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IITRI Project No. C06787
DOE Contract No. DE-AC05-93OR22161995
April 5, 1996

**DEMONSTRATION, TESTING, & EVALUATION
OF IN SITU HEATING OF SOIL**

Final Report

Volume I

Submitted to:

U. S. Department of Energy
Oak Ridge Operations Office
P. O. Box 2001
Oak Ridge, Tennessee 37831

Attention: Mr. Johnny Moore

Submitted by:

H. Dev
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MASTER

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FOREWORD

This document is a final report for US DOE contract entitled, "Demonstration Testing and Evaluation of In Situ Soil Heating," Contract No. DE-AC05-93OR22160, IITRI Project No. C06787. This report is presented in two volumes. Volume I contains the technical report and Volume II contains appendices with background information and data.

In this project approximately 300 cu. yd. of clayey soil containing a low concentration plume of volatile organic chemicals was heated in situ by the application of electrical energy. It was shown that as a result of heating the effective permeability of soil to air flow was increased such that in situ soil vapor extraction could be performed. The initial permeability of soil was so low that the soil gas flow rate was immeasurably small even at high vacuum levels. It was demonstrated that the mass flow rate of the volatile organic chemicals was enhanced in the recovered soil gas as a result of heating.

When scaled up, this process can be used for the environmental clean up and restoration of DOE sites contaminated with VOCs and other organic chemicals boiling up to 120° to 130° C in the vadose zone. Although it may applied to many types of soil formations, it is particularly attractive for low permeability clayey soil where conventional in situ venting techniques are limited by low air flow.

Respectfully Submitted,
IIT Research Institute

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SUMMARY

BACKGROUND AND APPLICABILITY

Production of nuclear weapons in the US required the use of a vast array of facilities -- mines, laboratories, nuclear reactors, chemical plants, foundries, machine shops, test sites, etc. A wide variety of wastes were produced. At all sites where the production or related activities took place, some environmental contamination occurred. In some cases the contamination is contained and it does not pose any hazard to the people and environment. In other sites there is wide spread contamination of soil and groundwater.

Several different types of waste have been generated. These are: High Level Waste, Spent Nuclear Fuel, Transuranic Waste, Low-Level Waste, Low Level Mixed Waste and Hazardous Waste. Of these, the Low Level Mixed Waste contains hazardous constituents which are regulated under RCRA by USEPA and it also contains radiological waste which are regulated under Atomic Energy Act by DOE and the Nuclear Regulatory Commission. Hazardous waste contains constituents regulated under RCRA by USEPA.

At many DOE installations, there is widespread contamination of soil over a large area but with low levels of both organic as well as radioactive waste. Many such sites are classified as low-level mixed-waste sites. Soil containing mobile organic and inorganic contaminants acts as a source for the continued future contamination of ground water. Any ground water treatment system designed to protect public health and welfare must take into account the reservoir of contaminants present in the overlaying soil which can be released to the groundwater over a period of time thus defeating the purpose of ground water treatment systems.

At many low-level mixed-waste sites the presence of radioactive contaminants is sometimes so low that if an economical and effective method is developed to remove or destroy the organic waste component of the contamination then the site can be effectively regarded as rehabilitated. Nevertheless, removal of the organic waste or its destruction can often permit the reclassification of the site as a radioactive waste site thus reducing the regulatory burden on the waste-site management activities.

Technology Development is an integral part of DOE's EM Program. DOE has established Technology Development Focus Areas and Cross Cutting Areas. The EM heating process will find application for problems being addressed by the Contaminant Plumes Containment and Remediation Focus Area as well as by the Efficient Separations and Processing Technology Development Cross Cutting Area.

PROCESS DESCRIPTION AND ADVANTAGES

The in situ EM heating process removes organic hazardous constituents from soil by heating it to a temperature range of 70 to 95° C. In this process the soil is heated in situ using electrical energy. The contaminants are removed from the soil due to enhanced vaporization, steam distillation and stripping. The vaporized contaminants, water vapor and air are recovered from the heated zone by means of a vacuum manifold system which collects gases from below surface as well

as from the soil surface. A vapor barrier is used to prevent fugitive emissions of the contaminants and to control air infiltration to minimize dilution of the contaminant gases and vapors. The recovered gases and vapors are conveyed to an on site vapor treatment system for the clean up of the vent gases.

Electrical energy is applied to the soil by forming an array of electrodes in the soil which are electrically interconnected and supplied with power. The electrodes are placed in drilled bore holes which are made through the contaminated zone.

This process is aimed at sites which contain hazardous constituents in soils where conventional in situ venting technology fails to remove hazardous volatile organic compounds because of low permeability of the soil to flow of air. The EM heating process can also be used at other sites to increase the partial pressure of the contaminants in the gas phase and thus increase their rate of removal.

In this project IITRI demonstrated the EM Treatment Technology for the in situ remediation of soils containing organic wastes. This technology can help DOE in the following ways:

- For sites containing low-level mixed-wastes, reduce the regulatory burden by removing the hazardous organic wastes and thus change the site to a radioactive waste site.
- Many DOE sites are treated as contaminated due to the presence of the organic substances. At these sites the radioactivity levels are so low that once the organic contaminants are removed by the EM technology the site may need no further remediation for the radioactive constituents.
- For hazardous waste sites where organics are the primary contaminants of concern, the EM technology can be used for economic and effective remediation.
- The process is a true in situ process. Massive soil excavation need not be undertaken, thus preventing exposure of the general and the occupational population to fugitive emissions and dust.
- The process can be used for rapid clean up of soils even when they contain contaminants trapped in clayey soil of low permeability--a challenging and intractable situation for in situ venting. Medium boilers such as those boiling in the temperature range of 110° to 130° C can be rapidly removed.

DEMONSTRATION RESULTS AND CONCLUSIONS

- About 300 cu. yd. of soil was heated in situ by the application of 60 Hz electrical power. The demonstration was performed in a vadose zone plume emanating from waste disposal pits in the Classified Burial Grounds 1070 C/D, K-25 Site, Oak Ridge. The actual pit was not heated.

- After 25 days, approximately 80 percent of the soil was heated to an average temperature of 90° C. Entire soil volume was heated to an average temperature of 75° C.
- Initial permeability to air flow was immeasurably low even at an applied vacuum of 26 to 28 in. Hg. Permeability increased with heating. At shut down it was 1 to 2 darcy. During the cooling period soil permeability continued to increase with soil venting. Final soil permeability was 5 to 7.5 darcy.
- The mass rate of recovery in the soil gas increased with heating. This happened due to increase in contaminant concentration and the total flow rate of the extracted soil gas. The ratio of initial to peak mass recovery rate varied between 10 to 53 depending upon the compound.
- Initial VOC concentration in soil was very low. Many samples were at or below the detection limit. Due to this reason, changes in VOC concentration of the soil as a result of heating could not be quantified.
- The results of the demonstration have shown that in situ heating can be used to increase the rate of contaminant removal by increasing the partial pressure of the chemicals in the gas phase as well as by increasing the flow of extracted gases through the soil.
- When scaled up, the process can be used for the remediation of clayey soil formations with low initial permeability where in situ venting is not economically feasible.
- In its current state of development the process is applicable to soils in the vadose zone for the removal of organic chemicals which exhibit a vapor pressure of 0.5 to 1 mm Hg at the treatment temperature. Some examples are: VOCs as defined by USEPA, tetrachlorobenzene, benzoic acid, 1-heptanone, 1,4-dibromobenzene, 3-chlorophenol, etc.
- A cost evaluation was done for the application of the process to several pits inside the 1070 C/D Classified Burial Ground located at the K-25 Site. The treatment cost was estimated to be \$144/ton. Details are presented in Section 10.
- Other cost studies by IITRI for the treatment of sites with 10,000 cu. yds. or more of contaminated soil have estimated that the cost of in situ EM heating to enhance in situ venting is in the range of \$30 to \$40/ton.

It is envisioned that with additional laboratory and field testing this in situ heating method can be developed for the treatment of dense non-aqueous phase liquids. Many chlorinated solvents and VOCs fall in this category when they are present in large quantities in soil and groundwater such that they exist as a second heavier than water liquid layer. There are no known cost effective remedies for DNAPL other than treatment of pumped ground water.

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LIST OF ACRONYMS

AC	Alternating Current
ACPS	AC Power Source
ANSI	American National Standards Institute
BTEX	Benzene, Toluene, Ethylbenzene, Xylenes
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
dB	Decibel
1,1-DCA	1,1-Dichloroethane
1,1-DCE	1,1-Dichloroethene
DNAPL	Dense Non-aqueous Phase Liquid
DOE	Department of Energy
EM	Electromagnetic or Environmental Management
GC/MS	Gas Chromatograph/Mass Spectrometer
HC	Hydrocarbon
HDPE	High Density Polyethylene
IITRI	IIT Research Institute
ISV	In Situ Venting
kW-hr	Kilowatt-hour
LMES	Lockheed Martin Energy Systems
LPT	Low Power Test
NEPA	National Environmental Policy Act
ORR	Oak Ridge Reservation
PCB	Polychlorinated Biphenyls
PCE	Perchloroethylene or Tetrachloroethene
PID	Photoionization Detector
RCRA	Resource Conservation and Recovery Act
RF	Radio Frequency
RPD	Relative Percent Difference
RSD	Relative Standard Deviation
SOP	Standard Operating Procedure
SVOC	Semi-volatile Organic Chemical
1,1,1-TCA	1,1,1-Trichloroethane
TCE	Trichloroethene
TDEC	Tennessee Department of Environment and Conservation
TEVES	Thermal Enhanced Vapor Extraction System
USAF	U. S. Air Force
USEPA	U. S. Environmental Protection Agency
VCS	Vapor Collection System
VOC	Volatile Organic Chemical

1. INTRODUCTION

1.1 Background

A number of DOE installations have soil contamination due, not only to the presence of hazardous waste materials, but also due to the co-presence of both organic, and inorganic hazardous waste as well as radioactive waste. At many installations, there is widespread contamination of soil over a large area but with low levels of both organic as well as radioactive waste. Many such sites are classified as low-level mixed-waste sites due to presence of both hazardous as well as radiological waste. Soil containing mobile organic and inorganic contaminants acts as a source for the continued future contamination of ground water. Any ground water treatment system designed to protect public health and welfare must take into account the reservoir of contaminants present in the overlying soil which can be released to the groundwater over a period of time thus defeating the purpose of ground water treatment systems.

At low-level mixed-waste sites the presence of radioactive contaminants is sometimes so low that if an economical and effective method is developed to remove or destroy the organic waste component of the contamination then the site can be effectively regarded as rehabilitated. Nevertheless, removal of the organic waste or its destruction can often permit the reclassification of the site as a radioactive waste site thus reducing the regulatory burden on the waste-site management activities. Soil remediation can allow new, economical and income producing uses of the land which otherwise would have to be kept unproductive or under utilized.

The fundamental goal of DOE's long term environmental program is to ensure that risks to human health and safety, and to the environment posed by DOE's past, present and future operations are eliminated or reduced to prescribed safe levels. In order to meet this goal, DOE has set itself, as one of the objectives of long term environmental restoration, the challenging task of development of new, efficient and effective methods and technologies for the management of wastes currently being produced and the environmental restoration of contaminated sites.

In this project IITRI demonstrated the EM Treatment Technology for the in situ remediation of soils containing organic wastes. This technology can help DOE in the following ways:

- For sites containing low-level mixed-wastes, reduce the regulatory burden by removing the hazardous organic wastes and thus change the site to a radioactive waste site.

- Many DOE sites are treated as contaminated due to the presence of the organic substances. At these sites the radioactivity levels are so low that once the organic contaminants are removed by the EM technology the site may need no further remediation for the radioactive constituents.
- For hazardous waste sites where organics are the primary contaminants of concern, the EM technology can be used for economic and effective remediation.
- The process is a true in situ process. Massive soil excavation need not be undertaken, thus preventing exposure of the general and the occupational population to fugitive emissions and dust.
- There is no in situ combustion. This is expected to make permitting of the process easier than most other on site ex-situ processes.
- The process can be used for rapid clean up of soils even when they contain contaminants trapped in clayey soil of low permeability--a challenging and intractable situation for in situ venting. Medium boilers such as those boiling in the temperature range of 110° to 130° C can be rapidly removed.
- Soil cuttings can be compacted on the surface of the heated zone and treated. Other solid or liquid waste generated by the vapor treatment system will require ultimate disposal.

Over the last nine years IITRI has been developing and testing the in situ heating and soil decontamination process for the remediation of soils containing hazardous organic contaminants. In this process the soil is heated in situ using electrical energy. The contaminants are removed from the soil due to enhanced vaporization, steam distillation and stripping. The vaporized contaminants, water vapor and air are recovered from the heated zone by means of a vacuum manifold system which collects gases from below surface as well as from the soil surface. A vapor barrier is used to prevent fugitive emissions of the contaminants and to control air infiltration to minimize dilution of the contaminant gases and vapors. The recovered gases and vapors are conveyed to an on site vapor treatment system for the clean up of the vent gases.

Electrical energy is applied to the soil by forming an array of electrodes in the soil which are electrically interconnected and supplied with power. The electrodes are placed in drilled bore holes which are made through the contaminated zone. Figure 1 is an artist's sketch illustrating the electrode array and the vapor barrier used for the implementation of the EM soil decontamination process. The tubular electrodes are made from pipe or tubing fabricated from copper, steel or aluminum. The electrodes are dropped into bore holes and electrically connected at the surface to the power source.

There are two versions of the in situ heating and soil treatment process: the first version is called the In Situ Radio Frequency (RF) Soil Decontamination Process and the second version is called the In Situ Electromagnetic (EM) Soil Decontamination Process. The first version, the RF Process, is capable of heating the soil in a temperature range of 100° to 400° C. The soil temperature in the second version, the EM Process, is limited to

In Situ Electromagnetic (EM) Heating Process for Soil Decontamination

Figure 1. Artist's Sketch Illustrating the EM Process.

the boiling point of water under native conditions. Thus, in the EM Process the soil will be heated to a temperature of about 70° to 95° C.

In this project IITRI demonstrated the EM Process for in situ soil decontamination at the K-25 Site, Oak Ridge, TN., due to the fact that most of the contaminants of concern are volatile organics which can be removed by heating the soil to a temperature range of 85° to 95° C.

The collected gases are treated on site by means of conventional gas treatment unit operations which depend upon the amount, concentration, and type of contaminants. In this project, because of the low concentration and total weight of contaminants, the recovered gases were released without treatment.

1.2 Site History

The demonstration project was conducted at the K-25 Site located in the Oak Ridge Reservation (ORR) in the city of Oak Ridge, TN. The reservation consists of 58,000 acres of federally owned land under the jurisdiction of Department of Energy. The ORR is bounded on the north and east by the city of Oak Ridge and on the south and west by the Clinch River. Three major DOE facilities are located on the Reservation. These are: the Oak Ridge National Laboratory, the Oak Ridge Y-12 Plant and the Oak Ridge K-25 Site. All three are operated by Lockheed Marietta Energy Systems (LMES).

The K-25 Site is located 13 miles west of Oak Ridge. Until the summer of 1985 when the gaseous diffusion process was shut down, the mission of the K-25 Site was ²³⁵U enrichment of uranium hexafluoride (UF₆) for eventual use as a fuel in nuclear reactors. The manufacturing activities at the K-25 Site produced a variety of waste streams containing heavy metals, hazardous organic substances and radioactive waste.

The demonstration project was conducted in an area adjacent to the K-1070-C/D Classified Burial Ground. The K-1070-C/D Classified Burial Ground is a 22-acre tract on the east side of the K-25 Site, inside the security perimeter fence. A security-cleared escort is required for entry by uncleared personnel. Figure 2 is a map illustrating the Burial Grounds. The K-1070 C/D Classified Burial Ground is composed of two distinctly bounded disposal areas: the K-1070-C maintenance equipment storage area and the K-1070-D disposal area. Prior to the establishment of K-1070-C as a maintenance equipment storage site (circa early 1975), the area was used as a burial ground for classified material. The K-1070-C area is currently serving as a maintenance equipment storage area. A shed and several piles of landscaping materials are located in this area. In general, the storage area is covered with gravel and serves as a parking lot. A natural drainage gully is located behind the shed; it channels surface water runoff from the K-1070-D hill. This ditch area and the boundary of the storage area are covered with vegetation.

Figure 2. Map of the K-1070 C/D Classified Burial Ground Showing Burial Areas and Prior Sampling Locations (Taken From Reference 11).

The K-1070-D area is mostly covered with scrub grass and small trees. Several large trees are located along the northeast and southern boundaries. The southern portion of the site, which slopes downhill, has been eroded by heavy rainfall events, and several deep gullies are present in this area. Surface water runoff in the southern portion of the burial ground is funneled down these gullies to the drainage ditch located in the K-1070-C area.

The K-1070-D disposal area is composed of multiple disposal sites, including 3 large trench burial areas, 3 earthen dike storage areas, 13 small pits, 3 glass pits, 2 land farms, and a concrete pad. A sub-surface plume of organic solvents, emanating from waste disposal pits inside the burial ground was the target of in situ thermal treatment.

1.3 Project History

This project was conducted under the auspices of a prime contract between Department of Energy and IIT Research Institute, contract number DE-AC05-93OR22160, dated September 30, 1993. IITRI started work on the project in October 1993. The site preparation activities were begun in February 1995. The field test was initiated on June 13, 1995 and the heating phase of the demonstration was terminated on July 8, 1995. Vapor collection and temperature data acquisition was terminated on September 11, 1995.

1.4 Summary of Results, Conclusions, and Recommendations.

A summary of results and conclusions of this project is presented below:

- About 300 cu. yd. of soil was heated in situ by the application of 60 Hz electrical power.
- After heating for 25 days, approximately 80 percent of the soil was heated to an average temperature of 90° C. Entire soil volume was heated to an average temperature of 75° C.
- Initial permeability to air flow was immeasurably low even at an applied vacuum of 26 to 28 in. Hg. Permeability increased with heating. At shut down it was 1 to 2 darcy. During the cooling period soil permeability continued to increase with soil venting. Final soil permeability was 5 to 7.5 darcy.
- The mass rate of recovery in the soil gas increased with heating. This happened due to increase in contaminant concentration and the total flow rate of the extracted soil gas. The ratio of initial to peak mass recovery rate varied between 10 to 44 depending upon the compound.

- Initial VOC concentration in soil was very low. Many samples were at or below the detection limit. Due to this reason, changes in VOC concentration of the soil as a result of heating could not be quantified.
- The results of the demonstration have shown that in situ heating can be used to increase the rate of contaminant removal by increasing the partial pressure of the chemicals in the gas phase as well as by increasing the flow of extracted gases through the soil.
- When scaled up, the process can be used for the remediation of clayey soil formations with low initial permeability where in situ venting is not economically feasible.
- In its current state of development the process is applicable to soils in the vadose zone for the removal of organic chemicals which exhibit a vapor pressure of 0.5 to 1 mm Hg at the treatment temperature. Some examples are: VOCs as defined by USEPA, tetrachlorobenzene, benzoic acid, 1-heptanone, 1,4-dibromobenzene, 3-chlorophenol, etc.
- A cost evaluation was done for the application of the process to several pits inside the 1070 C/D Classified Burial Ground located at the K-25 site. The treatment was estimated to be \$144/ton.
- Other cost studies by IITRI for the treatment of sites with 10,000 cu. yds. or more of contaminated soil have estimated that the cost of in situ EM heating to enhance in situ venting is in the range of \$30 to \$40/cu. yd.

2. TECHNOLOGY APPLICATION

The Department of Energy's Environmental Management (EM) Program was created in 1989 to manage waste and cleanup contamination produced as a results of 50 years of nuclear weapons production and research at 137 Department of Energy sites in 33 states and 1 territory. The department faces the challenging task of addressing nearly 10,000 individual remediation problems throughout the entire complex.¹

The Environmental Management Program activities are conducted in four functional areas:

- Environmental Restoration
- Waste Management
- Nuclear Materials and Facility Stabilization
- Technology Development

Production of nuclear weapons in the US required the use of a vast array of facilities -- mines, laboratories, nuclear reactors, chemical plants, foundries, machine shops, test sites, etc. A wide variety of wastes were produced. At all sites where the production or related activities took place, some environmental contamination occurred. In some cases the contamination is contained and it does not pose any hazard to the people and environment. In other sites there is wide spread contamination of soil and groundwater.

Several different types of waste have been generated ^{2,3}. These are:

- **High Level Waste.** This waste resulted from the chemical processing of spent nuclear fuel. High level waste is stored largely as a liquid or sludge.
- **Spent Nuclear Fuel.** This includes all nuclear fuel generated by DOE production reactors, research reactors and certain foreign research reactors.
- **Transuranic Waste.** This includes all wastes that contain alpha-emitting trans-uranium radio nuclides with half-life greater than 20 years and with 100 nanocuries per gram. This waste generally does not require remote handling needed for the two waste types listed above, but it contains radionuclides which remain radioactive for thousands of years.
- **Low-Level Waste.** This includes all radioactive wastes which is not classified in one of the three categories listed above. It also does not include uranium and thorium tailings.

- **Low-Level Mixed Waste.** This is low-level waste which is mixed with hazardous constituents regulated under Subtitle C of RCRA.
- **Hazardous Waste.** This is waste which is regulated under RCRA. It does not contain radioactive waste.

Technology Development is an integral part of USDOE's EM Program. DOE has established Technology Development Focus Areas and Cross Cutting Areas. The EM heating process will find application for problems being addressed by the Contaminant Plumes Containment and Remediation Focus Area⁴ as well as by the Efficient Separations and Processing Technology Development Cross Cutting Area.

The in situ EM heating technology is being developed to address the special needs of those sites in which soils have been contaminated with low-level mixed wastes or hazardous wastes. This process is aimed at sites which contain hazardous constituents in soils where conventional in situ venting technology fails to remove hazardous volatile organic compounds because of low permeability of the soil to flow of air. The EM heating process can also be used at other sites to increase the partial pressure of the contaminants in the gas phase and thus increase their rate of removal.

It is envisioned that with additional laboratory and field testing this in situ heating method can be developed for the treatment of dense non-aqueous phase liquids. Many chlorinated solvents and VOCs fall in this category when they are present in large quantities in soil and groundwater such that they exist as a second heavier than water liquid layer. There are no known cost effective remedies for DNAPL other than treatment of pumped ground water.

3. TECHNOLOGY DESCRIPTION

This section summarizes information on the following aspects of the EM process:

- Process Description
- Vadose Zone Decontamination Mechanism
- Saturated Zone Decontamination Mechanism
- Advantages
- Field Test Results
- Cost
- Limitations

Process Description: The in situ electromagnetic (EM) heating process utilizes an array of tubular metal electrodes which are energized with 60 Hz electrical power, to heat soil in situ, to temperatures in the range of 70° to 100° C. The electrode array is formed by inserting multiple rows of electrodes in bore holes made through the soil volume which is to be heated. The tubular electrodes are made from pipe or tubing fabricated from copper, steel or aluminum. The electrodes are dropped into bore holes and electrically connected at the surface to the power source. A rubber or plastic vapor barrier is placed on the surface to prevent fugitive emissions of gases and vapors formed upon heating of the soil. The vapors and gases are recovered by means of a vacuum manifold system which collects them from the surface of the heated zone as well as from perforated gas collection wells. A schematic of the EM heating process was illustrated in Figure 1.

A site specific electrode array is designed based on the geometry of the treatment volume, depth of contamination, soil permeability characteristics, and whether heating is to be performed from the soil surface down or within a specified depth interval below the soil surface.

The collected gases and vapors are conveyed through heated pipelines to an on site gas treatment system. The design of the vapor treatment train is site specific. It is based on the types of contaminants present and the local permitting requirements. In four previous in situ field experiments, IITRI's in situ heating systems were used in conjunction with four different vapor treatment systems.

The EM heating method is a volumetric process which does not rely on thermal conduction or mass transfer for the transport of energy from the electrodes to regions within the interior of the heated zone. Thus the soil can be heated rapidly. The process can remove chemicals which have a vapor pressure greater than 1 mm Hg in the treatment temperature range. Thus multiple contaminants at varying concentrations can be removed.

Vadose Zone Decontamination Mechanism: Decontamination of heated soil proceeds due to vaporization, steam stripping, and enhanced vaporization due to the sweep provided by steam and infiltrating air. Steam is generated by boiling native soil moisture. The gas sweep is induced by the vacuum manifold which is designed to recover the gases and vapors. Moreover, the sweep is induced in a well defined soil volume due to the development of effective permeability to gas flow in the heated zone. As the liquid phase pore-saturation decreases, the effective permeability to gas flow increases. Thus permeability can be induced in formation heterogeneities caused by clay lenses, stringers, presence of hard pan, etc.

In evaluating the applicability of ambient temperature in situ venting (ISV), a vapor pressure criterion is used. This criterion states that the vapor pressure of the contaminant should be in the range of 0.5⁽⁵⁾ to 1.0⁽⁶⁾ mm Hg. Most of the VOC chemicals of concern at USDoE facilities meet this criterion. In a recent USAF study⁽⁷⁾ on the rate of desorption of TCE from various types of dry soil, it has been reported that the desorption rate is slowest from plastic-clays. The partial pressure of adsorbed TCE over plastic clay at 25°C was approximately 1 mm Hg (at 25°C, pure TCE exerts a vapor pressure of 74 mm Hg). Upon heating to 100°C it increased to 4.5 mm Hg. Even though it is generally recognized that vapor pressure of contaminants adsorbed on soil is lower than that of pure component, the AF study clearly showed that even highly volatile contaminants such as TCE cannot be effectively removed from clayey soils using ISV. The study showed that heating the soil from 23°C to 100°C increased the desorption rate constant by a factor of 20. This clearly shows the benefits of conducting ISV at elevated temperature, when it is desired to reduce the treatment period. Other chlorinated solvents are expected to show similar relative improvement at elevated temperature.

IITRI has conducted bench scale experiments to study the removal of PCE and chlorobenzene spiked onto soil. Initial soil concentration was in the range of 9 to 9.5 ppm. The soil was heated to 90°C and 130°C. The residual concentration of PCE in soil after 4 hours at 90°C was 120 to 150 ppb. Residual chlorobenzene concentration was 190 to 250 ppb. In another set of experiments, soil containing 960 ppm of PCE was heated to a temperature of 90 to 102°C. Residual concentration of PCE after 4 hours was 18 to 60 ppm.

