enters the load frame 7 inches above its base, so this must be considered in setting the final depth for the load frame. It is permissible to add rocks under the load frame to obtain the correct depth for the load frame. The cable entry depth set by the I-beam spacer will be selected after the load frames are installed. The cable should be at the same elevation all around the trench unless we specify a depth variation to compensate for surface slope or density variation within the block. Carter Technologies will specify the relative depth adjustments after the initial survey of elevations.

Normally in a clean site, the slurry trench spoils would be stacked along the edge of the trench so that excess slurry can drain back into the trench. To demonstrate how potentially contaminated soil from C-749 would be handled; we plan to load the soil directly into a dump truck at the point of excavation. The dump truck will unload these spoils in an adjacent area of the site. This area will have a silt fence and a small catch berm to collect slurry coming off the spoils. As the excavation proceeds, the slurry trench will be maintained near full of bentonite and water slurry to minimize sidewall sloughing. The bentonite slurry will be mixed on site from potable water and stored in one of the water tanks until needed.

6.1 Excavation Spoils

We will conduct spot checks of the soil and water in the work area on a daily basis for significant levels of radiation with a hand held instrument. If we find materials that read significantly higher than background level, we will notify PGDP site safety personnel and ask them to make a determination if contamination exists. Since the excavated soil material will be wetted with the bentonite slurry, it will likely not present a inhalation dust hazard. If any odor or sheen of oils or solvents in the slurry is apparent, we will notify the PDGP groundwater manager assist in collecting samples for PGDP.

We anticipate that PGDP inspectors may also check to verify that the excavated spoils are free of contamination and we will cooperate with any such inspections. If contamination of soil is found, the material must be treated appropriately and replacement soil for a cap obtained at additional expense.

The spoils will be used to build the cap for the barrier vault. Once soil has been removed from the area of the trench, it no longer represents a demonstration of how we would handle contaminated materials, so we may use any available equipment to move it to the cap construction area. If the soil is to wet we will allow it to dry or exchange it with on-site borrow material at the construction subcontractors option. This assumes that the PGDP and state regulators have no objection to this practice and will issue any required permits.

6.2 Wire Rope

The wire rope used in this project is not used for lifting or hoisting but instead is used as a consumable underground cutting tool. For this reason, conventional factors of safety for wire rope in site safety manuals are not applicable to the EarthSaw cutting cable. The winch systems should be powerful enough to break the cable underground if this is operationally required. The engineering design of the process requires the wire rope be used at high stress levels and the winch systems must be able to break a stuck wire rope. The wire rope operates underground except for the winch itself and personnel will always be at least 40 feet from the winches during operation. The cable selected for this work is a 7/8" diameter torque-balanced 3-strand steel wire rope. It has a breaking strength between 85,000 and 100,000 pounds. Optionally we can upgrade to a stronger 1 inch diameter wire rope. We will obtain mill tests on the actual breaking strength of the material we purchase. This type of wire rope is very stiff and spooling onto or off the winch drum should be performed by persons with suitable wire rope experience.

6.3 Making Bentonite Slurry

During the slurry trenching work, a support operation will supply bentonite slurry to keep the trench full of slurry. This operation will be performed by an operator running a

mixing plant making the bentonite slurry and circulating it to a large tank. The operator will continually observe the fluid freeboard in the slurry trench and engage a pump on his mixer unit as needed to maintain the trench nearly full of slurry. The bentonite arrives at the site in 25 ton capacity pneumatic trucks. Whenever a truck arrives, the operator hooks it up to his mixer, mixes the entire truckload with water, and then pumps it into the tanks. The slurry is non-toxic by ingestion and dermal contact.

6.4 Installing the Load Frames and Winches

The next operation is the installation of the load frames and winches. There are several ways to do this. We plan to place the load frames into the trench separately, and then install the winches. The winches will be positioned near the load frame corners sitting upright on their base plates. The two load frames will be laid down next to the trench corners reserved for them. The 500 foot long steel wire rope will be pulled off its spool and laid out in a large “U” shape around the perimeter of the slurry trench area. The wire rope will be threaded through each load frame from the bottom up. About 10 feet of the wire rope will be pulled out the top of each load frame and tied off to the top of the load frame. The first load frame will be picked up by the crane and lowered into the trench corner. This will be repeated for the second load frame. Lines may be attached to the lower portion of the load frame to help position it during this process. These lines may be left attached as the unit is lowered into the trench and tied off by ground stakes at the surface. They can be reused during removal. After the load frame is in the trench, sand bags may be placed around it to steady it. The wire rope will be moved back and forth slightly to verify that the bottom pulley turns freely.

The winches are welded to a base plate (LFRAM028.gcd) that has four alignment pins that key and latch to the top of the load frame. This allows the winch and base plate to be quickly detached from the load frame for replacement in either the horizontal or the vertical position. The winch and base plate assembly is then picked up by the crane and set on top of each load frame. (Figure 1) The base plate legs are pinned to the load frame by inserting the two steel bars. The ends of the wire rope will then be attached to the winches and wound onto the winch drum. A small backhoe may be used at the far end of the site to tension the cable during this process. A pressure roller mechanism may optionally be constructed and installed to keep slack cable from uncoiling on the winch drum. The hydraulic power pack will be positioned separate from the winch on ground as shown in Figure 3. The control stands separate from the winches on 50 foot long lines.

It will be important to verify the depth of the cable where it begins to cut into the trench. It is likely that the excavation process will be unable to dig to a precise depth. If the depth of the slurry trenches is found to be imprecise, we will use a more positive method as follows: A pipe or I-Beam section will have a cross member fitted to it so that it can sink into the trench to some exact depth. The cutting cable will be attached to the bottom of this beam at the correct depth by a loop of plastic ties or bailing wire. The cable fits

loosely through the plastic tie and can slide back and forth. The I-beams will be inserted into the trench over 10 feet from the corners where the cutting begins. When the cable is tensioned by the winch, the cut will begin at the precise depth and sometime later, these ties will break away after the cable is established in its horizontal cut. The cable will continue its cut in a direct line to the pulley at the bottom of the load frame.

After the wire rope is in the trench, planks, gratings, or pallets may be placed over the slurry filled trench to prevent workers from falling in the trench. The health and safety team will review this issue to determine if having workers come near to the trench to place these covers is better than keeping them away from the trench.

Threading cable and installing load frame. Cable is tied off at top of load frame.

Steel spacer I-beams lower and position the cutting cable at a precise depth for cut to begin.

Cable at bottom of trench and beginning to cut soil.

6.5 Making Grout

In larger projects, we could use the same techniques to mix this grout as are used in making backfill for a conventional slurry wall. This consists of a dozer mixing the materials in a shallow pit. The mixing can also be done with concrete mixer trucks, which may produce a neater appearance at a slightly higher cost. Due to the relatively small size of this project, we plan to use the mixer truck technique. The grout will be made in a two step process, with the colloidal slurry portion made first and stored in tanks and then the dry additives mixed in a rotary mixer truck.

The colloidal premix will be mixed and allowed to pre-hydrate in the 4 frac tanks. A OSHA compatible batching stand of some type will be made from scaffolding complete with all safety rails, stairs and an automatic sack cutting hopper able to receive one or more super sacks at a time and funnel contents into a truck below. The mixing stand will be designed so that a worker may walk 360 degrees completely around the hopper to avoid wind blown dust.

Rotary concrete mixer trucks being loaded for the first time that day, or after cleaning, will first be verified to be empty by reverse rotating at top speed for 20 seconds and then pulled under the stand. The truck will then be filled with about 1000 gallons of the colloidal mixture. A crane will load 7 super sacks of dry additives into the truck. Workers will manually add 2 to 4 small sacks of admixture. Each truckload will carry about 8 cubic yards of product. We will make 100 to 120 truckloads of grout product.

We have located records indicating that the average soil density of the Paducah area is about 110 pounds per cubic foot. However until we test soil samples at the test area we can not be certain what the average soil density is and therefore we can not give precise numbers on the grout requirements. For planning, we assume a 27-inch average width trench averaging 30 feet deep with a freeboard of 1.8 feet and a final bottom barrier thickness of 3.5 feet and an average of 4-foot overlap at corners. We will need to make 24,000 cubic feet of grout.

The grout product will be mixed in the truck for 10 minutes before placing in the trench (or tremie pipe). The trench holds about 541 cubic feet per foot of depth. For a given specific gravity differential, to reach neutral buoyancy, we would need to place 14,000 cubic feet in the trench before cutting the bottom pathway. To get 6 inches of lift (4.8 feet freeboard) we will need another 271 cubic foot additional. During the horizontal cut, we would need to add another 1,234 cubic feet to maintain 6 inches of upward lift at the completion of the cut. We probably will add about half this much (617 cu ft is about 3 truckloads) to reduce lift near the end of the cut. The cut will take only 15 minutes, but we may stop and start to verify that we can work in both sawing mode and direct slicing mode. Mixing time for the first 14,000 cubic feet will be 63 truckloads divided by an estimated mix and dump time of 45 minutes would be 48 hours. Since the TECT B grout does not have a set time to force us to hurry, we will plan to do this over a 6 day period.

After cutting the horizontal pathway, we will mix and add the remaining 47 truckloads. This will require 36 hours (5 days) of additional work.

Plan view of site plan layout

6.6 Replacement of Slurry with Grout

A tremie pipe common to slurry trench work is typically about 12-inches in diameter and of a length to reach the bottom of the trench. The top has a funnel opening. This unit will be placed in the trench by the crane and tied off at the surface so that it cannot fall. Grout is poured down this tremie pipe to the bottom of the trench. The tremie pipe will be located on the end opposite the load frames. The grout may be pumped to the tremie pipe or discharged from mixer trucks. The grout, which is much denser than the slurry, fills the bottom of the trench while the lightweight slurry is pumped off at the surface and stored in tanks.

6.7 Survey of Initial Elevations

The elevations of the block and the outer perimeter will be surveyed and recorded on a drawing. A 5/8 inch by 3-foot long survey marker iron rod will be set at the 17 points to be surveyed for reference elevation. Optionally, a shorter rod with an earth auger type anchor may be used to help assure that the rod does not move vertically. Nine measurements will be taken on 25-foot centers beginning with the four corners and eight more measurements outside the corners and midpoints of the perimeter trench. Knowing the change in width of the trench at the surface and the change in tilt of the block allows us to calculate minimum sidewall thickness. It also allows us to balance the floating block after cutting the bottom barrier by redistributing soil in each area of the block to achieve uniform uplift at the nine points on the block, regardless of density variations within the block. For larger blocks containing undocumented waste, we would place the survey rods on 25-foot centers. This allows us to precisely balance the block to relieve all stress before lifting it to final elevation.

8.0 CUTTING THE BLOCK AND CONTROLLING UPLIFT

The winches that control the cable saw are operated from remote control stands which may be mounted anywhere on the site within 50 feet of the winch. For the Paducah demonstration, the computer friction model indicates that we will be able to function in either slicing or sawing mode at will. We will perform most of the job in slicing mode but we may also test the sawing mode at the beginning and end of the cut. In the slicing mode of operation, the winches will both be activated at once with full power. The operator will monitor the rotation of the winch drums to determine the progress of the cable. The winch drums will be painted to help make rotation visible. A video recorder will monitor the lift of the block and the rotation of both winches continuously during the cutting operation. The speed of rotation of the winches is proportional to the load so we may be able to visually see how much power is required to slice through the soil. We will place load cells between the winch base plate and the load frame to monitor actual cable tension. The grout feed operator will monitor the leading edge of the earth block and maintain the fluid level in the trench specified by the computer model to give 6 to 12 inches of lift. As soon as the cut proceeds substantially, the leading edge of the earth block will rise if we have accurately assessed the density of the soil block. If the block

does not begin to rise after a total of 50 feet of the cable has gone onto the winch drums, the grout level will be increased until the block begins to rise. From that point onward, the operator will monitor the uplift of the leading edge of the earth block and add grout when the uplift is less than 2 inches and stop adding grout when it is 4 inches high. This will require adding about 600 cubic feet of grout addition as the block is being cut. We will need to have 3 truckloads of grout standing by during the cutting process to provide this grout as needed.

After the block is cut loose and floating free about 2 inches higher than before the cut, a survey is performed to determine if the block has lifted uniformly at all points. If any area on top of the block has not risen the same vertical distance, then soil will be added or removed to balance the block. When soil is added to the area of a survey rod, a PVC tube is placed over the rod so that the next survey can still locate the top of the rod. After the block is completely balanced, all potential stresses have been relieved and additional grout may be added to the perimeter trench to raise the block to final elevation.

Since this 50' x 50' x 30' foot deep earth block is almost as thick as it is long, we expect that it will tend to lift as a solid unit rather than deforming flexibly as would be expected for a site with a greater length to depth ratio.

Figure 3 The cable saw will slice through the soil under the block.

8.1 Contamination Control

Since this work will be conducted in clean soil conditions, we do not plan to implement many of the routine contamination control measures that are available because we are primarily concerned with testing the EarthSaw technology. These include:

1. Lined and covered trucks for excavation spoils
2. Decon pad for trucks entering and leaving
3. Decon pad for trackhoe, crane, and load frames and winches
4. Thermal strippable coatings on load frames
5. Perimeter contamination reduction zones for personnel and equipment

6. Personal protective equipment such as disposable gloves, boots, and coveralls
7. Air monitoring systems, radiation monitor systems
8. Medical screening and evaluation
9. Enclosure covers over the load frame winch
10. Water separation systems for bentonite slurry trenching slurry
11. Water treatment system for collected ground water as well as studies of applicable permits from regulatory authorities.

If DOE requests, we can perform the work with any or all of these techniques at additional cost. We may want to test any technology that is unique to the EarthSaw such as a special wiper/cleaner system for the cable. We may also want to evaluate how easy it will be to clean the grout off the load frames and prepare them for storage or transport.

Contamination control is an inherent feature in most EarthSaw operations. TECT grouts are designed to capture contaminants. EarthSaw has the potential to allow construction outside and below the range of contaminated soil. However, due to adjacent structures or broad dispersion of contaminant plumes, it may be required that the barriers be cut through contaminated material. It is also possible that the bottom or sidewall cut may intersect unanticipated contamination. Note that intersecting the waste may not result in any spread of contamination. The EarthSaw perimeter trench is filled with high density TECT grout. This grout is added from the bottom of the excavated slurry trench by displacement. The high specific gravity and viscous nature of the grout prevent it from mixing with the slurry being displaced. The grout also provides a hydrostatic head that prevents contaminated ground water from entering the trench. Therefore, even if the trench was cut through contaminated soil, the contaminated groundwater will not contaminate the grout. There will however, be a few particles of soil distributed within the grout. Most of these particles will be very small. Larger particles will float to the surface. As the horizontal pathway is cut, some cuttings will be incorporated into the grout. If the cut is performed in slicing mode, very few cuttings will be generated. However, if the cut is made by the sawing mode, we would expect to generate significantly more cuttings.

In some cases, the cable may be required to cut through deposited waste. In this case, the grout should minimize the transport of contaminants to the surface and restrict the release of contaminants that make it to the surface. In order to be effective in this task, the grout has lubricity and film forming properties that make it tend to build up on surfaces. The winch, that is receiving cable, will receive a steady flow of grout from the cable coming out of the trench. In the pilot test configuration, this grout is expected to cover the drum of the winch and fall back into the open trench. In more contaminated conditions, we may wish to use an elaborate wiper or cable cleaning device, such as the one shown in the Interim Report, to keep this grout off the winch.

