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IN SITU STEAM ENHANCED RECOVERY PROCESS

Hughes Environmental Systems, Inc.

INNOVATIVE TECHNOLOGY EVALUATION REPORT

NATIONAL RISK MANAGEMENT RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
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NOTICE

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FOREWORD

The U.S. Environmental Protection Agency is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet these mandates, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory is the Agency's center for investigation of technological and management approaches for reducing risks from threats to human health and the environment. The focus of the Laboratory's research program is on methods for the prevention and control of pollution to air, land, water and subsurface resources; protection of water quality in public water systems ; remediation of contaminated sites and groundwater; and prevention and control of indoor air pollution. The goal of this research effort is to catalyze development and implementation of innovative, cost-effective environmental technologies; develop scientific and engineering information needed by EPA to support regulatory and policy decisions; and provide technical support and information transfer to ensure effective implementation of environmental regulations and strategies.

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

E. Timothy Oppelt, Director
National Risk Management Research Laboratory

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LIST OF ACRONYMS AND ABBREVIATIONS

ARAR	applicable or relevant and appropriate requirement
BTEX	benzene, toluene, ethylbenzene and xylenes
BTU	British thermal unit
CAA	Clean Air Act
CERCLA	Comprehensive Environment Response, Conservation and Liability Act of 1980
CERI	Center for Environmental Research Information
CFR	Code of Federal Regulations
CWA	Clean Water Act
DNAPL	dense non-aqueous phase liquids
FID	flame ionization detector
GC	gas chromatography
GPM	gallons per minute
in situ	in place
LEL	lower explosive limit
LLNL	Lawrence Livermore National Laboratory
LUFT	Leaking Underground Fuel Tank
MCL	maximum contaminant level
MCLG	maximum contaminant level goal
MS	matrix spike
MSD	matrix spike duplicate
NAAQS	National Ambient Air Quality Standards
NIOSH	National Institute for Occupational Safety and Health
NPDES	National Pollutant Discharge Elimination System
NPL	National Priority List
ORD	Office of Research and Development
OSHA	Occupational Safety and Health Administration
OSWER	Office of Solid Waste and Emergency Response
PEL	permissible exposure limit
POTW	publicly-owned treatment works
ppb	parts per billion
PPE	personnel protective equipment
ppm	parts per million
psi	pounds per square inch
QA	quality assurance
QAPP	Quality Assurance Project Plan
QC	quality control
RCRA	Resource Conservation and Recovery Act
RREL	Risk Reduction Engineering Laboratory
RWQCB	Regional Water Quality Control Board

LIST OF ACRONYMS AND ABBREVIATIONS (CONTINUED)

SAIC	Science Applications International Corporation
SARA	Superfund Amendments and Reauthorization Act
SCAQMD	South Coast Air Quality Management District
SCFM	standard cubic feet per minute
SDWA	Safe Drinking Water Act
SERP	Steam Enhanced Recovery Process
SITE	Superfund Innovative Technology Evaluation
SVOCs	semivolatile organic compounds
TDS	total dissolved solids
TOU	thermal oxidation unit
TPH	total petroleum hydrocarbons
TRPH	total recoverable petroleum hydrocarbons
USEPA	United States Environmental Protection Agency
VOCs	volatile organic compounds

ENGLISH TO METRIC CONVERSION FACTORS

To Obtain (metric unit)	Multiply (English unit) by	Conversion
meters	feet	0.305
liters	gallons	3.79
cubic meters (m^3)	cubic yards (yd^3)	0.764
dollars per cubic meter ($\$/m^3$)	dollars per cubic yard ($\$/yd^3$)	1.31
kilograms	pounds (mass)	0.454

Note: To convert °F to °C use °C = (°F-32)(0.56)

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EXECUTIVE SUMMARY

This report summarizes the findings of an evaluation of the *in situ* Steam Enhanced Recovery Process (SERP). This technology was operated by Hughes Environmental Systems, Inc. at the Rainbow Disposal site in Huntington Beach, California. The Rainbow Disposal site is an active municipal trash transfer facility that was contaminated by a spill of diesel fuel from a crushed underground pipeline. The evaluation of this technology was conducted under the U.S. Environmental Protection Agency (EPA) Superfund Innovative Technology Evaluation (SITE) Program in conjunction with a full-scale remediation using SERP at the Rainbow Disposal site.

The EPA SITE Program evaluated the SERP technology to develop full-scale process performance and cost data. The critical objectives for the Demonstration of the SERP technology were: (1) to evaluate the ability of the technology to meet the cleanup requirement set by the Regional Water Quality Control Board for the site soil, based on soil sampling results, and (2) to perform a detailed economic analysis of this full-scale application of the technology.

Conclusions from the SITE Demonstration

Based on the SITE Demonstration, the following conclusions can be drawn about the *in situ* SERP technology as applied to the Rainbow Disposal site remediation:

- The Demonstration results showed that the removal of contamination by the SERP technology was less complete than expected. Forty-five percent of the post-treatment soil sample results inside the treatment area were above the cleanup criterion (1,000 mg/kg [ppm] of total petroleum hydrocarbons, or TPH). Seven percent of the soil samples had TPH levels in excess of 10,000 mg/kg.

- A geostatistical analysis of the post-treatment soil data was conducted using a computerized model to assess the spatial variability of soil contamination and to determine a weighted average concentration of the soil sample results. From the geostatistical model, a post-treatment weighted average soil concentration of 2,290 mg/kg of TPH with standard error of 784 mg/kg was derived. Based on an approximate normal distribution for the weighted average, the 90 percent confidence interval for TPH concentration is 996 mg/kg to 3,570 mg/kg. This large interval is attributed to the variability of site soil sampling results due to the heterogeneity of the *in situ* soil contamination; analytical variability was within established quality control limits and contributed little to overall data variability. According to this analysis, at 90 percent confidence, the true average is probably higher than the cleanup criterion of 1,000 mg/kg.

- The geostatistical analysis results for total recoverable petroleum hydrocarbons (TRPH) yielded a weighted average post-treatment soil concentration of 1,680 mg/kg with a standard error of 608 mg/kg. The 90 percent confidence interval for the weighted average for TRPH is 676 mg/kg to 2,680 mg/kg. No cleanup criteria were set for TRPH. The TRPH analysis provides information similar to TPH but is performed using an EPA-approved method; the TPH method is widely used but is not an EPA-approved method.

- BTEX compounds were detected at low mg/kg levels in a few pre-treatment soil samples and were found at levels below the detection limit (6 μg/kg) in all post-treatment samples. Based on these results, the SERP technology may have effected removal of BTEX compounds from the *in situ* soil, but this is inconclusive due to the lack of positive BTEX results and the heterogeneous nature of *in situ* soil contamination at the site.

- Based on the weighted averages for the pre- and post-treatment soil data sets determined from geostatistical analysis, the technology may have removed 40 percent of the contamination from the site soil. Due to the high site soil contamination variability, at 90 percent confidence, the actual percent removal may have been significantly higher or lower. Calculation of percent removal was a secondary objective of the technology evaluation because pre-treatment data were collected by the developer before the initiation of a SITE Program Demonstration Quality Assurance Project Plan (QAPP).