Saturated Zone Decontamination Mechanism: In the saturated zone, where the pores are full of water or DNAPLs, in situ heating can be potentially used for its decontamination. The relative contribution of air sweep (as in ISV) as a carrier gas for the volatilized DNAPLs will be much less because of zero effective permeability to air flow. A steam sweep, with a stripping action, can be established when the mixture of the liquids boils and the vapors rise up through the porous soil matrix. When two immiscible liquid layer are present together, it is possible to steam distill the mixture at a temperature which is lower than the boiling point of either pure-component layer. Thus water and TCE can

be steam distilled at 73° C; 1,1,1-TCA and water at 65° C; PCE and water at 88° C. It may be possible to steam distill the DNAPLs from the saturated zone.

Advantages: In situ EM heating has the following advantages and unique features:

- At 90° C, vapor and partial pressure of VOCs will increase by 5 to 40 times -- increases removal rates; lowers residual concentration;
- Elevated temperature enhances desorption from naturally occurring organic carbon and clay deposits --- leads to more complete removal;
- Increases the diffusivity of contaminant vapors from dead end pores --- reduces untreated pockets in micro-pores;
- Development of effective permeability to gas flow in the vadose zone due to the removal of moisture from the pore spaces --- reduces vapor collection cost (blower costs) or allows higher air flow rates.
- In situ generation of steam sweep through low permeability formations such as clay lenses and stringers leads to a more uniform decontamination of soil.

Field Tests: In the first test of the EM in situ heating system, a demonstration of the Thermal Enhanced Vapor Extraction System (TEVES) was performed jointly by Sandia National Laboratory and IITRI. A former chemical waste disposal pit in silty sand was treated sequentially by ISV, by in situ EM heating in combination with vapor extraction, and by RF heating and vapor extraction. Volume of the heated zone was 650 yd³. This field demonstration was conducted in fall of 1994. The final report is being written.

During the EM and RF portions of the TEVES experiment significant increase in the gas phase concentration of organic chemicals increased by a factor of 10 and of total organics by a factor of 4, when compared with in situ venting.

Soil was heated to a temperature range of 60° to 100° C by the EM process. The EM heating process enhanced the concentration of total organic chemicals (VOCs and SVOCs) in the extracted gas by a factor of 4 and that of the volatile compounds by a factor of 10.

Process Cost: Major cost items are: installation of electrodes, power, and effluent recovery and treatment. Electrode installation costs are comparable or somewhat higher than the well installation costs for the conventional in situ vacuum extraction or soil washing technologies. Off gas treatment costs are similar to those incurred by the in situ vacuum extraction process. Approximately 100 to 140 kW-hr of electrical energy is required (incremental cost) to heat soil to about 100° C and to remove up to 20% moisture by weight. The estimated power cost is \$5 to \$14 per ton of contaminated soil. Total cost of

remediation of soil by the EM process technology is estimated to be in the range of \$40 to \$160/ton of soil depending upon the batch volume heated. This does not include the cost of water control or containment systems which may be needed at certain sites.

Limitations: The EM heating process relies on the presence of soil moisture to provide a mechanism for the dissipation of electrical power in the soil and hence to generate heat. Thus, this process cannot heat the soil beyond the native boiling point of moisture in soil. Under actual field conditions the temperatures will be in range of 70° to 100° C.

The technology cannot be implemented in soil volumes which are densely packed with metal debris and/or metal structures, such as drum burial areas, etc. Buried metal can be tolerated provided that there is no continuous metal connection between any two electrode rows. Buried metallic utility lines (piping, cabling, wiring) that cut through the heated volume will have to be taken out of service as a safety precaution. Plastic lines, and plastic-insulated cables that are exposed to the high temperature may be rendered unusable.

The EM heating process may not be used for the removal of inorganic wastes, heavy metals, etc., due to the low volatility of these wastes at the processing temperatures.

It may be necessary to install groundwater control systems (such as pumping wells or slurry walls) if the process is used for treatment of the saturated zones at sites with rapidly (greater than 1 ft/day) moving groundwater.

4. DEMONSTRATION OBJECTIVES

The overall objective of the proposed field experiment was to demonstrate the feasibility of the EM heating process to remove organic solvents from clayey soil. The viability of the EM heating process to remove organic solvents from clayey soils at DOE facilities and elsewhere depends on the following factors:

1. Ability to enhance air sweep
2. Ability to enhance volatilization
3. Energy consumption

The proposed treatability study was designed to obtain data required to assess each of the above 3 factors when the soil is heated in situ to a temperature range of 85° to 95° C. These are described below.

4.1 Ability to Enhance Air Sweep

Complete and uniform sweep of soil by air or another sweep gas is an important factor to achieve in situ soil treatment. EM heating of soil removes moisture in the soil pores and increases its permeability to flow of air. This will result in the flow of a higher volume of air for a given vacuum. The volume of fluids (air, steam, and hydrocarbons) drawn from the soil volume for a given value of applied vacuum will be estimated based on the rate of production of effluents. Enhancement in fluid flow and vacuum data will be used to estimate the permeability of soil at various times and the enhancement in permeability due to heating will be determined.

4.2 Ability to Enhance Volatilization

The rate of removal of the contaminants during SVE is directly proportional to the vapor pressure of the contaminants. Increase in temperature from 20° to 90° C increases the pure component vapor pressure of common solvents by a factor of 10 or more. Even though the vapor pressure of organic compounds mixed with each other and adsorbed on soil surfaces is considerably less than the pure component vapor pressure, vapor pressure of the contaminants will increase by about the same factor with an increase in temperature. Two factors will be used to determine ability of the EM heating process to enhance volatilization: increase in soil temperature, and concentration of the contaminants in effluents.

4.3 Energy Consumption

Energy consumed to increase the temperature of soil will be measured at the input to the multi-tap transformer. Energy consumption depends on soil characteristics, heat loss, and the volume of water added to maintain ohmic contact between soil and the electrodes. Design calculations indicate that energy consumption will be between 160 and 220 kWhr per cu. yd. of soil.

5. DEMONSTRATION SITE DESCRIPTION

5.1 Site History*

The K-1070-C/D Classified Burial Ground is a 22-acre tract on the east side of the K-25 Site, inside the security perimeter fence. A security-cleared escort is required for entry by unclassified personnel. The K-1070 C/D Classified Burial Ground is composed of two distinctly bounded disposal areas: the K-1070-C maintenance equipment storage area and the K-1070-D disposal area. Prior to the establishment of K-1070-C as a maintenance equipment storage site (circa early 1975), the area was used as a burial ground for classified material. The K-1070-C area is currently serving as a maintenance equipment storage area. A shed and several piles of landscaping materials are located in this area. In general, the storage area is covered with gravel and serves as a parking lot. A natural drainage gully is located behind the shed; it channels surface water runoff from the K-1070-D hill. This ditch area and the boundary of the storage area are covered with vegetation.

The K-1070-D area is mostly covered with scrub grass and small trees. Several large trees are located along the northeast and southern boundaries. The southern portion of the site, which slopes downhill, has been eroded by heavy rainfall events, and several deep gullies are present in this area. Surface water runoff in the southern portion of the burial ground is funneled down these gullies to the drainage ditch located in the K-1070-C area.

The K-1070-D disposal area is composed of multiple disposal sites, including 3 large trench burial areas, 3 earthen dike storage areas, 13 small pits, 3 glass pits, 2 land farms, and a concrete pad. A brief description of the pits is given below.

Pits

Ten pits (A-1, A-2, B-1, B-2, D-1, D-2, E-1, E-2, G-1, and G-2) are located on the west side of the K-1070-C/D Classified Burial Ground tract, and each measures ~20 x 20 x 20 ft. These pits were used from 1977 to 1979 for the disposal of various hazardous wastes, including laboratory quantities of corrosives, oxidizers, reducing agents, and chemical and pesticide containers. One of the "G" pits was used for the disposal of drum quantities of various solvents and organics including methylene chloride, freon, and trichloroethene. Liquid wastes were poured onto sand back-filled into the bottom of the pits.

* Taken from Reference 8.

Glass Pits

In addition to the pits described above, three more pits (glass pits H, I, and J) on the site were used for the disposal of plastic materials and waste glass. These three pits are located immediately adjacent to the pits listed above. All 13 pits were used from 1977 to 1979 for the disposal of hazardous wastes and are believed to be a significant source of contamination.

Perennial Spring

A perennial spring is located about 200 ft west of K-1070-C/D Classified Burial Ground. This spring is the result of efforts to route seepage in this area to a local storm drain. In the mid-1970s, a polyvinyl chloride pipe was inserted into the K-1070 C/D Classified Burial Ground hillside. The spring water is currently collected and trucked to a groundwater treatment facility.

5.2 Demonstration Site

Figure 3 illustrates the general area in the vicinity of the ten pits on the west side of Burial Ground K-1070-D⁹. Several soil borings are marked on Figure 3. Results of soil sample analysis indicate that the contaminant concentration is highest in the samples obtained from soil boring 71 which is near one of the pits. Figure 3 also indicates a fence running north south west of Bore Hole 71. The demonstration was conducted outside the north-south fence in a general area directly opposite (west of) Bore Hole 71.

5.2.1 Site Geology and Hydrogeology**

The Classified Burial Ground occupies a hilltop in the southeastern corner of the plant. The hill is underlain by siltstone, sandstone, shale, and carbonates of the Rome Formation. It is bounded on the west by a north-trending fault (Figure 4) that plunges easterly, at a relatively low angle beneath the site. Surface runoff drains the hilltop in all directions to the plant storm-drain system and eventually to Poplar Creek.

The Rome Formation is a sequence of interbedded sandstones, siltstones, shales, and limestones of variegated olive, maroon, and drab colors. Buff-colored sandstone ledges of the lower Rome Formation form Pine Ridge along the southern border of the plant area (Figure 4). The more shaley upper member of the Rome Formation forms the hill where sites K-1070-C and D are located. The lower member of the Rome Formation is characterized by substantial proportions of impure carbonates ranging from limestone to

** Material in this section taken from Reference 10.

Figure 3. Map Showing the Location of the Demonstration Site.

LEGEND:

-
	EXISTING BUILDING
	EXISTING FENCELINE
	EXISTING CONTOUR
	EXISTING TREELINE
	EXISTING TREE
	AREA OF CONTAMINATION (AOC)
	TANK PIT
	EXIST. MANHOLE
	EXIST. CATCH BASIN
	EXIST. FIRE HYDRANT
	EXIST. POWER POLE
	EXIST. LIGHT POLE
● BRW-11.....	BEDROCK WELL
● UNW-110.....	UNCONSOLIDATED WELL
● TMW-1.....	MONITORING WELL
▲ 16-A.....	PHASE 1 SOIL BORING
△ SB-025.....	PHASE 2 SOIL BORING
△ TMW-2.....	K-1414 SOIL BORING
◆ SW-28.....	PHASE 1 STORM WATER SAMPLE
◇ SW-022.....	PHASE 2 STORM WATER SAMPLE
◇ SD-001.....	PHASE 2 SEDIMENT SAMPLE
⊕.....	SURVEYED BUT NOT SAMPLED

Science Applications
International Corporation

K-1070 C/D CLASSIFIED
BURIAL GROUNDS
OAK RIDGE, TENNESSEE

REVISION	DRAWN BY:	CHKD. BY:	DATE:
0	R. BEYLER	D. KEEFER	02-20-94

XREFERENCES	PLOT FILES
/93043/XREF/5835S13	/93043/PLOT/31311x17
/93043/XREF/5835S14	
/93043/XREF/5835S18	
/93043/XREF/5835S19	

SHT. 1 OF 1	/94043/DWGS/31311X17	N/A
DRAWING {	CAD FILE {	ROT. ANGLE

Figure 4. Geology in the Vicinity of the Oak Ridge Gaseous Diffusion Plan (Reference 4).

dolostone. Ground-water movement in the Rome Formation is restricted to fractures in the shales and sandstones.

Nine shallow test holes were drilled at this site (Figures 5 and 6). The wells and piezometers penetrate clay and weathered siltstone or silty-shale to depths ranging from 14.5 to 39 ft. Slug tests conducted in two of the piezometers, UNP-1 and UNP-13, indicated a permeability of about 10^{-5} cm/sec. A third test, conducted in UNP-2, indicated a permeability of 10^{-6} cm/sec. Table 1 summarizes the results of hydraulic conductivity measurements.

Wells BRW-9 and BRW-12 were drilled through clay residuum and penetrated dolostone and limestone, as well as siltstone and shale from about 30 ft. to the total depths of 123 and 300 ft., respectively. No permeability tests were conducted at either well. BRW-9 was pumped dry during development and recovered so slowly during the following two weeks that permeability is presumed to be extremely low. The water level in BRW-9 now stands well above levels in the shallow wells. This may not be an indication of vertical head difference between the bedrock and residuum aquifers but may simply be due to the fact that BRW-9 taps the water table at the highest point on the hilltop. BRW-11, located on the west flank of the hill, was drilled through the fault between the sandy siltstone of the Upper Rome and limestone of the underlying Chickamauga Group. No water was noted at the contact, indicating that the fault may be sealed by secondary mineralization. Well BRW-10, located a few hundred feet southeast of BRW-11, was drilled entirely in the Chickamauga indicating that the fault trace surfaces between the two wells.

Ground water is presumed to move through the unconsolidated residuum that blankets the hilltop site of K-1070-C, D, down the slopes, in a radial flow pattern. Several ephemeral springs are reported at the break in slope where the hillside becomes less steep and merges with the plain on which the plant is situated. Ground-water levels from well clusters BRW-10/UNW-17 and BRW-11/UNW-18 show a pronounced downward vertical gradient between the unconsolidated zone and the bedrock. Well cluster BRW-12/UNW-19 shows approximately equal heads between the unconsolidated zone and the bedrock.

5.2.2 Soil Sample Analysis Results

Table 2 is a summary of soil sample analysis¹¹ for volatile hydrocarbons. The soil samples were obtained from Bore Holes 71, 75, 76 and 80 marked on Figure 3. As the data show the highest concentration of total volatile hydrocarbons occurs in hole 71. This hole also has the highest concentration of volatile chlorinated hydrocarbons. Due to these results the demonstration was located as close as possible to Bore Hole 71. Table 3 is a list of volatile hydrocarbons which were analyzed and found in the soil samples obtained from the four bore holes. The soil obtained from these four bore holes was also analyzed for semi-volatiles, pesticides and PCBs. Table 4 summarizes the results of these analyses. It should be noted that the concentration of the semivolatiles is low, ranging from less than 1 ppm to

Figure 5. Monitor Wells and Inferred Ground Water Flow in the Unconsolidated Zone at the K-1070-C/D Site (Reference 4).

Figure 6. Monitor Wells and Inferred Ground Water Flow in the Bedrock at the K-1070-C/D Site (Reference 4).

**Table 1. Hydraulic Conductivity Results From Slug Test of Wells
Around K-1070-C/D**

Well or Piezometer Number	Methods of Analysis		Average Permeability (cm/s Rounded)
	Bouwer (cm/s)	Hvorslov (cm/s)	
UNP-1*	5.34×10^{-6}	7.04×10^{-6}	10^{-5}
UNP-2	5.77×10^{-7}	6.15×10^{-7}	10^{-6}
UNP-13	2.20×10^{-5}	1.08×10^{-5}	10^{-5}
UNP-17	2.60×10^{-4}	8.10×10^{-3}	10^{-4}
BRW-9 ^a			

SOURCE: Reference 10

^a The well was pumped dry during development and took several weeks to recover. From this, the hydraulic conductivity was assumed to be very low; however, this is probably a very local condition (e.g., screened interval not in proximity of water-bearing fractures, screen inadvertently blocked, or other).

The paired wells BRW-12/UNW-19 appear to exhibit nearly equal piezometric levels between the two aquifer systems, but this is probably an anomalous situation for that particular location.

Table 2. Concentration of Volatile Organics, ppb

	Hole Number 71			Hole Number 75		Hole Number 76		Hole Number 80		
	5-10 ft	10-15 ft	15-20 ft	5-10 ft	10-15 ft	5-10 ft	15-18 ft	0-5 ft	10-15 ft	15-18 ft
Total Volatiles, ppb	5271	29510	54910	6938	6560	23	383	32	5940	4209
Total Chlorinated Volatile HCs, ppb	21	1100	4190	75	712	0	212	11	115	542

(Based on Preliminary Data, Reference 11)

Table 3. Volatile Hydrocarbons Found * in Bore Holes 71,75,76,80

Contaminants	Concentration Range, ppb
<u>Hydrocarbons:</u>	
Acetone	15-26,000
2-Butanone	10-16,000
Ethyl Benzene	15-180
Toluene	140-2200
2-methyl-2-pentanone	15-25
Benzene	up to 6
Carbon disulfide	up to 7
<u>Chlorinated Hydrocarbons:</u>	
Methylene Chloride	5-40
Tetrachloroethene	25-130
1,1,1-Trichloroethane	5-25
1,1,2-Trichloroethane	10-90
Trichloroethene	20-400
1,1-dichloroethane	15-60
1,2-dichloroethane	5-30
1,1,2,2-trichloroethane	up to 15

* Only those found at or above detection limit.
Based on preliminary data, Reference 11.

7 ppm. The maximum concentration of PCB was found in Bore Hole 71 which had 6.5 ppm of Aroclor 1248 and 4.1 ppm of Aroclor 1254.

Measurement of radioactivity from the soil samples at various depths was done. Table 5 summarizes the radiation level for soil samples as a function of depth and bore holes. As the data indicate, the specific activity of various radio-isotopes in the soil is quite low.

It should be noted that the information presented in this section and in Tables 2 to 5 is based on preliminary results from Reference 11.

5.2.3 Geophysical Soil Characterization

Soil characterization measurements were done in the vicinity of the pit area. A brief summary of the preliminary results is provided herein. Three soil borings were made, one each in the vicinity of B-70, B-79, and B-80. Grab samples were obtained at two depth intervals from each boring. The following measurements were made:

• Bulk density	• Cation Exchange capacity
• Specific gravity	• Grain Size distribution
• Hydraulic Conductivity	• Moisture, % Sat.
• Moisture, %	• Organic carbon (<75 microns)
• Organic Carbon(bulk)	• Permeability
• pH	• Porosity
• Void Ratio	

The results of these measurements are summarized in Table 6. The range of the measured parameter and the average values are shown for shallow and deep intervals. The shallow interval data is based on four different samples, while the deep interval data are based on two samples. It should be noted that the moisture content of the soil averages 21 percent in the shallow zone while it increases to 47 percent with depth.

In the shallow zone the permeability shows a wide variation, almost by four orders of magnitude. This is probably due to the presence of gravel which varies from 0 to 4 percent in the shallow zone, but is absent at depth. Due to the wide variation in the observed permeability and also due to limited data at depth the above conclusion should be used carefully. The soil particle size distribution indicates that in the shallow region the soil is clay or clay-loam, in texture, whereas at depth the soil is all clayey.

**Table 4. Semivolatiles Found* in Bore Holes
71, 75, 76, 80**

Contaminant	Concentration Range, ppb
bis(2-ethyl hexyl) phthalate	62 - 6600
Chrysene ²	250 - 1300
Di-n-butyl phthalate ²	400 - 650
Dimethyl phthalate	49
2,4-Dimethylphenol ²	42 - 77
Fluorene	58 - 160
Isophorone ³	140
2-methylnaphthalene	320 - 770
Naphthalene	63 - 360
2-nitrophenol	73 - 84
Naphthalene	63 - 360
2-nitrophenol	73 - 84
N-nitrosodiphenylamine ³	40
Pentachlorophenol ³	38 - 130
Phenanthrene	95 - 130
Pyrene ⁴	45
PCBs and Pesticides	
Aldrin ³	1.2
Aroclor ³ 1242	1200
Aroclor 1248	200 - 6500
Aroclor ² 1254	350 - 4100

* Based on preliminary data from Reference 11.

¹ Only those found at or above detection limit.

² Found in Blanks also.

³ In Bore hole 80 only.

⁴ In Bore hole 76 only.

Table 5. Measurement of Radioactivity in Soil Samples, pCi/gm

Radio-Isotope	Hole Number 71			Hole Number 75		Hole Number 76		Hole Number 80		
	5-10ft	10-15ft	15-20ft	5-10ft	10-15ft	5-10ft	15-18ft	0-5ft	10-15ft	15-18FT
Co-60	0.31	0.35	.3	0.32	0.27	0.28	0.22	0.23	0.27	0.28
Cs-137	0.22	0.06	0.16	0.3	0.26	0.17	0.27	0.3	0.31	0.28
Gross Alpha	28±10	36±9.5	26±8.5	20±7.3	31±9.3	21±9.7	19±7.8	24±9.1	25±8.2	37±9.8
Gross Beta	28±5	35±5.7	35±5.3	20±4.7N	42±5.7	35±5.6	26±5	27±5	25±5	48±5.9
Sr-90	0.53±0.73	1.50±0.54	0.49±0.86	-0.98±1.2	-1.80±4.5	2±2.6	-0.23±0.5	0.09±0.93	0.51±1.4	-1.20±1.3
Tc-99	0.06±1.2	0.73±1.2	0.72±1.2	0.70±1.2	1.70±1.2	0.80±1.2	1±1.2	1.30±1.2	0.86±1.2	0.99±0.28
U-234	1.30±0.32	1.0±0.33	0.90±0.27	0.68±0.24	0.78±0.26	1.30±0.35	0.03±0.32	1.70±0.4	1.30±0.35	0.80±0.28
U-235	0.07±0.08	0.02±0.05	-0.01±0.01	0.05±0.07	0.01±0.05	0.11±0.1	0.11±0.1	0.15±0.12	0.08±0.09	0.10±0.1
U-236	1.2±0.3	1.40±0.38	0.83±0.27	0.77±0.25	0.86±0.26	1.10±0.32	0.87±0.3	1.80±0.41	1.20±0.35	0.64±0.25

Based on Preliminary Data, Reference 10

Table 6. Soil Characteristics

Parameter, units	Shallow, 0-8 ft (n=4)		Deep, 13 to 18 ft (n=2)	
	Range	Average	Range	Average
Bulk Density, lb/cu. ft.	84-109	98.3	73-80	76
Cation Exchange Capacity, MEq/L	7.5-16	10.3	12-32	22
Specific Gravity	2.66-2.79	2.71	2.68-2.75	2.72
Hydraulic Conductivity, cm/sec, $\times 10^{-8}$	0.2-1200	302	0.3-2.72	1.51
Permeability, cm/sec, $\times 10^{-6}$	2.7-12500	3145	3-39	21
Porosity, %	34-57	42	52-58	55
Void Ratio	0.5-1.07	0.74	1.1-1.4	1.23
Moisture, % sat.	62-91	78	100	100
Moisture, wt %	15-35	21.4	44-50	47
Organic Carbon, (<75 microns), %	0.14-0.88	0.46	0.12-0.17	0.14
Organic Carbon (Bulk), %	0.15-0.70	0.38	0.1	0.1
pH	4.8-6.6		4.7-6.1	
Grain Size, (Clay), %	28-55	36	52-74	63
Grain Size, (Silt), %	25-47	34	24-33	29
Grain Size, (Sand), %	20-36	28	2-15	8
Grain Size, (Gravel), %	0-4	2	0	0

5.3 Contaminants of Concern

The main contaminants of concern are the volatile hydrocarbons and chlorinated hydrocarbons present at the site. Based on the concentration ranges given in Table 3 the main contaminants of concern for this demonstration belong to the following three families of compounds:

- Benzene, toluene, ethyl benzene, xylene (BTEX family)
- 2-Butanone
- Various chlorinated hydrocarbons derived from methane, ethane, ethylene

Table 7 is a list of the 15 chemicals of concern along with their normal boiling points, and vapor pressure in the temperature range of 85° C to 95° C.

Table 7. Vapor Pressure and Boiling Points of Contaminants of Concern

Contaminant	Normal Boiling Point ° C	Vapor Pressure, mm Hg	
		85° C	95° C
Benzene	80.1	881.8	1177
2-Butanone	79.6	897.3	1206
Ethyl Benzene	136.2	151.8	216.8
Toluene	110.6	345.1	476.8
Methylene dichloride	39.6		
Tetrachloroethene	121.1	246.8	345.9
1,1,1-Trichloroethane	74.1	1052	1389
1,1,2-Trichloroethane	113.9	303	425.2
1,1-dichloroethane	57.3		
1,2-dichloroethane	83.4	797.2	1059
1,1,2,2-Tetrachloroethane	145.1	106.2	155.5
Trichloroethylene	87.2		
Chloroethane	12.3	6338	7890
Chloroform	61.2	1554	2031
1,1-dichloroethene	31.6		

6. DEMONSTRATION SYSTEM DESIGN

6.1 System Design Goal

The main goals of the in situ heating system design were:

- Heat soil to a temperature range of 85° to 95° C
- Allow for the measurement of extracted gas flow rate from each of the four gas collection wells as a function of applied vacuum.
- Allow for the collection and condensation of extracted gas samples so that the increase in contaminant mass flow rate can be measured.
- Measure the amount of electrical power consumed to heat the soil
- Measure the temperature distribution of the soil as a function of time and location

6.2 Design Basis

The design of the demonstration is based on the following:

- The demonstration site is located outside the Q cleared fence in an area opposite Bore Hole 71. Bore Hole 71 is inside the Q fence.
 - Dimensions of the heated volume: 25 ft. length
16 ft. width
20 ft. depth
 - Heated Volume: 8000 ft³
 - Average Bulk Density 98 lb/ft³
 - Target treatment temperature range of soil 85°-95° C
 - The demonstration will be performed with a 200 kW AC power source supplied with utility power.
 - As far as possible, the soil cuttings generated during drilling will be spread over the heated area and compacted so that they are also heated along with the soil.