The grout should be capable of accepting and suspending cuttings without loss of its critical properties. TECT grouts may be designed to accept between 15 and 30 percent

cuttings, by mass, with minimal change in chemical and permeability properties. The particle size and chemistry of the cuttings can have a significant impact on fluidity of the grout, long before they have an influence on the final properties of the barrier. Small cuttings such as those generated in shale, limestone or volcanic tuff may be of near neutral buoyancy and their high surface area may increase grout viscosity. Management of these cuttings is potentially important. We can compensate for high loadings of cuttings by additional chemical additives or by flushing them with a stream of grout delivered to the edges of the cut by a tremie pipe. If cuttings contamination is anticipated, the grout may be designed with a lower initial viscosity. Grout flow through the horizontal cut may be increased by pumping to create a differential head from one side of the barrier to another. The initial buoyant lift on the block during the cut may also be increased to allow a more viscous grout to flow readily into the horizontal cut.

After completion of a cut the load frames and I-Beams would normally be removed from the trench and decontaminated. The decontamination would be done on a suitable decontamination pad. It would also be possible to leave these units in place if desired.

8.2 Documentation and Data Collection During Bottom Cut

A video camera image of the lift of the block will be provided to the operator controlling the winches if his control station is not positioned near the leading edge. The entire cable saw cutting process is expected to take less than an hour. We plan to measure cable tension by placing load cells between the top of the load frame and the winch base plate. We will use four LBO-50K load cells with a SJB-4 Summing Junction box and PHM-100 hand held indicator from Transducer Techniques Co. The load cells will be bolted or otherwise attached to bottom of the winch base plate. The cable force is expected to be erratic and vary from second to second so it will be damped and averaged by the readout instrument. The cable tension data will be compared with the data on soil cone penetrometer strength and used in the computer model to enhance the accuracy of the estimated power required to cut soil at the C-749 pit. For an additional cost, we may be able to automatically record this data with a time signal so that it may be compared to the video recording, but we plan to simply point the video camera at the display readout from time to time. We plan to run three video cameras continually during the cutting and raising operations to help document the work.

8.3 Winch Removal

The load frames stick out of the ground at least half a foot. The winch base plate rests on top of the load frame. As the last portion of the horizontal path is cut and the corner of the block rises, it will bear against the winch base plate and lift the load frame along with the block. This extra weight of the load frame and winch is capable of tipping the block slightly so the winch should be removed before the barrier thickness is homogenized and the thickness is increased. To remove the load frames, we first wind all the cable to one

winch. Then we attach a line to the two retainer pins and pull them out. The winch may then be lifted off with the crane. The load frames themselves could then be lifted out of the trench with the crane at this time but we plan to leave them in place as spacers until the final barrier thickness is achieved.

8.4 Load Frame Operations

The computer model projects loadings of less than 30,000 pounds for slicing the bottom of the demonstration block at Paducah. This is about 1/3 of the capacity of the winch and cable. When the cable reaches the end of its travel it will be stretched between the two load frames and may break unless stopped by the operator. For the purpose of this demonstration, it may be almost as desirable to let it break than to stop it. This would serve as a full load test of all equipment. Since personnel are not located near the winch breaking the cable should not be a hazard. However, we plan to simply wind the cable to one winch or the other and let it come off the drum. It should be possible to put a cover over the winch drum, but we do not feel this is necessary. If the load exceeds the strength of the cable, the cable will break. If the cable becomes stuck underground this can be helpful. The pressure roller on the winch will prevent backlash in the cable drum. Backlash in the winch is not a real problem since the broken cable would have to be removed from the winch and replaced anyway.

Computer modeling indicates that slicing and sawing action are equally feasible at this site. We would normally perform the entire cut with slicing since it is faster and creates no cuttings. However, in order to gather data we plan to saw for a few minutes at both the beginning and the end of the cut. This may be useful since the waste site at Paducah is 200 foot wide and may require the sawing mode of cutting.

If cable wear causes the cable to pull in two we will remove the load frames and install a new cable. Since the block is floating, we can pull back to about the same position we left. We can also increase the buoyancy, which may cause the block to cut more easily.

If high friction conditions cause the cable to become stuck, there are several options to recover from this problem. We can pull the cable in two and re-install a stronger cable or one with a smoother surface. If the condition occurs while sawing, we can simply switch to slicing mode, which requires less pull. If we are already slicing and run out of power, there are at least three options to recover:

- One of the winches and load frames may be removed from the trench and the cable threaded through a pulley block attached to the trackhoe bucket and tied off at the load frame end. The trackhoe would pull it through the trench toward the end of the trench opposite the load frames. This will reduce the friction contact angle and after untying the cable end, the remaining winch will be able to pull the cable out of the trench.
- An optional technique allows both load frames to remain in place and a breakaway lasso surrounding the pulley opening is activated to capture the cable and pull it to the surface. Capture of the cable may also be done with a mechanical tool on a pole in some cases if the total progress of the cut has not advanced very far. Once the cable is captured and lifted to the surface it is threaded through the pulley block and pulled with the backhoe as above. The

difference is that the cutting process may be immediately continued after the trackhoe pull alters the contact angle.

- However, the preferred option is to install a special hooked claw attachment on the trackhoe. This attachment would have a low friction surface or preferably a roller built into its shape such that it can be curled under the cable and provide the cable a low friction path that effectively reduces the contact angle of the cable. It can be easily engaged and disengaged without removing the load frame or the cable from the trench. This technique can also aid in increasing the maximum size of a barrier because it can reduce friction.

Optional trackhoe mounted hook claw tool reduces cable contact angle

For larger projects the claw tool may be employed to help deal with various unexpected conditions. If high friction conditions are encountered in the cable-sawing process, the special claw pulley tool may be attached to the trenching backhoe and curled under the cable to reduce the effective angle of contact. Use of this tool could significantly increase the maximum size block to be contained. This tool allows a project to proceed with only minor delay if unexpected high friction should occur. Friction model allows us to quickly evaluate the benefits of changing the angle of contact using such a tool. If we enter data into the force and friction model for a 2000 foot by 2000 foot site, using a 1 inch diameter 1.64 pound per foot torque balanced 3 strand cable with a maximum coefficient of friction of 1.0, the model would generate a stuck cable warning. Reducing the contact angle to 90 degrees results in 10,600 pounds of reserve power so that cable sawing should be possible.

8.5 Survey Elevations after Cut

After the bottom cut is complete and the block is floating, the elevations must be surveyed again and recorded on a drawing. This survey is compared to the initial survey to determine the surcharge weight needed to level the block. Note that this survey must be performed before any soil is added or relocated on the surface of the block.

8.6 Leveling the Earth Block

After the entire earth block is floating, it must have soil redistributed to balance and level the block before raising the block to final elevation. If one area of the block rises substantially more than another, the dozer or trackhoe will move dirt from the heavy area to the light area to balance the block. For a small earth block the weight of the dozer will be significant and will itself interfere with the survey measurement.

The objective of leveling is to have the original surface of the entire block parallel with its original position. Every point on the block must rise the same vertical distance. This assures a uniform thickness in the bottom barrier. (Dozers can push fill dirt right over the open trench, or a wooden crane mat may be laid over the trench.) If dirt is to be added, trucks may drive onto the block and dump in designated points. The trucks can deposit uniform weights of dirt in piles around the center of each quadrant. The process of moving soil and rechecking the survey elevations may require several iterations if a precise barrier thickness is desired. If the waste disposal areas may be denser than the soil then the edges of the block may rise while the center remains at original elevation. In this case we will add soil to the perimeter to push it back down while increasing the grout level until all portions of the block have been uniformly raised a few inches

When the horizontal cut is partially complete, reusable spacer I-Beams may be inserted in the trench to restrain lateral movement of the earth block. The load frames contain similar I-beams and will restrain the block at two corners. We plan to use only eight I-beams. They will be attached together in pairs for stability and used to restrain the block on the corners opposite from the load frames. If may have already placed these I-beams along with the cable to control initial depth of the cable cut.

Figure 1 Spacer I-beams (shown in green) may be placed around the perimeter of the block as shown to limit movement. Soil may be piled by dump trucks on the block to level the bottom barrier.

With a properly leveled block, floating in the center of the excavation the side walls of the barrier should be quite uniform. The I-Beam spacers may optionally be used to help verify the physical width of the trenches. The I-beams, and also the load frames will normally be removed before the top cap is installed.

8.7 Increasing Barrier Thickness

After the cut is complete and the earth block is leveled and then re-surveyed and each iron rod marker has seen the same elevation increase, additional grout is added to the trench to develop the final barrier thickness. Before doing this, the elevations of the top of the block and the surroundings must be surveyed and recorded and approved by the engineer. At this point adding grout to the trench to raise its fluid level will result in an equal increase in barrier thickness in the same way that a rising tide raises a boat at the dock.

8.8 Third Elevation Survey

After the block is raised to final elevation a final survey will be taken to determine final barrier thickness on both the sides and bottom. This survey must show all four corners and midpoint of both the inside and outside perimeter of the trench. Knowing the width of the trench at the surface and the tilt of the block allows us to calculate minimum sidewall thickness. If the block is not centered in the excavation, we can pump grout from one side to the other to push the block around.

8.9 Physical Verification Of Bottom Barrier Thickness.

The survey techniques are an accurate method of verifying the bottom barrier thickness but if there is any doubt, there is also a direct physical method to do this. If the barrier is three feet thick, it should be possible to pass a 24-inch diameter pipe completely under the floating block. For our 50 foot wide block we would do this with by obtaining a 52 foot long section of 24 inch diameter pipe having a one inch thick wall. A long sweep 90-degree bend of 5-inch pipe would be welded to each end of the pipe. A cable from the load frame would pass into the pipe through the 90-degree sweep, through the pipe, through the other sweep, and back to the other load frame. The pipe would be dropped into the trench

A 2-foot diameter pipe can be drawn under the floating block to verify barrier thickness and continuity.

opposite the load frames and allowed to sink to the bottom. The load frames would then pull the pipe laterally under the earth block. A secondary chain attached to each end of the pipe would then be used to pull the pipe out of the trench after the load frames are removed.

9.0 ENGINEERED TOP CAP

The test plan includes detailed construction drawings of the cap structure to be built. These will be completed after contract award and meetings with DOE, PGDP and state regulators.

9.1 Liner Cuff

The cuff liner is a folded 12 -20 mil thick HDPE liner made from an 18 foot wide roll of HDPE material. 250 linear feet of liner will be required for this project. This includes a 20 foot bonded overlap. The liner is folded along its length (or seamed) and then heat creased at the fold to make a “V” shaped “cuff”. One-inch rebar steel rods or other heavy pipes are placed inside this cuff. This folded cuff is lowered into the trench and additional grout is pumped into the cuff, beginning with the side opposite the seam, to cause it to sink.

The liner is sunk all the way around the perimeter of the earth block. Grout is added to sink it to the point where it is 2 feet above flush with the top of the block in the inboard

side, and flush with the ground level on the outboard side. The block side is then folded down as shown in the drawing below. Note that the grout level inside and outside the liner cuff will be the same. The purpose of this liner is to enhance the resistance of the TECT B grout to drying conditions and to form a durable air-tight bond to the synthetic top cap. A natural clay filler is then placed on top of the grout flush with ground level. This filler will be of lower density than the grout but will still increase the elevation of the block. This increase will tend to compensate for the decrease due to the curing of the grout and the construction of the top cap. The clay filler for this work will be at least one foot thick and require about 20 cubic yards of clay. This fill may optional be made with fiber reinforced concrete to provide a stable work platform around the block.

After the synthetic liner is in place the earthen portion of the cap may be installed immediately. Optionally for barriers made with hardening grouts the barrier material may be allowed to harden first. After leak testing of the top synthetic liner is complete the earthen portions of the cap are built up slowly working in uniform thin lifts to avoid creating uneven weight distributions that could cause tipping of the block.

9.2 Approach To Hydraulic Measurement

The primary performance goal in this demonstration is measurement of the hydraulic conductivity and thickness of the barrier from physical samples. Unlike conventional barriers, penetrating a TECT B grout barrier with a drill will not cause any damage, so we

can take the samples directly from the bottom of the barrier. However, since the vault formed by the EarthSaw creates an opportunity to conduct direct measurements of the barrier's potential total performance in keeping ground water out of the C-749 waste site, it seems reasonable to conduct some further testing.

There are at least two options for hydraulic verification of the barrier in a wet environment. One option is to fill the interior soil void space with water, increasing the water level inside the barrier. Then an instrument would monitor the water table level over time to see if it was leaking out. Conversely, we can reduce the interior water table within the block and monitor to see if water leaks back in. The best choice tends to depend on the ambient water levels before construction. The best approach for demonstrating performance suitable for the C-749 site may require discussion between the PGDP, DOE, and state regulators. We plan to drop the water table and measure leakage, if any, back into the barrier. Choosing this option also allows us to simultaneously test the barometric pressure based leak-testing method, which would be most suitable for dry sites. One potential problem with this method is that perched water inside the barrier and water separating from the grout itself during cure could interfere with accuracy. Small leaks into the barrier may take a long time to detect. We plan to do a long-term test for 12 months after completion of construction and final report. At the end of the 12 months, we will evaluate the data, restore the site and issue an addendum to the final report providing the additional results.

9.3 Barometric Pressure Testing

With a small amount of extra effort, we can seal the top cap to the walls of the EarthSaw barrier. If the bottom barrier is continuous, this should form a complete vault. The vault integrity can be measured by recording the barometric pressure differential between the inside and outside of the barrier. While natural atmospheric pressure varies from day to day, the pressure inside the barrier should not. We will begin with by artificially reducing the air pressure inside the vault and measure its response over time to determine if this leak detection method is feasible. Over time, we should be able to evaluate the air pressure integrity of the barrier. If the pressure inside the block is independent of the external pressure, we may infer that the bottom barrier is free of leaks. However, air pressure communication from inside to outside does not necessarily mean the bottom barrier is leaking because the top could also be the source of the leak. In western sites that are relatively dry most of the time, this type of testing could be an important tool to verify barrier integrity. We plan to conduct a long-term test to determine if this concept is feasible or not.

9.4 Top Cap And Experimental Plan

After the maximum amount of water has been removed from the block with the monitor wells, an electronic water level measurement system will be installed and the monitor

well will be sealed with an airtight seal. A Global Water brand WL-15 with built in data logger can be installed completely inside the well and collect data for up to a year. It may also be installed with the data logger outside the sealed portion of the well. We plan to use this approach. External barometric pressure sensors will be connected to the well casing by a small copper tube routed to a data logger. The sensor can also be installed inside a well. The details of the measurement plan will be worked out in cooperation with the PGDP site personnel and regulators after contract award.

The top of the monitor well casings will be at least 1 foot above the final surface of the earth block cap. A bulkhead-seaming collar will be placed around each well casing to allow it to be fusion welded to the HDPE liner. The top of the 50' x 50' earth block will then be covered with 12 to 20 mil HDPE and seamed to the Liner in the trench and the monitor well casing. The liner rising from the trench to the top of the block will first be folded over on itself as shown. (The material will wrinkle much as a rolled up sleeve but this is of no consequences.) This will allow the block to move up and down during the rest of the capping and curing process without damage to the liner. Damage to the liner is undesirable because leaks will diminish the accuracy of air pressure differential testing of the barrier integrity. A fitting with a valve will be installed in the liner or attached to the internal monitor wells, to allow hookup to a low vacuum source, such as an exhaust blower, or engine air intake, and the air removed from under the top liner. If the soil is not very porous, vacuum draw down to steady state conditions may take many days. After draw down, We will measure how well the system can hold 2 psi of vacuum. Leaks may be isolated with stethoscopes or other directional listening device means.