- Process data collected during treatment support the finding of a low to moderate removal efficiency. Approximately 700 gallons of diesel were collected in liquid form during treatment, while approximately 15,400 gallons were oxidized in the system's vapor treatment equipment. Therefore, a combined total of approximately 16,000 gallons of diesel were removed during treatment with SERP. Compared to the estimated initial diesel spill volume of 70,000 to 135,000 gallons, this represents a reduction of approximately 12 to 24 percent. This estimated removal is within the percent removal confidence interval for the soil data.

- The technology experienced significant amounts of downtime during treatment. All major equipment systems experienced problems during treatment. An on-line factor of 50 percent was experienced at this site for the technology application over the two years of treatment. Reliability in subsequent applications of the technology is expected to be higher since this was the first full-scale application of the technology.

- Based on soil temperature profiles from several areas of the site, heating of the soil took much longer than originally anticipated and high soil temperatures were not maintained in many areas. This may have been due to the way the process was operated initially (16 hours per day, 5 days per week) and to excessive operational downtime. The heating rate improved later in the application when the process operation went to a 24-hour per day, 6-day per week cycle. These operational factors may have contributed to the failure of the SERP technology to achieve the cleanup criterion for the site. More constant process operation and monitoring should improve the performance of this technology in subsequent applications.

- The costs for use of the technology at this site were relatively low; however, site remediation did not achieve the cleanup criterion. Actual costs at the Rainbow Disposal site were estimated to be approximately $46/cubic yard. A 50 percent on-line factor was determined for this case. Under idealized conditions at this site, which assumes a 100 percent on-line factor, the technology could have cost as little as $29/cubic yard. For a site similar to the Rainbow Disposal site, under typical operating conditions (on-line factor of 75 percent), the cost for use of SERP was estimated to be $36/cubic yard. The large amount of soil treated by the technology at the Rainbow Disposal site contributed to a relatively low cost per cubic yard. The cost for use of the technology is most sensitive to the duration of remediation, and start-up and utilities costs.

The *in situ* SERP technology was evaluated based on the nine criteria used for decision-making in the Superfund Feasibility Study process. Table ES-1 presents the results of the evaluation.

Another *in situ* steam technology, the Dynamic Underground Stripping Process, was demonstrated and evaluated by the Lawrence Livermore National Laboratory in conjunction with the University of California at Berkeley, College of Engineering. The results of this evaluation are presented in a case study in Appendix A of this report. The EPA SITE Program had limited participation in the evaluation of this *in situ* steam technology, which is similar to the *in situ* SERP discussed in this ITER.

Table ES-1. EVALUATION CRITERIA RESULTS FOR *IN SITU* SERP AT THE RAINBOW DISPOSAL SITE

	CRITERIA								
	Overall Protection of Human Health and the Environment	Compliance with ARARs	Long-term Effectiveness and Permanence	Reduction of Toxicity, Mobility or Volume Through Treatment	Short-term Effectiveness	Implementability	Cost	State Acceptance	Community Acceptance
RESULTS	Reduced soil concentrations without excavation May reduce the mobility of contamination into groundwater after treatment Did not appear to cause lateral or downward migration of contaminants	Did not meet soil cleanup criterion, on the average, in this application Less soil is excavated, thus less soil requires disposal Permits for drilling, operating, and air and water discharges are required	A portion of contaminants are permanently removed from the soil Removed contaminants can be incinerated or recycled Residual contamination presents reduced risk	Treated soil had lower concentrations overall, some areas were cleaned to well below the cleanup criterion Remaining contaminants may be less mobile Lower soil concentrations are amenable to natural or enhanced biodegradation Technology residuals are not of large volume as compared to the treated soil volume	Soil is treated below ground so potential air emissions are minimized Other activity can continue at surface of treatment area with minor disruption Drilling and treatment may cause emissions, noise and dust which can be mitigated	Technology uses widely available construction and process equipment Most regulatory permits are common and are readily acquired for fuel-related cleanups. Treatment of sites with other contaminating chemicals may require additional permitting requirements Operational problems can occur that may delay the remediation The technology may not be able to meet stringent cleanup requirements, necessitating post-processing such as assisted biodegradation	Ranged from $29 to $46 per cubic yard for a large site Capital equipment, start-up, and utilities costs are high Remediation time is the major factor in the costs Because the process operates *in situ*, off-site disposal costs are minimized	Minimizes excavation of and exposure to contaminated soil Potential exists for off-site subsurface migration of steam and contaminants Air emission permit may be required Wastewater discharge permits may be required	Site disturbance can be minimized Does not require major interruptions of existing operations May recover product for re-use or recycling May exceed noise limits in some areas

SECTION 1
INTRODUCTION

This section provides background information about the SITE Program, discusses the purpose of this Innovative Technology Evaluation Report (ITER), and describes the *in situ* Steam Enhanced Recovery Process (SERP) technology that was evaluated. For additional information about the SITE Program, the technology, and the Demonstration site, key contacts are listed at the end of this section.

1.1 BACKGROUND

In August of 1991, a site remediation using the *in situ* SERP process was started at the Rainbow Disposal site, an active municipal trash transfer facility in Huntington Beach, California. The site had been contaminated by a leak of diesel fuel from an underground pipeline used to supply fuel for trash trucks and other vehicles. SERP was selected by Rainbow Disposal, Inc. as a cleanup remedy for the contaminated soil based on a site-specific feasibility study. SERP was selected over other technologies since it required less excavation of soil, could be conducted during continuing operations on the site, and could be used beneath existing structures.

The full-scale remediation at the Rainbow Disposal site was seen by the SITE Program as an excellent chance to test the performance of the technology and to develop operating costs. The SITE Program became involved with the technology at the Rainbow Disposal site when it was being developed by Hydro-Fluent, Inc. Hydro-Fluent, Inc. ceased business operations in September of 1991. Hughes Environmental Systems, Inc. took over the contract and continued to operate the technology until the remediation was stopped in August 1993.

Pre-treatment sampling and analysis of the soil at the Rainbow Disposal site was conducted in September 1991 by the technology operator with oversight from the EPA SITE Program, but prior to full SITE Program involvement with the project. Post-treatment sampling and analysis was conducted in August and September of 1993 by the SITE Program using full quality assurance procedures.

SERP operates on contaminated soil *in situ* through wells constructed in the ground. Steam is injected into the soil through injection wells which are screened in the contaminated depth or depths. Extraction wells are operated using a vacuum to draw the steam, water, and contaminants from the soil and into an aboveground treatment system. Contaminant removal occurs below the soil surface, and, as was true at Rainbow Disposal, operations on the site surface can continue with minimal interruption.

SERP is similar in concept to several other *in situ* technologies including vacuum extraction and soil flushing. SERP differs from conventional *in situ* technologies in that it uses both steam injection and extraction of vapor and liquids under vacuum. The added heat from the steam is expected to increase the speed of remediation and make the technology more applicable to higher boiling point (less mobile) compounds that cannot be removed by other *in situ* technologies such as vacuum extraction or soil flushing.