6.3 Assumptions

The following assumptions were made in the preparation of the demonstration system design. Many of these assumptions were based on prior field observations, or on the results of prior soil core characterization studies. Once field work actually started some of the assumptions were found to be incorrect. These are pointed out below

- There is no bed rock in the depth interval of 0 to 20 ft. so that all the drilling activities can be accomplished with an auger. If bedrock is encountered, depth will be decreased. [Although bed rock was not encountered, layers of hard shale were found below a depth of 10 ft in some of the bore holes. This slowed down the boring operations and a larger cutting tool had to be used.]
- The water table is at least five feet below the bottom of the heated zone, that is the water table is at a depth in excess of 25 ft. Heating will be confined to a region in which there is no water table.
- Average moisture content of the heated zone is 30 % by wt. [Soil moisture analysis of core samples indicates that the moisture content varied between 7 to 38 percent.]
- Initial average permeability to gas flow is 30 millidarcy. [Initial permeability was immeasurable]
- The soil formation is stable so that the bore holes needed for electrode emplacement can be left unsupported for a period of 2 hours while the electrodes are being installed. This will allow smaller diameter holes to be drilled and will minimize the soil cuttings. [This assumption was confirmed during drilling operations.]
- There are no radioactive contaminants of concern. This was verified in the field by monitoring soil cuttings and the drill augers.
- It will be necessary to inject water outside the electrodes to keep the soil surrounding the electrodes moist. It was assumed that drinking water or water from a hydrant may be injected without restriction.

6.4 Estimate of Heating Time

An estimate of heating time was prepared to heat approximately 8,000 cu. ft. of soil from an initial temperature of 18° C (65 °F) to a final temperature of 95° C (203 °F). It was assumed that the average input power was 150 kW (75 percent of the power source capacity) and the daily operating factor was 95 percent. Table 8 summarizes the basis and

Table 8. Basis and Assumptions for Estimating Heating Time

Parameter	Value
Volume of Soil, cu. ft	8,000
Bulk Density of Soil, lb/cu.ft.	98
Specific Heat of Dry Soil, Btu/lb °F	0.2
Specific Heat of Water, Btu/lb °F	1
Latent Heat of Vaporization for Water, Btu/lb	970
Final Temperature, °F	203
Initial Soil Temperature, °F	65
Initial Soil Moisture, %	20 to 30
Percent of Native Water Boiled, %	75
Water Injected, lb	16000
Average Power Input, kW	150
Daily Operating Factor, %	95%
Assumptions:	
<ul style="list-style-type: none"> • The heat load due to contaminants may be neglected due to their low concentration • All the injected water will be boiled out • The heated volume is well above the water table • Water ingress rate is small compared to the native soil moisture and the water injection rate 	

assumptions used for the calculation of the heat load and heat up time. Table 9 summarizes the energy load calculation. The heating time ranges from 18 to 25 days as the native soil moisture varies from 20 to 30 percent.

Table 9 also shows that approximately 118,000 to 177,000 lbs (14,000 to 21,000 gallons) of native water will be boiled out of the soil as steam or water vapor.

Table 9. Estimate of Energy Required and Heating Time

Energy Load	Energy Required, Btu		
	Soil Moisture Content, %wt		
	20%	25%	30%
Sensible heat required to raise dry soil to 95° C	17,310,720	16,228,800	15,146,880
Sensible heat required to raise native soil moisture to 95° C	21,638,400	27,048,000	32,457,600
Latent Heat to Boil 75% of native soil moisture	114,072,000	142,590,000	171,108,000
Energy to raise native soil temperature, no heat loss	153,021,120	185,866,800	218,712,480
Heat loss, 25 percent of above	38,255,280	46,466,700	54,678,120
Total Energy to raise soil temperature to 95° C, Btu	191,276,400	232,333,500	273,390,600
kWhr	56,043	68,070	80,100
Sensible Energy required to raise injected water to 95° C	2,208,000	2,208,000	2,208,000
Latent Heat to boil 100% of injected water	15,520,000	15,520,000	15,520,000
Total heat load for injected water	17,728,000	17,728,000	17,728,000
Total Process Energy Requirement for Heating, Btu	209,004,400	250,061,500	291,118,600
kWhr	61,238	73,267	
Energy Available per day, kWhr/day	3,420	3,420	3,420
Heating Time, day	18	21	25
Native water boiled, lb	117,600	147,000	176,400

6.5 Site Layout

Figure 3 shows the location of the demonstration area outside the K-1070 burial ground. Figure 7 shows the initial site plan. The shaded area shows the location of the heated zone. This area was picked so as to keep the long dimension of the electrode array parallel to the Q fence and also to maximize the lateral distance between the array and the overhead power line. In addition, previous sampling had indicated that the high concentration plume lies between the two Bore Holes 74 and 75.

Figure 8 illustrates the actual location of the electrode array and the heated zone. As per the original plan the array was to be placed on the east shoulder of the road running outside the Q fence. However, the shoulder was on a steep rise and it was decided that it would

Figure 7. Initial Site Layout

Figure 8. Actual Location of the Electrode Array

not be safe to drill on the upper portion of the shoulder where the electrode row EC would have to be drilled as per the original plan. Thus the array was moved approximately 8 ft west of the location in the initial plan. This placed the A row in the road, the B row in the drainage ditch east of the road and the C row half way up the shoulder of the road.

6.6 Heating System Design

6.6.1 Electrode Array Plan

The design of the electrode array which was placed in bore holes located in the shaded rectangle of Figure 8 is described in this section. The electrode array was formed by drilling three rows of electrodes. Figure 9 is a plan view illustrating the electrode array dimensions, row spacing, electrode spacing and the size of the vapor barrier. The length of each of the two outer rows was 25 ft, the outer row separation was 16 ft and the electrode separation within any row was 2.5 ft. The outer rows were longer than the center row. Each outer row had 11 electrodes, while the center row had 9 electrodes. This configuration was selected in order to better control the fringing electrical fields near the ends of the array. There were four gas collection wells in the approximate center of each quadrant of the array. These wells were connected to a manifold by means of steel pipes. In addition two perforated horizontal gas collection lines were placed on the surface of the soil. These were used for collection of vapors that rose to the surface. All vapor collection lines were run under the vapor barrier until they cleared the perimeter of the barrier. All the lines were heat traced to prevent condensation of steam. Electrical insulators were installed in each metal pipe leaving the array to prevent accidental personnel injury when power is applied.

There were 7 thermowells which are marked by filled triangles and labelled MW01 through MW07. Wells MW01 through MW06 were located within the heated array, while MW07 was outside the array. In each of these wells, two polypropylene tubes, plugged at the bottom end were inserted to a depth of 20 ft. During operations, thermocouples were inserted in these tubes to measure the temperature of the soil at various depths as specified in the temperature monitoring plan described in Section 6.6.7.

The vapor barrier covered the entire area of the heated zone and extended outward a distance of 10 ft. all around the array. The purpose of the vapor barrier was to control fugitive emissions, control air infiltration and minimize heat losses from the soil surface. The vapor barrier was made in a single piece. It was made from Seaman Corporation's 8130 XR-5 SP Geomembrane.

Figure 9. Plan View of the Electrode Array
(water injection, instrumentation and power lines are not shown)

6.6.2 Typical Transverse Section

A central transverse section of the array is shown in Figure 10. This figure illustrates the depth of the outer and the central electrodes, the depth of the temperature monitoring wells, the thickness of the soil overpack and the location of the gas collection lines in a sectional view. The electrodes in the outer rows were 20 ft deep while those in the central row were 18 ft deep. It was originally estimated that the soil cuttings obtained from the drilling of the holes will form an overpack with a depth of 10 to 18 in. This was based on the assumption that the soil can be compacted to an average density of 50 to 100 lb/cu. ft., and that the soil in the area is stable so that empty bore holes will not collapse for a period of 1 to 2 hours while the electrodes are placed. In stable soil smaller bore holes can be drilled because a hollow stem auger will not be needed to provide support to the bore hole wall.

The actual amount of soil cutting was very small. Even after they were over packed, additional clean gravel was needed to cover the surface vapor collection lines and to make a smooth surface profile to allow for the spreading of the vapor barrier and control of water drainage above it.

6.6.3 Typical Electrode Design and Bore Hole Completion

The electrode design and the completion of the electrode bore holes is illustrated in Figure 11. All electrodes were made from 2-in. diameter Schedule 40 black iron pipes. The electrodes were capped at both ends. A standard pipe cap was used at the bottom of the electrodes. For the top a specially modified pipe coupling was used which provided for the attachment of the power cables and a pass through for the thermocouple wires exiting the electrode. Clamped to the outside surface of each electrode was a perforated copper tube filled with clean sand. Water was delivered to these tubes by means of a water distribution header.

6.6.4 Water Injection System

The flow diagram for the water injection system is illustrated in Figure 12. In Figure 11 a water distribution header was illustrated near the top of the electrode. There were three such headers, one for each of the three electrode rows. Each header supplied water to 9 to 11 electrodes by means of branches connected to the header. It was necessary to keep the soil moist around the electrodes in order to maintain a conductive current path. Figure 12 shows the water injection system flow diagram. A pressure reducing station was mounted to the fire hydrant and the water was conveyed in a hose to the water flow control system. The flow control system contained a filament filter, pressure gauges and three rotameters to set and measure the flow rate in each of the three legs of the water injection system. All water lines between the flow control center and the electrode array were made from plastic, thus electrically isolating the flow control system from the electrode

Figure 10. Central Transverse Section of the Electrode Array

Figure 11. Typical Electrode Design and Bore Hole Completion

Figure 12. Water Injection System Flow Diagram

array. The distance between the fire hydrant and the flow control system was approximately 100 yards. The long length of the rubber hose was sufficient to electrically isolate the fire hydrant from any stray electrical potential on the flow control system.

6.6.5 Gas Collection and Treatment System

Gas collection lines were shown in Figure 9 and 10. These lines were connected to four gas collection wells and to two horizontal perforated gas collection lines placed near the top surface of the soil, in the overpack. Figure 13 illustrates the completion of a typical gas collection well. The gas collection was made from stainless steel wire wound water well casing with an opening of 0.020 in. The depth of the casing was 20 ft below the original ground surface. The interval of 2 to 20 ft was slotted. There was a bentonite clay surface-seal from surface to a depth of 2 ft. The casing was placed through a hollow stem auger and the annular space was be filled with a medium to coarse sand. The ID of the bore hole was 8 in. An elbow was connected to the top of the casing inside the overpack as schematically illustrated in the flow diagram shown in Figures 14.

Hot gas and steam were collected from the gas recovery wells and conveyed through the vapor collection system by means of a Roots blower. Figure 14 illustrates the flow diagram of the vapor recovery system. This figure shows the six gas collection lines manifolded together at a vacuum manifold. All lines were heat traced as they left the heated soil area to keep the gases as close to the soil temperature as possible. This is desirable to minimize condensation in the line. A single heat traced gas line conveyed the gases from the manifold to a demister. Provision was made for the addition of ambient air to the hot gas upstream of the demister. The dilution air was added only when it became necessary to reduce the humidity of the gas stream entering the blower. Soil gas sampling was done at sample point S1 located upstream of the demister. Other instruments for the measurement of line pressure, temperature and flow rate were mounted in close proximity of the sampling point.

Downstream of the demister a humidity probe was installed in the line to record the gas humidity and temperature.

The hot gas lines were heat traced with a constant wattage electrical heating tape designed to maintain the pipe temperature at 100° C. The cable was rated for Class 1, Division 2 hazardous areas. Three local temperature controllers were used which were also rated for Class 1, Division 2 hazardous area.

Table 10 gives a list of all instruments and equipment used for the vapor collections system along with their manufacturer's name, model number, type, ratings etc.

Figure 13. Typical Gas Collection Well Completion Below Ground

Table 10. Vapor Collection System Equipment List			
Item	Manufacturer	Model No.	Rating
Vacuum Blower -- Rotary Positive Displacement	Roots	36URA1-B61	125 scfm
Fleximesh Line Separator	Koch Eng.	8	
Humidity Meter	VAISALA	HMP235	0-100°C rH
Flowmeter - Line	Avista	V-0103 3"	100-150 scfm
Differential Pressure Cell and Transmitter	Rosemount*	115DP*, 3E22B1	0-10 in H ₂ O
Differential Pressure Gauges for Flow Measurement	Dwyer	2210DP	0-10 in H ₂ O
Condensate Pump -- Peristaltic	Cole Parmer Inst. Co.*	N-07587-65	33 rpm TRFC-120V
Liquid Level Control Switch	Dwyer Inst.	L6EPB-B-S-3 Flotect	5 amp
Condensate Pump Controller Relay	Omega Eng.	SSRL2	10 amp
Manifold Vacuum Gauges and Hot Gas Line Pressure Gauge	Dwyer Inst.	2210DP	0-10 psig
Electrical Isolator	McMaster Carr*	High Temp. Silicone Hose	100 psig -65 to 350°F
Thermometers for Type K Thermocouples	Omega Eng.	HH26K	-222 to 1732°C ±1 °C
Flowmeter Dilution	Avista	V-0102 2' Vcone Flowmeter	75 scfm
Motor Starter	Square D	D321NRB	30 amp
Heat Tracing	Chromalox	CWM 12-1	12 watts/ft. 120V
Controller for Heat Tracing	Chromalox	RTBC-3EP	25 amp/120V
Thermocouples	Watlow-Gordon	Type K	1150°C ±1 °C
Insulation Connector	North Insulation	2" Fiberglass	0.2 BTU@100 °F

* Supplier

6.6.6 Vapor Barrier and Thermal Insulation

A vapor barrier was used to cover the heated zone. It extended approximately 10 ft outside the dimensions of the heated area. The plan view of the vapor barrier is illustrated in Figure 9. Figure 15 illustrates a cross sectional view of the vapor barrier. The vapor barrier was made from a Geomembrane manufactured by the Seaman Corporation. The membrane is made by coating a base fabric with ethylene interpolymers alloy (EIA). The base fabric is made from polyester fibers. The catalogue number of the membrane is 8130 XR-5 SP. The SP designation specifies the use of material suitable for solar pond applications. This grade was selected due to improved temperature resistance. The 8130 designation specifies the finished coated weight of the membrane.

A 2 in. thick thermal insulation blanket was placed on top of the geomembrane. The thermal insulation was covered with a single sheet of nylon cord reinforced HDPE. The HDPE cover was needed to protect the thermal insulation from rainfall. The thermal insulation covered the heated area and extended out by 3 ft, all around the array. The HDPE sheet will cover the heated area and extend 10 ft all around, outside the array.

6.6.7 Thermal Instrumentation

The progress of in situ heating and control of the power input was based on the measurement of the temperature (among other parameters) of the soil as a function of time and location within the array. For this purpose a number of thermocouples were attached to the inner walls of selected electrodes. In addition, thermocouples were inserted into polypropylene-tube thermowells inserted in bore holes drilled through the heated soil. The distribution of the thermocouples and the temperature measurement points in the thermowells are presented in this section.

The temperature data from thermocouples inside the electrodes of the two outer rows were measured by the data logger and displayed on a computer screen every two minutes. The data were written to memory storage every 4 hours. Acquisition of temperature data from the center row of electrodes and the thermowells required shut down of AC power input to the soil. Thus center row temperatures were measured during every shift change when there were two operators present at the site. The thermowell temperature measurements were made once a day, typically in the morning shift.

The thermocouple distribution is shown in the next five figures. Figures 16, 17, and 18 show the location of the thermocouples attached to the inner walls of the electrodes. Figure 16 illustrates the location of thermocouples in the outer row of electrodes, Row EA. There were a total of 12 thermocouples in this row. They were located at depths of 0.5, 9, 18 and 20 ft. Figure 17 illustrates the thermocouple distribution in the center row of electrodes, Row EB. In this row there were 13 thermocouples located at a depth of 0.5, 9 and 18 ft. Thermocouples in the second outer row of electrodes, Row EC, are illustrated

Figure 15. Vapor Barrier Construction Detail

Figure 16. Electrode Row EA Thermocouple Location and Numbering

Figure 17. Electrode Row EB Thermocouple Locations and Numbering

Figure 18. Electrode Row EC Thermocouple Locations and Numbering

in Figure 18. In this row there were 7 thermocouples located at a depth of 0.5, 9, 18, and 20 ft.

All thermocouples were Type K, ungrounded junction with a 12 in. long, 1/16 in. stainless steel (SS304) sheath.

The temperature monitoring points in the thermowells are illustrated in Figures 19 and 20. Figure 19 is a central transverse view of the array showing the location of the temperature monitoring points in the thermowells. These thermowells were made from 0.25 in ID polypropylene tubing which was plugged at the bottom end. A thin, 1/16 in. diameter thermocouple was inserted to the desired depth to read the temperature. Thermowells which were located under the vapor barrier were passed through the barrier so that the thermocouples may be inserted through them. Every pass-through was sealed to prevent gas leakage.

After site preparation, but before the start of the demonstration, Thermowells MW01 and MW05 were damaged and they could not be used.

Figure 21 illustrates a block diagram of the thermocouple wiring and data acquisition system. A bundle of thermocouple wires exited from each of the three electrode rows. The three bundles entered a disconnect box. Inside the disconnect box the thermocouple cables were connected to three other wire bundles leading to the multiplexer. This arrangement allowed disconnection of any wire bundle in case of spurious pickup of 60 Hz potential. In actual operation, the cables from the two outer rows were left connected at all times. The cable from the center row was connected to the multiplexer only when the power was switched off. An interlock switch on the door of the box was provided to prevent application of power to the array should the B row cables be left connected.

Table 11 is a list of key components used in the temperature data acquisition system.

6.6.8 Description of the AC Power Source

Figure 22 is a block diagram of the power supply to the electrode array. AC power from the 480 V supply was provided to IITRI's multi-tap isolation transformer which in turn supplied power to the electrode array.

Table 12 summarizes the various tap settings, voltages, current and the load impedance necessary to deliver the maximum 200 KVA power into the load. At a given voltage tap setting, the resistance of the load should be equal to or greater than the values listed in the last column in order to stay within the current capacity of the transformer.

Figure 19. Temperature Measurement Points in Thermowells—Vertical Section AA'

Figure 20. Temperature Monitoring Points in Vertical Section BB'

Figure 21. Block Diagram of Thermocouple Wiring and Temperature Data Acquisition System

Table 11. Key Components of the Temperature Data Acquisition System

Item	Supplier	Model No.	Rating
Thermocouples	Watlow-Gordon	Type K Chrome Alumel	1150°C±1 °C
Connectors	Newark Electronics	NA	Low Resistance
Data Logger	Campbell Scientific	CR10/AM416	
Conduit and Fittings	Wholesale Supply*	PVC	Std Electrical
Bulkhead Fittings	Swagelock	B-100-61	2700 psi -28 to 37 °C

Table 12. Voltage Taps on the AC Power Transformer

Tap No.	Voltage, V	Current, A	Load Resistance for Full 200 KVA power, Ohm
10	200	1000	0.2
9	400	500	0.8
8	600	333	1.8
7	800	250	3.2
6	1000	200	5
5	1500	133	11.3
4	2000	100	20
3	2500	80	31.3
2	3000	67	44.6
1	4000	50	80

Figure 22. Block Diagram of Power Supply to the Electrode Array

The multi-tap transformer and all the associated controls were installed in a 20 ft long trailer. This trailer was parked outside the safety exclusion zone and AC power lines were run in PVC conduit through the safety fence into the array.

6.6.9 Safety System

Due to the nature of the vertically emplaced electrode array used for this demonstration, and its extension through the soil surface, soil surface voltage gradients will result when the array is electrically energized. In order to restrict access to the area immediately over the subsurface electrode array and the nearby surrounding area, an electrical exclusion zone was established. This exclusion zone was designed to prohibit access to the area where the soil surface voltage gradients were predicted to be above the safe limit of 2 volts per meter. This safe limit was selected based upon ANSI/IEEE Standard 80 - 1986¹² and data acquired by IITRI's ELF program. It was selected to provide a high level of confidence that no electrical current would be perceived at voltage gradients at or below this limit value.

The placement of the exclusion zone was selected based on a series of analytical predictions of the soil surface voltage gradients or step potential contours. Two extremes of soil conditions were analyzed; initial and dried. Figures 23 and 24 illustrate the step potential contours around the electrode array for each of these two soil conditions at an applied energy level of 200 KVA, the maximum output of the AC power supply. The voltage gradient contours show the impact of the long grounded Q-fence. Also shown within these figures is the placement of the exclusion zone boundary. This placement was selected so as to completely contain the area where the soil surface voltage gradient or step potential was above the safe limit. This boundary was established by erecting a four foot high bright orange plastic construction fence.

In addition to the site administrative controls, such as the Lockout/Tagout procedure for the AC power supply, used to assure electrical safety, an external interlock string was established to de-energize the AC power supply's output and remove AC energy from the subsurface electrode array should any portion of the interlock string be opened. Figure 25 illustrates a schematic representation of the external interlock string. The external interlock string consisted of the following:

- a dual beam infrared photo-electric fence, just within the perimeter of the exclusion zone fence.
- three manually interruptable emergency stop buttons, located in the office trailer, outside of the exclusion zone fence personnel gate, and on the vapor collection system's blower platform.
- contact closures, required in order to energize the electrode array, located within the thermocouple disconnect box and at the exclusion zone fence personnel gate.

Initial Contour Plot of Step Potential @ 10, 5, 2, 1, 0.5, 0.2, 0.1 V/m

Depth (feet)= 0.20

Figure 23. Step Potential Contours at Soil Surface for Initial Soil Conditions.

Dried Contour Plot of Step Potential @ 10, 5, 2, 1, 0.5, 0.2, 0.1 V/m

Depth (feet)= 0.20

Figure 24. Step Potential Contours at Soil Surface for Dried-out Soil Conditions.

Figure 25. AC Power Supply External Interlock String

Two outdoor warning strobe lights were mounted atop the AC power supply. An amber light indicated that the power supply was energized. A red light indicated that AC power was being applied to the electrode array. A 100 dB audible alarm sounded prior to the application of AC power to the electrode array.

6.6.10 Gas Sampling System

The increase in the rate of removal of the soil contaminants was measured by determining their concentration in the extracted soil gas and its flow rate. Sampling procedure for the hot gas is described in this section.

Figure 26 is a flow diagram of the gas sampling system. The gas sampling point is marked as S1 on Figure 14. Table 13 is a list of components used in the gas sampling train. Once a day the gas sampling train was connected to the sampling point and a gas sample was drawn through two cold traps in series to condense and trap the contaminants present in the hot gas stream. The cold traps were pre-filled with water and methanol. Typically 20 liters of the hot soil gas were sampled. The liquid in the two cold traps was recovered and transferred to a volumetric flask where its volume was adjusted to a known level by the addition of clean 50/50 v/v% solution of purge and trap grade methanol and purified water. The sample was transferred to pre-cleaned 20 ml glass vials and capped with a screwed septa cap. The sample was stored in an ice chest and transferred to the laboratory for the analysis of VOCs by US EPA Standard Method 8260¹³. This method uses a purge and trap technique for sample concentration and introduction into a GC/MS system for separation, detection and quantification.

Table 13. Gas Sample Train Equipment List			
Item	Manufacturer	Model No.	Rating
Probe, Teflon Tubing	Cole Parmer*	None	
Heat Tape	Barns Tead/ Thermolyne	B00051-0B0	416 watts
Voltage Control	Variac	NA	0-140 VAC @10 amp
Shut Off Valve	Whitey	33VS4	235 psig @200 ° C
Flow Control Valve	Whitey	N1287-1	600 psig@150 ° C
Impinger	Ace Glass	Midget	**
Pump	Thomas	917CA18 TRE	Leak tight - 3.5@120V
Mass Flow Meter	TopTrack	NA	0-2 lpm
Totalizer	Omega	NA	-
Thermocouples	Watlow- Gordon	Type K	-222 to 1732 ±1 ° C
Thermometers	Omega Eng.	HH26K	-85 to 1100 ±1 ° C

* Supplier

** Not available at usage conditions

Figure 26. Gas Sampling Train Flow Diagram

7. DEMONSTRATION SYSTEM PERMITTING REQUIREMENTS

7.1 NEPA Review

NEPA review was performed by DOE Oak Ridge. The review was based on information provided by IITRI in the Demonstration System Design¹⁴ and Test Plan Documents¹⁵. The review concluded that a Categorical Exclusion applicable to technology demonstrations can be given to the project under DOE NEPA Implementing Procedures, Final Rule 57 FR15122, Subpart D Appendix B, p.15156 (1992)

7.2 Drilling Permit

A drilling permit was issued by Lockheed Martin Energy Systems based on the location of the planned drilling activities for the formation of the bore holes needed to install the electrode array. The locations were shown on Figures 3 and 8.

7.3 Air Emissions Review

IITRI estimated the potential emission of chlorinated solvents and other VOCs based on the soil characterization information available at the time of project document preparation. These concluded that the concentration of total VOCs in the air stream would be in the range of 0.3 to 13 ppmV. For chlorinated VOCs it was estimated that their concentration would be in the range of 14 ppbV to 1.1 ppmV. LMES also conducted a review and came to the conclusion that the VOC emissions would be less than 0.1 lb/hr. They concluded that source would be exempt from the permitting requirements of the TDEC.

The project test plan was submitted to TDEC and USEPA Region IV for review. Both agencies approved the plan as written. However, USEPA requested that a schedule with dates be submitted and a complete cost history of the project be prepared.

8. DEMONSTRATION SYSTEM OPERATION

8.1 System Start Up

8.1.1 Standard Operating Procedures (SOPs)

In preparation for the heating demonstration, a series of nine (9) Standard Operating Procedures (SOPs) were generated, reviewed, and adopted. These SOPs covered all aspects of the EM heating systems' operation and maintenance. Table 14 lists the SOPs used.

8.1.2 Readiness Review

A Readiness Review Meeting was conducted at the field site on June 6, 1995. Members from DOE and LMES and IITRI were present. A detailed review of checklist questions was conducted. The checklist review criteria for the in situ soil heating field demonstration facilities were grouped into the following three categories;

- management, regulatory control systems and procedures
- facilities and equipment
- personnel

In addition to the checklist review criteria a list of questions regarding conduct of operations guidelines was received from DOE personnel and reviewed as part of the meeting.

All questions posed throughout the course of the Readiness Review were adequately and sufficiently addressed during the review meeting. A set of interrupting current rating calculations were made and submitted on June 12, 1995. A Report of the Results of the June 6, 1995 Checklist Review of the In Situ Soil Heating Demonstration at K-25 Site, Oak Ridge, Tennessee was prepared by DOE program staff on June 13, 1995.

8.1.3 Pre-operational Check and Safety Measurements

The 200 KVA 60 Hz power supply (ACPS) was functionally tested under no-load conditions on June 8, 1995. As part of these tests, the proper operation of all components of the safety interlock string was verified without any electrical energy being applied to the electrode array. The ACPS was run through all voltage tap ranges to verify its proper operation.