After the active vacuum test experiment is complete, the cap will be sealed at reduced pressure and spoils from the trench excavation will be brought back to the work area and used to cover the trench and make a gently sloping transition ramp from the edge of the perimeter trench extending outward another 12 feet. (This will reach grade level at a 78-foot square size.) This will use about 5,000 cubic feet of soil 14,500 cubic feet available. The soil directly above the trench is built up to an elevation designed to keep the block at the desired final elevation. An upper liner of 40-mil rough surface HPDE liner material will be laid over both the block and the outer perimeter ramp. The outermost edge of this liner will be buried in a 12-inch deep trench 12 feet out from the perimeter of the block. We may make minor adjustments in these dimensions to use up all available soil from the trenches.

Since the cap is not intended for permanent use we do not plan to use the more sophisticated cap designs discussed in previous reports. We plan to re-use the excavated spoils from the vertical sidewalls for this work and we will not measure efforts to compact it. The 14,400 cubic yards of soil removed to dig the vertical sidewalls will be enough to form a cap at least 18 inches thick over the earth block. Since this site has a frost depth of 18 inches, we desire to make the top layer of soil at least 18 inches thick. The cap perimeter will come to grade at a size of about 90 foot on a side. If the top of the earth block is not level, then the top of the cap will not be level and no attempt should be made to level it, as this will tend to unbalance the block. The sloping sides of the cap

will be terraced to minimize erosion. The entire cap will be seeded with a hydro mulch type seed/fertilizer/binder spray. The as-built drawings for all structures will be supplied along with the final report.

10.0 DATA AND EVALUATION

10.1 Sample QA/QC And Data Collection

The EarthSaw test is not envisioned as a highly data intensive project. The most important factors at this stage of development are qualitative measures of operational success stated above. These include such questions as: Will the cable cut through the ground and will the block float? However, there are many types of data that are of secondary importance that we desire to collect and evaluate. Therefore, we plan the following measurement procedures.

10.2 Data to be collected and sample technique

1. **Soil strength.** Cone penetrometer readings will be taken from 27 feet to 33 feet of depth at each of the four corners just outside the 50 foot square area and in the center of the block. Cone penetration testing (CPT) is a process whereby subsurface soil characteristics are determined when a cone penetrometer, attached to a data acquisition system, is pushed into the subsurface using a hydraulic ram. The CPT provides a rapid, reliable and economical means of determining soil stratigraphy, relative density, strength and hydrogeologic information (hydraulic conductivity, static and dynamic pore pressure). Using direct-push methodology, CPT does not generate soil cuttings, thus eliminating special handling and costly disposal.
2. **Density of soil.** Collect continuous core samples from the four corners of the area to be excavated. Samples are to be prepared and density and strength measurements will be performed on site as the samples are removed. Standard ASTM and environmental lab methods are not sufficiently concerned with preservation and measurement of in situ moisture levels. We will write a custom testing protocol suitable to the task. We will core drill and recover core for the entire interval from surface to 30 feet deep. As the cores are removed from the hole, they will be cut into convenient and uniformly precise lengths (preferably 6 to 12 inches) and weighed to determine actual in place density. The measurement is to be performed within 15 minutes of bringing the core to the surface to minimize evaporation. After density testing, cores will be checked for **pocket penetrometer reading**, sealed in plastic bags, labeled and stored in the project office.

3. **The density of the grout.** The density of the grout from each truckload will be measured by standard API mud cup before discharge into the trench. Grout that varies from ideal density by more than 1 pound per gallon will be rejected for repair. After the density measurement, the sample will be placed into an airtight 5-gallon container for the composite sample. The samples may be stored at ambient conditions. When this is full, additional containers will be used. On a daily basis, this grout will be tested for density with a Halliburton pressurized mud scale, or other suitable device, to compensate for entrained air.
4. **Viscosity of the grout** will be monitored by a flow cone test. We will use a standard grout flow cone to provide a relative indication of viscosity.
5. **The permeability of the grout.** Samples will be collected as a composite from the samples used to measure density. One 200 cc sample will be pulled from each days mixing. Samples will be stored in airtight containers at ambient conditions or in office. At the end of the work the samples will be composited and two samples sent for lab permeability testing according to ASTM D-5084
6. **Permeability of in-place grout.** Just before the cap is installed we will obtain a sample from a measured depth in the cross trench outside the barrier. We will also obtain samples from each of the three augur drilled holes created to verify barrier depth and thickness. These samples will be tested for hydraulic conductivity by ASTM 5084.
7. **The maximum rise in the free edge of the block during the cut.** This will be measured optically and recorded with the video camera. We will place yardsticks fixed in the ground on both side of the trench and sight in the maximum and the average rise in the block during cutting operations.
8. **Measure the freeboard in the trench** at the four survey times and also document it with the yardsticks and video camera.
9. **Video of the defect trench construction.** Recorded from the trackhoe operators cab.
10. Video of the slurry trench construction.
11. Video of installing the load frames and winches.
12. Video of cutting the bottom pathway.
13. Video of raising the block.
14. Video of cap construction.
15. **Number and Dimensions of any visible cracks** appearing in the surface of the block. Cracks that appear to be deep are to be filled with cement and water slurry and then excavated for measurement. Measurement will be with a tape measure. Documented with a photograph of the cracks along with a ruler.
16. **The elevation of the corners and center of the top of the block** relative to exterior grade, at each of the four survey times. Also record the freeboard, fluid level elevation. This data along with the amount of surcharge soil allows us to calculate the barrier thickness maximum and minimum. This data is to be recorded by a professional surveyor.

17. **The water level in the monitor wells before construction.** This data is to be recorded by an instrument suited to the work, such as the Global Water brand, WL15. This device measures pressure on a sensor at a specific depth.
18. **Physical measurement of the bottom barrier depth and thickness** at 3 points in the block. This is to be done by auger drilling a hole at three points across a diagonal of the block. The auger drill will drill to within a foot of the predicted depth of the barrier, removing soil as it goes. The auger shaft will be carefully measured to allow depth determination from the point at which resistance stops and the drill bit breaks into the grout and the firm bottom depth.
19. Measure the leak down rate of a 2 psi pressure differential on the capped block. This measurement will be taken with a sensitive barometer device. Such as the Global Water brand WE100.
20. Record the internal and external barometric pressure during the long term permeation test period. This will also be recorded from the monitor wells with a sensitive barometer device. Such as the Global Water brand WE100 over the duration of the evaluation period.
21. Record the water table variation within the block and outside the block during the long term permeation test period. This will be done with a pressure sensor such as the Global Water brand WL15 over the duration of the evaluation period.
22. We will test three representative core samples, selected by Carter from the initial core drilling, of the soil from three different depths to form an estimate of the air permeability and water permeability of the native soil. These samples will be preserved in air-tight bags and placed in a cooler for transport to a lab. We will tests for water permeability by ASTM

10.3 Experimental Procedures

The experimental design of the project utilizes surface elevation measurement by standard land survey methods to verify the bottom barrier thickness. The sidewall thickness will be computed from the location and tilt of the surface survey. In addition to this we will also physically verify side wall thickness at several points by insertion of 24 inch wide Steel I-Beams to make sure the vertical barrier is at least 24 inches wide. The bottom barrier will also be at least 36 inches thick but we may make it thicker than this during cap construction.

We will attempt to physically verify the bottom barrier thickness by auger drilling a hole in the center of the block. Dry auger drilling a 3 to 6 inch hole at the center of the block, and (two other locations) to within 2 feet of the expected depth of the bottom barrier and verifying total drilled depth. Continue auger drilling by slow measured increments until breakout, as verified by the filling of the hole with grout or the falling of the drill rod. Measure how far the drill rod falls to calculate barrier thickness. Note this measurement accuracy will be on the order of plus or minus 4 inches because the point at which the

drill breaks into the grout will depend on soil strength and drill weight. Measurement of the drill rod fall will be performed by making chalk marks on the drill rod, opposite a fixed point, and measuring with a tape measure. The Hole will fill with grout to the level of grout in the perimeter trench. We will obtain a sample of the grout by pushing a 1-1/2 inch PVC pipe at least 3 feet into the grout. A string through the pipe connected to a 2-inch metal washer provides a crude bottom seal for the pipe during extraction. The sample will be placed in a sealed container and properly labeled with the date, time, block coordinates, and depth. Samples will be taken from each of the three augured holes. After the sampling task is completed, the remaining 4 to 5 feet of the hole will be partially filled with two bags of dry concrete mix and backfilled with soil before the top cap liner is installed.

The site is expected to contain perched water at depths from 10 to 20 feet. Regional water table is said to be about 50 feet deep. There is a possibility that no water table will be found within the 30 foot of depth but this is unlikely since the nearby monitor wells near C-749 often show water levels 10 to 20 feet deep. After construction of the bottom barrier the monitor wells will be used to dewater the soil block. We will remove all standing water from the interior of the block and measure any influx of water back into the block through the barrier. The monitor wells and the two ports in the top cap will be connected to a vacuum blower to reduce the pressure inside the barrier vault. After this process is complete, we hope to maintain a slight negative pressure on the entire earth block. The bottom barrier is made from a colloidal fluid material and is expected to provide an excellent seal. If we succeed in maintaining a negative pressure for an extended period, this will be additional evidence that the bottom barrier is both continuous and impermeable. It may take some time to bring the entire 75,000 cubic foot block to air pressure equilibrium.

10.4 Data Management

Data will be collected on hard copy bound journals with each page dated and signed by the person taking the data. Data will be transcribed to Microsoft Excel spreadsheets and drawings as needed, and the person entering and checking the data will be identified by name in the file along with the original data collection person. Elevation land survey data and trench depth data will be documented in the same way. Copies of the data will be converted to PDF files and provided to NETL.

10.5 Data Analysis and Interpretation

Data analysis of factors related to barrier construction will be performed by Carter. Problems encountered during construction will be described and improvements in methods proposed to solve them. This work will be to assess the permeability of the barrier. Carter will complete an engineering analysis of the constructability and performance of the barrier.

11.0 EQUIPMENT

- 1 Two Load frames according to the drawing LFRAM020.gcd
- 2 Two Winches: 100,000+ Lb@ 30 ft/min pull, 24 inch dia drum, configured for remote control operation.
- 3 One 350 horsepower hydraulic power unit
- 4 One 75 ton crane
- 5 One D-5 Dozer
- 6 One Cat 330 Trackhoe
- 7 One Case 580 D Utility backhoe
- 8 One 12 yd Spoils dump truck
- 9 Three, Concrete mixer trucks
- 10 One Batching platform
- 11 One Office trailer
- 12 One 50 KW Generator
- 13 One changing trailer
- 14 One Sanitary, shower, hand wash
- 15 Three eyewash facilities
- 16 Four 20,000 gal Water tanks
- 17 One Bentonite Slurry mixer
- 18 One Rough terrain forklift
- 19 20 cu yd Dumpster for grout bags and sacks
- 20 One Rough terrain cherry picker

12.0 ADDITIONAL PLANS

12.1 Environmental Impact

The planned work appears to pose very limited hazards to the environment, because no toxic materials are planned for the work. The site is not a wetland nor does it have any endangered species. The environmental hazards are limited to the potential for fuel or oil spillage from construction equipment. Some living creatures, such as insects, reptiles, and small mammals living within the block of earth to be isolated by this demonstration will be adversely affected by the cap structure that will cut off light and oxygen to the block of earth. Since this work will disturb an area smaller than 1 acre, this loss is not believed to be significant. If the cap structure is permitted to remain undisturbed and unmaintained, we hope to document its condition periodically to determine if these measures were effective. See the full NEPA document.

12.2 Environmental Safety and Health

The novel aspects of the EarthSaw construction method were designed using principles of inherently safer design. However, the technology also utilizes common industrial technology such as slurry trenching, cranes, dozers, dump trucks, forklifts, and concrete batching methods. Since these methods involve large machines with human operators, there is a potential for injuries to workers. The special equipment of the EarthSaw method is below ground and is not likely to present a hazard to workers. Other than motor fuels for the equipment, we do not expect to have any hazardous chemicals used in the work. We have conducted a review of the potential hazards in the Hazard Analysis and Comparison to Baseline document.

The Paducah site is located about 10 miles from the city of Paducah. The nearest medical emergency room is located in Paducah just off highway 24 at 1530 Loan Oak Road. A map of the emergency route is included in the attached full Health and Safety Plan.

12.3 Waste Management Plan

This project will produce waste bentonite slurry, soil, and water in roughly equal quantities. We plan to use permitted on-site disposal for these clean wastes. Since the project site is clean, we do not anticipate generating any contaminated wastes in this project.

If the project site turns out to be contaminated, the project may generate two potential types of wastes. First is the excavated soil from the vertical slurry trenches. In the unlikely event the soil is contaminated and we have to dispose it, we can take it to the PGDP onsite landfill. This is about one block away, but current security barriers may require us to detour about six miles to reach the disposal site. Disposal of soil and replacement soil will be additional cost.

The second type of waste generated by the work will be the residual bentonite slurry. This slurry contains about 5 percent bentonite clay. This slurry can be mixed with cement and disposed at the landfill. We can also treat this slurry material to separate most of the clay from the water, but it will still have some clay. If it is found to be contaminated, we will have to confer with PGDP environmental officials to determine the proper way to dispose of it.

12.4 Erosion Control Plan

We will establish a silt fence around the work area and around any soil storage areas outside the main area. The work area is flat and we do not plan to do any clearing and grubbing. The cap structure will be made with terraced slopes and seeded with hydro

mulch. Engineering drawings providing actual elevations, slopes and dimensions will be prepared and submitted for review DOE, PDGP and possibly the state of Kentucky.

The soil at the nearby borrow site used to close the C-404 landfill had a organic content of 2.76 percent and was classified as clay (cl) with the final surface being silty clay (ml) The universal soil loss equation was applied to tat site in accordance with WPA publication SW-867 and showed an expected annual loss of 1 ton per acre if it is immediately protected by hydro mulch versus 248 tons per acre if it is not protected.

12.5 Public Participation Plan

This project does not involve radioactive waste or environmental contamination, but it is a treatability test for remediation of C-749 site so we may need a plan for public participation. We would plan to make a presentation at one of the monthly public meetings. We will prepare a presentation based on our previous peer review presentation and present it at the monthly public meeting forum provided by DOE.

12.6 Schedule Plan

We expect that if we receive notice to proceed by November 2002, then we could begin mobilization in April of 2003. See the full schedule in the proposal.

12.7 Regulatory compliance Plan

The project team anticipates significant work and discussions with PGDP and state agencies to discover and comply with all applicable regulations. Regulatory issues may include obtaining a pumping or discharge permit. After we have constructed the basement barrier we may need to pump water out of it so that we can measure performance. However, we do not know if water pumped out may have to go to the PGDP water treatment plant, or it may be suitable for on site discharge.

We anticipate that the PGDP will require excavation permits. We also anticipate all workers and site managers will undergo up to 5 days of on-site training.

12.8 Project Organization Plan

Carter Technologies co will provide all engineering services and will serve as the general contractor. The project will be organized and managed by Ernest E. Carter, P.E. Principle of Carter Technologies Co and inventor of the technology. Carter Technologies

will also test and supply the load frames, cable, and winches. Carter will provide photography, video documentation, media kits, and VIP guest escort.

All proprietary grout materials will be pre-blended, weighed, certified, and shipped by Federal Industrial products. Materials provided by the Federal Industrial Products of MILLC, will be pre-blended and packaged in uniform weight units to facilitate reliable on-site mixing. Federal Industrial Products will also provide on-site technical advice and consultation to Carter Technologies.

All of the on-site construction work, including site prep, mobilization, well installation, slurry trench excavation, spoils handling and hauling, load frame, cable, and winch installation, grout mixing and placement, cable saw operations, block leveling, surveying, sampling, auger drilling, liner cuff and cap installation, vacuum draw down, water pumping, and demobilization will be performed by Inquip Associates Inc. under contract to Carter technologies Co. All workers at the site will be under the supervision of the Inquip supervisor. Inquip is a national slurry wall contractor with extensive experience in Corps of Engineers slurry trench projects and has a long association with the EarthSaw technology. See appendix for the qualifications of these companies.