Another steam injection technology is the Dynamic Underground Stripping process used at the Lawrence Livermore National Laboratory (LLNL), which uses electrical heating in addition to steam injection/vacuum extraction to increase removals of contaminants from low-permeability soils. This technology was recently demonstrated and evaluated by LLNL in conjunction with the University of California at Berkeley, College of Engineering. Appendix A to this ITER presents a case study of the Dynamic Underground Stripping process. The EPA SITE Program had a minor role in the evaluation of this technology.

1.2 BRIEF DESCRIPTION OF PROGRAM AND REPORTS

The SITE Program is a formal program established by EPA's Office of Solid Waste and Emergency Response (OSWER) and Office of Research and Development (ORD) in response to the Superfund Amendments and Reauthorization Act of 1986 (SARA). The SITE Program promotes the development, demonstration, and use of new or innovative technologies to clean up Superfund sites across the country.

The SITE Program's primary purpose is to maximize the use of alternatives in cleaning hazardous waste sites by encouraging the development and demonstration of new, innovative treatment and monitoring technologies. It consists of four major elements discussed below.

The objective of the Demonstration Program is to develop reliable performance and cost data on innovative technologies so that potential users may assess the technology's site-specific applicability. Technologies evaluated are either currently available or close to being available for remediation of Superfund sites. SITE Demonstrations are conducted on hazardous waste sites under conditions that closely simulate full-scale remediation conditions, thus assuring the usefulness and reliability of information collected. Data collected are used to assess the performance of the technology, the potential need for pre- and post-treatment processing of wastes, potential operating problems, and the approximate costs. The Demonstrations also allow for evaluation of long-term risks and operating and maintenance costs.

The Emerging Technology Program focuses on successfully proven bench-scale technologies that are in an early stage of development involving pilot- or laboratory-scale testing. Successful technologies are encouraged to advance to the Demonstration Program.

Existing technologies which improve field monitoring and site characterizations are identified in the Monitoring and Measurement Technologies Program. New technologies that provide faster, more cost-effective contamination and site-assessment data are supported by this Program. The Monitoring and Measurement Technologies Program also formulates the protocols and standard operating procedures for demonstrating methods and equipment.

The Technology Transfer Program disseminates technical information about innovative technologies in the Demonstration, Emerging Technology, and Monitoring and Measurements Technologies Programs through various activities. These activities increase the awareness and promote the use of innovative technologies for assessment and remediation at Superfund sites. The goal of technology transfer activities is to develop interactive communication among individuals requiring up-to-date technical information.

Technologies are selected for the SITE Demonstration Program through annual requests for proposals. ORD staff review the proposals to determine which technologies show the most promise for use at Superfund sites. Technologies chosen must be at the pilot- or full-scale stage, must be innovative, and must have some advantage over existing technologies. Mobile technologies are of particular interest.

Once EPA has accepted a proposal, a cooperative agreement between EPA and the developer establishes responsibilities for conducting the Demonstrations and evaluating the technology. The developer is responsible for demonstrating the technology at the selected site and is expected to pay any costs for transport, operations, and removal of the equipment. EPA is responsible for project planning, sampling and analysis, quality assurance and quality control, preparing reports, disseminating information, and transporting and disposing of treated waste materials.

The results of the SERP Demonstration are published in two basic documents: the SITE Technology Capsule and this Innovative Technology Evaluation Report (ITER). The SITE Technology Capsule provides relevant information about the technology, emphasizing key features of the results of the SITE field Demonstration. Both the SITE Technology Capsule and the ITER are intended for use by remedial project managers making a detailed evaluation of the technology for a specific site and waste. A companion document to the ITER, called the Technical Evaluation Report (TER) is published in limited quantities in unbound form. The TER contains raw data from the testing and evaluation, and other information on which the ITER is based. The TER is primarily designed to allow a quality assurance evaluation of the ITER.

1.3 PURPOSE OF THE INNOVATIVE TECHNOLOGY EVALUATION REPORT

This ITER provides information about the SERP technology and includes a comprehensive description of the SERP Demonstration and its results. It is intended for use by EPA remedial project managers, EPA on-scene coordinators, contractors, and other decision-makers for implementing specific remedial actions. The ITER is designed to aid decision-makers in further evaluating specific technologies for further consideration as an applicable option in a particular cleanup operation. This report represents a critical step in the development and commercialization of a treatment technology.

To encourage the general use of demonstrated technologies, EPA provides information regarding the applicability and performance of each technology to specific sites and wastes. This ITER includes information on cost and site-specific characteristics. It also discusses advantages, disadvantages, and limitations of the technology.

Each SITE Demonstration evaluates the performance of a technology in treating a specific waste. The waste characteristics of other sites may differ from the characteristics of the treated waste. Therefore, successful field demonstration of a technology at one site does not necessarily ensure that it will be applicable at other sites. Data from the field Demonstration may require extrapolation for estimating the operating ranges for which the technology will perform satisfactorily. Only limited conclusions can be drawn from a single field Demonstration.

1.4 TECHNOLOGY DESCRIPTION

SERP is an *in situ* process designed to remove volatile and semivolatile organic contamination using steam to provide heat and pressure. The process is applicable to the treatment of contaminated soils and groundwater.

The process works by injecting high quality steam through wells (injection wells) constructed to a depth at or below the contamination at a site. Additional wells (extraction wells) are operated under vacuum to create a pressure gradient in the soil to draw the liquids, vapor, and contaminants through the soil. Liquid and vapor streams removed by the extraction wells are directed to an aboveground liquid and vapor treatment system.

The geology of the site is influential in determining whether SERP will be applicable. There are several site requirements for effective operation:

- The contamination must consist of volatile and/or semivolatile compounds, such as those found in spilled fuel contamination.
- The soil must have moderate to high permeability.
- The subsurface geology must provide a confining layer below the depth of contamination. This layer can take three forms: (1) a continuous low permeability layer such as a clay layer; (2) a water table, for compounds with liquid phases lighter than water and low solubility; or (3) a continuous high permeability strata filled with steam prior to treatment of the contaminated depth, for compounds with boiling points lower than that of water [1].
- A low permeability surface layer may be needed to prevent steam breakthrough for shallow treatment applications.

The removal of volatile and semivolatile contamination from the soil by SERP is effected by several mechanisms. The high-quality, high-temperature steam (at approximately 250°F) heats the soil mass to the steam temperature in a pattern radiating from the injection wells toward the extraction wells, following the pressure gradients applied to the soil. As the soil heats, contaminants which have boiling points lower than that of water will vaporize. The vapor will then be pushed ahead of the steam front by the difference in pressure. Since the steam front moves through the soil faster than heat can be conducted, the temperature gradient just ahead of the steam front is steep. The vaporized contaminants move into the cooler soil and condense until the steam front arrives. This results in a band of liquid contaminant that is formed just ahead of the advancing steam. When the steam front reaches an extraction well, the vapor, liquid, and contaminants are removed.

Compounds with boiling points higher than that of water will not totally vaporize ahead of the steam front. However, the introduction of steam and heat onto the soil matrix enhances the vaporization and removal of these compounds due to the increased vapor pressure along with the increase in temperature.