A low power test (LPT) was conducted on June 9, 1995 by applying 10 kW to the subsurface electrode array. The performance of the ACPS and its associated metering was verified. Initial measurements were made of the soil surface step potentials and touch voltages as described in the related SOPs. The purpose of these measurements was to

Table 14. Standard Operating Procedures for the EM Heating Demonstration at K-25 Site.	
SOP Number	Title
C-Field-001-00	Operational and Emergency Shut-Down Procedures for 200 KVA 60 Hz Power Supply.
C-Field-002-01	Gas Sampling Procedure and Equipment.
C-Field-003-00	Calibration and Use Procedure for the Photoionization Detector (PID).
C-Field-004-00	Step Potential Measurement Procedure.
C-Field-005-00	Touch Voltage Measurement Procedure.
C-Field-006-00	Gas Recovery Blower Maintenance Schedule.
C-Field-007-00	Lockout/Tagout Procedure for the AC Power Supply Transformer.
C-Field-008-00	Soil Temperature Measurement Procedure.
C-Field-009-00	Shift Changeover Procedure.

ensure safe operating conditions for all site personnel and equipment and facilities at full power (up to 200 kW applied). All measurement data, collected during the LPT, was extrapolated to full power operating conditions and examined for any problem areas external to electrical exclusion zone. No problems were identified at these extrapolated values of step potential and touch voltage.

Designated measurement locations and radial measurement paths were identified and established for future measurements of step potential and touch voltage. Figure 27 illustrates the relative locations of the six (6) established step potential measurement locations. Figure 28 and Table 15 illustrate and identify the 23 established touch voltage measurement locations.

The Vapor Collection System (VCS) was functionally checked on June 11, 1995. It was during this functional testing that the initial soil permeability measurements were made.

Figure 27. Location of Step Potential Measurement Points.

Figure 28. Location of Touch Voltage Measurement Points.

Table 15 Established Touch Voltage Measurement Locations.

Location #	Description
1	3 Inch Vapor Line - Sample Port
2	Methanol Pump
3	Methanol Underground Storage Tank Breather Vent
4	Metal Post - East
5	Metal Post - Middle
6	Metal Post - West
7	"Q" Fence - Standard
8	"Q" Fence - Gate Post - North
9	"Q" Fence - Gate Post - South
10	Culvert Near "Q" Fence
11	West Monitoring Well - Outside Electrical Exclusion Zone
12	West Monitoring Well - Inside Electrical Exclusion Zone
13	Culvert
14	AC Load Center
15	VCS Blower
16	VCS Condensate Pump
17	ACPS Trailer Hitch
18	"Q" Fence - At Electrical Exclusion Zone
19	"Q" Fence - 3 Standards North
20	"Q" Fence - 6 Standards North
21	"Q" Fence - 12 Standards North At Gate
22	Control/Office Trailer
23	Water Injection System Frame

8.1.4 Start of EM Heating Demonstration

The VCS was turned on to begin collecting gases and vapors from the soil volume at ambient temperature on June 12, 1995 at 1030 hours, prior to the start of the EM heating. The ACPS was turned on to begin the heating demonstration on June 13, 1995 at 2000 hours, at an applied power level of 25 kW. The power level was increased in approximately 25 kW increments each day over the next 3 days to a maximum applied power level for this demonstration of ~105 kW. All electrical safety measurements were conducted for each increase in the applied power to the array. Step potential and touch voltage measurements were periodically checked throughout the duration of the EM heating. At no time during the application of electrical energy did any measured step potential or touch voltage exceed the safe limits of operation, described in Section 6.6.9

8.2 Chronology of Events

Table 16 gives a chronology of major events during the course of this project.

8.3 List of Data Measured and Recorded

8.3.1 Electrical

During the course of the EM heating demonstration project both manual and automated measurements were made regarding the operation of the ACPS. Those manually recorded by the shift operator from the ACPS metering and control displays include the following:

- ACPS Input Data - Voltage, current, both real (kW) and total (KVA) power, cumulative energy (KWHR), power control potentiometer setting, transformer secondary tap setting, transformer ON hours, and trailer temperature.
- ACPS Output Data - Voltage and current. Output power applied (KVA) to the array was calculated by multiplying the voltage times the current. The array resistance was calculated by dividing the voltage by the current.
- During ACPS lockout/tagout, the status of the disconnect switch was recorded.

The above measurements were recorded in the project logbook at least once every 4 hours of operation.

Measurements were automatically recorded by means of a Campbell Scientific datalogger and multiplexer. The measured and calculated values were available to the shift operator for real time monitoring in the control trailer and were refreshed every 30 seconds.

Table 16. Chronology of Selected Events.	
Date	Event
11/1/93	Project Kick off meeting was held
2/24/95	Drilling for Electrode Array Installation was begun
	Three month gap in field activities
5/15/95	Resumed system installation activities in the field
6/6/95	Readiness Review was held in the field
6/9/95	Low power test conducted at 10 kW.
6/12/95	Vapor collection system turned on.
6/13/95	Power applied to electrode array at 25 kW - Start of Heating.
6/16/95	Applied power increased to 100 kW (25 kW/day).
6/16/95 to 6/22/95	Pressure in B row water injection manifold increased from 15 to >100 psig. Flow to B row manifold decreased from 1.3 (set) to a maximum of 0.5 gph.
6/20/95	Rate of increase of average temperature of the entire heated soil volume (excluding the A & C row perimeter) has plateaued at 84°C.
6/29/95	Average temperature of the entire heated soil volume (excluding the A & C row perimeter) dropped to 81°C.
6/29/95	Water injection flow rate to the B row manifold rapidly increased to 5 to 6.5 gph from 0.5 gph.
7/5/95	Average temperature of the entire heated soil volume (excluding the A & C row perimeter) - Increased to a maximum of 92.5°C.
7/8/95	Heating phase over
9/22/95	Soil sampling was started
10/6/95	Demobilization completed

The data collected by the datalogger was stored for final reporting every 15 minutes. The data collected by the datalogger include:

- Input power to the ACPS measured and recorded in both real (kW) and total (KVA) values.

- ACPS output voltage and current were recorded. Output power applied (KVA) to the array was calculated by multiplying the voltage times the current. The array resistance was calculated by dividing the voltage by the current.
- Datalogger status - battery voltage and multiplexer temperature.

8.3.2 Thermal

Thermal data acquisition was concerned with the measurement and recording of the soil temperature. There were 32 thermocouples installed in selected electrodes. All of these thermocouples were connected to a data logger by means of a multi-plexer. Thermocouple data were automatically acquired and stored in the data logger memory module from the two outer rows of electrodes. This was done once every 4 hours starting at midnight. The thermocouples in the center row of electrodes were normally kept disconnected from the multi-plexer. These were manually connected approximately three times a day for reading the temperature and storing the information. Once per day the data from the data logger memory were transferred to a file on the hard drive of a personal computer.

In addition to the 32 thermocouples, there were 20 temperature measurement points located in five thermowells. These were measured once per day by manually inserting a long thermocouple into each of the five wells. The data were recorded by hand into a project logbook and also entered into a computer file.

8.3.3 Vapor Collection and Soil Permeability

The following operational data for the vapor collection system were recorded:

- Vacuum in each of the six legs of the vapor collection manifold
- Vacuum in the hot soil gas line
- Total gas flow rate in the hot soil gas line
- Internal temperature of the hot soil gas line
- External skin temperature of the hot gas line
- Flow rate of dilution air, if any
- Humidity of the combined gas stream, that is, hot gas and dilution air
- Vacuum at the suction inlet of the gas collection blower
- Amount of condensate collected

While measuring the soil permeability the same information was collected while applying vacuum to each of the four gas collection wells individually.

9. DEMONSTRATION DATA

9.1 Soil Temperature Data

Soil temperature was measured by means of thermocouples and thermowells as described in section 6.6. There were a total of 32 thermocouples in the electrode array. Of these twelve thermocouples were installed inside the 11 electrodes of row EA, thirteen were installed in the 9 electrodes of the center row EB, and there were 7 thermocouples in the second outer row EC. The thermocouples were attached to the inner wall of the electrode at four different depths: 0.5 ft, 9 ft, 18 ft and 20 ft. The distribution of the thermocouples in the electrodes was illustrated in Figures 16 to 18.

The average temperature of the thermocouples in outer electrode row EA is plotted as a function of time in Figure 29. At the end of the experiment the average temperature on Electrode Row A had reached approximately 47°C . The temperature of the other outer row of electrodes, EC is illustrated in Figure 30. By the end of the experiment, the average temperature in row EC had reached 52°C . The average temperature in the center row, EB is illustrated in Figure 31. The average temperature in this row at the end of the experiment was approximately 120°C . There was a substantial temperature gradient in the transverse direction as illustrated by the contour plot shown in Figure 32. This figure illustrates temperature contours in a vertical transverse plane which cuts through the middle of the array. The figure shows that the central portion of the array was warmer than the edges along the two outer rows of electrodes. Further the temperature increased with depth up to 18 feet and then it decreased.

Temperature of the soil was also measured by inserting thermocouples into several thermowells which were placed in the soil. Figures 19 and 20 show the thermowell locations. Temperature was measured at a depth of 0.5, 9, 18 and 20 ft inside these thermowells. Seven thermowells were installed, however, two of these broke during system installation. Data were obtained from the remaining five thermowells: MW02, MW03, MW04, MW06 and MW07. The data from these thermowells as well as the thermocouples were used to prepare temperature contours in three horizontal planes located at a depth of 0.5, 9 and 18 ft. Figure 33 illustrates all three in a projection chart. The temperature variation is indicated by three different patterns for three ranges. These are: area with a temperature of less than 70°C , from 70 to 100°C and greater than 100°C .

Simple arithmetic average of the soil temperature indicates that a maximum average temperature of 72 to 75°C was achieved between 22nd and the 25th day of the demonstration. If all the temperature measurement points located around the perimeter of the array are discarded from the average, then the average of the interior volume was 92°C . The perimeter of the array is expected to have a lower temperature due to heat loss into

Figure 29

TEMPERATURE IN ELECTRODE ROW A
(Heating Started at 2000 hr, 6/13/95)
(Symbol Frequency: Once per 24 hr)

AROW Jan. 23, 1996 6:26:05 PM

Figure 30

TEMPERATURE IN ELECTRODE ROW C
(Heating Started at 2000 hr, 6/13/95)
(Symbol Frequency: Once per 24 hr)

CROW Jan. 23, 1996 6:06:46 PM

Data thru 0800hr 7/8/95

Figure 31

TEMPERATURE IN CENTER ELECTRODE ROW
(Heating Started at 2000 hr, 6/13/95)
(Symbol Frequency: every third)

CENTEROW Jan. 23, 1996 5:41:15 PM

Data thru 0845 HR. 7/8/95

Figure 32

Vertical Transverse Plane Temperature Contours, K-25 Site
(Temperature (C) in Central Plane. After 24.6 Days of AC Heating)

VERT0708 Jan. 23, 1996 5:29:22 PM
Data thru 0952 HR 7/8/95

Figure 33. Horizontal Plane Temperature Contours, K-25 Site, Oak Ridge
 (Data as of July 8, 1995, End of AC Heating)

PROCONT3 Feb. 8, 1996 9:45:56 AM

the surrounding cool soil where there is no dissipation of energy. An examination of Figure 32 indicates that the temperature profile from the center towards the outer rows is not linear. As one moves out from the center row, the rate of temperature drop increases.

Appendix C gives some additional contour plots and the temperature data tables for the duration of the experiment and for the cool down period.

9.2 Contaminant Concentration In Soil

9.2.1 Sampling Procedure

Pre-demonstration soil core samples were taken during the installation of the electrode array. These samples were taken from electrode bore holes and from one of the thermowells. Electrode bore holes EA03, EA09, EB01, EB05, EB09, EC02, EC06, EC10 and thermowell MW02 were sampled. The location of these bore holes is shown in Figure 9. From each bore hole soil core samples were obtained in a 1-in diameter, 2-ft long split spoon lined with a stainless steel liner. Four six-inch long liners were inserted in the 2-ft spoon. When the spoon was removed from the bore holes the liners were removed and quickly sealed with a teflon lined end cap. The external surface of the capped liners was wiped down, dried and labelled with the sample identification information. The liners were sealed in a zip lock bag which was stored in an ice-chest for shipment to the laboratory. Prior to shipment a chain of custody form was completed and the samples were inspected by LMES health physics personnel to assure absence of radioactivity.

From each bore hole samples were obtained in three depth intervals. These were 1 to 3 ft, 8 to 10 ft and 15 to 17 ft. During drilling of the electrode holes, a hard layer of shale was encountered below a depth of 10 to 15 feet. In most of the bore holes drilling through the shale with the hollow stem auger was not possible and in these instances samples could not be obtained from deeper zones. Samples in a depth range of 15 to 17 feet were obtained from three bore holes EA03, EB09, and MW02. Table 17 is a list of pre-demonstration samples indicating the bore hole number and depth interval from which the sample was taken.

As mentioned above, four six-inch liners were placed in the split spoon for every interval that was sampled. It was observed that sample recovery varied from 30 to 90 percent. Only those liners which were completely filled were analyzed for target VOCs. In the laboratory, completely filled liners were individually emptied into clean glass jars.

Two soil samples were obtained from each jar and analyzed. In most cases, only one of the four liners from each sampled interval was analyzed. A total of 25 samples were analyzed in duplicate. The soil samples were analyzed by a modified version of USEPA's standard method 8260¹³. The soil samples were extracted and the extracts were introduced into a purge trap device prior to injection into a GC/MS system for separation and

Table 17. Pre-Demonstration Soil Sample ID and Moisture Content (Page 1 of 2)				
Bore Hole ID	Sample ID	Depth, ft	Moisture, %, by Wt.	Laboratory ID No.
EA03	EA03U0103-1	1-3	24.62	9181
	EA03U0103-1, Dup	1-3	24.36	9182
	EA03U0810-1	8-10	9.35	9183
	EA03U0810-1, Dup	8-10	11.01	9184
	EA03U1517	15-17	11.57	9185
	EA03U1517, Dup	15-17	3.27	9186
EA09	EA09U0103-1	1-3	27.61	9145
	EA09U0103-1, Dup	1-3	26.14	9146
	EA09U0103-2, dup	1-3	27.79	9148
	EA09U0103-2	1-3	26.22	9147
	EA09U0810-1	8-10	8.68	9149
	EA09U0810-1, Dup	8-10	8.62	9150
EB01	EB01U0103-1, Dup	1-3	23.93	9141
	EB01U0103-1	1-3	20.57	9140
	EB01U0810-1, Dup	8-10	8.95	9143
	EB01U0810-1	8-10	8.99	9142
EB05	EB05U0103-1	1-3	19.22	9136
	EB05U0103-1, Dup	1-3	13.4	9137
	EB05U0810	8-10	10.9	9138
	EB05U0810, Dup	8-10	11.28	9139
EB09	EB09U0103-1	1-3	14.78	9130
	EB09U0103-1, Dup	1-3	13.73	9131
	EB09U0810-1	8-10	7.31	9132
	EB09U0810-1, Dup	8-10	11.15	9133
	EB09U1517, Dup	15-17	19.06	9135
	EB09U1517	15-17	12.66	9134

Table 17. Pre-Demonstration Soil Sample ID and Moisture Content (page 2 of 2)				
Bore Hole ID	Sample ID	Depth, ft	Moisture, %, by Wt.	Laboratory ID No.
EC02	EC02U0103-2	1-3	26.85	9065
	EC02U0103-1	1-3	25.47	9063
	EC02U0103-1, Dup	1-3	26.02	9064
	EC02U0103-2, Dup	1-3	25.51	9066
	EC02U0507-1, Dup	5-7	15.58	9070
	EC02U0507-1	5-7	23.49	9069
	EC02U0810-1, Dup	8-10	11.01	9074
	EC02U0810-1	8-10	8.26	9073
EC06	EC06U0103-1	1-3	37.77	9053
	EC06U0103-1, Dup	1-3	35.26	9054
	EC06U0507-1, Dup	5-7	10.5	9056
	EC06U0507	5-7	11.36	9055
	EC06U0810-1, Dup	8-10	12.66	9060
	EC06U0810-1	8-10	12.48	9059
EC10	EC10U0103-1	1-3	23.3	9045
	EC10U0103-1, Dup	1-3	29.3	9046
	EC10U0810-1	8-10	21.05	9049
	EC10U0810-1, Dup	8-10	12.09	9050
MW02	MW02U0103-1, Dup	1-3	21.91	9176
	MW02U0103-1	1-3	23.29	9175
	MW02U0810-1, Dup	8-10	8.41	9178
	MW02U0810-1	8-10	8.89	9177
	MW02U1517, Dup	15-17	21.02	9180
	MW02U1517	15-17	11.99	9179

quantification. The first modification of the method involved the use of the single ion monitoring mode to obtain lower detection limits. The second modification was that the method was also used to analyze for ketones. The following VOCs were analyzed by this method:

- Acetone
- 2-Butanone
- 4-methyl-2-pentanone
- Ethyl Benzene
- Toluene
- Benzene
- Carbon Disulfide
- Methylene dichloride
- Tetrachloroethene
- 1,1,1-Trichloroethane
- 1,1,2-Trichloroethane
- Trichloroethene
- 1,1-dichloroethane
- 1,2-dichloroethane
- 1,1,2,2-Tetrachloroethane

9.2.2 Pre-Demonstration Soil Sample Analysis Results

The results of the soil analysis are summarized in this section. Laboratory reports of individual samples are presented in Appendix A. The overall conclusion of the soil analysis effort was that the concentration of the contaminants in the soil was very low and, in many cases, it was below the detection limit. The detection limit for most analytes was 5 part per billion (ppb). Table 18 summarizes the minimum, maximum and average concentration of VOCs in the soil samples obtained prior to the demonstration. As the table indicates, there were many samples in which the concentration of the analytes was below the detection limit. The data in Table 18 show that most of the VOCs were present at a concentration of less than 1 part per million (ppm) or 1 mg/kg of soil. The results for the analysis of the three ketones and methylene chloride are suspect due to poor results of spiked samples and liquid check standards given to the laboratory for analysis as unknown samples. Toluene, tetrachloroethene, 1,1,1-trichloroethane, trichloroethene and 1,1-dichloroethane frequently exceeded their detection limit.

The laboratory spiked some field samples with a solution of known VOCs. The results of spiked soil samples are summarized in Table 19. Three field soil samples were spiked. These results show that the spike recovery for all three ketones is in the unacceptable range. The recovery of benzene, toluene, ethylbenzene was in the range of 58 to 198 percent. The relative percent difference (RPD) for these compounds was in the

Table 18. Pre-Demonstration Soil Sample Analysis -- Selected Statistics					
(K-25 Site Oak Ridge, TN)					
	Concentration, mg/kg				
	Min.	Max.	Average	RSD	n*
Acetone	0.19	17.8	4.026	99%	43
2-Butanone	0.149	1.18	0.399	55%	49
4-Methyl-2-Pentanone	0.09	2	0.825	59%	44
Ethylbenzene	0.002	0.123	0.041	86%	12
Toluene	0.006	0.345	0.034	170%	41
Benzene	0.002	0.018	0.009	68%	7
Carbon disulfide					0
Methylene chloride	0.019	0.245	0.068	69%	49
Tetrachloroethene	0	0.076	0.016	96%	21
1,1,1-Trichloroethane	0.005	1.14	0.151	216%	19
1,1,2-Trichloroethane	0.005	0.005	0.005		1
Trichloroethene	0.008	0.235	0.052	115%	13
1,1-Dichloroethane	0.006	0.163	0.041	132%	12
1,2-Dichloroethane	0.006	0.025	0.016		2
1,1,2,2-Tetrachloroethane	0.023	1.16	0.267	133%	10
* Number of samples greater than detection limit. Total Samples 50					
RSD: Relative Standard Deviation					

Table 19. Results of Matrix Spikes--For Pre-Demonstration Soil Sample Analyses (mg/kg)

Chemical Name	SAMPLE NUMBER																
	EA09U0810-1DUP							EA03U1517-1DUP				EC02U0103-1DUP					
	Sample Analysis	Spiked Sample Analysis	Spike Recovery	Spike Sample Analysis	Spike Recovery	RPD	Spike Amount	Sample Analysis	Spiked Sample Analysis	Spike Recovery	Spike Amount	Sample Analysis	Spiked Sample Analysis	Spike Recovery	Spike Sample Recovery	RPD	Spike Amount
Acetone	2.9	4.08	295%	5.63	682%	79%	0.4	5.03	1.89	-785%	0.4	0.005 LT	0.478	118%	0.329	81%	37%
2-Butanone	0.451	0.652	50%	0.637	47%	8%	0.4	0.164	0.314	37%	0.4	0.38	0.896	129%	0.894	129%	0%
4-Methyl-2-Pentanone	1.52	1.49	-8%	1.32	-50%	148%	0.4	0.005 LT	0.367	90%	0.4	0.594	1.13	134%	1.04	112%	18%
Ethyl Benzene	0.002 LT	0.067	144%	0.091	198%	31%	0.045	0.017	0.067	111%	0.045	0.002 LT	0.068	147%	0.053	113%	26%
Toluene	0.008	0.085	100%	0.111	134%	29%	0.077	0.076	0.152	99%	0.077	0.01	0.071	79%	0.055	58%	30%
Benzene	0.002 LT	0.085	184%	0.085	184%	0%	0.045	0.003	0.047	98%	0.045	0.002 LT	0.09	196%	0.072	156%	23%
Carbon disulfide	0.005 LT	0.058	83%	0.083	122%	38%	0.064	0.005 LT	0.054	77%	0.064	0.005 LT	0.085	125%	0.068	98%	24%
Methylene chloride	0.043	0.058	22%	0.109	99%	126%	0.067	0.035	0.112	115%	0.067	0.066	0.117	76%	0.127	91%	18%
Tetrachloroethane	0.005	0.115	134%	0.132	155%	14%	0.082	0.014	0.111	118%	0.082	0.005 LT	0.086	99%	0.085	73%	30%
1,1,1-Trichloroethane	0.005 LT	0.184	267%	0.259	379%	35%	0.067	0.034	0.26	337%	0.067	0.005 LT	0.092	130%	0.07	97%	29%
1,1,2-Trichloroethane	0.005 LT	0.093	131%	0.126	181%	32%	0.067	0.005 LT	0.12	172%	0.067	0.005 LT	0.059	81%	0.04	52%	43%
Trichloroethene	0.005 LT	0.107	138%	0.147	192%	33%	0.074	0.053	0.162	147%	0.074	0.005 LT	0.104	134%	0.07	88%	41%
1,1-Dichloroethane	0.005 LT	0.103	77%	0.153	116%	41%	0.128	0.022	0.128	83%	0.128	0.005 LT	0.061	44%	0.062	45%	2%
1,2-Dichloroethane	0.005 LT	0.085	125%	0.078	114%	9%	0.064	0.005 LT	0.054	77%	0.064	0.005 LT	0.062	89%	0.062	89%	0%
1,1,2,2-Tetrachloroethane	0.005 LT	0.103	118%	0.159	186%	44%	0.083	0.005 LT	0.21	247%	0.083	0.005 LT	0.09	102%	0.062	69%	39%

LT = Less Than

range of 0 to 31 percent. The recovery of the chlorinated solvents was in the range of 44 to 379 percent. The RPD for these compounds was in the range of 0 to 44 percent.

Liquid standards at a known concentration were prepared by IITRI in its laboratory. These samples were given to the laboratory for analysis. The laboratory personnel knew that these samples were different from those obtained from the field because of the different matrix and also because of the sample numbering scheme. Two check standards and one blank were given to the laboratory, identified as QAQC2, QAQC3 and QAQC4. The concentration of the QAQC2 check standard was in the range of 2 to 5 mg/liter and that of the QAQC3 check standard was in the range of 0.8 to 2 mg/liter. QAQC3 was a solvent blank. Table 20 summarizes the results of the analysis of the liquid check standards given to the laboratory. Any errors in these measurements is a reflection of the performance of the purge and trap device and down-stream instruments (GC/MS). The results again show that the analysis for ketones has very poor reliability as evidenced by the percent recovery data. For other chemicals the results are in the similar range as those for spiked sample recovery discussed above.

The results of soil samples obtained from the field are given in Tables 21 through 24. Table 24 also gives the results of a field rinsate from the cleaning of the split spoon.

9.2.3 Post Demonstration Soil Sampling

Post demonstration soil sampling was done after the soil had cooled down. Twelve new bore holes were drilled for the collection of these samples. Thirty six new samples were taken and each was analyzed in duplicate. The sampling procedure was the same as that utilized for the soil sampling prior to the demonstration. Figure 34 illustrates the plan view of the electrode array and the location of the 12 new borings labelled S201 through S212. From each bore hole soil core samples were retrieved from three 2-ft intervals located at 1-3 ft, 7-9 ft and 13-15 ft. Table 25 is a list of sample identification numbers, laboratory ID and soil moisture content.

9.2.4 Post Demonstration Soil Sample Analysis Results

Table 26 is a summary of results of post demonstration soil sample analysis. This table presents the minimum, maximum, and average concentration for each of the target VOC analytes. The table also indicates the number of samples in which the concentration was above the detection limit. The results show that the concentration of the various VOCs was quite low and in the same range as in the pre-demonstration soil samples. Further, there were few samples in which the concentration exceeded the detection limit except with the exception of toluene, 1,1,1-trichloroethane, trichloroethene and 1,1-dichloroethane.