12.9 Independent Sampling, measurement and control Plan

An independent inspection, measurement, verification program will be instituted by Carter to verify compliance with quality control specifications. Carter will provide a contracted inspector to verify measurement and sampling procedures are followed. We plan to hire an independent surveyor to perform surveying tasks. This individual will also record measurement data from all onsite measurements such as density, cable tension, water levels oversee data collection and verify that written sampling and data collection procedures are followed. He will provide written reports on data collection directly to the NETL representative with copies to Carter Technologies. Actual operations will all be video taped for detailed analysis. Copies of raw videotapes will be provided to NETL with the final report.

12.10 Equipment Clean Up / Decontamination Plan

Heavy excavation equipment and trucks will be cleaned with a portable pressure washer. Since no contamination is anticipated at this site this work will not require a special decontamination pad or contamination reduction zones. The primary objects to be cleaned will be the load frames themselves. They will be covered with grout when removed from the trenches. These load frames will be laid on their sides over a grassy area and washed with a pressure washer to clean them. If additional cleaning is required it will be done off- site at a regulated truck wash facility. The load frames are designed for simple cleaning and outdoor storage between projects. The winches will be cleaned in the same manner. After cleanup is complete, the crane will load the equipment on

trucks. The load frames will need the services of the crane during the cleaning process as well as loading for demobilization.

The load frames, winches, hydraulic power units, and spacer beams will be loaded on trucks and taken to the PGDP designated storage area. If no storage area is available, These items may be stored at the Inquip property to await additional work. At DOE's option the load frames may also be stored on government property.

12.11 Final Report

After the construction is complete and the groundwater permeation test is running, we will demobilize, evaluate data, and prepare a final report on the project based on the success criteria described in section 2.

1.12 Long Term Permeation Test Methodology

A secondary goal of this project is to demonstrate that we can evaluate the integrity of the barrier on an annual basis after construction. We will remove water from the interior of the soil block and measure and measure the response of the barrier to external variation of water table and barometric pressure.

The nature of the test demonstration requires a long test period to verify long-term performance through one complete annual cycle of water table variation. We believe the permeation test portion of the project should run 12 months. At the end of that period, we will provide an addendum report to the final report. This addendum will report and examine the water levels in the monitor wells inside the barrier and in the monitor well outside the barrier.

Success criteria for this portion of the work will be for the interior monitor wells to remain at a constant water level, lower than the average water level in the monitor well outside the contained area. If the water table outside the barrier is lower than the depth of the monitor wells inside the barrier then this portion of the test will be inconclusive.

The test will also measure and record the barometric pressure inside the monitor well inside the contained area and the barometric pressure outside the contained area. The data-logging device will be set to record measurements every 4 hours for the duration of the test. Success criteria for this experiment will be that the data set from the isolated well should not show a statistical correlation with the data from the external well. The external well will show daily variation with ambient weather change but the isolated well should not show any influence.

12.13 Site Restoration Plan

DOE will have the option of leaving the structure in place for further research or restoring the ground to a natural appearance at a slightly raised grade level.

For restoration, we propose removing all instruments and removing the top 4 feet of the cap by grading it down flush with the surrounding 1 acre area. The HPDE liner material over the top of the soil block will be graded off and any recoverable portions will be placed in a dumpster and disposed separately as non-hazardous solid waste. We will establish a final grade about a foot above the original grade. The bottom barrier and the 2 foot thick side barriers will remain in place. We will backfill the top five feet of the perimeter trench with native clay soil. Any fugitive grout will be blended with soil and covered with at least 12 inches of plain soil. The bottom barrier will remain substantially intact and the residual soil will be contoured around the site. We will use a backhoe to remove the top portion of the monitor well and PVC pipes to a depth of 5 feet deep. We will backfill this area with native clay material. We would then re-seed the disturbed areas with hydro mulch. We will provide DOE with as-built drawings showing the final condition of the site in the addendum report to the final report.

Appendix C: HEALTH AND SAFETY PLAN FOR FIELD-SCALE TEST

CARTER TECHNOLOGIES CO.

Draft Site Specific
Health and Safety Plan

DOE Contract No. DE-AC26-01NT41144
National Energy Technology Laboratory
United States Department of Energy

Research and Development Test of
EarthSaw Containment of Pits and Trenches
at
Paducah Gaseous Diffusion Plant
Paducah, Kentucky

Prepared By:
Carter Technologies Co
July 15, 2002

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PGDP Site Safety Officer

The following plan is a draft. The final plan will be developed in compliance with PGDP standards and approved by PGDP

Draft Site Specific Health and Safety Plan

Table of contents

1.0	INTRODUCTION
1.1	Scope
1.2	Site Description
1.2	Contractors
2.0	KEY PERSONNEL
3.0	SITE OPERATIONS AND ACTIVITIES
3.1	Site Operations Summary
3.1a	Verifying Perimeter Pathway
3.1b	Excavating Slurry Trench Around Perimeter
3.1c	Making Bentonite Slurry
3.1d	Installing the Load Frames and Winches
3.1e	Grout Manufacture and Replacement of Slurry with Grout
3.1f	Activating Cable Saw
3.1g	Completing the Horizontal Cut
3.1h	Leveling the Earth Block
3.1i	Increasing Barrier Thickness
3.1j	Installing Cuff Liner In Trench
3.2k	Engineered Top Cap
4.0	HAZARD DESCRIPTION
4.1	Chemical Hazards
4.2	Biological Hazards
4.3	Confined Space, fire and explosion
4.4	Collapsing Excavations
4.5	Physical Hazards
4.6	Radiological Hazards
5.0	TRAINING, MONITORING AND PPE
5.1	Pre-Mobilization Sampling
5.2	Personnel Training Requirements
5.3	Monitoring Program and Equipment
5.4	PPE Equipment
5.5	Procedures for initiating a change in PPE criteria
5.6	Levels of Protection
5.7	Specific Levels of Protection Planned for the Site
5.8	Exposure/Injury Medical Support
6.0	SITE CONTROL MEASURES
6.1	Buddy System
6.2	Site Communications
6.3	Perimeter Control

- 6.4 Decontamination Plan
- 6.5 Standard Operating Procedures
- 6.6 Equipment Decontamination
- 6.7 Personnel Decontamination Area
- 6.8 Disposition of Decontamination Wastes
- 7.0 EMERGENCY RESPONSE/CONTINGENCY PLAN
 - 7.1 Definitions
 - 7.2 Pre-Emergency Planning
 - 7.3 Personnel Roles and Lines of Authority
 - 7.4 Emergency Recognition/Prevention
 - 7.5 Emergency Contact Notification System
 - 7.6 Emergency Medical Treatment Procedures
 - 7.7 MAP and DIRECTIONS to Emergency Room
 - 7.8 Fire or Explosion (Unconfined)
 - 7.9 Spills or Leaks
- 8.0 ACCIDENT REPORTS
- 9.0 PLAN APPROVAL

Appendix AA Training and Review of Plan _____

Appendix BB Incident Report _____

Appendix CC Site Responsible Persons/Emergency Contacts

1.0 INTRODUCTION

This project is a full-scale field demonstration of a construction technology capable of placing an impermeable barrier under a closed radioactive waste burial site. We will be demonstrating the technology on government property adjacent to the Paducah Gaseous Diffusion Plant (PGDP). The site for the demonstration is considered to be clean, but caution will be exercised just as if this were a real waste site. The technology allows a buried waste site to be cut off from the environment and isolated without excavating or drilling into the actual disposed waste so it offers a significant measure of safety compared to baseline excavation methods.

1.1 Scope

A core drilling sampling program and cone penetrometer testing will be performed to determine physical conditions of the soil and tested to detect contaminants common to the adjacent plant area.

Equipment will be mobilized and setup on the natural grade to minimize erosion and concerns about potentially contaminated topsoil.

The EarthSaw construction method begins with the excavation of a conventional 2 foot wide slurry trench around the four sides of the 50-foot square by 30-foot deep soil block to be isolated. At the two corners of one side of the soil block, the crane will lower in a hollow steel load frame structures that have large pulleys at their base. A steel wire rope cable extends from a powerful winch at ground level down through the load frame to the pulley at the bottom of the load frame. The cable runs around the pulley and then horizontally around the other three sides of the soil block, and back up the second load frame to the second winch. The lightweight slurry used in slurry trench construction will be pumped out of the trench as it is replaced with special super dense grout that is pumped into the bottom of the trench. When the winches are activated, the cable saws horizontally under the soil block and gravity forces the fluid grout to flow into the cut and buoyantly float the soil block. Adding more grout to the perimeter trench raises the fluid level and the block floats upward as the thickness of the bottom layer of grout increases.

A special airtight plastic liner cap will be keyed into the grout in the perimeter trench and an earthen cap installed above that. This cap will be constructed using earthen materials excavated from the slurry trench. All excavated earthen material will be incorporated into the cap. The water will be removed from the isolate soil block through shallow wells and vacuum pumps will remove air from the block to provide for leak testing of the barrier over a period of many months.

1.2 Site Description

The work site is an open field on flat terrain outside the west fence of the PGDP. The site is covered in native grass and is patrolled and maintained for site security. The site has no overhead power lines, or buried lines.

Figure 2 View from west side of Paducah site. Test site is below right corner of circle.

The test site is an area just outside the west fence along the Kentucky Pollutant Discharge Elimination System, (KPDES outfall 015)

Figure 3 Plan view of test site and proximity to C-749 site. Long rows are stored cylinders of solidified Uranium Hexafluoride.

1.3 Contractors

Inquip Associates Inc will be the construction subcontractor responsible for all construction work on the site. Inquip has offices in McLean, Virginia and highly experienced in slurry wall construction in hazardous environments.

Contractor personnel and vendor personnel will not be allowed to enter the site unattended unless they have been briefed with regard to the potential hazards associated with the site and their respective role (if any) in the Site Health and Safety Plan.

2.0 KEY PERSONNEL

Ernest E. Carter, P.E. the president of Carter Technologies and inventor of the technology. Mr. Carter has over 20 years experience in underground soil modification and grouting technology. Mr. Carter will be the on-site Technical Adviser and Principal Investigator. Mr. Carter will approve all work plans, document results, record data, and

develop alternative procedures if problems develop in the course of the work. Carter will approve all changes to equipment, procedures, methods, and materials during the course of the project.

Dominique Namy, Phd, will be the contract and technical manager for Inquip Associates Inc. Dr. Namy will evaluate the safety and feasibility of all activities to be performed and will advise Carter of changes suggested or required. The Inquip Site Supervisor, and Site Safety Officer will be named when a final mobilization date is confirmed, both will report to Dr. Namy. It is anticipated that there will be a total of 8 to 10 persons on site for the bulk of the project.

Project organization

3.0 SITE OPERATIONS AND ACTIVITIES

3.1 Hazard Survey

The following Hazard analysis summary is intended to describe general operations and discuss specific potential hazards of each operation. For a complete description of operations, refer to the primary test plan document.

3.1a Verifying Perimeter Pathway

The EarthSaw is intended to construct a barrier outside the horizontal perimeter of contamination, and preferably below the vertical limits of contamination. The first step in planning a EarthSaw™ project is to determine the horizontal and vertical extent of contamination and to determine if the work will be done in clean or contaminated soil. This is generally done through a combination of historical records, interviews with workers, and non-invasive imaging and measurement technologies. Making these determinations and choosing where to place the barrier is inherently the site owners responsibility. However, even after the probable limits are determined, core drill boreholes would be drilled to verify absence of contamination along the path of the vertical perimeter trench. Cone penetrometer readings would also be taken at intervals. These technologies have well documented safety procedures and will not be discussed in detail, except to say that all such work should assume potential for contamination if it is adjacent to a contaminated area.

Primary hazards in core drilling are mechanical pinch points, and heavy pipe falling on workers. Safety equipment includes gloves, steel toe boots, and hard hats.

A hand held radiation counter will be used on site to spot survey for radioactive materials. Many common materials such as cement and fly ash will register higher than background levels. Materials that register significantly higher than common levels will be reported to PGDP site health and safety personnel so that they can make a determination concerning the material.

A dry trench will be excavated in the middle of the work area before construction begins. This trench is designed to create a plane of weakness in the soil. It will be immediately backfilled, and will not require shoring.

The **Primary hazard** here is that the trench could cave in and cause the ground surface along side the trench to slide into the excavation. To minimize this hazard, no personnel will be allowed to walk within 20 feet of the trench while it is open. A secondary hazard is that buried waste from historic times when the site was a munitions factory could be encountered. This hazard is minimized by using a long stick excavator so that the operator is about 20 to 40 feet away from where the excavating bucket is working. If waste is encountered we will stop operations and leave the work area until PGDP safety personnel evaluate conditions and provide further instructions.

3.1b Excavating Slurry Trench Around Perimeter

Once the outline of a clean perimeter to be isolated is evaluated and notification to proceed is received, the soil in the vertical perimeter trench will be excavated by a standard slurry trenching process. The spoils will be stacked directly into a dump truck and not placed on the ground. This work will be performed by an operator in a large tracked excavator (trackhoe). The trench depth must be carefully measured and this may pose a hazard for inspectors. Hazards consist of the slippery and wet ground surfaces near the excavation of the clean soil and the open fluid filled trench. Movement of the heavy equipment is also a hazard. Emergency air packs and supplied air will not be required at this site. The excavation material is wet and covered with slurry so dust is not expected to be a hazard. The equipment will need to be refueled each day from a fuel service truck. Existing site safety standards will apply to refueling operations. The spoils of the trench will be stacked outside the perimeter of the trench in a designated area.

The primary hazard in this operation is the possibility of heavy equipment such as the dump truck and the backhoe striking a man on foot. To minimize this problem we plan to keep workers on foot away from these two operations. Workers and inspectors will be permitted in the active trench area only when the excavator machine is not operating.

During the slurry trenching, the trench will be filled with slurry that is 10 to 20 percent heavier than water. The trench is also quite narrow at only two foot wide and is usually filled within a foot of the surface. The risks of suffering harm from falling into the trench are limited by our use of the buddy system. At the end of each shift, workers will place covers, such as wooden pallets, over the completed portion of the trench to avoid the hazard of personnel falling into the fluid filled trench. This site may not have controlled access during off hours. No nighttime lighting is planned. Animals and security guards can also fall in trenches if they explore the work area overnight.

Inspectors will drop weighted measuring lines to verify depth of the trench. Spoils may then be scooped up by heavy equipment and stockpiled for use in cap construction. If contamination of spoils is found, the material must be treated appropriately. Since the material will be wetted with the bentonite slurry, it will likely not present a dust hazard.

3.1c Making Bentonite Slurry

During the slurry trenching work, a support operation will supply bentonite slurry to keep the trench full of slurry. This operation will be performed by an operator running a mixing plant, making the bentonite slurry and circulating it to a large tank or pond. The operator will continually observe the fluid freeboard in the slurry trench and engage a pump on his mixer unit as needed to maintain the trench nearly full of slurry. The bentonite arrives at the site in 25 ton capacity pneumatic trucks. Whenever a truck arrives, the operator hooks it up to his mixer and mixes the entire truckload with water

and then pumps it into the storage tanks. The slurry is non-toxic by ingestion and dermal contact.

Primary hazards for the operator are breathing excess silica dust, from the pneumatic transfer. Both of these operations are common to the conventional slurry trench operation. The equipment is designed to allow an operator to move away from dusty areas. Dust PPE devices will be available to the operator at all times and he will be required to wear them if dust conditions appear to be heavy.

3.1d Installing the Load Frames and Winches

The next operation is the installation of the load frames and winches. There are two basic options for installing these items. The load frame with the cable already threaded through it will be placed into the trench first and the winch then placed on top of it.