Organic contaminants in soil will collect on the surface of the mineral particles due to intermolecular forces. The energy derived from the condensation of the steam onto the soil may be sufficient to release these adsorbed contaminants and allow them to be removed by the flow of steam and liquids.

The Rainbow Disposal site was contaminated by a spill of diesel fuel, which is primarily composed of longer chain hydrocarbon compounds (8 or more carbon atoms). Diesel compounds, although less dense than water, are heavier than those in most other petroleum-based fuels (e.g., gasoline or jet fuel) and are consequently less volatile and more viscous. These properties make diesel a more difficult contaminant to remove from the soil than most other petroleum-based fuels.

SERP was applied to a treatment area at the Rainbow Disposal site covering a lateral area of approximately 2.3 acres. The developer designed the system of process wells to treat the entire area concurrently. Thirty-five (35) steam injection wells and 38 vapor/liquid extraction wells were constructed in the treatment area. The wells were placed in a repeating pattern of four injection wells surrounding each extraction well. The well configuration at the Rainbow Disposal site is shown in Figure 1-1.

The distance between adjacent injection well/extraction well pairs on this site was approximately 45 feet; between adjacent wells of the same type, the spacing was approximately 60 feet. Well spacing for a site is determined based on the permeability of the soil in the treatment area, the size of the area, and the depth and concentration of the contaminants.

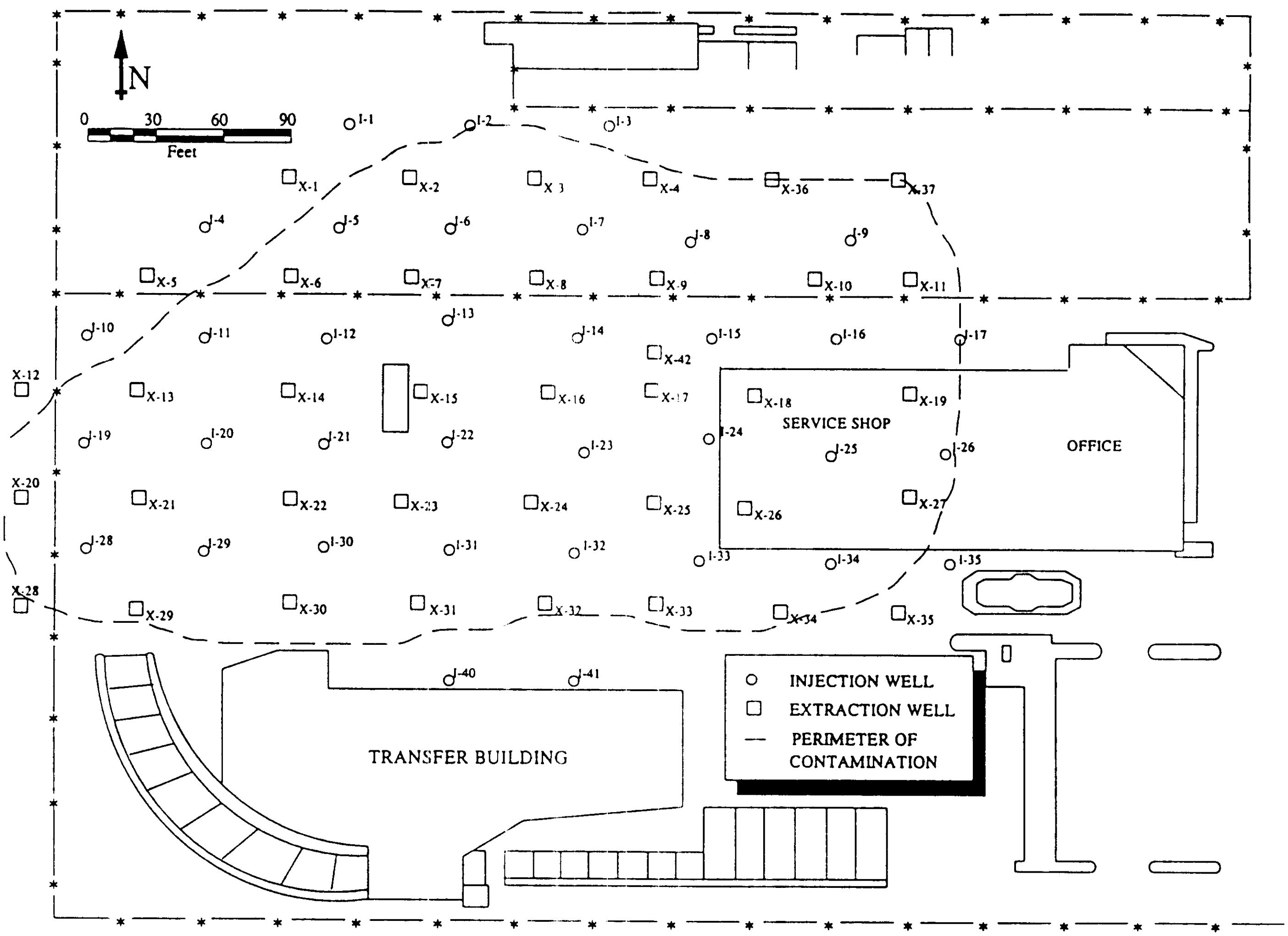


Figure 1-1. Layout of Injection and Extraction Wells at the Rainbow Disposal Site

The injection wells were constructed to a depth of 40 feet and slotted over the lower ten feet. The extraction wells were screened from the bottom of the shallowest clay layer (approximately ten feet below the soil surface) to two feet into the B aquitard (a total depth of approximately 35 feet). Piping was used to conduct the steam flow to the injection wells and to extract the liquids and vapors from the wells. Well heads and pipe on the active portion of the Rainbow Disposal site were installed in trenches below the ground surface. The trenches were backfilled and metal plates were used to cover the piping and backfill to protect the pipes from pressure caused by truck traffic on the surface. Some of the process wells were installed beneath the concrete floor of the service shop building.

Figure 1-2 is a schematic of the aboveground treatment system for steam generation and liquid and vapor treatment. Water from a nearby deep well was pumped to a water softening system for conditioning. The softened water was directed through a heat recovery heat exchanger designed to pre-heat the boiler feedwater while also cooling the liquids removed from the extraction wells. Two chemical additives, a polymer dispersant and an oxygen scavenger, were mixed with the feedwater to protect the boilers from scaling and corrosion. The pre-heated water was then fed to one of two boilers on the site (only one boiler was used at a time). Steam at approximately 15 pounds per square inch (psi) was produced by the boiler and injected into the soil through the injection wells.

The liquid and vapor were removed from the extraction wells using pumps and compressors. The liquid was pumped back through the heat recovery heat exchanger to be cooled by the boiler feedwater. Vapor from the extraction wells was directed to a knock-out pot which removed entrained particles and liquid. The liquid from the knock-out pot was then combined with the liquid from the extraction wells in an oil/water separator. A condenser, fabricated of copper piping placed in a large water bath, was constructed during the remediation to cool the liquid from the knock-out pot and enhance the operation of the oil/water separator. The oil/water separator was designed to remove the diesel compounds from the water by gravimetric separation. The water phase discharged from the separator was treated by filtration and carbon adsorption before being discharged to a storm sewer. The diesel phase (recovered product) was collected in a 4,000-gallon tank for recycling or disposal off-site.