The laboratory spiked five field samples with a known spiking solution to determine the analytical systems performance in terms of recovery and precision. The results of these

Table 20. Analysis of Prepared Liquid QA/QC Standards

Tested On ----->	03/10/95	Actual		03/10/95	03/10/95	Actual		03/10/95	Actual
TEI # ----->	9258	Concentration		9259	9259	Concentration		9257	Concentration
IITRI No. ----->	QAQC2	In Prepared	Percent	QAQC3	QAQC3	In Prepared	Percent	QAQC4	In Prepared
Chemical Name	As Analyzed	Standard	Recovery			Standard	Recovery		Standard
		QAQC2	In Analysis			QAQC3	In Analysis		QAQC4
									(Water blank)
By SW846 Method 8260 (modified)									
Acetone	44.65	5	893%	0.32	16	2	800%	0.321	0
2-Butanone	12.8	5	256%	0.259	12.95	2	648%	0.25	0
4-Methyl-2-Pentanone	15.25	5	305%	1.62	81	2	4050%	1.05	0
Ethyl Benzene	3.55	2	178%	0.029	1.45	0.8	181%	0.006	0
Toluene	1.65	2	83%	0.017	0.85	0.8	106%	0.006	0
Benzene	1.55	2	78%	0.01	0.5	0.8	63%	<0.002	0
Carbon Disulfide	2.35	0	ERR	0.01	0.5	0	ERR	<0.005	0
Methylene Chloride	4.85	2	243%	0.021	1.05	0.8	131%	0.029	0
Tetrachloroethene	1.1	2	55%	0.012	0.6	0.8	75%	0.007	0
1,1,1-Trichloroethane	3	2	150%	0.018	0.9	0.8	112%	<0.005	0
1,1,2-Trichloroethane	0.25	2	13%	0.011	0.55	0.8	69%	<0.005	0
Trichloroethene	1.45	2	73%	0.009	0.45	0.8	56%	<0.005	0
1,1-Dichloroethane	1.65	2	83%	0.014	0.7	0.8	88%	<0.005	0
1,2-Dichloroethane	<0.25	2	<13	0.014	0.7	0.8	88%	<0.005	0
1,1,2,2-Tetrachloroethane	1.25	2	63%	0.016	0.8	0.8	100%	<0.005	0
Surrogates	% Recovery			% Recovery			% Recovery		
d4 1,2-Dichloroethane	111			111			111		
Bromofluorobenzene	123			121			114		

Concentration in units of mg/liter

Table 21. Pre-Demonstration Soil Sample from Bore Holes in Electrode Row EA

Sample bore hole ID No. -----> Sampling Date -----> Shipping Lot No. -----> Laboratory Code -----> Depth Interval, ft -----> Liner No. ----->	EA09 2/24/95 2						EA03 3/1/95 3					
	9145	9146	9147	9148	9149	9150	9181	9182	9183	9184	9185	9186
	1-3	1-3	1-3	1-3	8-10	8-10	1-3	1-3	8-10	8-10	15-17	15-17
	L1	L1	L2	L2	L1	L1	L1	L1	L1	L1	L1	L1
Acetone	3.23	0.246				2.9	2.3	0.764	1.75	2.99	4.34	5.03
2-Butanone	0.653	0.548	0.537	0.712	0.479	0.451	0.3	0.189	0.172	0.227	0.149	0.164
4-Methyl-2-Pentanone	1.77	1.7	1.62	2	1.31	1.52	0.318		0.244			
EthylBenzene	0.008										0.032	0.017
Toluene	0.039	0.012	0.011	0.013	0.009	0.008	0.006				0.042	0.076
Benzene												0.003
CarbonDisulfide												
MethyleneChloride	0.07	0.057	0.06	0.07	0.061	0.043	0.02	0.019	0.024	0.029	0.034	0.035
Tetrachloroethene	0.006			0.005		0.005					0.021	0.014
1,1,1-Trichloroethane	0.006						0.015		0.005		0.133	0.034
1,1,2-Trichloroethane												
Trichloroethene	0.01										0.018	0.053
1,1-Dichloroethane	0.007										0.007	0.022
1,2-Dichloroethane												
1,1,2,2-Tetrachloroethane											0.108	

Concentration in units of mg/kg

Table 22. Pre-Demonstration Soil Sample from Bore Holes in Electrode Row EB

Sample bore hole ID No. -----> Sampling Date -----> Shipping Lot No. -----> Laboratory Code -----> Depth Interval, ft -----> Liner No. ----->	EB09 2/21/95 2						EB05 2/22/95 2				EB01 2/23/95 2			
	9130	9131	9132	9133	9134	9135	9136	9137	9138	9139	9140	9141	9142	9143
	1-3	1-3	8-10	8-10	15-17	15-17	1-3	1-3	8-10	8-10	1-3	1-3	8-10	8-10
	L1	L1	L1	L1	L1	L1	L1	L1	L1	L1	L1	L1	L1	L1
Acetone			1.43	13.9	6.38	5.21	0.978	1.4	8.91	3.19	0.19		8.54	12.4
2-Butanone	0.263	0.281	0.236	0.313		0.328	0.292	0.245	0.238	0.215	0.593	0.626	0.418	0.403
4-Methyl-2-Pentanone		0.993	0.751	0.999		0.914	0.968	0.829	0.732	0.75	1.62	1.7	0.853	0.844
EthylBenzene					0.033					0.036			0.002	0.073
Toluene		0.017	0.006	0.008	0.144	0.014	0.006	0.007	0.008	0.077	0.011	0.011	0.012	0.345
Benzene					0.018					0.016				0.009
CarbonDisulfide														
MethyleneChloride	0.035	0.04	0.032	0.036	0.087	0.04	0.043	0.041	0.098	0.108	0.071	0.068	0.093	0.245
Tetrachloroethene	0.011				0.028			0.028		0.012				0.024
1,1,1-Trichloroethane					1.14	0.008			0.009	0.168			0.013	0.159
1,1,2-Trichloroethane														0.005
Trichloroethene					0.09					0.028				0.235
1,1-Dichloroethane					0.163					0.018			0.012	0.158
1,2-Dichloroethane									0.006					0.025
1,1,2,2-Tetrachloroethane						0.067								0.023

Concentration in units of mg/kg

Table 23. Pre-Demonstration soil Sample from Bore Holes in Electrode Row EC

Sample bore hole ID No. -----> Sampling Date -----> Shipping Lot No. -----> Laboratory Code -----> Depth Interval, ft -----> Liner No. ----->	EC10 2/17/95 1				EC08 2/18/95 1						EC02 2/18/95 1							
	9045	9046	9049	9050	9053	9054	9055	9056	9059	9060	9063	9064	9065	9066	9069	9070	9073	9074
	1-3	1-3	8-10	8-10	1-3	1-3	5-7	5-7	8-10	8-10	1-3	1-3	1-3	1-3	5-7	5-7	8-10	8-10
	L1	L1	L1	L1	L1	L1	L1	L1	L1	L1	L1	L1	L2	L2	L1	L1	L1	L1
Acetone	0.954	0.306	1.4	1.97	1.18	0.31	3.36	5.95	6.1	9.95	0.905		2.72	0.871	1.68	7.88	9.32	17.8
2-Butanone	0.458	0.402	0.452	0.405	0.44	0.474	0.324	0.228	0.326	1.17	0.309	0.38	0.564	0.701	0.553	0.6	0.4	1.18
4-Methyl-2-Pentanone	0.727	0.629	0.731	0.661	0.664	0.757	0.445	0.361	0.436	1.59	0.492	0.594	0.87	1.03	0.798	0.09	0.585	0.566
EthylBenzene													0.01				0.088	0.123
Toluene	0.009	0.009	0.085	0.008	0.01	0.01	0.008	0.007	0.026	0.026		0.01	0.018	0.013	0.012	0.009	0.04	0.068
Benzene													0.013				0.003	0.002
CarbonDisulfide																		
MethyleneChloride	0.079	0.067	0.063	0.059	0.085	0.077	0.05	0.043	0.06	0.228	0.049	0.066	0.147	0.151	0.104	0.101	0.099	0.114
Tetrachloroethene									0.011	0.076	0.011		0.01			0.025	0.012	0.01
1,1,1-Trichloroethane		0.005							0.017		0.018						0.007	0.0135
1,1,2-Trichloroethane																		
Trichloroethane			0.008								0.018		0.008				0.019	0.032
1,1-Dichloroethane											0.011						0.006	0.01
1,2-Dichloroethane																		
1,1,2,2-Tetrachloroethane										0.337	0.141					0.024	0.692	0.079

Concentration in units of mg/kg

Table 24. Pre-Demonstration Soil Sample from Bore Holes in Thermowell MW02, and a Field Blank

Sample bore hole ID No. -----> Sampling Date-----> Shipping Lot No. -----> Laboratory Code -----> Depth Interval, ft -----> Liner No. ----->		DI Water	MW02 2/28/95 3						
		2	9144	9175	9176	9177	9178	9179	9180
		Site rinse		1-3	1-3	8-10	8-10	15-17	15-17
				L1	L1	L1	L1	L1	L1
Acetone		0.264	0.897	0.469	2.35	3.17	7.2	4.05	
2-Butanone		0.389	0.159	0.234	0.202	0.184	0.207	0.185	
4-Methyl-2-Pentanone		1.14	0.237	0.284	0.267	0.246	0.258	0.242	
EthylBenzene							0.026	0.039	
Toluene		0.008					0.069	0.09	
Benzene									
CarbonDisulfide									
MethyleneChloride		0.039	0.02		0.022	0.033	0.031	0.037	
Tetrachloroethene						0.005	0.01	0.015	
1,1,1-Trichloroethane						0.007	0.076	1.04	
1,1,2-Trichloroethane									
Trichloroethene							0.083	0.077	
1,1-Dichloroethane							0.032	0.049	
1,2-Dichloroethane									
1,1,2,2-Tetrachloroethane							1.16	0.039	

Concentration in units of mg/kg
Site Rinsate in units of mg/liter

Post Demonstration Soil Sample Bore Hole Locations

Table 25 Post Demonstration Soil Sample ID and Moisture Content
(page 1 of 2)

Sample Bore Hole	Sample ID	Sample Depth, ft	Laboratory ID No.	Moisture Content
S201	S02010103	1-3	12583	20.3
	S02010103 Dup	1-3	12584	21.1
	S02010709	7-9	12585	12.8
	S02010709 Dup	7-9	12586	20.4
	S02011315	13-15	12587	21.9
	S02011315 Dup	13-15	12588	19.7
S202	S02020103-1	1-3	12599	26.4
	S02020103-1 Dup	1-3	12600	24.1
	S02020709-1	7-9	12601	26.2
	S02020709-1 Dup	7-9	12602	16.3
	S02021315	13-15	12603	14.9
	S02021315 Dup	13-15	12604	23.5
S203	S02030103-1	1-3	12617	21.6
	S02030103-1 Dup	1-3	12618	19.1
	S02030709	7-9	12619	15.7
	S02030709 Dup	7-9	12620	22.3
	S02031315	13-15	12641	2.7
	S02031315 Dup	13-15	12642	2.8
S204	S02040103	1-3	12611	25.9
	S02040103 Dup	1-3	12612	12.2
	S02040709	7-9	12613	13.3
	S02040709 Dup	7-9	12614	14.8
	S02041315	13-15	12615	5.3
	S02041315 Dup	13-15	12616	16.5
S205	S02050103	1-3	12633	18.6
	S02050103 Dup	1-3	12634	15.5
	S02050709-1	7-9	12635	9.7
	S02050709-1 Dup	7-9	12636	10.8
	S02051315-1	13-15	12637	8.8
	S02051315-1 Dup	13-15	12638	10.7
	S02051719	17-19	12639	6.9
	S02051719 Dup	17-19	12640	6.6
S206	S02060103	1-3	12627	27.2
	S02060103 Dup	1-3	12628	26.7
	S02060709	7-9	12629	11.4
	S02060709 Dup	7-9	12630	28.3
	S02061315	13-15	12631	13.0
	S02061315 Dup	13-15	12632	20.8

Table 25 Post Demonstration Soil Sample ID and Moisture Content
(Page 2 of 2)

Sample Bore Hole	Sample ID	Sample Depth, ft	Laboratory ID No.	Moisture Content
S207	S207-0103-1	1-3	12477	29.22
	S207-0103-1 Dup	1-3	12577	30.43
	S207-0709-1	7-9	12478	21.8
	S207-0709-1 Dup	7-9	12578	17.9
	S0207-1315-1	13-15	12479	19.6
	S0207-1315-1 Dup	13-15	12579	12.1
S208	S208-1-3-1	1-3	12474	23.5
	S208-1-3-1 Dup	1-3	12574	26.1
	S208-7-9-1	7-9	12475	18.0
	S208-7-9-1 Dup	7-9	12575	16.3
	S208-1315-1	13-15	12476	12.1
	S208-1315-1 Dup	13-15	12576	12.3
S209	S02090103	1-3	12589	23.0
	S02090103 Dup	1-3	12590	23.6
	S02090709	7-9	12591	19.3
	S02090709 Dup	7-9	12592	11.4
	S02091315	13-15	12593	19.4
	S02091315 Dup	13-15	12594	8.1
S210	S02100103-1	1-3	12605	23.1
	S02100103-1 Dup	1-3	12606	21.8
	S02100709	7-9	12607	22.7
	S02100709 Dup	7-9	12608	14.4
	S02101315	13-15	12609	17.2
	S02101315 Dup	13-15	12610	22.6
S211	S02110103	1-3	12595	21.2
	S02110103 Dup	1-3	12596	23.8
	S02110709-1	7-9	12597	11.1
	S02110709-1 Dup	7-9	12598	10.2
	S02111315	13-15	12643	21.0
	S02111315 Dup	13-15	12644	14.9
S212	S02120103	1-3	12623	24.4
	S02120103 Dup	1-3	12624	22.8
	S02121315	13-15	12621	19.9
	S02121315 Dup	13-15	12622	20.2

Table 26. Post-Demonstration Soil Sample Analysis--Selected Statistics
(K-25 Site, Oak Ridge, TN)

	Concentration, mg/kg			RSD %	n*
	MIN	MAX	AVERAGE		
Acetone	0.006	6.610	0.793	190%	57
2-Butanone	0.011	2.280	0.271	170%	41
4-Methyl-2-Pentanone	0.027	1.200	0.423	122%	9
Ethylbenzene	0.002	0.418	0.047	209%	17
Toluene	0.006	0.469	0.038	201%	45
Benzene	0.007	0.022	0.014		2
Methylene Chloride	0.007	1.530	0.139	135%	68
Tetrachloroethene	0.012	0.150	0.065	84%	9
1,1,1-Trichloroethane	0.006	0.437	0.082	143%	31
1,1,2-Trichloroethane	0.011	0.062	0.031	58%	8
Trichloroethene	0.018	1.460	0.186	190%	15
1,1-Dichloroethane	0.005	0.132	0.032	105%	19
1,2-Dichloroethane					0
1,1,2,2-Tetrachloroethane	0.404	0.404	0.404		1

* Total Number of samples in which the concentration was greater than the detection limit. Total Samples 72 including duplicates
 RSD: Relative Standard Deviation

matrix spikes are presented in Table 27 through 31. The results show that the recovery of the three ketones were in the unacceptable range: it ranged from -112 to 2500 percent. A negative recovery indicates that the spike sample concentration results were smaller than the unspiked sample result. The RPD for the ketones ranged from 10 to 1900 percent again indicating that the results for the ketones are unreliable. The recovery of the three hydrocarbons, benzene, toluene, ethylbenzene ranged from -42 to 178 percent of the amount spiked. Again, in two instances the amount of toluene recovered from the spiked sample was less than the amount present in the unspiked sample as indicated by the negative recovery. The RPD for the three hydrocarbons varied from 0 to 35 percent. The recovery of the chlorinated solvent spikes ranged from -115 to 290 percent again indicating that in some analyses the amount recovered was less than the amount present in the original in spiked sample. The RPD for the chlorinated solvents ranged from 2 to 43 percent with methylene chloride showing a RPD of 2970 percent in one instance.

Liquid standards at a known concentration were prepared by IITRI in its laboratory. These samples were given to the laboratory for analysis. The laboratory personnel knew that these samples were different from those obtained from the field because of the different matrix and also because of the sample numbering scheme. Two check standards and one blank were given to the laboratory, identified as QAQC13, QAQC14 and QAQC15. The concentration of the QAQC13 check standard was in the range of 2 to 5 mg/liter and that of the QAQC14 check standard was in the range of 0.08 to 0.2 mg/liter. QAQC15 was a solvent blank. Table 32 summarizes the results of the analysis of the liquid check standards given to the laboratory. Any errors in these measurements is a reflection of the performance of the purge and trap device and down-stream instruments (GC/MS). The results again show that the analytical system was experiencing difficulty when these samples were analyzed.

The results of the post demonstration soil sample analysis are organized in five tables. As mentioned previously, 12 new bore holes were made and 36 new soil samples were retrieved. These were analyzed in duplicate. The soil borings were made in five rows three of which corresponded to the three electrode rows. One row containing two bore holes was made just inside the outer electrode row EA and a fifth row was made half way between electrode rows EA and EB. Tables 33 through 37 summarize the soil data. As these data indicate that there were many samples in which the analyte concentration was at or below the detection limit which was, for most cases, 5 ppb.

9.2.5 Comparison of Pre- and Post-Demonstration VOC Concentration in Soil

Comparison of pre and post demonstration concentration of selected VOCs is given in this section. A review of Figure 34 will reveal that for most of the pre-demonstration soil sampling bore hole locations, there is a post-demonstration bore hole within 1.5 ft. So a comparison of the change, if any, in the soil concentration of VOC from these paired locations may be done. Further, comparisons may be made for differences within a

Table 27. Spike Recovery for Sample S2020103

Compound	Field Sample Spiked: S02020103-1							
	Shipping Lot 2							
	Lab. ID. 12599							
	Unspiked sample Analysis	First Spike		Second Spike		Recovery, %		Relative Percent Difference
		Spiked Sample Analysis	Amount Spiked	Spiked Sample Analysis	Amount Spiked	Spike 1	Spike 2	
Acetone	0.131		0	0.105	0.054		-48.1	
2-Butanone			0	0.094	0.056		167.9	
4-Methyl-2-Pentanone			0	0.134	0.055		243.6	
Ethyl Benzene		0.086	0.067	0.073	0.059	128.4	123.7	4%
Toluene	0.014	0.087	0.067	0.073	0.059	109.0	100.0	9%
Benzene		0.085	0.068	0.076	0.06	125.0	126.7	1%
Carbon Disulfide		0.096	0.098	0.085	0.086	98.0	98.8	1%
Methylene Chloride	0.019	0.179	0.104	0.179	0.091	153.8	175.8	13%
Tetrachloroethene		0.153	0.127	0.114	0.11	120.5	103.6	15%
1,1,1-Trichloroethane		0.106	0.103	0.089	0.09	102.9	98.9	4%
1,1,2-Trichloroethane		0.094	0.112	0.127	0.098	83.9	129.6	43%
Trichloroethane		0.135	0.114	0.115	0.099	118.4	116.2	2%
1,1-Dichloroethane		0.123	0.091	0.133	0.08	135.2	166.3	21%
1,1,2,2-Tetrachloroethane		0.109	0.124	0.143	0.108	87.9	132.4	40%

Concentration in units of mg/kg

Table 28. Spike Recovery for Sample S2020709

Compound	Field Sample Spiked: S2020709--1							
	Shipping Lot 2							
	Lab . ID 12601							
	Unspiked sample Analysis	First Spike		Second Spike		Recovery, %		Percent Difference
		Spiked Sample Analysis	Amount Spiked	Spiked Sample Analysis	Amount Spiked	Spike 1	Spike 2	
Acetone	0.071	0.217	0.047	0.105	0.052	310.6	65.4	130%
2-Butanone		0.317	0.049	0.086	0.054	646.9	159.3	121%
4-Methyl-2-Pentanone		1.2	0.048	0.151	0.052	2500.0	290.4	158%
Ethyl Benzene		0.087	0.052	0.085	0.057	167.3	149.1	11%
Toluene	0.009	0.087	0.052	0.095	0.057	150.0	150.9	1%
Benzene		0.082	0.053	0.093	0.057	154.7	163.2	5%
Carbon Disulfide		0.064	0.082	0.017	0.082	78.0	20.7	116%
Methylene Chloride	0.172	0.353	0.08		0.087	226.3	-197.7	2970%
Tetrachloroethene		0.15	0.097	0.151	0.106	154.6	142.5	8%
1,1,1-Trichloroethane		0.139	0.079	0.112	0.086	175.9	130.2	30%
1,1,2-Trichloroethane		0.126	0.086	0.158	0.094	146.5	168.1	14%
Trichloroethane		0.131	0.087	0.144	0.095	150.6	151.6	1%
1,1-Dichloroethane		0.109	0.07	0.129	0.077	155.7	167.5	7%
1,1,2,2-Tetrachloroethane		0.123	0.095	0.152	0.104	129.5	146.2	12%

Concentration in units of mg/kg

Table 29. Spike Recovery for Sample S2050709

Compound	Field Sample Spiked: S02050709-1							
	Shipping Lot 1 Lab. ID 12635							
	First Spike		Second Spike		Recovery, %		Percent Difference	
	Unspiked sample Analysis	Spiked Sample Analysis	Spiked Sample Analysis	Amount Spiked	Spiked Sample Analysis	Spiked Amount	Spike 1	Spike 2
Acetone	0.155	0.234	0.041	0.041	0.374	0.043	192.7	509.3
2-Butanone		0.041	0.043	0.043	0.078	0.045	95.3	173.3
4-Methyl-2-Pentanone		0.137	0.065	0.065	0	0.044	210.8	0.0
Ethyl Benzene		0.067	0.045	0.045	0.07	0.047	148.9	148.9
Toluene		0.08	0.045	0.045	0.079	0.047	177.8	168.1
Benzene		0.069	0.046	0.046	0.073	0.048	150.0	152.1
Carbon Disulfide		0.073	0.066	0.066	0.085	0.069	110.6	123.2
Methylene Chloride	0.019	0.148	0.07	0.07	0.141	0.073	184.3	167.1
Tetrachloroethene		0.125	0.085	0.085	0.123	0.089	147.1	138.2
1,1,1-Trichloroethane		0.084	0.069	0.069	0.086	0.072	121.7	119.4
1,1,2-Trichloroethane		0.101	0.075	0.075	0.082	0.079	134.7	103.8
Trichloroethane		0.109	0.076	0.076	0.11	0.08	143.4	137.5
1,1-Dichloroethane		0.097	0.061	0.061	0.104	0.064	159.0	162.5
1,1,2,2-Tetrachloroethane		0.175	0.083	0.083	0.181	0.087	210.8	208.0

Concentration in units of mg/kg

Table 30. Spike Recovery for Sample S02061315

Compound	Field Sample Spiked:S02061315-1 Shipping Lot 1 Lab. ID 12631							
	Unspiked sample Analysis	First Spike		Second Spike		Recovery, %		Percent Difference
		Spiked Sample Analysis	Amount Spiked	Spiked Sample Analysis	Amount Spiked	Spike 1	Spike 2	
Acetone	0.403	0.588	0.38	3.64	0.39	48.7	830.0	178%
2-Butanone	1.46	2	0.39	1	0.41	138.5	-112.2	1909%
4-Methyl-2-Pentanone	0.079	1.56	0.38	1.8	0.4	389.7	430.3	10%
Ethyl Benzene	0.015	0.052	0.041	0.054	0.043	90.2	90.7	1%
Toluene	0.15	0.138	0.041	0.132	0.043	-29.3	-41.9	35%
Benzene	0.007	0.053	0.042	0.053	0.044	109.5	104.5	5%
Carbon Disulfide		0.05	0.06	0.027	0.062	83.3	43.5	63%
Methylene Chloride	0.168	0.33	0.064	0.272	0.066	253.1	157.6	47%
Tetrachloroethene	0.019	0.075	0.077	0.088	0.08	72.7	86.2	17%
1,1,1-Trichloroethane	0.007	0.069	0.063	0.061	0.066	98.4	81.8	18%
1,1,2-Trichloroethane	0.055	0.18	0.068	0.126	0.071	183.8	100.0	59%
Trichloroethane	0.213	0.133	0.069	0.128	0.072	-115.9	-118.1	2%
1,1-Dichloroethane	0.015	0.084	0.056	0.078	0.058	123.2	108.6	13%
1,1,2,2-Tetrachloroethane		0.22	0.076	0.186	0.079	289.5	235.4	21%

Concentration in units of mg/kg

Table 31. Spike Recovery for Sample S02080709

Compound	Field Sample Spiked:S02080709–1							
	Shipping Lot 1							
	Lab. ID 12475							
	Unspiked sample Analysis	First Spike		Second Spike		Recovery, %		Percent Difference
Spiked Sample Analysis		Amount Spiked	Spiked Sample Analysis	Amount Spiked	Spike 1	Spike 2		
Acetone	0.378	0.129	0.043	1.58	0.043	*	*	
2–Butanone	0.024		0.045	0.033	0.049	–53.3	18.4	410%
4–Methyl–2–Pentanone			0.044	0.056	0.047	0.0	119.1	200%
Ethyl Benzene		0.043	0.047	0.049	0.051	91.5	96.1	5%
Toluene		0.04	0.047	0.056	0.051	85.1	109.8	25%
Benzene		0.044	0.048	0.047	0.052	91.7	90.4	1%
Carbon Disulfide		0.06	0.068	0.057	0.074	88.2	77.0	14%
Methylene Chloride		0.068	0.072	0.087	0.079	94.4	110.1	15%
Tetrachloroethene		0.073	0.088	0.089	0.096	83.0	92.7	11%
1,1,1–Tichloroethane	0.006	0.079	0.072	0.06	0.078	101.4	69.2	38%
1,1,2–Trichloroethane		0.059	0.078	0.054	0.085	75.6	63.5	17%
Trichloroethane		0.07	0.079	0.078	0.086	88.6	90.7	2%
1,1–Dichloroethane	0.016	0.056	0.064	0.061	0.069	62.5	65.2	4%
1,1,2,2–Tetrachloroethane		0.059	0.086	0.054	0.094	68.6	57.4	18%

* Spiked amount is too small compared to the amount in the sample

Concentration in units of mg/kg

Table 32. Analysis of Prepared Liquid QA/QC Standards (mg/L)