The primary hazards here include those common to lifting equipment with cranes and PGDP site safety procedures would apply. No heavy lift in excess of 3 tons will be performed without a site safety meeting immediately preceding it. All personnel will be advised of their responsibilities and designated areas they are to be in during the lift. All crane operators must be certified competent to operate the equipment. There are also hazards of falls due to the slippery bentonite slurry which may be spilled on the ground. To minimize this hazard, we will cover with dirt or scrap up areas of slurry spilled on the ground surrounding the trench.

The load frames must have the cable treaded through them before they are picked up by the crane and lowered into the trench intersection. Lines may be attached to the base of the load frame to help position it during this process. After the load frame is in the trench, sand bags may be placed around it to steady it.

The winches are welded to a base plate (LFRAM028.gcd) that has four alignment pins that key and latch to the top of the load frame. This allows the winch and base plate to be quickly detached from the load frame. Load cells between the top of the load frame and the winch base plate measure the cable tension. Welding safety procedures require that a helper stand by with a fire extinguisher during all welding work. The PGDP hot work permit and rules must also be followed. After the winch is installed on the load frame the locking pins must be inserted and the cable attached to the winch.

Primary hazard here is the potential for pinch points and mechanical injury. To minimize this hazard we will pre-train the workers performing this work in a safety meeting to make sure they understand the proper way to assemble the equipment.

The cable can now be placed in the trench and allowed to fall to the bottom within a loop of rope line, or placed to correct depth by a positive mechanical means such as a pipe or I-beam structure lowered to a specific depth. We plan to attach the cable loosely to the bottom of an I-Beam, and then place that I-Beam into the trench to a specific depth dictated by a cross bar which limits its descent into the trench.

Primary hazard is a worker on the ground being hit by the steel beam being swung by the crane. To minimize this hazard this work will be done only by a worker trained in spotting and guiding a crane operator. The spotter must be skilled in all the standard hand sign signals. Additional hazards here include slips and falls and crane and rigging dangers.

Figure 4 Winch mounted before load frame installation

The Hydraulic power pack can be mounted on the winch or on the ground as shown Here.

Figure 5 Winch mounted before load frame installation

3.1e Grout Manufacture and Replacement of Slurry with Grout

The grout will be made in ready mix concrete trucks . A specific volume of Premixed colloidal slurry will be added to an empty truck. This truck will then move under a feed hopper, which receives cubic yard size sacks lowered into it by a crane. The feed hopper is mounted on a special stand with ladders and safety rails. A specific number and type of sack materials will be loaded into each truck. The truck will mix the materials and discharge them into a tremie pipe hopper in the trench.

Primary hazards here are that workers on top of the loading hopper and encounter pinch points, fall off the stand, breath excessive dust or the truck may strike the stand. To minimize these hazards the worker will have safety railings, guards, and OSHA compatible stair or ladder. The worker will be able to move to any side of the hopper to stay upwind of any fugitive dust. The stand will be well anchored so that it will not fall over if struck by a truck.

A tremie pipe common to slurry trench work is typically about 14-inch diameter and of a length to reach the bottom of the trench. The top has a funnel opening. This unit will be placed in the trench by the crane and tied off at the surface so that it cannot fall. Grout is poured down this tremie pip to the bottom of the trench. The grout may be pumped to the tremie pipe but in this work it will be discharged from mixer trucks. The grout, which is

much denser than the slurry, fills the bottom of the trench while the lightweight slurry is pumped off at the surface and stored in tanks.

Primary hazard here is traffic hazard with the concrete mixer trucks. There will be three or more of these trucks and at the same time this operation is going on there will be other workers pumping slurry out of the trench. We will conduct safety meetings to train drivers to be careful and workers on foot not to assume they are visible to drivers.

3.1f Activating Cable Saw

The winches that control the cable saw are operated from remote control stands that may be mounted 50 feet from the winches. If we desire a slicing mode of operation, the winches will both be activated at once with full power. The operator will monitor the rotation of the winch drums to determine the progress of the cable. For larger projects the winches may be equipped with footage counters but not for this project. The grout feed operator will monitor the leading edge of the earth block and maintain the fluid level in the trench specified by the computer model to give 4 inches of lift. As soon as the cut proceeds substantially, the leading edge of the earth block will rise. If the block does not begin to rise after the cable has advanced a distance along the centerline equal to the depth of the cut, the grout level will be increased until the block begins to rise. From that point onward, the operator will monitor the uplift of the leading edge of the earth block and add grout when the uplift is less than 2 inches and stop adding grout when it is 4 inches high.

As the winches are activated, all personnel must be kept at least 40 feet away from the winches. The steel cable may be highly stressed during certain operations but it is also substantially submerged in viscous grout underground.

If the cable becomes wedged over a sharp rock or the frictional load exceeds the strength of the cable, the cable may break. Stress on the cable is normally highest at the winch because of the high friction of the cable around the curvature of the underground cut. If a pressure roller is not on the winch, the cable may uncoil off the drum to some extent. It is however possible that the cable could break underground if it becomes weakened by pressing over a sharp rock.

Primary Hazard is that breakage of the cable can cause a short but potentially violent movement of the winch and load frame assembly. Stored energy due to cable stretch is limited in the field demonstration since vertical cable length is only 30 feet and horizontal cable length is less than 150 feet. This hazard will be minimized by keeping all persons more than 40 feet away from the winches when they are making the bottom cut.

On larger or deeper projects, higher energy levels could be stored by the cable. In these cases the cable could pass through a device stretched between supports located under the

winch. This device would help clean the cable and help suppress any sudden motions of the cable.

Figure 6 General configuration while making the bottom cut

3.1g Completing the Horizontal Cut

At the end of the cut, both load frame structures may move suddenly as the cable finishes its cut. At this time the corner of the block under the winch, base plate will rise several inches and may press against the winch base plate.

Primary hazard is that a worker could be a pinched or injured by this sudden movement. To minimize this hazard no persons will be allowed near the winch during the bottom cut.

When the cable reaches the end of its travel it will be stretched between the two load frames and could break if the operator was using full power to finish the cut in slicing mode. Since personnel are not located near the winch breaking the cable should not be a hazard. It is more likely that the cable tension will reduce significantly in the last few feet of cut. Once the cut is complete, we will simply wind all the cable onto one winch.

If we want to pass the cable under the floating block again, we can snag it with a hook on a pole and lift it out with the crane, as the winch pays out cable. The cable may be extended and dropped in the perimeter trench to pull through the horizontal cut again. This will demonstrate that the pathway is still continuous. This optional activity represents a potential hazard since the cable would be covered with slippery grout. We do not plan to do this since the continuity of the bottom barrier can be inferred from the movement of the top of the block.

3.1h Leveling the Earth Block

In larger projects, if one quadrant of the block rises substantially more than another, the work would be stopped and dozers would begin moving dirt to the light corner to balance the block. (Dozers can push dirt right over the open trench, or a wooden crane mat may be laid over the trench.) If dirt is to be added trucks may also drive onto the block and dump in designated points. The trucks can deposit uniform weights of dirt in piles around the center of each quadrant. The piles do not have to be leveled immediately.

Primary hazard is that the trucks may get stuck and a dozer will have to hook on to the truck to drag it out of the mud. Over stressed chains and pinch hazards during hook up can cause personal injuries. To minimize this problem we will have suitable safety chains and safety meeting discussions on how to use them. In order to avoid this problem we will use the trackhoe to perform any addition of dirt from outside the

Leveling the Earth Block

perimeter of the block.

LFRAM032.gcd

The I-Beam spacers may be used to help verify where to place additional weight. This may be done by moving the top of the I-Beam back and forth longitudinally with the trench. The radius of the motion will indicate the depth at which the beam is pinched by the earth block.

Primary hazard; If a worker on the ground is used in this operation, it may represent a hazard common to heavy equipment spotter assistance. We will only use spotters who are specially trained.

3.1i Increasing Barrier Thickness

After the cut is complete, additional grout is added to the trench to develop the final barrier thickness. Before doing this, the elevations of the top of the block and the surroundings must be surveyed and recorded. At this point adding grout to the trench to raise its fluid level will result in an equal rise in the top of the block. Increasing the barrier thickness does not appear to present any special hazard.

Primary hazard is that due to mixing grout and mixer truck traffic previously discussed.

As soon as the barrier is complete, the wells will be fitted with suitable pumps or vacuum well points to remove all standing water from the soil block. After this water is removed, we will periodically measure water levels in the wells to determine how much water makes its way back through the barrier.

3.1j Installing Cuff Liner In Trench

The cuff liner is a folded HDPE liner made from a roll of HDPE material. The liner is folded along its length and seamed at the fold to make a point. This folded cuff is dropped into the trench and additional grout is pumped into the cuff to cause it to sink.

The liner is sunk all the way around the perimeter of the earth block and then overlapped at the ends.

Primary hazard here includes slips and falls and heavy equipment/worker on foot interactions. This work will require many workers. They will all be wearing gloves and steel toe boots. If a worker should fall into the trench, he will float waste high and can

will be easily pulled out by others. Eyewash and hand wash stations should be kept nearby for routine use, and clean up. The grout is like thick paint in many ways and

availability of wash water for personnel and tools should be maintained in close proximity to the work as a housekeeping measure. **Secondary hazard** is the wind blowing the liner and knocking some one down or into the trench. To minimize this we will perform this work in the still air very early in the morning.

3.1k Engineered Top Cap

After the concrete ring cap is complete, the liner is seamed to another section of HDPE covering the top of the earth block and an area around the perimeter.

Primary hazard is slips and falls when walking on the liner. We plan to use a special rough surface HDPE material for the upper liner.

An engineered earthen cap is then constructed on top of the block. Sensors and wells may be placed under the cap and in the surrounding areas. This construction does not present any unusual hazards beyond keeping personnel on foot clear of heavy equipment.

After the engineered top cap is in place additional negative air pressure tests will be conducted. The wells will be attached to vacuum blowers and the pressure of the earth block reduced. This will result in a some compaction and drying of the soil within the earth block.

Primary hazard here is the proper hook up of electrical operated blower equipment. To minimize this hazard all non-plug in wiring will be performed by licensed electrician.

-----End of Site operations description-----

4.0 Hazard Description

4.1 Chemical Hazards

Known Chemical hazards may include dusts from materials used in the grout and the bentonite slurry. These include silica dust which is present in all earthen materials but which can be a serious lung hazard with long term exposure. The duration of exposure in this work will be short and individuals who are required to be in areas of visible dust will be provided with respiratory protection PPE.

The grout may also contain Portland cement which is another source of silica but also contains free lime that is a high pH material able to cause burns to skin and eyes and lungs with prolonged exposure. The grout may also contain sodium carbonate that is also a high pH material able to cause the burns to skin, eyes and lungs. The grout also contains red iron oxide that is a mechanical irritant to eyes and lungs and stains exposed skin. The grout contains elemental sulfur, which is a mechanical irritant to eyes and skin. The grout is non-toxic by ingestion but is an eye irritant. Skin contact is not expected to cause irritation but will strongly stain skin and clothing. Eye and hand wash stations should be kept in close proximity to use and manufacture of the grout. The grout is not expected to cause any distress to plants if dispersed in soil, in total concentrations less than 10 percent. Spillage of grout on personnel should be washed off as soon as practical with a water hose, followed by soap and water cleanup.

4.2 Biological Hazards

Biological hazards that may be present at the site are snakes, fire ants, and mosquitoes. Caution should be exercised in marsh and/or grassy areas of the site. Snakes should be avoided if sighted. If a worker is bitten by a snake, ice should be placed on the bite area and the worker immediately transported to the nearest hospital. Ointment and repellent should be utilized for protection from mosquito bites and fire ants. Directions and a map to the nearest hospital are included in the appendix. Infection hazards for cuts and puncture wounds are also a possibility and should be treated at once with proper first aid.

4.3 Confined Space, fire and explosion

Confined space, fire, and explosion hazards are possibilities in a metal tank. Confined space entry is not anticipated during the project. This project will use large 21,000 gallon tanks for water storage, and slurry storage during the project. These tanks are used for various liquids and have the potential to create an atmosphere that is toxic, oxygen deficient, and/or explosive in nature. Confined spaces shall not be entered until air monitoring has established the lower explosive limit (lel), the benzene/hydrocarbon concentration (ppm), and the oxygen content.

We do not anticipate any event that would require our personnel entering any tank, but a tank-cleaning subcontractor will be required to clean the water tanks at the end of the job. Tank cleaning contractors will not be allowed to enter a confined space without the prior approval of the site health and safety manager and evidence that they are trained to do the work safely according to OSHA rules.

Heavy equipment will have fire extinguishers on board and fuel stored on the work site will be in accordance with federal state and local regulations.

4.4 Collapsing Excavations

The potential for excavation walls and slopes to collapse would present an immediate threat to the health and safety of personnel in or beside an excavation site. Because of the unpredictable nature of excavation walls, no personnel shall enter an open excavation unless slopes are, at a minimum, excavated or shored in accordance with applicable osha regulation (29 cfr 1926.652). Excavations requiring entry of personnel are not anticipated in the project. Personnel will not stand or walk near an unsupported excavation. Temporary trenches 2 to 3 foot wide and up to 30 feet deep may be prepared in portions of the work. If these trenches are empty and not filled with slurry or grout, personnel may not stand or walk within 15 feet of the edge of the trench. This boundary must be staked and marked with safety tape before being excavated. Persons shall not walk or stand closer to a grout or slurry trench than $\frac{1}{2}$ of the freeboard distance unless they are standing on plank, grating, pallet or other structure that bridges the trench by at least a foot on either side of the trench. Free board is the distance from the grade level to the fluid level.

No trench not filled with grout or slurry shall be allowed to stand open overnight. All slurry filled trenches must be covered by planks, gratings, or pallets each night to minimize the possibilities of persons falling into the trench.

4.5 Physical Hazards

The work contains many common physical hazards such as heavy equipment working, crane operations lifting and lowering equipment, and dump truck operation. Uncommon hazards include highly stressed wire rope below ground, and open trenches containing high specific gravity grout. Physical hazard protocol is as follows:

- a. Only qualified, trained personnel shall operate heavy equipment.
- b. All machine safeguards must remain in place.
- c. All overhead objects (i.e. power lines) and underground objects (utility lines, etc.) must be located before excavation or trenching. Locating these utilities is the responsibility of the PGDP, since the PDGP has selected this location for testing and the facility deals with special and classified materials.
- d. Heat Stress - All personnel will be visually monitored for evidence of heat stress. Workers will be encouraged to drink adequate amounts of water and to recognize signs of over-exertion.

- e. All equipment used to specifically move personnel shall be designed and operated in accordance with OSHA standards. Personnel will not ride in the back of trucks.
- f. Elevated platforms such as that for mixing the grout will be equipped with railings and OSHA ladders or stairs.
- g. Dump trucks shall be equipped with back up alarms.
- h. Work shall only be performed in daylight hours.
- i. Excavation shall stop immediately if man made objects, such as boxes, drums, barrels, or unusual materials are discovered.
- j. No personnel shall come within 40 foot of the winches when they are operating under more than nominal load. (Personnel may be as near as required for cable installation. The winch must turn to load and unload the cable and to position the cable in the trench.)

4.6 Radiological Hazards

No radiological hazards are anticipated in this project however due to the proximity to a facility handling radioactive materials, and the need to demonstrate safe operating procedures for radioactive waste sites we will perform some testing. There may be a small but measurable natural radiation in the cement and other mined natural materials used in the grout. Housekeeping measures to prevent excessive breathing of dust created by these materials will minimize any hazard.