The vapor from the knock-out pot was directed to the thermal oxidizing unit (TOU). The TOU is a self-contained regenerative vapor incineration system that used electric power and ceramic rods to heat a bed of gravel-sized rocks to destroy the organic compounds in the vapor stream. The TOU was designed to effect greater than 99.99 percent destruction and removal efficiency of the organic compounds in the gas stream. The gas exiting the TOU was exhausted to the

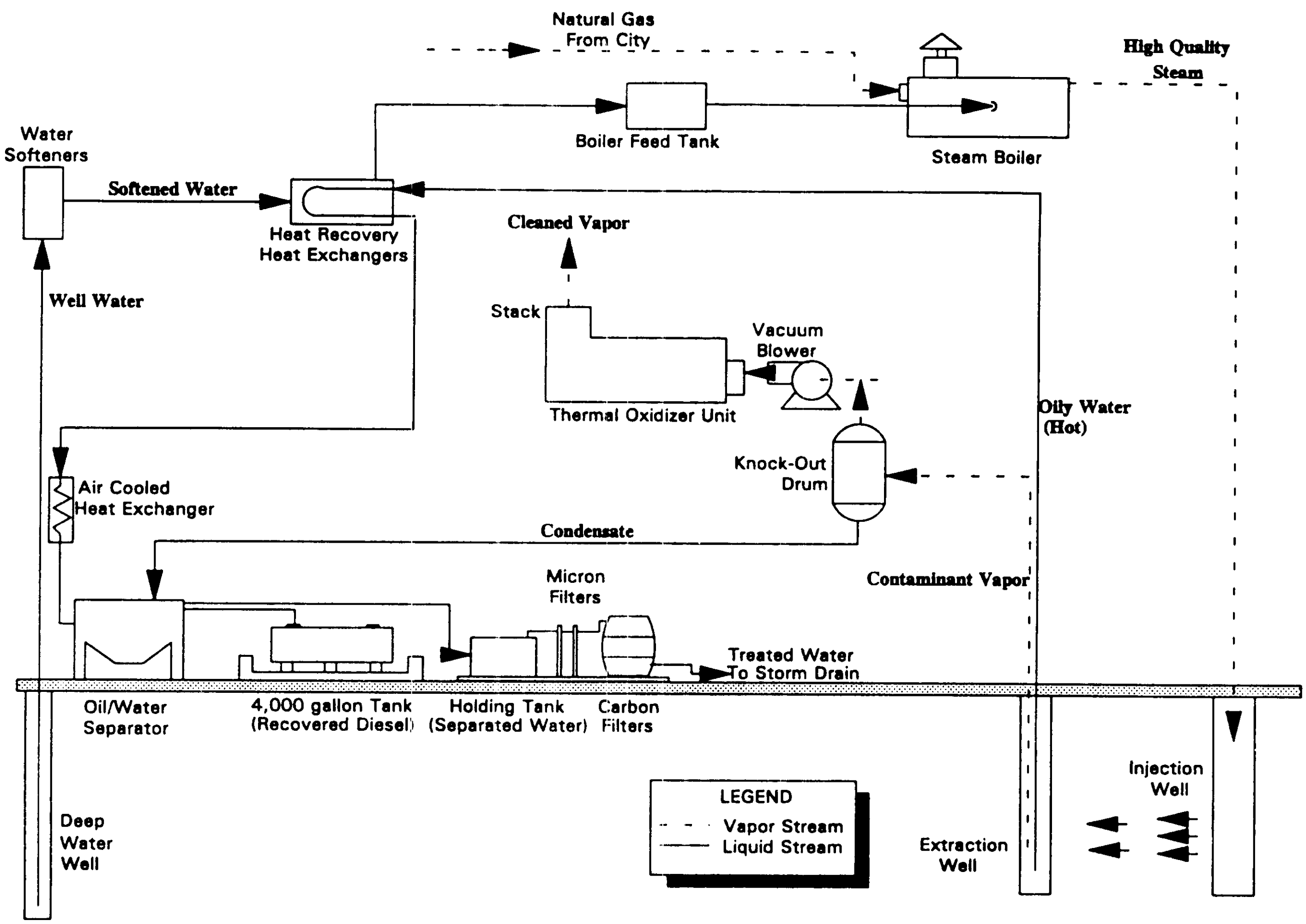


Figure 1-2. Aboveground SERP Treatment Train

atmosphere. A Ratfisch flame ionization detector and a lower explosive limit meter were connected to the inlet of the TOU to measure the concentration of total hydrocarbons being burned and to ensure that safe operating conditions were maintained in the unit.

The aqueous phase from the oil/water separator was discharged to the water treatment system, which used 5-micron filters and activated carbon beds to remove residual organics to meet NPDES permit requirements for discharge to the storm sewer. The spent carbon and filters were containerized in appropriate drums and sent off-site for disposal when spent. Other residuals from the process included excess soil from boreholes drilled for wells or sampling, and used disposable clothing and equipment.

1.5 KEY CONTACTS

Additional information on *in situ* steam technologies and the SITE Program can be obtained from the following sources:

Potential Contractor for Thermal Enhanced Soil and Groundwater Remediation

John F. Dablow III
Groundwater Technology, Inc.
741 East Ball Road
Suite 103
Anaheim, CA 92805
(714) 991-7112
FAX: (714) 991-8805

Hughes Environmental Systems, Inc. is no longer vending the SERP technology for use at other sites.

Information on the Dynamic Underground Stripping Process at Lawrence Livermore National Laboratory

Dr. Roger Aines
Earth Sciences Department
Lawrence Livermore National Laboratory
7000 East Avenue, Mail Stop 219
Livermore, CA 94550
(510) 423-7184
FAX: (510) 422-0208

The SITE Program

Robert Olexsey
Director, Superfund Technology Demonstration Division
U.S. Environmental Protection Agency
26 West Martin Luther King Dr.
Cincinnati, OH 45268
513-569-7861
FAX: 513-569-7620

Paul de Percin
EPA SITE Project Manager
U.S. Environmental Protection Agency
26 West Martin Luther King Dr.
Cincinnati, OH 45268
513-569-7797
FAX: 513-569-7620

Information on the SITE Program is also available through the following on-line information clearinghouses:

- The Alternative Treatment Technology Information Center (ATTIC) System (operator: 301-670-6294) is a comprehensive, automated information retrieval system that integrates data on hazardous waste treatment technologies into a centralized, searchable source. This database provides summarized information on innovative treatment technologies.

- The Vendor Information System for Innovative Treatment Technologies (VISITT) (hotline: 800-245-4505) database contains information on 154 technologies offered by 97 developers.

- The OSWER CLU-IN electronic bulletin board contains information on the status of SITE technology Demonstrations. The system operator can be reached at 301-585-8368.