Tested On -----> TEI # -----> IITRI No. -----> Chemical Name	10/12/95 12696 QAQC13 As Analyzed	Actual Concentration in Prepared Standard QAQC13	Percent Recovery In Analysis	10/12/95 12697 QAQC14 As Analyzed	Actual Concentration in Prepared Standard QAQC14	Percent Recovery In Analysis	10/12/95 12698 QAQC15 As Analyzed	Actual Concentration in Prepared Standard QAQC15 (Water blank)
By SW846 Method 8260 (modified)								
Acetone	0.238	5	5%	0.512	0.2	256%	<0.005	0
2-Butanone	0.53	5	11%	0.048	0.2	24%	<0.005	0
4-Methyl-2-Pentanone	0.062	5	1%	0.168	0.2	84%	<0.005	0
Ethyl Benzene	0.033	2	2%	0.214	0.08	268%	<0.005	0
Toluene	0.042	2	2%	0.17	0.08	213%	0.016	0
Benzene	0.996	2	50%	0.109	0.08	136%	<0.005	0
Carbon Disulfide	0.063	0		0.102	0		<0.005	0
Methylene Chloride	0.066	2	3%	0.736	0.08	920%	2.74	0
Tetrachloroethene	0.083	2	4%	0.202	0.08	253%	<0.005	0
1,1,1-Trichloroethane	0.005	2	0%	0.005	0.08	6%	<0.005	0
1,1,2-Trichloroethane	0.658	2	33%	0.028	0.08	35%	<0.005	0
Trichloroethene	0.192	2	10%	0.105	0.08	131%	<0.005	0
1,1-Dichloroethane	0.02	2	1%	0.148	0.08	185%	<0.005	0
1,2-Dichloroethane		2			0.08	0%	<0.005	0
1,1,2,2-Tetrachloroethane	0.91	2	46%	<0.005	0.08	0%	<0.005	0
Surrogates	% Recovery			% Recovery			% Recovery	
d4 1,2-Dichloroethane	8490			88.1			119	
Bromofluorobenzene	120			123			137	

Table 33. Post-Demonstration Soil Sample Analysis in Electrode Row EA

Sample Bore Hole ID No.	S201						S202					
	09/27/95	09/27/95	09/27/95	09/27/95	09/27/95	09/27/95	09/26/95	09/26/95	09/26/95	09/26/95	09/26/95	09/26/95
Sample Date	2	2	2	2	2	2	2	2	2	2	2	2
Shipping Lot No.	1	1	1	1	1	1	1	1	1	1	1	1
Liner No.	12583	12584	12585	12586	12587	12588	12599	12600	12601	12602	12603	12604
Laboratory Sample ID	1 TO 3		7 TO 9		13 TO 15		1 TO 3		7 TO 9		13 TO 15	
DEPTH, FEET												
Acetone	0.693	0.118		0.116		0.5	0.131		0.071	0.241	0.604	0.266
2-Butanone	0.052										0.048	0.049
4-Methyl-2-Pentanone												
Ethylbenzene			0.067									
Toluene			0.01			0.03	0.014		0.009	0.007	0.022	
Benzene												
Methylene Chloride	0.06	0.04		0.009	0.074	0.096	0.019	0.021	0.172	0.184	0.076	0.059
Tetrachloroethene			0.092									
1,1,1-Trichloroethane	0.01		0.02	0.012		0.096		0.053			0.053	0.103
1,1,2-Trichloroethane												
Trichloroethene			0.084								0.027	
1,1-Dichloroethane				0.006							0.035	
1,2-Dichloroethane												
1,1,2,2-Tetrachloroethane												

Concentration in units of mg/kg

Table 34. Post-Demonstration Soil Sample Analysis Near Electrode Row EA

Sample Bore Hole ID No.	S209						S210					
	09/26/95	09/26/95	09/26/95	09/26/95	09/26/95	09/26/95	09/26/95	09/26/95	09/26/95	09/26/95	09/26/95	09/26/95
Sample Date	2	2	2	2	2	2	2	2	2	2	2	2
Shipping Lot No.	1	1	1	1	1	1	1	1	1	1	1	1
Liner No.	12589	12590	12591	12592	12593	12594	12605	12606	12607	12608	12609	12610
Laboratory Sample ID	1 TO 3		7 TO 9		13 TO 15		1 TO 3		7 TO 9		13 TO 15	
DEPTH, FEET												
Acetone							0.35	0.554	0.471	0.311	0.365	0.179
2-Butanone			0.178	0.135	0.278	0.397	0.033	0.048	0.05		0.025	0.011
4-Methyl-2-Pentanone												
Ethylbenzene			0.015								0.009	
Toluene						0.023	0.008	0.009	0.008	0.009	0.023	0.01
Benzene												
Methylene Chloride	0.022	0.029	0.121	0.083	0.099	0.182	0.155	0.167	0.166	0.222	0.164	0.214
Tetrachloroethene			0.036								0.014	
1,1,1-Trichloroethane			0.11	0.066	0.018		0.04					
1,1,2-Trichloroethane			0.036	0.011								
Trichloroethene			0.102			0.028					0.041	
1,1-Dichloroethane				0.007		0.018					0.027	
1,2-Dichloroethane												
1,1,2,2-Tetrachloroethane												

Concentration in units of mg/kg

Table 35. Post-Demonstration Soil Sample Analysis Midway Between Electrode Rows EA and EB

Sample Bore Hole ID No. Sample Date Shipping Lot No. Liner No. Laboratory Sample ID DEPTH, FEET	S211						S212			
	09/27/95	09/27/95	09/27/95	09/27/95	09/27/95	09/27/95	09/26/95	09/26/95	09/26/95	09/26/95
	2	2	2	2	2	2	2	2	2	2
	1	1	1	1	1	1	1	1	1	1
	12595	12596	12597	12598	12643	12644	12623	12624	12621	12622
	1 TO 3		7 TO 9		13 TO 15		1 TO 3		13 TO 15	
Acetone	0.35	0.08	6.42	1.66	0.422			0.071		0.021
2-Butanone			0.209	0.066					0.037	0.032
4-Methyl-2-Pentanone								0.027		
Ethylbenzene			0.418	0.142	0.025	0.009				0.004
Toluene			0.469	0.189	0.044	0.033		0.008		0.011
Benzene			0.022							
Methylene Chloride	0.057	0.021	0.383	0.112	0.042	0.037	1.53	0.112	0.166	0.094
Tetrachloroethene				0.15	0.014					
1,1,1-Trichloroethane			0.332		0.021	0.027				0.07
1,1,2-Trichloroethane			0.062							
Trichloroethene			1.46	0.355	0.027					
1,1-Dichloroethane			0.098	0.028					0.132	
1,2-Dichloroethane										
1,1,2,2-Tetrachloroethane			0.404							

Concentration in units of mg/kg

Table 36. Post-Demonstration Soil Sample Analysis in Electrode Row EB

Sample Bore Hole ID No.	S203						S204						S205					
Sample Date	09/26/95	09/26/95	09/26/95	09/26/95	09/26/95	09/26/95	09/26/95	09/26/95	09/26/95	09/26/95	09/26/95	09/26/95	09/25/95	09/25/95	09/25/95	09/25/95	09/25/95	09/25/95
Shipping Lot No.	2	2	2	2	2	2	2	2	2	2	2	2	1	1	1	1	1	1
Liner No.	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Laboratory Sample ID	12617	12618	12619	12620	12641	12642	12611	12612	12613	12614	12615	12616	12633	12634	12635	12636	12637	12638
DEPTH, FEET	1 TO 3		7 TO 9		13 TO 15		1 TO 3		7 TO 9		13 TO 15		1 TO 3		7 TO 9		13 TO 15	17 TO 19
Acetone			0.045	0.023	0.26	0.14	0.173	0.055	0.075	0.073	0.144	0.129	0.814	0.239	0.155	0.216	0.484	0.455
2-Butanone	0.043	0.065	0.092	0.067									0.484	0.378		0.178		0.02
4-Methyl-2-Pentanone													1.13	1.2		1.12	0.054	
Ethylbenzene								0.004						0.002				0.005
Toluene	0.008	0.007	0.007	0.008	0.037	0.032	0.007	0.007	0.007	0.006		0.007	0.011	0.007				0.033
Benzene																		0.01
Methylene Chloride	0.069	0.11	0.098	0.117	0.11	0.097	0.144	0.191	0.098	0.141	0.123	0.125	0.164	0.076	0.019	0.007	0.011	0.032
Tetrachloroethene																		0.115
1,1,1-Trichloroethane					0.022			0.052	0.022								0.012	0.012
1,1,2-Trichloroethane											0.02							
Trichloroethene																		0.025
1,1-Dichloroethane										0.077								
1,2-Dichloroethane																		
1,1,2,2-Tetrachloroethane																		

Concentration in units of mg/kg

Table 37. Post-Demonstration Soil Sample Analysis in Electrode Row EC

Sample Bore Hole ID No.	S206						S207						S208					
	09/25/95	09/25/95	09/25/95	09/25/95	09/25/95	09/25/95	09/22/95	09/22/95	09/22/95	09/22/95	09/22/95	09/22/95	09/22/95	09/22/95	09/22/95	09/22/95	09/22/95	09/22/95
Shipping Lot No.	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Liner No.	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Laboratory Sample ID	12627	12628	12629	12630	12631	12632	12477	12577	12478	12578	12479	12579	12474	12574	12475	12575	12476	12576
DEPTH, FEET	1 TO 3		7 TO 9		13 TO 15		1 TO 3		7 TO 9		13 TO 15		1 TO 3		7 TO 9		13 TO 15	
Acetone	0.141	0.491	0.634	0.67	0.403	0.32	0.575	0.25	1.54	5.3	5.84	2.25	0.006		0.378	0.46	0.788	6.61
2-Butanone	0.038	2.28	1.25	0.063	1.46	1.21	0.046		0.102	0.445	0.365	0.12		0.17	0.024	0.033	0.046	0.435
4-Methyl-2-Pentanone		0.118	0.034		0.079	0.046												
Ethylbenzene			0.002	0.003	0.015									0.007			0.04	0.036
Toluene	0.01	0.009	0.011		0.15	0.009			0.016	0.041	0.007	0.071					0.141	0.125
Benzene					0.007													
Methylene Chloride	0.09	0.124	0.152	0.219	0.168	0.225	0.186	0.223	0.286	0.343	0.221	0.244				0.023	0.032	0.03
Tetrachloroethene					0.019												0.143	0.105
1,1,1-Trichloroethane		0.034			0.007	0.046	0.377	0.033	0.071		0.011	0.019			0.006	0.006	0.437	0.367
1,1,2-Trichloroethane			0.019	0.011	0.055	0.035												
Trichloroethene					0.213					0.041		0.052				0.018	0.175	0.136
1,1-Dichloroethane					0.015		0.011		0.013	0.011	0.005	0.014			0.016	0.024	0.032	0.032
1,2-Dichloroethane																		
1,1,2,2-Tetrachloroethane																		

Concentration in units of mg/kg

horizontal plane as well as for the total volume. Comparison of Tables 18 and 26 reveals that there were very few contaminants for which the majority of samples were above the detection limit. Four such contaminants were toluene, tetrachloroethene, 1,1,1-trichloroethane, and trichloroethene. Tables 38 through 41 present data for each of these contaminants comparing their pre- and post-demonstration soil concentration. The geometric mean concentration for the entire volume was calculated for the pre- and post-demonstration samples. The results show that there was no significant difference in the concentration. It should also be pointed out that the comparison involves quantities which are very close to the method detection limits and the standard deviations are high thus evaluation of the soil data in this instance does not reveal any information about the removal of the VOCs. However, as shown in the next section, there was substantial increase in the concentration of the extracted soil gas.

The comparison of the geometric means was made because most environmental samples are known to follow the log-normal rather than the normal distributions. Ketones were not selected for the comparison because the analytical results for these chemicals are known to have more uncertainty than those for other analytes.

9.3 Rate of Contaminant Removal in Extracted Soil Gas

Hot soil gas samples were obtained once every 24 hours. These samples were obtained in an impinger train as described in Section 6.6.10. The liquid samples were analyzed by SW846 standard method 8260 for volatile organic chemicals. The concentration of selected VOCs in the hot gas was calculated from the concentration of the impinger liquid, its total volume, and the known gas sample volume. The rate of contaminant flow was determined by combining the concentration of the VOC with the standard volumetric flow rate of the hot gas measured at the time the sample was obtained. The sample gas volume was adjusted for the amount of water condensing in the impinger train.

As it has been mentioned before, the concentration of the VOCs in the soil was very low, so their concentration in the hot gas stream was also low. However, the increase in concentration as a result of heating was measurable for several chlorinated solvents. These data are presented in this section along with a discussion of the quality of the analytical data.

Table 42 presents the results of the gas sample analysis in micrograms/liter of the liquid collected in the impinger train. As the results show, despite the large amount of gas sampled the concentration of the VOCs was quite low. Among the various VOCs listed in Table 42, those which are above the horizontal line in column 1 represent the contaminants of concern for this demonstration. As it can be seen there were approximately three hydrocarbons and six chlorinated hydrocarbons which consistently appeared in most of the samples. These chemicals are:

Table 38. Comparison of Pre- and Post-Demonstration Soil Concentration of Toluene
(Concentration in ppb)

Soil Sample Bore hole Postreat_No	DEPTH INTERVAL, ft											
	Upper				Middle				Lower			
	Post, 1–3 ft		Pre, 1–3		Post, 7–9 ft		Pre, 8–10 ft		Post, 13–15 ft		Pre, 15–17	
S201	5	EA03	5.5	S201	7.5	EA03	5	S201	17.5	EA03	59	
S202	9.5	EA09	18.8	S202	8	EA09	8.5	S202	13.5	EA09		
S203	7.5	EB01	11	S203	7.5	EB01	178.5	S203	34.5	EB01		
S204	7	EB05	6.5	S204	6.5	EB05	42.5	S204	6	EB05		
S205	9	EB09	11	S205	5	EB09	7	S205	5	EB09	79	
S206	9.5	EC02	11.5	S206	8	EC02	36	S206	79.5	EC02		
S207	5	EC06	10	S207	28.5	EC06	26	S207	39	EC06		
S208	5	EC10	9	S208	5	EC10	46.5	S208	133	EC10		
S209	5			S209	5			S209	14			
S210	8.5	MW02	5	S210	8.5	MW02	5	S210	16.5	MW02	39	
S211	5			S211	329			S211	38.5			
S212	6.5			S212	8			S212	133			

	Arithmetic		N
	Average	STD	Count
All Post Test	28.9	59.4	36
All Pre Test	29.5	39.0	21

	Geometric		N
	Avg	STD	Count
All Post Test	12	3	36
All Pre–Test	17	3	21

Value in each cell of the table above is the arithmetic average of duplicate analysis. Individual results below detection limit were set equal to the limit

Blank Cell: not analyzed. Most Cells containing values around 5 ppb contain at least one analyses with results below detection limit.

Detection limit is 5 ppb

Table 39. Comparison of Pre- and Post-Demonstration Soil Concentration of Tetrachloroethene
(Concentration in ppb)

Soil Sample Bore hole Postreat_No		DEPTH INTERVAL, ft											
		Upper				Middle				Lower			
		Post, 1–3 ft		Pre, 1–3	Post, 7–9 ft		Pre, 8–10 ft	Post, 13–15 ft		Pre, 15–17			
S201	5	EA03	5	S201	48.5	EA03	5	S201	5	EA03	17.5		
S202	5	EA09	5.25	S202	5	EA09	5	S202	5	EA09			
S203	5	EB01	5	S203	5	EB01	14.5	S203	5	EB01			
S204	5	EB05	16.5	S204	5	EB05	8.5	S204	5	EB05			
S205	5	EB09	8	S205	5	EB09	5	S205	5	EB09	16.5		
S206	5	EC02	7.8	S206	5	EC02	11	S206	12	EC02			
S207	5	EC06	5	S207	5	EC06	43.5	S207	5	EC06			
S208	5	EC10	5	S208	5	EC10	5	S208	124	EC10			
S209	5			S209	20.5			S209	5				
S210	5	MW02	5	S210	5	MW02	5	S210	9.5	MW02	12.5		
S211	5			S211	10			S211	9.5				
S212	5			S212				S212	5				

	Arithmetic		N
	Average	STD	Count
All Post Test	10.7	20.9	35
All Pre Test	10.1	8.7	21

	Geometric		N
	Avg.	STD	Count
All Post	6.6	2.0	35
All Pre	8.1	1.8	21

Value in each cell of the table above is the arithmetic average of duplicate analysis. Individual results below detection limit were set equal to the limit

Blank Cell: not analyzed. Most Cells containing values around 5 ppb contain at least one analyses with results below detection limit.

Detection limit is 5 ppb

Table 40. Comparison of Pre- and Post-Demonstration Soil Concentration of 1,1,1-Trichloroethane
(Concentration in ppb)

Soil Sample Bore hole Postreat_No		DEPTH INTERVAL, ft									
		Upper			Middle				Lower		
		Post, 1-3 ft		Pre, 1-3	Post, 7-9 ft		Pre, 8-10		Post, 13-15 ft		Pre, 15-17
S201	5	EA03	10	S201	7	EA03	5	S201	50.5	EA03	83.5
S202	29	EA09	5.3	S202	5	EA09	5	S202	78	EA09	
S203	5	EB01	5	S203	5	EB01	86	S203	13.5	EB01	
S204	28.5	EB05	5	S204	13.5	EB05	88.5	S204	5	EB05	
S205	5	EB09	5	S205	5	EB09	5	S205	8.5	EB09	574
S206	19.5	EC02	8.3	S206	5	EC02	71	S206	26.5	EC02	
S207	205	EC06	5	S207	38	EC06	11	S207	15	EC06	
S208	5	EC10	5	S208	6	EC10	5	S208	402	EC10	
S209	5			S209	88			S209	11.5		
S210	23	MW02	5	S210	5	MW02	6	S210	5	MW02	558
S211	5			S211	168.5			S211	24		
S212	5			S212				S212	37.5		

	Arithmetic		N
	Average	STD	Count
All post test	38.9	76.2	35.0
All pretest	73.9	162.4	21.0

	Geometric		N
	Avg	STD	Count
All Post Test	15	3	35
All Pre Test	15	5	21

Value in each cell of the table above is the arithmetic average of duplicate analysis. Individual results below detection limit were set equal to the limit

Blank Cell: not analyzed. Most cells containing values around 5 ppb contain atleast one analyses with results below detection limit.

Table 41. Comparison of Pre- and Post-Demonstration Soil Concentration of Trichloroethene
(Concentration in ppb)

Soil Sample Bore hole Postreat_No	DEPTH INTERVAL, ft											
	Upper				Middle				Lower			
	Post, 1–3 ft		Pre, 1–3		Post, 7–9 ft		Pre, 8–10 ft		Post, 13–15 ft		Pre, 15–17	
S201	5	EA03	5	S201	44.5	EA03	5	S201	5	EA03	35.5	
S202	5	EA09	6.3	S202	5	EA09	5	S202	16	EA09		
S203	5	EB01	5	S203	5	EB01	120	S203	5	EB01		
S204	5	EB05	5	S204	5	EB05	16.5	S204	5	EB05		
S205	5	EB09	5	S205	5	EB09	5	S205	5	EB09	47.5	
S206	5	EC02	9	S206	5	EC02	25.5	S206	109	EC02		
S207	5	EC06	5	S207	23	EC06	5	S207	28.5	EC06		
S208	5	EC10	5	S208	12.5	EC10	6.5	S208	155.5	EC10		
S209	5			S209	53.5			S209	16.5			
S210	5	MW02	5	S210	5	MW02	5	S210	23	MW02	80	
S211	5			S211	907.5			S211	16			
S212	5			S212				S212	5			

	Arithmetic Average	STD	N Count
All Post Test	43	151	35
All Pre Test	19	29	21

	Geometric Avg	STD	N Count
All Post Test	10	3	35
All Pre Test	10	3	21

Value in each cell of the table above is the arithmetic average of duplicate analysis. Individual results below detection limit were set equal to the limit

Blank Cell: not analyzed. Most Cells containing values around 5 ppb contain at least one analyses with results below detection limit.

Detection limit is 5 ppb

Table 42. Analysis of Hot Soil Gas Sample Collected in an Impinger Train, $\mu\text{g/L}$ (Page 1 of 4)

Sampled On	Actual				Actual							
	06/13/95	06/14/95	06/15/95	06/16/95	06/17/95	06/18/95	06/19/95	06/20/95	06/20/95	06/20/95	06/21/95	
Standard Labs. #	57252	57253	57254	57255	57256	57257	57258	57315			57316	
IITRI No.	S160131900	S206141726	S306151515	S406161620	S506171627	S606181706	S706190925	S106200917	S106200917	S106200917	S106210826	
Chemical Name												
Acetone	17592	1267.00	28701.00	840.00	202.00	346.00	583.00	2730	F		1760	F
2-Butanone	17.2	28.80	26.60		35.90	43.80	72.80	289		165	335	
4-Methyl-2-Pentanone			16.70					19.9			13.1	
Ethyl Benzene	3.72	10.50	7.20			7.70	17.70	150		145	95.6	
Toluene	60.8	461.00	194.00	28.40	32.90	115.00	148.00	612		603	428	
Benzene	5.35	1.57	2.55		2.43	6.63	7.56	27.3		26.9	17.6	
Carbon Disulfide											1.78	
Methylene Chloride		49.70	58.40			112.00	116.00	2280	F	1682	1660	F
Tetrachloroethene	2.94		7.11		5.31	20.40	23.10	130		125	89.7	
1,1,1-Trichloroethane	23.7 ?	3.31	256.00	88.50	316.00	894.00	910.00	855		802	1140	F
1,1,2-Trichloroethane	2.19	6.70	8.17			6.20	15.80	75.9		75.4	69.8	
Trichloroethene	2.68		5.78		4.64	42.60	52.10	372		357	320	
1,1-Dichloroethane	2.49		46.60	17.50	28.60	80.80	77.50	170		164	146	
1,2-Dichloroethane							4.08	25.1		22.8	13	
1,1,2,2-Tetrachloroethane								4.04		7.44	3.07	
Bromomethane	25											
2-chloroethylvinyl ether	24.4		25.70		24.50	24.30	25.70					
Chloroform	4.47	4.29	4.92					7.96		7.81		
1,1-dichloroethene	6.92		6.62			24.60	26.60	89		4.3	141	
methyl methacrylate	2.28	3.48	2.54									
o-xylene	2.46	12.40	9.95			7.64	23.10	169		162	120	
m+p-xylene	8.37	37.60	24.10	6.11		22.60	59.20	445		429	290	
ethyl methacrylate	2.79	8.69	9.49									
styrene	0.7	0.86	0.95					6.36		6.47	5.17	
2-hexanone			15.00									
isobutyl alcohol	2.91		3.40	31.70		2.47	15.50	1.56		3.65	2.81	
Propionitrile			7.25									
1,2-dichlorobenzene								1.73		2.01	1.86	
1,4-dichlorobenzene										3.83	3.58	
trans 1,2-dichloroethene								4.06		4.37		
Naphthalene								21.9		19.7	13.5	
Chlorobenzene	0.84							1.79		2.12	2.07	
trans-1,4-dichloro-2-butene												
vinyl acetate												
Bromodichloromethane												
Tribromomethane												
Carbon tetrachloride												
Chlorodibromomethane												
1,2-Dichloropropane												
cis-1,3-Dichloropropene												
trans-1,3-Dichloropropene												
Pentachloroethane												
Acrylonitrile												
1,2-Dibromomethane												
cis-1,4-Dichloro-2-butene												

Table 42. Analysis of Hot Soil Gas Sample Collected in an Impinger Train, $\mu\text{g/L}$ (Page 2 of 4)

Sampled On ----->	06/22/95	06/23/95	06/23/95	06/24/95	06/25/95	06/26/95	06/28/95	06/29/95	06/30/95	07/01/95
Standard Labs. # ----->	57317	57325		57326	57327	57328	57446	57447	57448	57454
IITRI No. ----->	S10620838 ?	S106230928	S106230928 Dup.	S106240917	S106250855	S106260810	S106280456	S106290459	S106300233	S107010918
Chemical Name										
	Final	Final	Final	Final	Final	Final	Final	Final	Final	Final
Acetone	1010 F	2040	2010	3060	3810	4340	2230	1140	202	1060
2-Butanone	150			44.1	70.7	41.2	61.9			90.6
4-Methyl-2-Pentanone		13	11.6							
Ethyl Benzene	20.1 F	41.5	41.6	21.2	27	4.34				4.57
Toluene	124 F	260	259	157	226	42.4	11.8	3.13		22.6
Benzene	6	13	13	9.63	11.5	5.46	1.81	2.45		1.82
Carbon Disulfide										
Methylene Chloride	2260 F	340	313	918	570	443	255	123		160
Tetrachloroethene	18.2 F	40.6	40.6	48.1	59	9.89				
1,1,1-Trichloroethane	250 F	523	511	860	885	165	12.2			26.4
1,1,2-Trichloroethane	26.2 F	37	38	5.59	11.3	2.5	4.92			6.86
Trichloroethene	93.8 F	197	197	187	190	43.2	11.6			16.8
1,1-Dichloroethane	78.2	118	114	91.2	109	44.7	4.06			7.73
1,2-Dichloroethane	4.93	9.23	8.46			3	<			
1,1,2,2-Tetrachloroethane		2.88								
Bromomethane										
2-chloroethylvinyl ether										
Chloroform										
1,1-dichloroethene	44.9	36.6	31.7	322	124	44.6	4.47			
methyl methacrylate										
o-xylene	26.9 F	50.1	50.4	16.5	23.3					6.14
m+p-xylene	64.7 F	130	133	61.3	79.6	12.6	8.56			14.4
ethyl methacrylate										
styrene		2.31	2.48		1.43					
2-hexanone										
isobutyl alcohol	2.05 F	2.06	2.2			5.64	55.2	9.61	6.62	3.41
Propionitrile										
1,2-dichlorobenzene										
1,4-dichlorobenzene										
trans 1,2-dichloroethene										
Naphthalene										
Chlorobenzene										
trans-1,4-dichloro-2-butene					6.68					
vinyl acetate										
Bromodichloromethane										
Tribromomethane										
Carbon tetrachloride										
Chlorodibromomethane										
1,2-Dichloropropane										
cis-1,3-Dichloropropene										
trans-1,3-Dichloropropene										
Pentachloroethane										
Acrylonitrile										
1,2-Dibromoethane										
cis-1,4-Dichloro-2-butene										

Table 42. Analysis of Hot Soil Gas Sample Collected in an Impinger Train, $\mu\text{g/L}$ (Page 3 of 4)