5.0 TRAINING, MONITORING AND PPE

5.1 Pre-Mobilization Sampling

We believe that the PDGP will desire to conduct their own testing for radiological hazards before allowing us access. However, we will also perform limited testing of a level appropriate for a site having a small potential for unknown contamination. This will include a surface soil sample from zero to 1 inch deep collected from at least 20 locations on the site. We will also test random soil and water each day. These samples will be tested by a hand held radiation meter such as the model INSPECTOR-EXP from Stormwise company in Yantis TX. If any samples are found which seem to be significantly above background levels we will report this to the PGDP health and safety personnel and request that they make a determination of any hazard or any required upgrade of PPE.

5.2 Personnel Training Requirements

All personnel who perform project work at the site will be required to have a minimum 40 hours OSHA Health & Safety [OSHA CPR 1910.120 (q)] training, and be current with respect to OSHA training guidelines. This training will provide employees with the knowledge and skills necessary to perform their job assignments with minimal risk to their safety and health. Inquip and Associates Inc., will supply and supervise all workers on the site. Inquip maintains OSHA 40 hour training for hazardous waste workers, certification on all these workers. At a minimum, all site personnel are required to be trained to recognize the hazards on-site, the provisions of this plan, responsible personnel, and their role with respect to emergency response actions.

All personnel will also be required to complete training which may be required by and provided by the PGDP health and safety department. Further discussions with PGDP after contract award will clarify the requirements for visitors and delivery truck drivers.

5.3 Monitoring Program and Equipment

Medical monitoring programs are designed to track the physical condition of employees on a regular basis as well as survey pre-employment or baseline conditions prior to potential exposures. Inquip's workers have medical monitoring as a part of their normal work under. OSHA CPR 1910.120

We plan to perform regular testing of the materials and soil on the site for radiation. Samples will be tested with a portable radiation meter such as the model INSPECTOR-EXP from Stormwise company in Yantis TX. This device is a GM tube type rated 0.001 to 100 MR/Hr with accuracy within 15% up to 30 MR/Hr. This meter will also be used to spot survey the excavation spoils on a daily basis. If there is any visual evidence or smell of organic vapors in the soil we request that PGDP health and safety personnel investigate and advise us if additional PPE is recommended. Water produced from the dewatering wells will be tested for TCE contamination. Water that is verified clean of TCE and radioactive contamination by certified laboratory test, will be discharged in accordance with local and state regulations. Contaminated water may be cleaned at additional expense or may be transported to the PGDP water treatment system.

5.4 PPE Equipment

The base level of PPE on this project will be level D with hard hat, safety glasses, steel toe shoes and coveralls. Personnel may optionally wear disposable coveralls and boot covers to protect clothing from stains. Personnel exposed to visible levels of dust will wear suitable respiratory protection as determined by the site safety officer.

5.5 Procedures for initiating a change in PPE criteria

The Inquip site supervisor may order an upgrade in the level of Personal Protective Equipment at will or upon a recommendation from the Carter Technologies representative or the PGDP representative. Reduction to a lower level of PPE will require agreement between Carter and Inquip.

5.6 Heat Stress

Heat stress is perhaps the most common serious injury to hazardous waste and construction workers. If the project is done in hot weather this is a serious hazard. In hot weather workers should be required to consume generous quantities of water every day. If the site is not contaminated, and if PGDP agrees, our workers will be provided with chilled bottled water in break areas, and permitted to take the bottles to their work location to encourage water consumption. Break areas will be air conditioned so that workers may escape the heat periodically.

5.6 Levels of Protection

Personnel will wear PPE when activities involve known or suspected atmospheric contamination, when vapors, gases, or particulate may be generated by site activities, or when direct contact with skin-affecting substances may occur. Half facepiece respirators protect lungs and gastrointestinal tract against airborne toxicants. Chemical-resistant clothing protects the skin from contact with skin- destructive and absorbable chemicals.

The specific levels of protection and necessary components for each have been divided into four categories according to the degrees of protection afforded:

Level A: Should be worn when the highest level of respiratory, skin and eye protection is needed.

Level B: Should be worn when the highest level of respiratory protection is needed, but a lesser level of skin protection. Level B is the primary level of choice when encountering unknown environments.

Level C: Should be worn when the criteria for using air-purifying respirators are met, and a moderate level of skin protection is needed.

Level D: Consists of a work uniform or coveralls with hard hat, safety glasses and safety shoes. Gloves may be used to upgrade for limited skin protection against solid phase

materials such as oily soil. Not suitable for any area with respiratory or acute skin hazards. It provides minimal protection against chemical hazards.

The Level of protection selected is based upon the following:

- ✓ Type and measured concentration of the chemical substance in the ambient atmosphere and its toxicity.
- ✓ Potential for exposure to substances in air, splashes of liquids, or other direct contact with material due to the type of work conducted.
- ✓ Knowledge of chemicals on-site along with properties such as toxicity, route of exposure, and contaminant matrix.
- ✓ In situations where the type of chemical, concentration, and possibilities of contact are not known, the appropriate level of protection must be selected based on professional experience and judgement until the hazards can be assessed.
- ✓ Based on experience at the site to date, and the materials which are to be used or known to have spilled, it is not expected that any employee will be required to wear protection greater than Level D. Almost all anticipated work may be completed in Level D with gloves. If an instance should arise that requires Level B protection, all employees will be evacuated from the area, and the Site Health and Safety Plan re-evaluated prior to re-entry.

Level C Personal Protective Equipment:

- Full-face or half-face (with chemical splash resistant goggles), air purifying, organic vapor canister equipped respirators (NIOSH approved).
- Hooded/non-hooded chemical/splash resistant clothing (coveralls; two-piece chemical-splash suit; disposable chemical/splash-resistant overalls)*.
- Coveralls.
- Safety glasses
- Gloves, chemical resistant.
- Boots, chemical resistant steel toe and shank. . Hard hat (if overhead/bump hazards exist). . Leg protectors (in snake-prone areas)*

* Optional

Level C should be used when:

1. The atmospheric contaminants, liquid splashes, or other direct contact will not adversely affect or be absorbed through any exposed skin,
2. The types of air contaminants have been identified, concentrations measured, and an air purifying respirator is available that can remove the contaminants, and all criteria for the use of air purifying respirators are met.

Level D Personal Protective Equipment:

- . Coveralls
- . Gloves (if handling soil)
- . Boots, chemical-resistant (steel toe and shank recommended) . Safety glasses
- . Hard hat (if overhead/bump hazards exist) . Leg protectors (in snake-prone areas)*

* Optional

Level D protection should be used when:

1. The atmosphere contains no hazards, and
2. Work functions preclude splashes, immersion, or the potential for unexpected inhalation of or contact with hazardous levels of any chemicals.

5.7 Specific Levels of Protection Planned for the Site

The following levels of protection will be utilized during activities at the project site:

- Level D: During all site activities.

5.8 Exposure/Injury Medical Support

As a follow-up to an injury or possible exposure above established exposure limits, all employees are entitled to and encouraged to seek medical attention and physical testing. Depending upon the type of exposure, it is critical to perform follow-up testing as soon as possible.

6.0 SITE CONTROL MEASURES

The following section defines measures and procedures for maintaining site control. Site control is an essential component in the implementation of the site health and safety plan.

6.1 Buddy System

During all activities when some conditions present a risk to personnel, the implementation of a buddy system is mandatory. A buddy system requires at least two people who work as a team; each looking out for each other.

6.2 Site Communications

A portable telephone will be located in the field command center. This phone will be for work related and emergency use only. Two-way radios will be utilized for person to person communication on the project site as needed.

6.3 Perimeter Control

Existing fencing and ditches will be utilized where possible to maintain control of the project perimeter. It may not be possible to prevent unauthorized visitors from entering this site. PGDP security personnel have authority over this area and can not be prohibited from entering the site. The Inquip representative will be prepared to stop the work and at any time if the presence of visitors presents a safety hazard. Inquip will place barrier tape lines around work in progress which presents a hazard to visitors which stop to observe the work.

6.4 Decontamination Plan

Table II lists the tasks and specific levels of protection required for each task. Consistent with the levels of protection required. Since this work will be in level D the decontamination issues will be preventing tracking of the red grout out of the work area and removal of soil which may spill in any roadway. These procedures should be modified to suit site conditions.

6.5 Standard Operating Procedures

Decontamination involves the orderly controlled removal of contaminants. All site personnel should minimize the need for extensive decontamination.

The Inquip Site Safety Officer or his designee is responsible for monitoring decontamination procedures and determining their effectiveness.

6.6 Equipment Decontamination

Heavy excavation equipment and trucks will be decontaminated by digging clean soil until the excavator bucket is relatively clean. If the wheels or tracks of a unit become contaminated they will be decontaminated with a portable pressure washer and the impacted soil removed. Since no contamination is anticipated at this site this work will not require a special decontamination pad or contamination reduction zones. The primary objects to be decontaminated will be the load frames themselves. They will be covered with grout when removed from the trenches. We estimate that about 20 cubic feet of grout will remain on each after removing it from the trench. These load frames will be laid on their sides and washed with a pressure washer to clean them. Any recovered groundwater, which has already been verified to be clean, may be used for this cleanup process. Additional cleaning will be done off-site at a regulated truck wash facility. The load frames are designed for simple cleaning and outdoor storage between projects. The load frames will need the services of the crane during the cleaning process as well as loading for demobilization.

6.7 Personnel Decontamination Area

Personnel decontamination is not expected to be necessary for this site due to the absence of hazardous or radioactive material. If contamination is discovered and personnel decontamination is required, it will most probably be accomplished with plastic sheeting, a boot wash tub filled with an Alconox detergent solution, a rinse tub filled with water, and a disposable clothing disposal container. A spray bottle of methyl alcohol will also be used to clean off any contamination on equipment or delicate instruments. Long handled brushes will be provided to clean the boots.

At the end of a work shift or prior to leaving the immediate work area or entering eating, smoking or drinking areas, employees will remove any contaminated clothing and dispose of it appropriately. Discarded clothing will not be reused until it is properly cleaned, but respirators can be reused once they have been decontaminated (washing with soap and water). On sites with substantial probability of workers' clothing being contaminated, a small changing tent or trailer will be available to facilitate workers changing out of contaminated clothing before leaving the site.

As soon as possible, after removal of personal protective gear, employees will wash their hands and face. If shower facilities are available, employees will shower and change into uncontaminated clothing. If shower facilities are not available, employees will be provided with a portable hand and face wash station. Employees will be encouraged to shower at the end of each shift.

6.8 Disposition of Decontamination Wastes

The sacks containing dry grout materials are non-hazardous and will be accumulated in a commercial dumpster and disposed in accordance with state and local regulations. Disposable personal protective equipment such as Tyvec suits, gloves, paper wipes, and tape will be collected at the Personnel Decontamination Area. These items will be placed in a labeled fiber drum with a removable lid. If no contamination has been found at the site at the end of the work, this drum will be disposed in the commercial trash dumpster along with the grout material sacks. If contamination is discovered this waste will be disposed of accordingly. Should cotton coveralls, regular clothing, or undergarments become contaminated, commercial laundries or cleaning establishments that decontaminate protective clothing or equipment shall be informed of the potentially harmful effects of exposures. The fluids generated from decon activities involving more than 100 gallons (per site) of water will be removed for offsite disposal. Small quantities less than 100 gallons (such as from a garden hose spray or a boot wash tub) and which show no visible oil sheen will be disposed to normal surface drainage.

EMERGENCY RESPONSE/CONTINGENCY PLAN

This section describes contingencies and emergency planning procedures to be implemented at the site. This plan should be compatible with local, state and federal disaster and emergency management plans as appropriate. We anticipate that any emergency response plan for the proposed work may have more to do with the materials inside the fence than those outside the fence where our work area is located. The types of events that may require emergency response will be discussed with the PGDP health and safety professionals before completing this section. The following is an outline of the elements we would expect to include in such a plan.

7.1 Definitions

Emergency Coordinator - employee(s) who are given the responsibilities of the Emergency Coordinator if required during an emergency situation.

Confined - Within specific bounds; unable to spread further; under control using site spill control equipment; poses no threat to human health or environment as assessed by the Emergency Coordinator.

Contained - Within specific bounds; unable to spread further; under control utilizing site fire control equipment and personnel; poses no threat to human health or environment as assessed by the Emergency Coordinator.

Emergency Coordinator - One employee at the location (usually the Site Safety Manager) with the responsibility for coordinating all emergency response measures. The Emergency Coordinator shall be familiar with all aspects of the operational activities on-

site, the location and characteristics of materials on-site, the location of records for the project, the location of project sites, and all aspects of the Emergency Response Plan. The Emergency Coordinator has the authority to commit the resources necessary to fully implement any Emergency Response Plan. Potential causes of an emergency response include gas and electric line ruptures and medical emergencies at the work site.

Emergency Response - Response efforts by employees from outside the immediate release area or by other designated responders (i.e. mutual-aid groups, local fire departments, etc.) to an occurrence, which results, or is likely to result, in an uncontrolled release of a hazardous substance. An emergency situation which is deemed so by either the or Emergency Coordinator.

Human Health, Property, or Environmental Hazard - Potential for extensive property damage; release of hazardous substance as a result of the explosion; variable chance of recurrence; poses threat to human health or the environmental as assessed by either the Emergency Coordinator; implementation of the Emergency Response Plan utilizing outside emergency response parties.

7.2 Pre-Emergency Planning

During the site briefings held initially and periodically thereafter, all employees will be trained in and reminded of provision of the emergency response plan, communication systems, and evacuation routes.

7.3 Personnel Roles and Lines of Authority

The Emergency Coordinator has primary responsibility for responding to and correcting emergency situations at the project site during remediation activities. This includes taking appropriate measures to ensure the safety of site personnel and the public. Possible actions may involve evacuation of personnel from the site area, and evacuation of adjacent residents. He/she is additionally responsible for ensuring that corrective measures have been implemented, appropriate authorities notified, and follow-up reports completed. An alternate may be called upon to act on the behalf of the Emergency Coordinator, and will direct responses to any emergency.

7.4 Emergency Recognition/Prevention

Section 4.0 provides a description of chemical and physical hazards on-site. Personnel will be familiar with techniques of hazard recognition from Pre-assignment training and site specific briefings.

7.5 Evacuation Routes/Procedures.

In the event of an emergency which necessitates an evacuation of the site, the following procedures will be implemented:

- . Personnel will be expected to proceed from the work area with their buddy, and mobilized to the designated safe area.
- . Personnel will remain at that area until an authorized individual provides further instructions.
- . The Emergency Coordinator or his designee shall notify any other occupants of the property of the hazard and perform a head count and roll call to determine all necessary persons have evacuated the site.

7.6 Emergency Contact Notification System

Table III will provide names and telephone numbers for emergency contact personnel and emergency assistance/notification agencies. This table will be completed after the responsible parties at the PGDP and DOE are identified. In the event of a medical emergency at the project site, personnel will take direction from the Emergency Coordinator or his designated alternate(s) and notify the appropriate emergency organization. In the event of a fire or spill, the Emergency Coordinator will notify the appropriate client personnel.

7.7 Emergency Medical Treatment Procedures

If working in a contaminated area, any person who becomes ill or injured in the project area must be decontaminated to the maximum extent possible. If the injury or illness is minor, full decontamination should be completed and first aid administered prior to transport. If the patient's condition is serious, at least partial decontamination should be completed (i.e., complete disrobing of the victim and redressing in clean coveralls or wrapping in a blanket.) First aid should be administered by the Site Safety Manager or his designee while awaiting an ambulance or paramedics. All injuries and illnesses must immediately be reported to the PGDP Site Representative.

Any person being transported to a clinic or hospital for treatment should take with them information on any chemical(s) they have been exposed to at the site if applicable.

Any vehicle used to transport contaminated personnel will be cleaned as necessary.