Technical reports may be obtained by contacting the Center for Environmental Research Information (CERI), 26 West Martin Luther King Drive in Cincinnati, Ohio, 45268. The telephone number is 513-569-7562.

SECTION 2
TECHNOLOGY APPLICATIONS ANALYSIS

This section of the report addresses the general applicability of the SERP technology to contaminated sites. The analysis is based primarily on the SITE Program SERP Demonstration results. Additional data from bench-scale and pilot-scale studies of the process have been used where applicable.

2.1 OBJECTIVES—PERFORMANCE VERSUS ARARS

Under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), as amended by the Superfund Amendments and Reauthorization Act of 1986(SARA), remedial actions undertaken at Superfund sites must comply with federal and state (if more stringent) environmental laws that are determined to be applicable or relevant and appropriate requirements (ARARs). ARARs are determined on a site-specific basis by the remedial project manager. They are used as a tool to guide the remedial project manager toward the most environmentally safe way to manage remediation activities. The remedial project manager reviews each federal environmental law and determines if it is applicable. If the law is not applicable, then the determination must be made whether the law is relevant and appropriate. For example, a requirement under the Resource Conservation and Recovery Act (RCRA) is to provide secondary containment for hazardous waste storage tanks. In the process of treating fuel-contaminated soil using SERP, liquid product is extracted. The extracted fuel product must be stored in a tank. The storage tank would not be considered a hazardous waste storage tank, as defined by RCRA, since fuel is not hazardous waste. However, RCRA's secondary containment requirements for hazardous waste storage tanks may be relevant and appropriate.

A discussion of the federal and state environmental laws that are applicable or relevant and appropriate to SERP follows. A table of ARARs as they relate to the process activities conducted at the Rainbow Disposal site for the SERP technology is presented in Table 2-1.

2.1.1 Comprehensive Environmental Response, Compensation, and Liability Act

CERCLA authorizes the EPA to provide liability, compensation, cleanup, and emergency response for hazardous substances released into the environment and the cleanup of inactive hazardous waste disposal sites. Facilities become "Superfund sites" when they have been listed on the National Priorities List.

SARA directed the EPA to use remedial alternatives that permanently and significantly reduce the volume, toxicity, or mobility of the contamination; select remedial actions that are protective, cost-effective, and involve alternative treatment technologies to the maximum extent possible; and avoid off-site transport and disposal of untreated hazardous substances.

The Rainbow Disposal site is not a Superfund site; however, CERCLA/SARA is relevant and appropriate for the treatment technology occurring on-site. Using the SERP technology at the Rainbow Disposal site met all of the SARA criteria. It was an *in situ* treatment technology, thus the treatment process occurred in place and the removal of the contamination was permanent and protective to human health and the environment; the volume and mobility of the waste diesel in the soil was reduced; SERP was cost-effective and an alternative treatment technology; and, as stated above, untreated waste was not transported off-site for disposal. Also the extracted contaminants could potentially be concentrated and reused on-site as a fuel supplement or transported off-site for fuel recovery. Unfortunately, the treatment technology did not meet the cleanup standard imposed by the California Regional Water Quality Control Board (1,000 mg/kg total petroleum hydrocarbons as diesel).

Table 2-1. FEDERAL AND STATE ARARS FOR THE SERP TECHNOLOGY

Process Activity	ARAR	Description	Comment
Waste characterization of untreated waste	RCRA: 40 CFR 261	Untreated waste should be characterized to determine if it is a hazardous waste, and if so, if it is a RCRA-listed waste.	Applicable
Drilling activities related to well installation	OSHA: 29 CFR 1910.120	Personnel need to be protected from volatile emissions and airborne particulates during soil boring activities. Personnel need to be provided with protective equipment and be involved in a medical monitoring program.	Provide air monitoring equipment during drilling; Use a fan to keep personnel upwind of vapors.
Waste processing using SERP technology	RCRA: 40 CFR 264 Subpart J and 270 (or State Equivalent)	Treatment of a RCRA hazardous waste requires a permit. If non-RCRA waste, then a permit or a variance from the State hazardous waste agency may be required.	If activity is conducted within one year on remediation wastes, full RCRA permit may not be required.
	RCRA: 40 CFR 266 Subparts D or E, and H	Hazardous waste and oil burned for energy recovery must meet the reporting and record keeping requirements. Permits are required for hazardous waste burned in boilers and industrial furnaces.	Applicable
	CAA: 40 CFR 50, and 52 (Subpart F)	Emissions from vapor treatment system must be monitored to meet NAAQS; air permit may be necessary.	Applicable
	SDWA: 40 CFR 144 and 146 Subpart F	Injection of steam requires a Class V permit.	Applicable
Cleanup standards are established	SARA Section 121(d)(2)(A)(ii); SDWA: 40 CFR 141; H&SC Chapter 6.75	Remedial actions of surface and groundwater are required to meet MCLGs (or MCLs) established under SDWA. Corrective actions of leaking underground fuel tanks in California must be consistent with waste discharge requirements.	Applicable for surface and groundwater; Relevant and appropriate if drinking water source could be affected.
	LUFT	California Regional Water Quality Control Board establishes clean up standards for fuel-contaminated soil and water using a decision matrix found in the LUFT.	Applicable, relevant and appropriate.

Table 2-1. (Continued)

Process Activity	ARAR	Description	Comment
Storage of waste	RCRA: 40 CFR Part 264 Subpart J (or State Equivalent)	Storage tanks for recovered liquid waste (i.e., recovered diesel) must be placarded appropriately, have secondary containment, and be inspected daily.	If storing non-RCRA wastes, RCRA requirements are still relevant and appropriate.
	RCRA: 40 CFR Part 264 Subpart I (or State Equivalent)	Containers of contaminated soil from soil borings and process stream residuals (separator sludge, filters) need to be labeled as a hazardous waste, the storage area needs to be in good condition, weekly inspections should be conducted, and storage should not exceed 90 days unless a storage permit is acquired.	Applicable for RCRA wastes; relevant and appropriate for non-RCRA wastes.
Waste Disposal	RCRA: 40 CFR Part 262	Generators of hazardous waste must dispose of the waste at a facility permitted to handle the waste. Wastes generated include soil cuttings and recovered product. Generators must obtain an EPA ID No. prior to waste disposal.	Applicable
	CWA: 40 CFR Parts 403 and/or 122 and 125	Discharge of wastewaters to a POTW must meet pre-treatment standards; discharges to a navigable water must be permitted under NPDES.	Applicable
	RCRA: 40 CFR Part 263; HWCA: H&SC Chapter 13	Hazardous wastes transported off-site for treatment or disposal must be accompanied by a hazardous waste manifest. Hazardous waste haulers operating in California must be registered with the State and inspected by the California Highway Patrol.	Applicable
	RCRA: 40 CFR Part 268	Hazardous wastes must meet specific treatment standards prior to land disposal, or must be treated using specific technologies.	Applicable

2.1.2 Resource Conservation and Recovery Act

As opposed to CERCLA, RCRA regulates solid and hazardous wastes managed (generated, treated, stored, and disposed of) at operating facilities to minimize the need for corrective action in the future. Wastes are defined as RCRA hazardous wastes if they meet one of the characteristics (toxic, ignitable, corrosive, or reactive) as discussed in 40 CFR Part 261 Subpart C, or if they are listed in 40 CFR Part 261 Subpart D. RCRA contains specific requirements for any unit managing hazardous wastes including proper labeling, condition of containers, and secondary containment. In addition, RCRA contains specific requirements for personnel handling hazardous waste including training, inspections, medical monitoring, and record keeping. In 1984, RCRA was amended by the Hazardous and Solid Waste Amendments which added requirements for corrective action and restrictions on land disposal.