Sampled On	07/02/95	07/03/95	07/04/95	07/05/95	07/06/95	07/06/95	07/07/95	07/08/95	07/10/95	07/11/95	07/12/95	07/13/95
Standard Labs. #	57455	57456	57551	57552	57553	57554	57557	57558	57559	57610	57611	57612
IITRI No.	S107021526S	S107030824	S107040755	S107050802	S107060807	S307061032	S107070820	S107080807	S107100800	S107110943	S107120243	S107130843
Chemical Name	Final											
Acetone	615	303	322	257	219	<116	509	702	170	197	143	235
2-Butanone	63.5	41.2	39.2	36.6		<32.3	63.8	83.9	47.8	54.2	40.6	
4-Methyl-2-Pentanone												
Ethyl Benzene	22.1	9.12	12.5	13.5	9.43	<3.6	7.39	42.9	21.8	11.2	7.6	6.78
Toluene	162	58.3	87.8	88.2	60.4	<3.1	56.2	248	87.1	59.3	39	33.4
Benzene	11.3	5.35	7.88	5.83	5.67	<1.6	6.89	11.7	5.98	3.07	2.93	1.96
Carbon Disulfide									2.54			
Methylene Chloride	186	110	104	107		<98.4	120	149	188	138		103
Tetrachloroethene	47.7	18.5	26.3	25.8	19.5	<5.2	15.8	71.4	34.5	20.3	14.1	13.9
1,1,1-Trichloroethane	541	138	227	157	136	<3.6	115	328	160	132	112	101
1,1,2-Trichloroethane	8.78	3.39	4.44	5.21	3.36	<2.2	4.15	12.2	5.7	2.86		
Trichloroethene	137	78.2	86.3	95.4	78.2	<3.8	66.9	243	116	81.3	57.4	52.1
1,1-Dichloroethane	87.5	33.2	45.5	32.8	33.1	<1.6	31.8	71.3	22.7	15.9	13.7	12.6
1,2-Dichloroethane						<3.8						
1,1,2,2-Tetrachloroethane		2.96			2.92	<2.8		9.13	10.5	3.8		2.91
Bromomethane										41.9	26	
2-chloroethylvinyl ether												
Chloroform	7.87					<7.4	7.7	9.17		9.17	8.86	9.77
1,1-dichloroethene			69.6	49.1	36.5	<4.3	20			8.28		6.81
methyl methacrylate												
o-xylene	20.4	8.61	10.2	11.6	8.46	<4.0	6.8	38.3	21.4	10.3	6.64	6.33
m+p-xylene	67.6	29.4	36.2	41.9	29.6	<5.8	22.2	134	70.7	36	23.1	21.5
ethyl methacrylate												
styrene						<1.3		1.92	1.68			
2-hexanone												
isobutyl alcohol	4.64	2.88	3.16	4.69	4.69	3.8	19.1	2.29	35.1	51.7	40.2	8.43
Propionitrile												
1,2-dichlorobenzene												
1,4-dichlorobenzene												
trans 1,2-dichloroethene												
Naphthalene									8.36			
Chlorobenzene												
trans-1,4-dichloro-2-butene	8.37			6.92	7.23	<6.6		16.9	16			
vinyl acetate						<1.5			1.85			
Bromodichloromethane												
Trbromomethane												
Carbon tetrachloride												
Chlorodibromomethane												
1,2-Dichloropropane												
cis-1,3-Dichloropropene												
trans-1,3-Dichloropropene												
Pentachloroethane												
Acrylonitrile												
1,2-Dibromoethane												
cis-1,4-Dichloro-2-butene												

Table 42. Analysis of Hot Sol Gas Sample Collected
in an Impinger Train, $\mu\text{g/L}$ (Page 4 of 4)

Sampled On ----->	07/21/95	07/19/95	07/28/95	08/07/95	08/07/95
Standard Labs. # ----->	57713	57747	57857	57918	57919
IITRI No. ----->	S107210922	S107190215	S107280935	S1082071035	S108071345
Chemical Name	Duplicate of 57918				
Acetone	191		274	156	
2-Butanone		71.4			
4-Methyl-2-Pentanone		42.7			
Ethyl Benzene	6.56	5.23			
Toluene	17.7	5.19	16	10.1	9.97
Benzene	2.64	2.28	5.2	1.74	1.82
Carbon Disulfide					
Methylene Chloride			98.6	883	591
Tetrachloroethene	10.7	6.8			
1,1,1-Trichloroethane	63.5		28	42.7	42.4
1,1,2-Trichloroethane		4.56			
Trichloroethene	32.8	5.63	16	18.8	18.4
1,1-Dichloroethane	9.46		4.7	8.25	8.19
1,2-Dichloroethane					
1,1,2,2-Tetrachloroethane	3.88	13.5			
Bromomethane	43.7	36.6			
2-chloroethylvinyl ether		6.75			
Chloroform		22.1			
1,1-dichloroethene	24.2				
methyl methacrylate		12.3			
o-xylene	4.61	5.4	5		
m+p-xylene	11.3	9.85	12	6.81	6.98
ethyl methacrylate		4.22			
styrene	2.9	4.45			
2-hexanone		46.3			
isobutyl alcohol	3.03	8.1	20	15.8	2.54
Propionitrile					
1,2-dichlorobenzene		3.05			
1,4-dichlorobenzene		3.53			
trans 1,2-dichloroethene					
Naphthalene			18		
Chlorobenzene	1.79	3.74	1.4		
trans-1,4-dichloro-2-butene		11.9			
vinyl acetate		2.28			
Bromodichloromethane					
Tribromomethane		5.91			
Carbon tetrachloride					
Chlorodibromomethane		2.43			
1,2-Dichloropropane					
cis-1,3-Dichloropropene					
trans-1,3-Dichloropropene					
Pentachloroethane					
Acrylonitrile		24.3			
1,2-Dibromoethane		2.69			
cis-1,4-Dichloro-2-butene		10.5			

- Ethylbenzene
- Toluene
- Xylenes
- 1,1-Dichloroethene (1,1-DCE)
- 1,1-Dichloroethane (1,1-DCA)
- 1,1,1-Trichloroethane (1,1,1-TCA)
- 1,1,2-Trichloroethane (1,1,2-TCA)
- Trichloroethene (TCE)
- Tetrachloroethene (PCE)

The initial and peak flow rates of these compounds in the hot gas stream are given in Table 43. The initial rates were measured 24 hours after the start of soil venting at ambient temperature. The peak rate occurred during heating. As the data indicate, the ratio of peak to initial rate varied from 10 to 53 depending upon the chemical. Figures 35 through 44 show the mass flow rate as a function of time for the chemicals listed above. Appendix B contains additional figures which illustrate the hot soil gas concentration versus time for these chemicals.

The total flow rate of the hot gas varied during the course of the demonstration. Initially, there was no appreciable flow from the four gas collection wells, and so the collected gases were coming through the two surface gas collection lines. As the permeability in the formation developed, flow through the collection wells increased with time. However, there were relatively long periods extending over several hours when the surface lines were shut off in an attempt to develop permeability in the gas collection wells. During such times the hot gas flow rate decreased drastically. Figure 45 illustrates the hot gas flow rate as a function of elapsed time.

The quality of data generated by the laboratory during the analysis of the gas samples was assessed in two ways. First, liquid check standards were given to the laboratory for analysis. These standards were prepared by IITRI in its laboratory. Table 44 gives the results of analysis of these check standards. The first page of this table contains data from standards given to the lab. prior to the start of the demonstration. These samples were identified in such a manner that the laboratory personnel would have known about their purpose. The second page of Table 44 contains results of check standard analysis obtained during the course of the demonstration. These samples were identified such that the laboratory personnel could not distinguish them from the field samples.

The second method for judging the quality of data was to assess the recovery and precision of spikes and spike duplicates. The laboratory performed matrix spikes on unknown samples sent from the field. The quality of the spike recovery data was judged by calculating the absolute recovery of the spike as a percentage of the amount spiked. Acceptable range for spike recovery was 100 ± 25 percent. Precision of analysis was judged by computing the relative percent difference (RPD) of recoveries of spikes from a duplicate

Table 43. Initial and Peak Flow Rates of Selected Contaminants in Extracted Soil Gas (In Situ EM Heating at K-25 Site, Oak Ridge, TN)		
Name	Flow rate, mg/hr	
	Initial	Peak
Hydrocarbons:		
Ethylbenzene	5	57
Toluene	75	700
o-Xylene	2	65
meta + para-xylene	10	170
Chlorinated Hydrocarbons:		
1,1-Dichloroethene	8	290
1,1-Dichloroethane	2	88
1,1,1-Trichloroethane	15	800
1,1,2-Trichloroethane	3	30
Trichloroethene	5	170
Tetrachloroethene	2	50
Initial rate measured after 24 hours of in situ venting at ambient temperature.		
Peak rate occurred during heating.		

analysis. Acceptable range for RPD for duplicate spikes recoveries was 100 ± 10 percent. The laboratory also ran its own check standards. A check standard analysis was considered acceptable when the analytical value was within 10 percent of the known value, that is, a recovery of 100 ± 10 percent.

Table 45 gives the number of samples in which the VOCs were detected. It also gives the number of samples in which spikes were added for a given analyte identified in the table. Thus it can be seen that spikes were run at a substantial rate, approximately 10 to 40 percent, depending upon the analyte. Table 46 gives the percentage of spikes that met the quality standard for spike recovery and RPD. It also gives the percentage of reference standard analysis that met the criteria of 100 ± 10 percent recovery.

Figure 35. Ethylbenzene in Extracted Gas
(milligram/hr)

Figure 36. Toluene in Extracted Gas
(milligram/hr)

Figure 37. o-Xylene in Extracted Gas
(milligram/hr)

Figure 38. m+p-Xylene in Extracted Gas
(milligram/hr)

Figure 39. 1,1-Dichloroethene in Extracted Gas
(milligram/hr)

Figure 40. 1,1-Dichloroethane in Extracted Gas

(milligram/hr)

Figure 41. 1,1,1-Trichloroethane in Extracted Gas
(milligram/hour)

Figure 42. 1,1,2-Trichloroethane in Extracted Gas
(milligram/hour)

Figure 43. Trichloroethylene in Extracted Gas
(milligram/hr)

Figure 44. Tetrachloroethene in Extracted Gas
(milligram/hr)

Figure 45. Total Soil Gas Flow Rate, SCFM

(Data Corresponds to Gas Sampling Time)

Table 44. Analysis of QA/QC Check Standards (Page 1 of 2)
(Units $\mu\text{g/L}$)

Tested On Standard Labs. # IITRI No. Chemical Name	-----> -----> ----->	06/06/95 57019 QAQC5 As Analyzed	Actual Concentration in Prepared Standard QAQC5	Percent Recovery In Analysis	Error %	06/06/95 57020 QAQC6	Actual Concentration in Prepared Standard QAQC6	Percent Recovery In Analysis %	Error	06/06/95 57021 QAQC7	Actual Concentration in Prepared Standard QAQC7
Acetone		3316.5	2500	133%	33	<11.68	250	0%	-100	<11.68	0
2-Butanone		3419	2500	137%	37	<3.23	250	0%	-100	<3.23	0
4-Methyl-2-Pentanone		3246.5	2500	130%	30	248.7	250	99%	-1	<1.0	0
Ethyl Benzene		1241	1000	124%	24	112.5	100	113%	13	3	0
Toluene		1177	1000	118%	18	108.4	100	108%	8	7.5	0
Benzene		1068	1000	107%	7	96	100	96%	-4	2.5	0
Carbon Disulfide		876.5	1000	88%	-12	4.3	100	4%	-96	<0.16	0
Methylene Chloride		1116.5	1000	112%	12	84.4	100	84%	-16	153.5	0
Tetrachloroethene		1499.5	1000	150%	50	109.3	100	109%	9	2	0
1,1,1-Trichloroethane		924.5	1000	92%	-8	84.3	100	84%	-16	1	0
1,1,2-Trichloroethane		1193.5	1000	119%	19	103.9	100	104%	4	2	0
Trichloroethene		1203	1000	120%	20	109.3	100	109%	9	2	0
1,1-Dichloroethane		950	1000	95%	-5	84	100	84%	-16	<0.16	0
1,2-Dichloroethane		1135.5	1000	114%	14	105.9	100	106%	6	<0.38	0
1,1,2,2-Tetrachloroethane		1158	1000	116%	16	96.6	100	97%	-3	4.5	0

Table 44. Analysis of QA/QC Check Standards (Page 2 of 2)
(Units µg/L)

Sampled On ----->	07/06/95	07/19/95			07/19/95			06/01/95			06/01/95			07/19/95
Standard Labs. # ----->	57554	57710	Known	Percent	57711	Known	Percent	57712	Known	Percent	57748	Known	Percent	57747
IITRI No. ----->	S307061032	S107191050	Concentration	Error	S107191115	Concentration	Error	QAQC6	Concentration	Error	QAQC5	Concentration	Error	S107190215
Chemical Name	Field Blank	QAQC9	QAQC9		QAQC10	QAQC10		QAQC6	QAQC6		QAQC5	QAQC5		QAQC11
														Blank
Acetone	<116	51580	50000	3.16	5870	5000	17.4	354	250	41.6	1890	2500	-24.4	
2-Butanone	<32.3	57400	50000	14.8	6700	5000	34	288	250	15.2	2070	2500	-17.2	71.4
4-Methyl-2-Pentanone		53100	50000	6.2	6130	5000	22.6	257	250	2.8	1660	2500	-33.6	42.7
Ethyl Benzene	<3.6	23300	20000	16.5	2250	2000	12.5	106	100	6	1070	1000	7	5.23
Toluene	<3.1	22000	20000	10	2290	2000	14.5	110	100	10	978	1000	-2.2	5.19
Benzene	<1.6	20100	20000	0.5	1990	2000	-0.5	90.6	100	-9.2	878	1000	-12.2	2.28
Carbon Disulfide		21900	NU		2180	NU		83.4	NU		505	NU		
Methylene Chloride	<98.4	21350	20000	6.75	2200	2000	10	149	100	49	1010	1000	1	
Tetrachloroethene	<5.2	25800	20000	29	2870	2000	43.5	139	100	39	1210	1000	21	6.8
1,1,1-Trichloroethane	<3.6	17100	20000	-14.5	1790	2000	-10.5	88.1	100	-11.9	831	1000	-16.9	
1,1,2-Trichloroethane	<2.2	21700	20000	8.5	2340	2000	17	100	100	0	923	1000	-7.7	4.56
Trichloroethene	<3.6	20900	20000	4.5	2340	2000	17	112	100	12	982	1000	-1.8	5.03
1,1-Dichloroethane	<1.6	19000	20000	-5	1920	2000	-4	84.9	100	-15.1	828	1000	-17.2	
1,2-Dichloroethane	<3.6	19500	20000	-2.5	2040	2000	2	94.6	100	-5.4	892	1000	-10.8	
1,1,2,2-Tetrachloroethane	<2.6	20800	20000	4	2390	2000	19.5	101	100	1	720	1000	-28	13.5
Bromomethane					262			123			29.8			36.6
2-chloroethylvinyl ether											6.02			6.75
Chloroform	<7.4	19700	20000	-1.5	2030	2000	1.5	104	100	4	919	1000	-8.1	22.1
1,1-dichloroethene	<4.3	17800	20000	-11	1920	2000	-4	26	100	-74	39.6	1000	-96.04	
methyl methacrylate			NU			NU			NU		6.25	NU		12.3
o-xylene	<4.0	22400	20000	12	2360	2000	16	115	100	15	1060	1000	6	5.4
m+p-xylene	<5.8	39700	40000	-0.75	4180	4000	4.5	209	200	4.5	1880	2000	-7	9.85
ethyl methacrylate			NU			NU			NU			NU		4.22
styrene	<1.3	21300	NU		2200	NU		107	NU		1010	NU		4.45
2-hexanone		54000	50000	8	6450	5000	29	244	250	-2.4	1570	2500	-37.2	46.3
isobutyl alcohol	3.6	537	NU		19	NU		5.85	NU		3.33	NU		8.1
Propionitrile		433	NU		47.8	NU			NU			NU		
1,2-dichlorobenzene			NU			NU			NU			NU		3.05
1,4-dichlorobenzene			NU			NU			NU			NU		3.53
trans 1,2-dichloroethene		19300	NU		2000	NU		94.2	NU		705	NU		
Naphthalene			NU			NU			NU			NU		
Chlorobenzene		20400	20000	2	2170	2000	8.5	108	100	8	965	1000	-3.5	3.74
trans-1,4-dichloro-2-butene	<6.6		NU			NU			NU		8.36	NU		11.9
vinyl acetate	<1.5	21500	20000	7.5	1200	2000	-40	22	100	-78	393	1000	-60.7	2.28
Bromodichloromethane		19700	NU		2090	NU		95.1	NU		917	NU		
Tribromomethane		19500	NU		2160	NU		87.5	NU		823	NU		5.91
Carbon tetrachloride		17400	20000	-13	1810	2000	-9.5	86.4	100	-13.6	844	1000	-15.6	
Chlorodibromomethane		19800	NU		2190	NU		96.3	NU		933	NU		2.43
1,2-Dichloropropane		20900	20000	4.5	2260	2000	13	102	100	2	897	1000	-10.3	
cis-1,3-Dichloropropane		24400	NU		2650	NU		121	NU		1130	NU		
trans-1,3-Dichloropropane		20500	NU		2230	NU		98.9	NU		946	NU		
Pentachloroethane		282	NU		22.2	NU			NU		9.47	NU		
Acrylonitrile			NU			NU			NU			NU		24.3
1,2-Dibromoethane			NU			NU			NU			NU		2.69
cis-1,4-Dichloro-2-butene			NU			NU			NU			NU		10.5

NU: Not used in check standard

Table 45 Frequency of Detection and Spikes for Selected Contaminants		
	Number of Samples in which Detected	Number of Samples Spiked
Hydrocarbons		
Ethylbenzene	31	10
Toluene	37	11
o-xylene	30	8
m-, p-xylene	35	4
Chlorinated Hydrocarbons		
1,1-dichloroethene	24	10
1,1-dichloroethane	35	9
1,1,1-trichloroethane	37	13
1,1,2-trichloroethane	28	9
Trichloroethene	37	10
Tetrachloroethene	15	7

The data of Table 46 indicate that the spikes met the quality goal for precision. For all but one analyte, the spikes also met the quality goal for spike recovery. Spikes for tetrachloroethene met their quality goal about 43 percent of the time.

9.4 Permeability of Soil to Air Flow

As mentioned before, provisions were made for the collection of soil gas by means of a gas collection blower. There were four gas collection wells and two perforated horizontal gas collection lines at the surface. Initial measurement of permeability of each well was made prior to the start of in situ heating. These measurements were made by individually applying a vacuum to each of the four wells and noting the flow rate. In all four cases the initial permeability in each of the four wells was immeasurably low. During the course of the demonstration, the permeability of individual wells was measured by isolating the remaining five gas collection points from the gas collection blower. It was observed that as the soil was heated the permeability to air flow increased to approximately 1 to 2 darcy in all four wells. The permeability continued to increase during the cool down period as the soil moisture was removed from the hot soil. Towards the end of the cool down period the permeability had increased to 5 to 7 darcy.

Table 46. Frequency With Which Matrix Spikes and Reference Standards Met their Quality Standard			
	Matrix Spikes		Reference Standards
	Percent with Acceptable RPD	Percent with Acceptable Spike Recovery	Percent Meeting Quality Criterion
Hydrocarbons:			
Ethylbenzene	100	100	50
Toluene	91	100	55
o-Xylene	100	100	25
m- & p-Xylene	100	100	50
Chlorinated Hydrocarbons:			
1,1-Dichloroethene	100	90	60
1,1-Dichloroethane	100	100	100
1,1,1-Trichloroethane	92	92	85
1,1,2-Trichloroethane	100	100	100
Trichloroethane	100	100	20
Tetrachloroethene	100	43	14

RPD: Relative Percent Difference
Acceptable RPD: $100 \pm 10\%$
Acceptable Spike Recovery: $100 \pm 25\%$ of amount spiked

The location of the four gas collection wells is shown in Figure 34. The location of the horizontal gas collection lines is shown in Figure 9. Figures 46 through 49 illustrates the development of permeability in each of the four wells which are identified as NW, NE, SE and SW. These figures also show the average soil temperature as a function of time. Energy input to soil was stopped on the 25th day. Two soil temperature averages were computed. The first average was based on all the temperature measurement points including those at the perimeter of the heated zone. This yielded a lower average than the second method. In the second method all the perimeter points were excluded. Thus the

Figure 46

PERMEABILITY TO GAS FLOW, NE WELL
(In Situ EM Heating, K-25 Site, Oak Ridge, TN)
(Heating Ended on 25th Day)

PERM_NE1 Feb. 6, 1996 8:45:13 AM

Figure 47

PERMEABILITY TO GAS FLOW, NW WELL (In Situ EM Heating, K-25 Site, Oak Ridge, TN) (Heating Ended on 25th Day)

Figure 48

PERMEABILITY TO GAS FLOW, SE WELL
 (In Situ EM Heating, K-25 Site, Oak Ridge, TN)
 (Heating Ended on 25th Day)

Figure 49

PERMEABILITY TO GAS FLOW, SW WELL (In Situ EM Heating, K-25 Site, Oak Ridge, TN) (Heating Ended on 25th Day)

PERM_SW1 Feb. 6, 1998 9:57:07 AM

second method represents the average temperature of approximately 80 percent of the heated volume.

The development of permeability is a beneficial effect of heating. It allows the removal of volatile organic compounds from soils which have a low permeability under native conditions such as the case at the K-25 Site. Thus heating allows the application of in situ venting techniques at sites which would otherwise be considered unsuitable for vacuum extraction of VOCs.

9.5 Electrical Data

9.5.1 AC Power Delivery System Performance

The operational performance of the AC power delivery system, which consisted of the ACPS, the subsurface electrode array, and the interconnecting cabling and bus hardware, was evaluated by monitoring the AC energy delivered to the electrode array and by tracking the array's electrical resistance.

A water injection system was installed to assist in maintaining a low contact resistance between each electrode and the surrounding soil. The water injection system was set up to deliver water to each row of electrode and, by means of individual electrode row manifolds, to each individual electrode. The center row electrodes predominantly require this water addition since they reach the boiling point of water first.

Difficulties in delivering sufficient water to the center row electrode during the first half of the heating led to the erratic behavior in the electrode array's resistance as the contact resistance to each of the center row electrodes varied widely. These difficulties were later found to be a result of salts precipitating out of the injected water. These salts bridged the sand pack in the water injection tubing and it is suspected (based on measurements made on recovered tubing) that it reduced the permeability of the pack.

Fire hydrant water was used for injection after filtration through a wound filter cartridge. Water samples were later sent for analysis. It was found that the water contained 160 to 176 mg/liter of dissolved solids. The water had a bicarbonate alkalinity of 80 mg/liter. The bicarbonate would precipitate out as the water is heated in the tubing running through the hot soil.

Figure 50 illustrates the tracking of the electrode array's resistance throughout the entire demonstration. The first 6 to 7 days show what would be a very controlled resistance trend with sufficiently low electrode to soil contact resistance. Figure 51 illustrates these first days of the heating. After the first 5 days of heating the water injection rate to the electrode array was limited to 0.5 gph even when the injection pressure was increased to

Figure 50. Electrode Array Resistance Versus Time.

Figure 51. Initial Electrode Array Resistance.

about 100 psig. As mentioned above this was probably due to the plugging of the sand packed the water injection tubing.

Figures 52 and 53 display the applied power level delivered to the electrode array for both the entire demonstration and for the first 6 to 7 days, respectively. The resistance trend and applied power curves shown in the figures indicate the loss of contact between the electrode and surrounding soil as the water injection rate was limited. In an attempt to help re-establish the contact, the power was switched off for several hours at a time while injecting water. This seemed to provide a temporary re-establishment of the electrical contact with a low resistance. However, within a short duration of resuming power input to the soil the contact resistance would increase again thus limiting power input. We had the ability to increase the applied voltage to compensate for the increasing resistance. The power source was capable of providing up to 4000 volts, however, a limitation of 2000 volts was established for the field operations.

Figure 54 illustrates the cumulative energy delivered to the soil throughout the demonstration. A total of 25,900 KWHR was delivered in the 24.5 days of AC heating.

9.5.2 Electrical Safety Measurements

Prior to the start of the heating demonstration, a low power test of the AC power system was conducted. During this test, measurements were made of the soil surface voltage gradients along eight (8) selected radials around the electrode array. Selected touch voltage locations were also identified, examined, and measured during the low power test. Throughout the heating demonstration. Whenever the power applied to the array was increased by 25 kW or more, all designed step potential and touch voltage locations were measured to assure that all values were below the accepted safe limits of 2 V/m (step potential) and 6 volts to ground (touch voltage). These safe limits were never exceeded during the entire heating demonstration.

As part of the measurement of the step potential radials, a comparison was made between the extrapolated measured values (to an applied power level of 200 KVA) and the original analytical predictions of the step potential contours. Appendix D presents measured versus predicted data for all eight (8) radials. Figure 55 illustrates the close agreement that was found. Figure 56 also illustrates good agreement between measured and predicted values. This figure points out an additional ambient condition present to the southwest of the electrode array. As seen in the figure, the measured curve reaches a near constant value of step potential beyond 50 feet from the center of the array. It is at this point and further to the southwest that the buried methanol tank was located with its cathodic protection system energized. The measured step potential values were recorded and showed that the frequency locked on 120 Hz not 60 Hz. This indicated some other local power source operating at a different frequency, other than the ACPS:

Figure 52. Applied Power as a Function of Time.

Figure 53. Applied Power in Days 0 to 7.

Figure 54. Energy Input as a Function of Time.

Northwest Radial

Figure 55. Comparison of Measured vs. Predicted Step Potential -- Northwest Radial.

Southwest Radial

Figure 56. Comparison of Measured vs. Predicted Step Potential -- Southwest Radial.

10. ECONOMIC ASSESSMENT AND SCHEDULE

10.1 Scope

In this section the cost of remediation of the pits in the classified burial ground is presented. The purpose of the economic study was to develop an estimate which would prove to be within +/- 40 percent of the actual cost of the process. A system built around a trailer mounted 200 kW EM power source was designed. In preparing this cost estimate it was assumed that several pits will be remediated in a sequential order. Thus some of the costs of design, permitting, site preparation and mobilization can be amortized over several pits.

It was further assumed that the clean up will be conducted by a commercial entity well established in the business of offering environmental clean up services. Because of this it was assumed that the organization offering the remediation services will have enough back log of work for the EM system so that it can be productively employed for the treatment of at least 9200 tons/year. Thus the capital cost was amortized over a period of 8 years and over the estimated annual capacity of the system.