7.8 Map And Directions To Emergency Room

In the event of an emergency, the direction to be taken to the nearest hospital is proceed south of Riceville Rd 2.8 miles,

Turn LEFT (East) onto US-60 [Hinkleville Rd] and go 10 miles

At I-24 Exit 4, turn RIGHT (South) onto I-24 and go 2.5 miles

At I-24 Exit 7, turn LEFT (North-East) onto US-45 [Lone Oak Rd] and go 0.2 miles

Arrive Lordes Emergency Room, 1530 Lone Oak Rd, Paducah, KY 42003

7.9 Fire or Explosion (Unconfined)

In the event of an unconfined fire or explosion in the project area, the local fire department should be summoned immediately. Upon their arrival, the Emergency Coordinator or designated alternate will advise the fire commander of the location, nature, and identification of the hazardous materials on site.

If it is safe to do so, site personnel may:

- . Use fire fighting equipment available on-site to control or extinguish the fire; and,
- . Remove or isolate flammable or other hazardous materials that may contribute to the fire.

The following procedures will be implemented in the event of a fire that will not be responded to by an outside emergency response team.

- . Determine the extent and source of the fire. If the source of the fire can be slowed or stopped by a mechanical source (i.e. valve closure) do so prior to fighting the fire.
- . Put the fire out using the Emergency Coordinator's approved method and appropriate equipment.
- . Once the fire is out, keep the area secured and have an employee watch the area if it is possible, the fire may re-ignite.
- . Secure the area to ensure personnel are not exposed to heat, flames, or vapors.
- . Secure electric power, gas, and hazardous material that might create a health or safety problem.
- . Notify the Emergency Coordinator of the event. Return fire fighting equipment to its proper store area.
- . Salvage all material possible. Take steps to protect buildings and equipment from further damage.

7.10 Spills or Leaks

In the event of a spill or a leak, site personnel will:

- . Inform the Site Safety Manager immediately;
- . Locate the source of the spillage and stop the flow if it can be done safely; and,
- . Begin containment and recovery of the spilled materials.

8.0 Accident Reports

Once the emergency is under control, the Emergency Coordinator or his designated alternate will complete an Incident Investigation Report (See APPENDIX B). The Emergency Coordinator will also document all notifications made to authorities regarding the incident (if necessary). Copies of this report will be forwarded to the Environmental Coordinator(s).

PLAN APPROVAL

This site specific safety plan has been prepared for use by Carter Technologies Co. and subcontractors directly contracted by Carter. The plan is written for specific site conditions, tasks, dates, and must be amended if these conditions change. The subcontractor shall insure all of his personnel present during the project have been made aware of and understand this Site Safety Plan. Trained personnel shall sign the form in APPENDIX AA

Appendix CC Site Responsible Persons/Emergency Contacts, shall be posted on the door of all portable buildings on site and next to the phone in the office.

APPROVED BY: _____ Site Safety Manager _____ Date

APPROVED BY: _____ PGDP Safety Officer _____ Date

APPROVED BY: _____ DOE Representative _____ Date

Appendix AA:

Health and Safety Plan Training

This plan has been reviewed by the following site participants.

[illegible]

APENDIX BB
INCIDENT INVESTIGATION REPORT **Page 1 of 2**

Property: Project site;

Date of Incident: Time of Incident: Type of Accident:

Equipment / Materials /Quantity /Involved:

What work was being Performed when the Accident Occurred?

What Happened?

Employees Involved: Others Involved:

Extent and nature of any Injuries:

INCIDENT INVESTIGATION REPORT Page 2 of 2

What Action was taken to Control the Incident and Prevent Personal Injury or Environmental Damage?

Assessment of Actual/Potential Hazards to Human Health or the Environment?

What Proper Operating Procedures and Safety Requirements were being followed when the Accident Occurred? If not, Explain:

What other Factors contributed to Cause this Incident?

Recommendations to Prevent a Recurrence or Similar Accident:

Name of persons completing this
report. _____

Report Date. _____

Appendix CC Note this page can not be completed until lines of authority are
established in meetings with PGDP site personnel.

Site Responsible Persons/Emergency Contacts

Name _____

Cell phone

Office phone

Hotel/home phone

Responsibilities

End of the Health and Safety Plan

Appendix D: SCREEN SHOTS FROM THE COMPUTER MODEL

The computer model is best viewed in Microsoft Excel. The Screen shots are shown with
data from the Paducah site.

EarthSaw surface Block Elevation

Select Chart and 3-D view to re-color or stretch

File: EarthSaw In-Situ Containment of Pits and Trenches, contract DE-AC26-01NT41144

Developed by Carter Technologies Co, Sugar land, Texas Ernie Carter, P.E. 281-495-203

Model of Buoyancy in multiple subsurface conditions vertical block method, Version 24 dated March 14, 2002

This program is intended to allow a user to model the final buoyant condition of a block of earth.

The user first inputs the site dimensions, the density of the soil, the density of the waste, and the density the earth layer under the waste as well as the water table and porosity of these three zones.

The program deals with tilted formations and variable density by dividing the site into 4 equal quadrants and specifying average density and depth of each layer at the corners. A user will then input the preferred depth of cut at each corner, minimum thickness and the density of the grout. The graphic will then show the resulting barrier thickness and warn if it is thinner than specified.

By altering the depth of cut, the grout density and the surcharge you can achieve a uniform barrier thickness.

The EarthSaw barrier does not have to be rectangular, It could take many shapes.

Assume a 4 sided shape with vertical walls. This is known as a Trapezium.

Cells in red require user input.

Cells in green are calculated values

The area of a Trapezium is

$$(b(h1+h2)+a*h1+c*h2)/2$$

Input dimensions in feet below.

Where h1 is equal or greater than H2

a or c may be positive, zero, or negative

0	a	Length of side a
180	b	Length of side b
20	c	Length of side c
180	h1	Height h1
170	h2	Height h2
	side 1	200.0
	side2	171.2
	side3	180.3
	side4	180.0

If we divide the Trapezium into 4 equal area quadrants, the area of each quadrant is 1/4 the total area.

Assume the average depth interpolated from corner to center point E

	sq ft area	Avg. depth	cu ft volume
Entire Block	33,200	35.280	1,171,296
Quadrant A	6,640	34.345	228,051
Quadrant B	6,640	35.195	233,695
Quadrant C	6,640	35.195	233,695
Quadrant D	6,640	36.495	242,327

Center area E **6,640** 35.50 **235,720**
90.00 calculated Angle of corner A
83.29 Calculated Angle of corner B
99.89 Calculated angle of corner C
86.82 Calculated angle of corner D

86.82 calculated angle of rectangular portion of corner D
93.18 calculated angle of rectangular portion of corner C
6.71 Calculated Angle of triangle portion of corner C
0.00 Calculated Angle of triangle portion of corner D

The following input data describe a block that may have tilted
rock layers, variable water table, and variable density soil.
Note: Soil density is expressed as drained density

Note: if the yellow instruction box gets in your way while entering data, drag it away or activate the microsoft office assistant and it will move.

123 Drained Soil Density near surface at corner A
122.9 Soil Density near surface at corner B
123 Soil Density near surface at corner C
122.8 Soil Density near surface at corner D
122.925 **Interpolated Soil density near surface at E**

110 Drained Soil Density near bottom at corner A
110 Soil Density near bottom at corner B
110.1 Soil Density near bottom at corner C
109.9 Soil Density near bottom at corner D
110 **Interpolated Soil Density near Bottom at E**

20 Depth of density change at corner A
21 Depth of density change at corner B
21 Depth of density change at corner C
20 Depth of density change at corner D
20.5 **Interpolated Depth of density change at point E**

33.3 Depth of corner A from surface
35 Depth of corner B from surface
35 Depth of corner C from surface
37.6 Depth of corner D from surface
35.5 **Estimated Depth of actual cut at center point E**
35.225 **Calculated depth of a true planar cut**

The effective depth, freeboard, and block thickness are altered by the initial elevation differences

60.06% Percent of total depth having this density
60.00% Percent of total depth having this density
60.00% Percent of total depth having this density
53.19% Percent of total depth having this density
57.75% Percent of total depth having this density

39.94% Percent of total depth having this density
40.00% Percent of total depth having this density
40.00% Percent of total depth having this density
46.81% Percent of total depth having this density
42.25% Percent of total depth having this density

33.30 depth og grout at A
34.78 Depth of grout at B
35.15 Depth of grout at C
36.95 Depth of grout at D
35.39 Depth of grout at E

- 0 Surface elevation a corner A relative to corner A
- 0.22 Surface elevation of corner B relative to corner A
- 0.15 Surface elevation of corner C relative to corner A
- 0.65 Surface elevation of corner D relative to corner A
- 0.11 Surface elevation at E relative to corner A

Assume surcharge is uniformly distributed over each quadrant

- 5 Tons of surcharge weight added in quadrant A
- 0 Tons of surcharge weight added in quadrant B
- 4 Tons of surcharge weight added in quadrant C
- 49 Tons of surcharge weight added in quadrant D
- 40 Total surcharge weight added to center

- 1.99 Effective freeboard at A adjusted for surface and surcharge
- 2.22 Effective freeboard at B adjusted for surface and surcharge
- 1.84 Effective freeboard at C adjusted for surface and surcharge
- 2.53 Effective freeboard at D adjusted for surface and surcharge
- 2.21 Effective freeboard at E adjusted for surface and surcharge

- 0.0122 Equivalent feet thickness in Quadrant A
- 0.0000 Equivalent feet thickness in Quadrant B
- 0.0098 Equivalent feet thickness in Quadrant C
- 0.1202 Equivalent feet thickness in Quadrant D
- 0.0980 Equivalent feet thickness at E

Note: these determine "effective freeboard" above

Assuming all waste is in the upper layer

- 2.00% Percentage of upper quadrant A containing waste
- 2.00% Percentage of upper quadrant B containing waste
- 4.00% Percentage of upper quadrant C containing waste
- 4.00% Percentage of upper quadrant D containing waste
- 3.00% Interpolated Percentage of upper point E containg waste

- 165 Bulk density of waste in quadrant A
- 180 Bulk density of waste in quadrant B
- 216 Bulk density of waste in quadrant C
- 180 Bulk density of waste in quadrant D

185.25 Interpolated Bulk density of waste at point E

62.4 Water Density

\$4.89 Grout cost, dollars per gallon, Grout cost can vary significantly according to location, quantity, and required properties

2 Freeboard in perimeter trench at corner A after cutting is complete (feet) After cut is complete fluid level is increased

28 Vertical Trench width, (inches)

32 Total feet of overlap at corners

10.00 Water table depth below Corner A

10.00% Percent effective porosity of upper zone

50.00% Vertical Percent of upper zone saturated

25.00% Percent effective porosity of lower zone

100.00% Vertical Percent of lower zone saturated

150.00 Grout density used (pounds per cubic foot)

Blue is corner A, White is corner B

To see a more detailed 3-D graphic please go to sheet 2 and click on the blue button or the NETL logo

Note: the barrier thickness is equal to the rise above ground minus any surcharge soil adder

Table of bottom barrier thickness

D	3.25		3.25	3.25	3.25	3.25	3.25	3.25	3.25	3.25	C
		3.25	3.25	3.25	3.25	3.25	3.25	3.25	3.25	3.25	
		3.25	3.25	3.25	3.25	3.25	3.25	3.25	3.25	3.25	
		3.25	3.25	3.25	3.25	3.25	3.25	3.25	3.25	3.25	
		3.25	3.25	3.25	3.25	3.25	3.25	3.25	3.25	3.25	
		3.25	3.25	3.25	3.25	3.25	3.25	3.25	3.25	3.25	
		3.25	3.25	3.25	3.25	3.25	3.25	3.25	3.25	3.25	
A	3.25		3.25	3.25	3.25	3.25	3.25	3.25	3.25	3.25	B

Table of elevation of top of block										
D	0	0	0	0	0	0	0	0	0	C
0	3.13		3.16	3.16	3.17	3.19	3.20	3.21	3.23	3.24
0	3.14		3.16	3.18	3.20	3.23	3.22	3.23	3.23	3.24
0	3.16		3.18	3.20	3.23	3.27	3.24	3.23	3.23	3.24
0	3.17		3.19	3.22	3.26	3.31	3.27	3.25	3.24	3.25
0	3.18		3.20	3.22	3.27	3.35	3.27	3.23	3.24	3.25
0	3.20		3.21	3.24	3.28	3.32	3.28	3.26	3.25	3.25
0	3.21		3.22	3.24	3.27	3.30	3.27	3.25	3.25	3.25
0	3.22		3.23	3.24	3.26	3.27	3.26	3.26	3.25	3.25
0	3.24		3.24	3.24	3.24	3.25	3.25	3.25	3.25	3.25
0	0	0	0	0	0	0	0	0	0	0
A	B									

Our approach to this model is to divide the area into 4 or more quadrants and to evaluate the buoyancy of each quadrant as a finite element.

We will assume that the bock varies uniformly from edge to edge in all respects.

First we interpolate from the known corners to obtain an estimate of the specifications of the center point "E"

The we compute the average density of the entire block at each corner and center point.

Density = ((upper density x 1-percent waste fill)+ (waste density x percent waste fill)) x percent upper depth) + (lower density x percent depth) + (water density x upper zone Porosity x percent depth) + (water density x lower zone porosity x percent depth)

126.42 Average density of block at corner A (pounds per cubic foot)

126.54 Average density of block at corner B

128.18 Average density of block at corner C

126.94 Average density of block at corner D

126.94 Average density of block at center point E

Note these densities do not include surcharge

128.18 Maximum known density at any point

Output Data computed by model

$T_{bb} = T_b - \{(D_b / D_g) \times T_b\} - F$

Where;

T_b = the vertical thickness of the block of earth

T_s = the vertical thickness of the portion of the block of earth submerged in the grout

D_g = the density of the grout

D_b = the density of the block of earth

T_{bb} is the thickness of the bottom barrier or the vertical lift above grade.

F is the freeboard depth of the grout fluid level below the grade level.

2.5 Minimum desired bottom thickness, feet

1.50 Minimum acceptable side wall thickness

3.25 Feet of barrier thickness (or rise of block) at corner A

3.25 Feet of barrier thickness (or rise of block) at corner B

3.25 Feet of barrier thickness (or rise of block) at corner C

3.25 Feet of barrier thickness (or rise of block) at corner D

3.25 Feet of barrier thickness (or rise of block) at Point E

3.25 Actual calculated Minimum Bottom barrier thickness (feet)

3.25 Maximum Calculated Bottom barrier thickness, (feet)

0.00 Displacement of bottom edge along line from A to B

0.00 Displacement of bottom edge along line from A to D

2.33 Actual Minimum side wall thickness, if block is centered at surface, (feet)

Trench volume = trench length x depth of grout x trench width

15,500 Grout quantity required in trench 1, A to B (cubic feet less wasted portions)

13,769 Grout quantity required in trench 2, B to C (cubic feet less wasted portions)

14,877 Grout quantity required in trench 3, C to D (cubic feet less wasted portions)

14,827 Grout quantity required in trench 4, D to A (cubic feet less wasted portions)

58,974 Grout quantity in all 4 trenches, cu ft

107,922 Grout quantity in bottom barrier, cu ft

166,896 Total grout required, cu ft

6,104,572 Cost of grout, dollars

Blue is corner A, White is corner B

Mini Graphic of barrier thickness at poin

D	3.25	3.25	3.25	C
	3.249	3.25	3.252	
A	3.25	3.251	3.25	B

To make the barrier a uniform thickness try changing the c

A zero thickness indicates the block is not floating at that point

Right click on the above graphic and select 3-D view to see it from

To see a more detailed 3-D graphic please go to sheet
and click on the blue button or the NETL logo

Note: the barrier thickness is equal to the rise above gro

Note that for earth composed of gravel or fractured rocks where the grout is free to penetrate the spaces between the individual rocks, those individual rocks can fall through the grout if they have a density greater than the grout. For this reason, when working in such rock we should use a grout which has a density higher than the density of the individual rocks. Otherwise rocks can fall down into the pathway being cut by the cable saw and perhaps disrupt its operations.