The SERP technology can treat RCRA-listed wastes containing volatile and semivolatile organics in soil. After treatment, the extracted liquid waste must meet specific treatment standards prior to being land disposed. The waste would need to be transported off-site to a permitted treatment facility or treated on-site. If treated on-site, the facility would require a RCRA permit. Under the corrective action regulations, a treatment unit used to treat "remediation wastes" may not require a full RCRA permit if that treatment activity occurred in one year or less. RCRA wastes generated during SERP treatment may include extracted waste, contaminated filters, contaminated activated carbon, and wastewater; these must be transported off-site for further treatment and disposal. In some cases, the recovered product could be used as a fuel for the steam generation system. In this case, the standards applicable to units burning hazardous waste, or oil, for energy recovery apply, 40 CFR 266, Subparts D or E.

The Rainbow Disposal site is not a RCRA facility in that it does not manage RCRA wastes. In addition, the released diesel product and the waste streams generated during the SERP treatment process are not RCRA wastes since 40 CFR 261.4 exempts releases from underground storage tanks undergoing corrective action from the RCRA regulations. Thus, the diesel waste would not be required to be disposed of at a RCRA hazardous waste facility. However, RCRA is an appropriate and relevant requirement. The 4,000-gallon diesel tank should have secondary containment. Drums of soil cuttings should be leak-free and marked with the contents and the date of accumulation.

2.1.3 Clean Air Act

The Clean Air Act establishes national primary and secondary ambient air quality standards for sulfur oxides, particulate matter, carbon monoxide, ozone, nitrogen dioxide, and lead. It also limits the emissions of hazardous air pollutants, including vinyl chloride, arsenic, asbestos, and benzene. States are responsible for enforcing the Clean Air Act. In so doing, Air Quality Control Regions were established. If necessary, and for purposes of efficiency and effectiveness, an Air Quality Control Region may be broken up into Air Quality Management Districts. The Air Quality Control Region establishes allowable emissions, on a site-specific basis, depending upon whether or not the site is located within an air basin in attainment with the National Ambient Air Quality Standards (NAAQS).

The SERP technology extracts volatile and semivolatile organics from soil in both liquid and gaseous forms. NAAQS for nitrogen oxides and carbon monoxide and emission standards for benzene may be applicable to the SERP technology's vapor treatment system and steam generation system; thus, an air permit from the Air Quality Control Region may be required. In addition, any unit that may emit a pollutant to the air during normal operations requires an Authority to Construct permit. In order to operate the unit, a Permit to Operate must be obtained.

The Rainbow Disposal site is located within the South Coast Air Quality Management District (SCAQMD) in Orange County, California. Orange County is in non-attainment status for all primary and secondary air quality standards except sulfur dioxide. Emission standards were established by the SCAQMD for the thermal oxidizer unit: benzene in the exhaust stream (0.041

pounds per day); volatile organic compounds in the inlet stream (4,200 ppmv); and hydrocarbon vapors in the outlet stream (5 percent of the inlet stream).

2.1.4 Clean Water Act

The objective of the Clean Water Act is to restore and maintain the chemical, physical, and biological integrity of the nation's waters. To achieve this objective, effluent limitations of toxic pollutants from point sources were established. Publicly-owned treatment works (POTW) can accept wastewaters with toxic pollutants from facilities; however, pre-treatment standards must be met and a discharge permit may be required. A facility desiring to discharge water to a navigable waterway must apply for a permit under the National Pollutant Discharge Elimination System (NPDES). When a NPDES permit is issued, it includes waste discharge requirements.

Since water is extracted along with the organic contamination using SERP, wastewater must be properly managed. Depending on the type of contaminant and the facility at which the technology is being employed, three options are open for water disposal: off-site disposal at a RCRA treatment facility; discharge through a sanitary sewer under an industrial pre-treatment permit; and discharge to the waterways of the United States under a NPDES permit. Wastewater generated at the Rainbow Disposal site using the SERP technology was first polished in an activated carbon system and then discharged to the storm sewer system under NPDES permit number CA 8000176.

2.1.5 Safe Drinking Water Act

The Safe Drinking Water Act establishes primary and secondary national drinking water standards to protect human health and the public welfare. The drinking water standards are expressed as the maximum contaminant levels for the various constituents. Under SARA Section 121(d)(2)(A)(ii), remedial actions of groundwater and surface water are required to at least meet the standards of the maximum contaminant level goals (MCLGs) if they are relevant and appropriate. MCLGs have been established for several organic, inorganic, and microbiological contaminants. Some MCLGs for organic compounds capable of being remediated by SERP include toluene (1 mg/L), xylene (10 mg/L), and ethylbenzene (0.7 mg/L). For contaminants with MCLGs set at 0 mg/L, the maximum contaminant level (MCL) for that constituent must be attained when groundwater or surface water is remediated. MCLs for contaminants capable of being remediated by SERP include vinyl chloride (0.002 mg/L), benzene (0.005 mg/L, and trichloroethylene (0.005 mg/L). Since some contamination may remain in the soil after remediation with SERP which may reach groundwater, a regulatory agency may require that MCLGs or MCLs, as appropriate, be used as standards for determining if the remedial action met its pre-specified cleanup criteria.

Although groundwater treatment was not evaluated at the Rainbow Disposal site, MCLGs may be appropriate and relevant action levels for ascertaining a successful remediation of the site, should contaminants remain in the soil that could potentially leach to the groundwater. Benzene, toluene, xylene, and ethylbenzene (BTEX) were constituents of interest at the Rainbow Disposal site. During pre-treatment soil sampling, toluene and xylene were detected at low concentrations. Post-treatment soil samples had non-detectable concentrations.

The Safe Drinking Water Act also contains requirements for the Underground Injection Control Program. Any operator injecting water underground must first obtain approval from the authorized State agency. No underground injection authorization can be granted if it results in any of the following: a fluid containing any contaminant moves into underground sources of drinking water, a contaminant causes a violation of the primary drinking water standards, or a contaminant adversely affects human health. Underground injection wells are divided into five classes. Class V wells are those not covered by Classes I through IV and include injection wells used in experimental technologies. Criteria and standards applicable to Class V injection wells can be found in 40 CFR Part 146, Subpart F.

The SERP technology injects steam, thus the wells used for this purpose would fall under the requirements of the Underground Injection Control Program. Steam injection wells would require a Class V permit. The primary drinking water standard that would have to be monitored is total dissolved solids (must be less than 10,000 mg/kg).