In making this cost estimate the following assumptions were made about the site:

- heated dimensions of each pit will be: Length 25 ft, width 25 ft, and depth 20 ft. At least 6 pits will be treated sequentially at the site.
- bottom of the pit is well above the saturated zone (that is at least 5 ft or more above the water table).
- site characterization data are available, including information about the contents of the pits, particularly with respect to the amount and density of metal drums or containers in them.
- Some pits may be densely packed with drums which will rule out the use of a tri-plate array on technical grounds. So a two-row (bi-plate) electrode array will be used. Gas collection will be done by means of vertical wells drilled into the pit. This cost estimate is based on the use of a biplate electrode array.

The cost of full scale remediation was developed by individually estimating the following cost components of the EM in situ heating process:

For the Entire System:

- Cost of Site Specific Design, HASP, Work Plan, QAPP, NEPA Review, Permitting

For In Situ Heating:

- Capital cost of equipment
- Cost for mobilization and demobilization of equipment
- Site preparation and equipment installation
- Cost of AC power and other consumables
- Operating labor cost

For Vapor Treatment

- Capital cost of equipment
- Mobilization and demobilization cost
- Field installation, piping and hook up
- Cost of utilities and other consumables
- Operating labor cost
- Misc

The vapor treatment system can be used in conjunction with other waste treatment technologies and its use is not limited to the EM heating system. Thus it could be used with an in situ venting system, or other above ground thermal desorption systems. In this estimated we have assumed that the system will be dedicated for use with the EM heating system.

The cost estimate does not include in it an allowance for the following types of cost.

- Treatment and/or ultimate disposal of process wastes such as the condensed aqueous and organic phases, activated carbon, etc. We assumed that the waste aqueous phase liquids will be treated at the waste treatment plant at K-25 Site and the hazardous solid waste (spent carbon) and liquid organic waste will be incinerated at the ORR incinerator.
- Site logistics and infrastructure development such as:
 - AC power service drop from a pole
 - Any new roads, access, telephone, potable and process water supply, etc.
- We have not allowed for any costs which are site specific and/or related to site specific administrative procedures or work practices. Examples are:
 - Training
 - Verification Sampling (but soil and gas sampling and analysis is included)
 - Site Construction Management contractor
 - Health Physics
 - Oversight/support by site M&O contractor

The capital cost of the equipment was estimated based on recent IITRI experience at the K-25 Site and the field demonstration of the TEVES system at Sandia National Laboratory, Albuquerque, NM. The cost of system installation and operation was based on an estimate of the effort needed to install and operate the system. The effort was estimated on the basis of the recent experience at the K-25 site.

10.2 Design Description

10.2.1 Electrode Array

The electrode array for the treatment of the pits will be made from two rows of electrodes. The array dimensions will be similar to those of the array used during the demonstration, with the following exceptions: the center row will be eliminated; the row separation will be 25 ft, the depth of the electrodes will be 22 ft below ground surface so that the heated depth will be 20 ft. All other aspects of the array and electrode dimensions will be the same. Thus there will be 11 electrodes in each row spaced at a distance of 2.5 ft. There will be four vertical gas collection wells drilled through the pit, one in each quadrant. There will be approximately 32 thermocouples installed in the heated zone with

some attached to the inner wall of the electrodes and some to the wall of the gas collection wells. There will be no thermowells drilled through the pit.

10.2.2 Vapor Treatment System

Hot gases containing water vapor (steam), air and contaminants will be recovered by means of vapor collection wells. It was assumed that the soil in the pits has 1,000 to 10,000 ppm of volatile organic contaminants. In this concentration range the amount of organic waste present in the soil has no significant impact on the heating costs. An on site system will be needed, however, to treat the hot gas prior to discharge of the air to the atmosphere. Two options were considered for the vapor treatment system, but only one of these was included in the final cost analysis. Flow diagrams for these are presented in Figures 57 and 58.

Figure 57 illustrates the catalytic incineration system. This system is based on cooling of the hot gas stream followed by catalytic incineration of the residual gas stream. The condensed water phase will be treated on site in an activated carbon bed and discharged or transported to K-25 Site industrial waste water treatment facility. The condensed organic phase will be sent for disposal at the incinerator located on ORR. There will be no treatment of the gas phase by activated carbon.

Figure 58 illustrates a vapor treatment system based on cooling/chilling of the hot gas stream to condense out a large fraction of the water vapor and most of the contaminant vapors. The cooled gas stream is reheated to adjust its relative humidity prior to final clean up in an activated carbon bed. The condensed liquid is separated into three phases in the oil water separator. The organic phase is collected for ultimate destruction at an off site facility. It was assumed that the organic phase can be disposed off at DOE's incinerator located at ORR. The water phase is treated through an activated carbon bed and discharged or transported to K-25 Site industrial waste water treatment facility.

For this economic assessment it was assumed that the catalytic incineration system illustrated in Figure 57 will be used.

10.3 Process Economics

This section documents the results of and the approach to estimating the cost of in situ soil treatment using the in situ EM heating process at burial pits.

10.3.1 Basis and Assumptions

Numerous assumptions had to be made and a design basis had to be selected prior to the development of the cost estimate for the treatment of soil. Some of the more general assumptions and design basis were summarized in Section 10.1. Many more were made

Figure 57. Vapor Treatment System, Alternative I

Figure 58. Vapor Treatment System, Alternative II

relating to the process design, estimation of treatment capacity calculations, and to develop process economics. These are summarized in this sub-section.

General

- EM in situ treatment will be implemented in the depth interval of 0 to 20 ft (measured from pit surface) by heating the soil to an average temperature range of 90° C.
- The heated area will be 25 ft by 25 ft per pit. At least 6 pits will be treated at K-25 site.
- Adequate power is available at the site or else will be provided to permit soil heating operation at or near 200 kW.
- Waste water produced by the process will be sent to K-25 Site waste water treatment plant after activated carbon treatment. No allowance for additional cost for treatment in the water treatment plant.
- Condensed liquid hydrocarbon phase and any spent activated carbon or hazardous solid waste produced by the process will be treated at the incinerator located on ORR. No allowance for additional cost for treatment in the incinerator.
- The only overhead recovery is limited to 100 percent of operating staff salary. This may or may not be adequate to fully recover all overhead expenses after paying for operating staff benefits. Other overhead costs for which explicit allowance has not been made are: insurance, laboratory charges, rent or lease of space, executive and supporting staff salaries, research and development, taxes, royalty, licensing fees, medical, safety, general plant overhead, etc.

Physical & Thermodynamic Properties

• Initial soil temperature	65° F
• Final average temperature of soil	194° F (90° C)
• Specific Heat of dry soil	0.20Btu/lb °F
• Specific heat of moist (18% moist.)soil	0.34Btu/lb °F
• Water boils under native conditions at	212° F

- Latent heat of vaporization for water 970 Btu/lb
- Average Latent heat of vaporization for contaminants 125 Btu/lb
- Bulk density of soil 98 lb/ft³
- Average soil moisture 18 % wt., wet basis
- Organic contaminant concentration 1 % wt., wet basis

Electrical Power

- Power distribution losses 1.5 % of output power
- Power source rating 200 kW
- Cost of AC power \$0.05/kw-hr

Operating Factors:

- Operating days per year for energy input to soil 330 days
- Power Source operating capacity 90% of rating
- Power source operating hours per 24-hour operating day 22.8 hr

Economic Factors

- Interest rate 8.25 % per year
- Amortize capital equipment cost over 8 years
- Number of payments 12/year
- Equipment salvage value \$0

Personnel Salaries

• Working man-hours per year	2080
• Plant Supervisor's	\$57,000/yr + 100% \$54.81/hr
• Plant Engineer	\$52,000/yr + 100% \$50.00/hr
• Maintenance Mechanic	\$31,000/yr + 100% \$29.81/hr
• Shift Operator	\$31,000/yr + 100% \$29.81/hr

10.3.2 Energy Needed To Heat Soil

The in situ EM soil treatment process is based on heating the soil to the design processing temperature of 90° C and boiling out a major fraction of the soil moisture along with the hydrocarbon contaminants. In this process, 100 percent removal of moisture cannot be accomplished because the heating effect is produced due to the presence of water. If all the water boils away, generation of heat also stops. During in situ heating, it is necessary to keep the annular region around the electrodes moist. To help prevent water from boiling in this region, it will be necessary to inject water around the electrodes. It was estimated that approximately 16,000 lbs of water will be injected. It was assumed that all of this water will be boiled out of the soil in addition to the native soil moisture.

Thermal energy needed for heating the soil to the treatment temperature, T_f (= 194° F), can be expressed in terms of three different heat loads: sensible heat to raise moist soil from ambient temperature to the final temperature, T_f ; second, latent heat of vaporization for water, and third, latent heat for vaporization of the hydrocarbon contaminants. Sensible heat requirements can be estimated based on the following equation:

$$Q_s = m \times C_p \times \Delta T$$

where:

Q_s = sensible heat, Btu

m = mass, lb

C_p = specific heat, Btu/lb ° F

ΔT = rise in temperature, ° F

The latent heat of vaporization can be determined by the following equation:

$$Q_L = m \times f \times \lambda$$

where:

Q_L = latent heat, Btu

f = fraction of water boiled or vaporized

λ = latent heat of vaporization, Btu/lb

The actual energy needed for heating the soil to the desired temperature will be more than the amount calculated by the equations discussed above. Additional energy is needed to compensate for heat loss due to thermal conduction from the heated zone into the surrounding soil, to outside air through the vapor barrier and to any infiltrating air moving through the heated zone. The total amount of heat lost to the surrounding soil is a function of the surface to volume ratio of the heated zone, total surface area of the heated zone in contact with surrounding soil, and heating time. Heating time is a function of the total heat load (volume of soil heated) and the capacity of the EM power source. Smaller volumes of soil will have a proportionately higher heat loss due to the high surface to volume ratio. Longer heating time will result in higher heat loss due to conduction. In this study it was assumed that 25 percent of the total thermal energy deposited into the soil will be lost to the surroundings.

Table 47 summarizes the energy needed to heat one ton of soil as a function of the fraction of water boiled. These calculations were based on the equations discussed above and the properties listed in Section 10.3.1.

The cost estimate and the calculation of the operating capacity of the 200 kW power source is based on the assumption that 72 percent of the native water will have to be boiled out of the soil during the time needed to remove the hydrocarbon contaminants present in this soil. For removing 72 percent of water as vapor while heating the soil to 90°C, the energy required is 144.67 kW-hr/ton of soil.

10.3.3 Operating Capacity

The daily operating capacity of the power source, in tons of soil per day, is a function of the energy needed to heat the soil and on the total energy available per day. The available energy is calculated based on the daily operating time, and any power distribution losses. It was assumed that the power source would operate for a period of 22.8 hr per day at 90 percent of its rated capacity of 200 kW. The distribution losses were assumed to be 1.5 percent. Thus the energy available on a daily basis is:

$$200 \text{ kW} \times 0.90 \times (1-0.015) \times 22.8 \text{ hr/day} = 4,042 \text{ kW-hr/day}$$

Table 47. Energy Needed to Heat Soil to 90° C

Fraction Water Boiled	Sensible Heat to 90° C kW-Hr/ton	Latent Heat Water kW-Hr/ton	Latent Heat Hydrocarbon kW-Hr/ton	Total Heat, kW-Hr/ton	
				No Heat Loss	With Heat Loss
Injected Water	1.0	7.4	0	8.4	
0.0	25.7	0	0.73	34.84	46.45
0.3	25.7	30.69	0.73	65.53	87.38
0.36	25.7	36.83	0.73	71.67	95.56
0.5	25.7	51.16	0.73	86.00	114.66
0.72	25.7	73.67	0.73	108.51	144.67
0.75	25.7	76.74	0.73	111.57	148.77
1.00	25.7	102.31	0.73	137.15	182.87

The daily treatment capacity of the power source is, therefore:

$$(4,042 \text{ kW-hr/day}) / (144.7 \text{ kW-hr/ton}) \\ = 28 \text{ tons per day}$$

10.3.4 Estimate of Heating Time per Pit

The heating time per pit after the power is turned on is a function of the daily treatment capacity and the total weight of soil in each pit. The heated volume of soil in each pit is:

$$\text{Volume} = 25 \text{ ft} \times 25 \text{ ft} \times 20 \text{ ft} \\ = 12,500 \text{ ft}^3$$

Using a bulk density of 98 lb/ft³, the weight of soil in each pit is:

$$\begin{aligned}
 \text{Weight} &= 12,500 \text{ ft}^3 \times 98 \text{ lb/ft}^3 \\
 &= 1.225 \times 10^6 \text{ lb} \\
 &= 613 \text{ tons soil in each pit}
 \end{aligned}$$

Thus the heating time to reach 90° C, and remove 72 percent of the soil moisture is:

$$\begin{aligned}
 \text{Heating Time} &= 613 \text{ tons}/(28 \text{ tons/day}) \\
 &= 22 \text{ operating days per pit}
 \end{aligned}$$

10.3.5 Treatment Cost

The development of an estimate for the treatment cost requires separate estimates of the capital cost, the total duration of the treatment project and the operating cost. In the following pages the cost per ton of soil is developed.

10.3.5.1 Summary

The remediation cost per ton of soil was developed by separately estimating the capital and operating cost. The details of the estimate are provided in the next two sections. The cost estimate is based on the sum of in situ heating costs and vapor treatment cost. The estimated capital cost to heat soil to 90° C and boil out approximately 72 percent of the soil moisture is \$7.14 per ton of soil. The estimated operating cost of the soil treatment system is \$137 per ton of soil. The total cost of soil treatment is estimated to be \$144 per ton of soil. This estimate assumes that there is no separate requirement for a Q-cleared guard and escort. The total cost will increase by \$48.62 per ton to \$193 per ton, if they are required.

The operating cost of the EM process is a strong function of the amount of soil heated in a single batch and on the amount of soil at a single site. Increasing batch size reduces the unit labor cost (i.e., \$/ton of soil) and the unit drilling cost. Cost studies done by IITRI for other clients have shown that the cost can be as low as \$30 to \$40 per ton when treating 200,000 to 500,000 tons (375,000 cu. yd) at a site.

10.3.5.2 Capital Cost Estimate

The total capital cost of the treatment system is equal to the cost of the equipment which can be used for the treatment of several pits. The cost of the following equipment is included in the capital cost:

- EM power source, controls, and power distribution system
- Electrodes

- The vapor barrier/rain cover/thermal insulation
- The vapor treatment system
- Above ground components of the vapor collection system

Table 48 summarizes the capital cost of the heating system. The cost of the EM

Table 48. Capital Cost of Equipment

Item	\$
EM Power Source, controls distribution system, power source shelter	53,400
Electrode materials	2,600
Vapor Collection System	6,000
Vapor Treatment System (w/blower & scrubber)	200,000
Vapor Barrier	2,000
Instrumentation (Thermal)	9,400
Safety Equipment	13,300
Water Injection System	4,000
Power Distribution Load Center	25,000
Computer	5,000
Mobile Laboratory	30,000
Subtotal	350,700
Contingency, 10% of total	35,000
Total	385,700
Annual Capital Charges	66,000
Annual Treatment Capacity, tons	9,240
Capital Charge, \$/ton soil	7.14

power source includes the cost of a multi-tap isolation transformer, power instrumentation and controls, and a trailer.

The capital charge per year was calculated based on the amortization of the capital cost over a period of eight years and an annual interest rate of 8.25 percent. The cost per ton of soil was estimated to be \$7.14

10.3.5.3 Operating Cost

Separate estimates were prepared for the following operating cost elements. The costs were expressed on a per ton of soil basis. Table 49 summarizes the various operating costs. The total operating cost was estimated to be \$137/ton excluding Q-cleared escort and guard.

- AC power costs
- Operating Labor cost during heating
- Vapor Treatment system operating cost
- Miscellaneous supplies and other costs
- Labor and supplies during Installation of electrodes, vapor collection and air injection wells, vapor barrier etc.

AC Power Costs: AC power is needed for heating the soil and boiling out the water from the soil. In addition AC power is needed for the operation of the gas collection and vapor treatment system, for heat tracing of the gas collection lines, site lighting and instrumentation. Power needs for heating soil on a per ton basis were discussed earlier. The energy needed to heat the soil was estimated to be 144.7 kW-hr/ton of soil. Due to losses the power consumed by the EM power source will be actually higher than the above value. We had assumed that the distribution losses would be 1.5 percent. Hence the power needed by the power source will be 146.9 kW-hr/ton. Using energy cost at \$0.05/kW-hr, the cost of AC power to heat the soil was estimated to be \$7.35/ton of soil.

AC power for other needs was estimated to be of the order of 25 kW for 60 days, which includes the cool down period. This translates to approximately \$30 per day or \$2.94/ton of soil.

Labor Cost During Heating Operations: During the heating phase of the treatment cycle, there will be one 8-hr shift. In the morning shift there will be one full time person and two others on a part time basis. The part time persons will devote the remaining time for the site preparation of other adjacent pits for subsequent treatment. The daily operating labor cost is listed below in Table 50. The daily operating labor cost during heating operations is \$432/day. The daily treatment capacity was previously estimated to be 28

Table 49. Operating Cost Summary, \$/Ton of Soil

Cost Item	\$/ton
Drilling for Electrode Array Emplacement/Soil Sampling	21.79
System Installation and Shakedown	30.55
Operating Labor During heating (see Table 4) (includes maintenance and supervisor)	15.43
Installation Supplies	4.56
Operating Supplies (includes all utilities, carbon, catalyst)	16.00
Soil Sample Analysis	15.50
Liquid Sample from Impingers	3.78
Demobilization (includes bore hole abandonment, soil sampling, etc.)	23.47
Sub-total Cost, \$/ton	131.08
Design (\$2.6 to \$26/ton for 10 to 1 pit, respectively)	4.33
Permitting (\$1.20 to \$12/ton for 10 to 1 pit, respectively)	2.00
Total Operating Cost	\$137.41

tons/day. Therefore the labor cost per ton of soil processed during the heating period is \$15.43/ton of soil.

Labor Cost During Site Preparation and System Installation: During the installation of the heating system in the pit numerous activities will be undertaken. These are:

- Drilling of Electrode Bore holes and sampling of soil
- Installation of the skid mounted vapor treatment system and its interfacing with the vapor collection lines, hook-up with AC power, check out and shake down
- Installation of individual electrodes in bore holes, and interconnection of electrodes with bus bars and hook up to the power source.
- Installation of surface piping between gas collection wells and the vapor treatment system

Table 50. Labor Cost During Heating

Shift/Personnel	Hrs/shift	Salary \$/hr	Total \$
<u>Day Shift:</u>			
Plant Supervisor	1	54.81	55
Maintenance Engineer	1	50.00	50
Maintenance Mechanic	3	29.81	89
Shift Operators	8	29.81	238
<u>Second Shift:</u>			
Shift Operators	0	29.81	0
Total \$/day			\$432
Labor Cost, \$/ton soil			\$15.43

- Hook up of the power source to the AC power supply, check out, shake down and debug
- Hook up of all process instrumentation, check out and shake down

The total cost for each of these activities was estimated based on engineering judgement of the man hours needed to accomplish individual tasks. It was assumed that the personnel would be paid as per the salary schedule listed in Section 10.3.1.

Operating Costs Associated with the Vapor Treatment System Operation: The operating cost of the incineration system is primarily dependent upon the method of operation. There are two ways to operate the incineration system: first way is to direct all the hot gases and steam to the incinerator without cooling and condensation to reduce the load on the incinerator. The advantage of this approach is that no activated carbon is needed for either gas phase or liquid phase treatment. The disadvantage is that the system must be designed to handle large volumetric flow rates of gas. Another disadvantage is that additional air may have to be added to provide oxygen for combustion as well as to dilute the concentration of the contaminants and thus control the heat release and temperature rise.

In this cost estimate the second version of the thermal incineration system is proposed. The hot gases will be cooled to approximately 40° C before entering the incinerator. Thus liquid side activated carbon treatment will be necessary as well as disposal of liquid organic condensate. Activated carbon cost of \$650 per pit and a catalyst replacement cost of \$540 per pit were included in the estimate of operating supplies.

Gas side activated carbon treatment will not be necessary with the incinerator. But, gas side scrubbing will be required to remove hydrochloric acid. This will generate a waste water stream containing sodium chloride. It is estimated that the flow rate of this stream will be 3,500 gallon/day. It was assumed that this stream would be sent to the on site water treatment plant without additional cost to the process.

The thermal incineration system will require caustic soda for the operation of the scrubber. The amount of caustic soda needed was conservatively estimated by assuming that all the chlorinated organics will be converted to hydrochloric acid. It was further assumed that the chlorine content of the waste is 30 percent by weight of the organic contamination in the soil. This yields a sodium hydroxide requirement of 6.76 lb/ton of soil. The cost of caustic was estimated to be \$1.15/ton of soil.

Labor Cost During Cool Down: There is no separate estimate of the cost of labor during cool down. It was assumed that there will be personnel on site working on the preparation or treatment of the next pit and they will be able to devote time to monitor the operation of the vapor collection and treatment system. It is estimated that approximately 1 hour per day will be required to monitor this system.

10.4 Conceptual Schedule

The schedule for the treatment of the first pit located on the Classified burial grounds is presented in Figure 59. It was assumed that the documents prepared for the demonstration of the EM process will be revised to complete all the necessary documents for operation in side the Burial Grounds.

10.5 Cost Comparison

Figure 60 illustrates the cost comparison of EM heating at the burial ground pits with other in situ technologies ¹⁶. The upper curve shows the costs associated with technologies that are based on soil excavation followed by above ground thermal desorption. The lower curve is for technologies based on enhanced in situ venting with concurrent in situ heating. It should be noted that all of these comparisons are for the treatment of soils containing organic hydrocarbon wastes. No allowance has been made for costs associated with security requirements and other site specific administrative procedures and associated costs. Two estimates for the EM system are provided. One in which the system will be used to treat

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Figure 59. Schedule for Decontamination of the First Pit in the Burial Ground (page 1 of 2)

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Figure 59. Schedule for Decontamination of the First Pit in the Burial Ground (page 2 of 2)

the pits at the K-25 site with a volume of 400 cu. yd. per heating batch. The other is for the treatment of soil in excess of 10,000 cu. yd. per batch at a given site.

Symbols used in Figure 60 have the following meaning:

ATP:	Soil Tech STP System Inc.
IT:	Data on excavation and enhanced SVE provided in a report by IT Corporation
LT:	Low temperature thermal treatment, developed by Roy F. Weston
LTTA:	Low temperature thermal aeration process, developed by Cannonie Environmental Services
SERP:	In Situ steam enhanced recovery process, Hughes Environmental Systems
SVVS:	Subsurface volatilization and ventilation system
X* TRAX:	Model 200 thermal desorption system, developed by RUST Remedial Services

Figure 60. Cost of EM Treatment Versus Other Treatment Technologies.

11. RESULTS AND CONCLUSIONS

The results of the field demonstration show that the soil was heated to an average temperature range of 75 to 92° C. The interior 80 percent of the soil volume achieved the higher average temperature. The entire volume was heated to an average temperature of 75° C.

As the soil was heated, its permeability to air flow gradually increased. The initial permeability of soil was immeasurably low. No flow could be measured even when applying a vacuum of 26 to 28 in. Hg. As heating progressed, permeability was induced, and towards the end of the experiment it was in the range of 1 to 2 darcy. During soil cool-down period, the permeability continued to develop as soil moisture was removed with continued soil gas extraction. At the end of the cool-down period the permeability was in the range of 5 to 7 darcy.

The results of hot gas sampling indicate that the concentration of the VOCs in the extracted soil gas increased with heating. These results also show that the mass removal of VOCs increased with heating. Thus the ratio of peak mass removal rate to the initial rate for several compounds was in the range of 10 to 53. These results have shown the feasibility of enhancing VOC removal rates by in situ heating while extracting soil gas.

The initial concentration of VOCs in the soil was extremely low. This was because the electrode array was installed in a plume emanating from the burial ground. Soil concentrations would have been much higher in the waste disposal pits which were located inside the classified burial ground. The initial soil concentration of many samples was at or below the detection limit. Thus 25 samples were taken and analyzed in duplicate. As Table 18 shows the average concentration of samples that exceeded the detection limit was in the range of 16 to 150 ppb for the chlorinated VOCs of concern.

Approximately 36 new soil samples were taken at the end of the demonstration and analyzed in duplicate. The results of these analysis were also at or near the detection limit. The average concentration of chlorinated VOCs, in samples where they exceeded the detection limit, was in the range of 30 to 400 ppb with relative standard deviation of 58 to 190 percent (Table 26). The most frequent VOC was 1,1,1-TCA which was found in 31 of the 72 samples analyzed. Due to high standard deviation of the analytical results as well as the large proportion of sample below detection limit, no conclusive comparison of these data can be made with the pre-demonstration soil sample analytical results.

During the course of the demonstration difficulty was encountered with the injection of water around the electrodes. Water injection is necessary to maintain a low contact resistance between the electrode and the soil. It was found that the water supply from the fire hydrant had a high dissolved solid content including high bicarbonates. Water injection

systems should use water with low total dissolved solids to prevent precipitation in the lines as the water is heated and boiled.

Approximately 25,900 kWhr of energy was used during the course of the demonstration. This corresponds to approximately 87 kWhr/cu.yd. or 65 kWhr/ton of soil. Eventually, energy input was limited in this demonstration due to the inability to inject water around the electrodes at the desired rate as a results of salt precipitation.

The results of this field demonstration have proven that VOC removal from soils with low initial permeability can be enhanced by heating of the soil while extracting vapors. This technology should be applicable for the remediation of such spill sites which contain chlorinated solvents, hydrocarbons and other VOCs in the vadose zone.

A cost evaluation for the cleanup of pits located inside the Classified Burial Ground 1070 C/D was made. It was estimated that the treatment cost was approximately \$144/ton. This figure does not include costs related to any site-specific administrative and management procedures, use of escorts and guards, etc.

The cost per ton is dependent upon the batch size. When larger volumes of soil are heated in a single batch the treatment cost can be reduced significantly. For example, if 10,000 cu. yds. or more of soil are present at a site, then the estimated treatment cost falls to \$30 to \$40/ton.

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