File: EarthSaw In-Situ Containment of Pits and Trenches, contract DE-AC26-01NT41144

Developed by Carter Technologies Co, Sugar land, Texas Ernie Carter, P.E. 281-495-203
Revision 5 dated 2/06/02

Subtask 2.25, Numerical predictive model, Cable force and friction.

This Spreadsheet is intended to define relationships and provide data for development of a detailed computer model. The calculation is based on the vertical block method with vertical sides using the following input data:

Force displayed in pounds, Distance in feet, Cable diameter in inches

Required User input cells shown in red

Input Data	Calculated values shown in green
	Load frames located at corners B and C as on sheet 1
180	Width of the cut (in feet) from sheet 1
173.29	Contact Angle (in degrees) from sheet 1
190	Length of the cut from sheet 1
20	Soil in situ horizontal bearing strength (in pounds per square inch)
1	Cable Diameter (in inches)
1	Coefficient of friction between cable and soil, (Macro scale)
100,000	Winch pull capacity (in pounds) at T1 Yellow background indicates insufficient pull for slicing mode
1.64	Cable weight per foot, Pounds
0	Length of cable dragging above ground on T2 side
300	Pounds friction loss in sheaves and fluid drag
103,000	Minimum breaking strength of cable
560	Maximum length of cable dragging on soil in cut and on ground surface when first arc is formed.
919	Pounds of drag due to cable weight on horizontal surface
3639	Cable force available for sawing action at T2
44,119	Pounds winch pull required at both winches to slice through soil

Computation indicates that Cable Sawing Motion is Possible !

Computation indicates this soil block may be sliced by direct pull on both winches at once

EarthSaw cutting bottom pathway

Basis of the calculations:

If we are passing the cable around a section of earth and pulling from one end with a coefficient of friction of (?) then the ratio of the tension on the pulling cable to the drag on the trailing cable will be (T1/T2).

We will call this the drag factor. (If drag weight+ winch drag equals) x (drag factor) = T1 then sawing stops!

In our field experiments with 1 inch diameter cable the weight of the cable provides significant friction just laying on the ground.

We will call this the "drag weight" and it also includes all friction in the straight part of the cable path on the trailing side.

The winch drag on the trailing side includes all the back tension drag from the winch and any pulleys.

$T_1/T_2 = e^{\mu a}$ where μ is the coefficient of friction and a is the angle of contact in radians.

At 180 degrees the angle is 3.141 radians. Note that the formula applies to any shape arc.

If we pull uniformly from both ends to slice through the soil the shape would be a catenary.

If we use a reciprocating cable motion the cut will approximate the shape shown with the side being pulled straightening out.

If we use a continuous cable, and pull in one direction only, the curve will be skewed strongly to one side.

Field experience indicates that the cable cuts mostly on the side being pulled so the shape of the arc is non-uniform.

If the cable saw cuts by slicing mode rather than sawing mode the maximum width of cut will be limited by the available cable tensor

If the cable cuts by sawing against the face of the soil, cuts several hundred feet wide may be possible.

In order to saw rather than slice in a given 1 inch long segment of the arc of contact, the cable tension times the sine of that 1° contact angle must be less than the bearing strength of the soil.

Due to friction with the soil, the bulk of the pulling force will be concentrated on the pulling side of the arc **decreasing exponentially relative to the contact angle.** This allows us to calculate the tension in the cable at any point.

For a given set of input data we can calculate the cable tension which will exceed the soil strength.

During the initial cutting of the corners of the rectangular block, we will of course be slicing through the soil, but as the arc of the cut becomes a full 173.2901632 degree arc, we can approximate the contact force as follows:

The length of a circular arc is **272.1522013 feet** Frontal area of 1 degree arc of cable = 18.846 sq inches

The included angle for a 1 square inch face of cable = (contact angle / inches total arc length) / inches Cable thickness

So 1 sq inch frontal area of cable extends an arc of: **0.0530617 degrees** or 0.000926101 Radians

Note: Excel uses Radians for all trig functions.

The contact force between the soil and the cable is given by the sine of the angle times the tension force.

To achieve sawing motion with no slicing of the soil...

Soil psi must be less than the sine of 0.0009261 times the Maximum Cable Tension

Soil strength / sine of the angle = Cable tension for soil slicing to occur.

20 psi / Sine 0.0009261 radians

21,596 Pounds = Max cable tension at any point along circular curve to avoid slicing

formula is soil strength x sin(1/(length/angle))

For 180 degree arcs, the arc of the cut will not stay circular for long and will quickly become a catenary

(A catenary is the curve made by a cord of uniform weight suspended freely between two points.)

Calculating a catenary length is complex but assume for a cut whose length is twice the width, it is about 4 x the width

Since arc length is longer than a circular arc the contact surface area is greater and thus the contact pressure would be lower.

when the 180 degree cut is about the same length as width, the arc length is about 2 x the cut width.
This would still be longer than the circular arc so the contact pressure is still lower.

For a 180 degree starting arc:

As we approach the end of the cut the length of the arc will approach the width of the cut but the contact angle also decreases.
Assume that at half the original contact angle (180/2) the arc length will be width times 1.15

The catenary arc length would be **207 feet** Frontal area of 1 degree arc of cable= 27.6 sq in
a one square inch section of cable extends an arc of **0.0725 degrees** or 0.001264731 Radians
15,814 Pounds = **Max cable tension at any point along the curve near end of cut, to avoid slicing.**

This is still higher than for the circular arc so the risk of slicing decreases as we approach the end of the cut.

The Drag factor increases as we move around the curve from T1 to T2

Drag factor	T1/T2 = e ^{2a} =	111.32	23.14	10.55	4.81	2.85	1.69	1.30
	270 degrees	180 degree	135 degree	90 degrees	60 degrees	30 degrees	15 degrees	

For a given Pull force at T1, the maximum cable tension at any point along the arc = T1 / Drag factor

For the data values keyed into the red space above, the cable tension at T2 is: **4,858 Pounds**

For the same conditions the actual cable tension at 15 degrees from T1 is: **76,967 Pounds**

If this is less than the maximum allowable cable tension calculated above then the cable will not slice in at this point.

The chart below shows the cable tension for six different positions along the curve with various T1 pull force in pounds.

The chart indicates the cable tension at which the cable will begin slicing into the soil.

You may enter new values (pounds) for the pull force in the **blue T1** column.

Arc of Contact	Pull force, (T1)	Drag to stop, (T2) =		Cable tension at various degrees from T1					
	0 degrees	270 degrees	180 degree	135 degree	90 degrees	60 degrees	30 degrees	15 degrees	
	10,000	90	432	948	2079	3509	5924	7697	
Note: You may	15,000	135	648	1422	3118	5264	8886	11545	
change the pull	20,000	180	864	1896	4158	7018	11848	15393	
force values	25,000	225	1080	2370	5197	8773	14810	19242	
shown in	30,000	269	1296	2843	6236	10528	17772	23090	
blue to get	40,000	359	1729	3791	8315	14037	23695	30787	
more precise	50,000	449	2161	4739	10394	17546	29619	38483	
answers	60,000	539	2593	5687	12473	21055	35543	46180	
	70,000	629	3025	6635	14552	24564	41467	53877	
	80,000	719	3457	7582	16630	28074	47391	61573	
	90,000	808	3889	8530	18709	31583	53315	69270	
	100,000	898	4321	9478	20788	35092	59238	76967	
	110,000	988	4754	10426	22867	38601	65162	84663	
	120,000	1078	5186	11374	24946	42110	71086	92360	
	130,000	1168	5618	12321	27024	45620	77010	100057	
	140,000	1258	6050	13269	29103	49129	82934	107753	
	150,000	1347	6482	14217	31182	52638	88858	115450	

Conditions highlighted in orange will be in slicing mode.

Conditions with a stuck cable shown in a strike-through font

The 15 degree column indicates the maximum pulling force to avoid significant slicing action.

Note that if the "drag to stop" at 180 degrees is less than the friction due to weight of the cable it will be stuck!

Friction due to weight of cable around a pathway 560.27756 foot long = 918.8552 Pounds

If we operate in slicing mode we must calculate how much pull force T1 and T2 will be required to slice through the full

180 foot width of the cut with uniform pull at both T1 and T2 winches.

If we assume that cutting with an arc across the width takes the same force as a straight right angle cut:

Then the pull to slice the entire width = (Width in inches x cable thickness) x PSI soil strength plus drag weight **44,119 Pounds**

Care must be taken not to exceed the breaking strength of the cable.

Therefore to cut the specified soil block in sawing mode we should select the highest T1 pull force

that does not exceed the slicing threshold in the 30 or 60 degree column.

If the width of the site is small and friction is high sawing may not be possible because the drag friction will cause the cable to stick.

Generally the wider the cut and the harder the soil, the more likely you will be able to operate in the sawing mode.

If the cable is blocked by one large rock the cable will slice through adjacent soil until it makes a sharp "V" bend over the rock.

Then the cable will saw through that rock with all force concentrated on the rock.

Sawing mode may be facilitated by reducing the coefficient of friction through grout design, cable type or by reducing the contact angle

Of course there is nothing wrong with slicing through the soil...if there are no big rocks and you have enough winch power.

Horizontal Directional Drilled Holes

When operating from directional drilled holes the total angle increases by the total vertical angle change from the cutting zone to the surface. This HDD modeled condition is represented by the 270 degree column of data above.

The HDD method is more likely to operate in slicing mode since it has an additional 90 degrees of contact angle.

Will the cable slice into the sides of the HDD bore, and thus reduce the depth of the bottom barrier?

If the directionally drilled hole has an included angle of 45 degrees and is 500 feet long what is the maximum cable tension allowable to prevent upward slicing from the bottom horizontal portion. (Assume a uniform radius of curve)

Note: upward slicing is undesirable because it could cause the bottom barrier to be more shallow than desired.

If the force normal to the cable at half the included angle is greater than the strength of the soil, we will have slicing!

The formula is = soil strength / sin(1/(length/angle) x cable cross section)

Input data

220 Included vertical angle of the HDD bore, Degrees

500 Length of the HDD bore, feet

20 Maximum Force normal to the curve, psi

546 Maximum pounds cable tension, at half included angle, (horizontal midpoint of hole) 110 degrees

3721 Maximum pulling force at T1 to avoid slicing at horizontal midpoint of HDD hole

File: EarthSaw In-Situ Containment of Pits and Trenches, contract DE-AC26-01NT41144

Developed by Carter Technologies Co, Sugar land, Texas Ernie Carter, P.E. 281-495-203

Graphic Model of Earth block fracture during undercutting, Version 1.0 dated March 15, 2002

Note: This is only a preliminary graphic model for planning purposes.

See the detailed finite element model for actual stress calculations.

180 Feet Length of block
200 Feet Width of block
35.5 Feet Thickness or depth of block
20 psi tensile strength of block
3,000,000 psi elastic modulus of block
126.94 Density of block, pounds per cubic foot

150.00 Density of grout, pounds per cubic foot
0.50 Feet of uplift buoyancy
0.043403 PSI of net upward force
110 Feet of cut progress at apex of cable
180 feet of cut progress at edges of block.

Stress is in force/ area =psi, Strain = change in length/original length Linear feet of block required to rise to equilibrium
Stress/strain - elastic modulus

25,004 sq ft Area exposed to uplift buoyancy
78138.75 pounds Uplift force
144000 sq in Area of applied stress
0.54263 PSI net upward Stress along horizontal fracture point

Plan View
Horizontal fracture
Uncut soil
Cut bottom exposed to pressure
Cable Saw
End of fracture

180 Length of block
200 Width of block
36,000 Total area of block
70 Length along center line remaining to be cut
10,996 Area of block not yet cut
25,004 Area of block already cut and exposed to buoyant force

fractures in soil and rock form along the lines of least principal stress. This is why deep oil well fractures are vertical and near surface fractures are horizontal. As we lift the block on one end, the forces along the sides are still compressing the block with about the same force as when the block is in undisturbed soil. If the soil has any cohesive strength, this will add to its resistance to vertical fracture. If it has no cohesive strength, it will deform to adjust to a new shape. In order to fracture vertically it must first overcome the preload placed on it by the grout. If the apex of the cut is 100 feet from the edge of the block and we raise it 6 inches, then we have a "beam" bending equation with one end of the beam free and the other end fixed. It seems the beam would be a sort of S bend according to the modulus of the soil or rock and the total strength of the beam.

A true catenary shape is complex and the actual shape will be skewed according to operating conditions so...

Assume that the catenary cut is shaped like half an ellipse. The area for half an ellipse is $0.5 \times 0.7854 (2 \times h \times w)$ where h is height and w is width. Assume that the half ellipse begins at the load frames and that w is the distance

between the load frames and h is the the cable apex must travel along the centerline to complete the cut. The uplift force on the apex of the cut is very large because it comes from the entire area cut so far and it is concentrated at the point just ahead of the apex of the cutting cable. This point is likely to experience horizontal fracturing ahead of the cutting cable as shown in the above sketch. If any vertical fractures develop they will extend tangent to this same point.

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Developed by Carter Technologies Co, Sugar land, Texas Ernie Carter, P.E. 281-495-203

Predictive model of grout preparation logistics. Task 2.33 version 1 January 28

166,896 cubic feet of grout required for task

58,974 cubic feet of slurry trench excavation slurry

1.20 Expansion factor for spoils

1.50 Approximate tons of dry materials per cubic yard of final grout.

5.00 Approximate gallons of liquid additives per cubic yard of grout

12.0 trucks per day, bulk dry material, received and unloaded to silo

200.0 tons of storage capacity on site

6,181 Cubic yards volume of grout required

15.00 gallons of water required per cubic yard of grout

9,272 tons of dry materials required

30,907 gallons of liquid additives required.

92,720 gallons of water required

370.9 number of 25 ton truckloads of dry material required

14.2 Days time required to make grout

103.0 Number of 300 gallon tote tanks required

6.0 Number of trucks to deliver tote tanks

2621 cubic yards of spoils produced by excavation

166.15 Number of truck loads to remove spoils off site

24.00 Number of spoils disposal trucks loaded per day

6.92 Time to remove spoils

Pereparation of the required quantity of grout to make the thick and homogenous barriers installed by the Earth Large volumes of grout in a relatively short period of time. The quatity of grout required is simply the volume of the vertical trench plus the volume of the desired bottom barrier.

When excavating the vertical slurry wall we will need a volume of bentonite slurry smilar to the vertical trench volume. Slurry for excavating the vertical wall sections would be made from a 5 to 6 percent bentonite slurry. This could be made in "frac" tanks, which hold 2,800 cubic feet each, or more economically held in a small pond if site conditions permit. The grout materials will be brought to the area by rail cars and transferred by trucks to large silos. The grout volume of the kind used to deliver ready mixed concrete. The mixer trucks will first receive the liquid components of the grout in the silo to receive the dry ingredients. The materials will then be mixed while being taken to the site. A tremmie pipe will be installed on two opposite sides of the trench. This tremmie pipe will have a large funnel-like opening at the top and a 16 inch opening very near the bottom of the vertical trench. The concrete trucks will discharge directly into these pipes. If access is not available, grout will discharge into concrete pumps which will transfer the grout to the tremmie pipes.

Production rates are limited by the dry material storage capacity in site,

The bentonite slurry displaced by the heavy grout will be pumped into tanks for disposal. In some cases it may be necessary to manufacture the grout or other cap materials.