2.1.6 Occupational Safety and Health Act

CERCLA remedial actions and RCRA corrective actions must be conducted within the requirements of the Occupational Safety and Health Act. Personnel working at a hazardous waste site are required to complete a 40-hour initial training, 3-day on-site supervised training, and annual 8-hour refresher courses. Personnel must also be in a medical monitoring program that first establishes a medical baseline. Annual monitoring is performed to determine if an individual was exposed to hazardous substances or conditions. Requirements are also established for confined space entry, trenching and shoring, and personnel protective equipment such as steel-toed boots, hard hats, and hearing protection.

2.1.7 California Hazardous Waste Control Act

California's Hazardous Waste Control Act, included in the Health and Safety Code, Sections 25000 *et. seq.*, is comparable to RCRA in many ways. California's hazardous waste regulations are promulgated in Title 22, California Code of Regulations. The similarities include waste management requirements, handling requirements, training, inspections, and emergency planning requirements. However, there are differences which make the Hazardous Waste Control Act more stringent. One difference is how California regulations define a waste as hazardous. Certain wastes are hazardous in California and not considered hazardous under RCRA. These include waste oil, asbestos, PCBs, and waste fuels (including diesel). Treatment of these wastes would be considered a hazardous waste treatment requiring a hazardous waste facility permit. Also, tank systems holding more than 5,000 gallons of a hazardous waste are defined as storage tanks and require a hazardous waste storage permit. California offers variances from the permitting requirements if a facility is treating a non-RCRA waste and meets specific requirements.

The SERP technology treats hazardous waste in that it removes the hazardous constituents from the soil and concentrates them. A hazardous waste permit may be required unless the treatment occurs as part of a CERCLA remediation activity or a RCRA corrective action (lasting less than one year).

2.1.8 California Petroleum Underground Storage Tank Cleanup Act

Chapter 6.75 of the Health and Safety Code, Petroleum Underground Storage Tank Cleanup, was added in 1989 to address corrective action pertaining to leaking underground fuel tanks. The statute requires corrective actions to be consistent with applicable waste discharge requirements or other applicable state policies for water quality control.

2.1.9 California Leaking Underground Fuel Tank Field Manual

The Leaking Underground Fuel Tank (LUFT) field manual was prepared by a multiagency task force involving personnel from the California Department of Toxic Substances Control, California Department of Health Services, California State Water Resources Control Board, California Regional Water Quality Control Boards, and various County Health Departments. The LUFT field manual was created to provide guidance for regulatory agencies responsible for dealing with leaking fuel tank problems. The primary jurisdiction for overseeing cleanups of fuel from underground tanks lies with the California State Water Resources Control Board. Using this manual, the California Regional Water Quality Control Boards set cleanup standards for petroleum-contaminated soil and water. The Regional Water Quality Control Board established a 1,000 mg/kg cleanup limit for diesel (total petroleum hydrocarbons) in soil and 100 mg/L limit for diesel in groundwater for the Rainbow Disposal site.

2.2 OPERABILITY OF THE TECHNOLOGY

Because SERP operates on contaminated soil *in situ,* the use of the technology is site-specific. The size of the site, the type of contamination and its extent, the geology, and the geographical location all influence the suitability of the technology, the way the technology is implemented, and the effectiveness of the technology on treating the waste. The Rainbow Disposal site had several features which determined the method by which the technology was implemented. A discussion of some of those characteristics and their effects follow.

The site is approximately 2.3 acres in size, which posed logistical challenges during installation and operation. The size of the site required a large number of injection and extraction wells (73 total) for complete coverage, at a well spacing of 45 feet between each injection well and the nearest extraction wells. Well installation and maintenance was more difficult because most of the well heads in the active area were installed below grade and under metal plates. While this configuration allowed operation of the transfer facility to continue without major interruption, downtime for SERP was increased when problems could not be detected or repaired as quickly as they might be otherwise.

The underground conditions influenced design requirements. This included the depth and interval of contamination. Process wells (injection and extraction) were constructed to 40 feet deep. The injection wells were screened in the contaminated sand zone between approximately 35 and 40 feet. Extraction wells had 25-foot screens. The site geology was not constant over the entire treatment area. The same alternating layers of sand and clay which directed the flow of contamination in the site soil also influenced the treatment process. Removal of contamination trapped in the less permeable clay layers was difficult because the steam and heat could not penetrate these areas easily and flow patterns could have been developed which bypassed less permeable areas altogether.

Underground utilities and other objects were present in the treatment area. While the technology was capable of treating around the obstructions, some of them posed specific challenges. Early in the treatment process, steam became channeled into a gravel conduit for the phone cables on the site, leading to steam breakthrough in an on-site utility shed. The treatment process was shut down while the damage was repaired and the water was removed. Several underground fuel tanks were present in the middle of the treatment area. Because these tanks contained residual fuel, the technology operator had to be careful not to expose them to excessive heat. Extra temperature monitoring probes were placed near the tanks, and the injection wells nearby were kept turned off until late in the treatment process. The result was that the area either reached the steam temperature late in the process or not at all; therefore, those areas were probably not effectively treated.

No vapor condensation system was designed and included in the aboveground treatment system. Most of the contamination removed from the site by the SERP technology remained in the vapor phase during treatment in the aboveground treatment process. Only about 4,700 gallons of diesel were collected in the aboveground storage tank during treatment according to measurements taken by the developer. About 4,000 gallons of this was free product that was removed from some of the wells before treatment with SERP commenced. It is estimated that at least 15,400 gallons of removed diesel were oxidized in the TOU during treatment with SERP.

Although the treatment system was initially designed to operate for only eight months, treatment operations occurred for a period of two years. Several factors were responsible for the large increase in operating time. Knowledge of the process was limited prior to remediation at the Rainbow Disposal site, and no application of this size had been designed or attempted. For example, the operators learned from the process that more time would be needed to heat and remediate the site. Major and minor operational problems that stopped or slowed operation were also quite common during treatment. Both boilers experienced frequent and sometimes lengthy breakdowns. The TOU required frequent service and could take more than a day to return to operating temperature after repair. During the winter of 1991-1992, both boilers were shut down for a period of more than two months due to operational and structural problems. This long shutdown probably allowed the site to cool considerably and, therefore, delayed the treatment even further. Process operation changed in October 1992, from a 16-hour per day, five days per week cycle to a 24-hour per day, six days per week cycle. Operational efficiency for heating the soil seemed to increase after this change, and more constant operation was felt to be less stressful on the boilers and other components as well.

Although some of the diesel contamination was removed from the soil, the process did not meet the cleanup level of 1,000 mg/kg total petroleum hydrocarbons. This may be due to the factors mentioned above. In the initial plan for treatment of the site, it was known that the technology was not capable of removing all of the contamination from the site. It was believed, however, that the cleanup level could be obtained rapidly, and the residual contamination would be low enough for natural biodegradation to become effective.

2.3 APPLICABLE WASTES

According to the developer and operators of SERP, the technology can be applied to many *in situ* contaminant situations. The contamination must consist of volatile and/or semivolatile organic compounds. Because of the addition of heat (steam) to the soil, SERP is applicable to compounds that are less volatile than those which would be removed solely by vacuum extraction. Wastes containing a mixture of compounds of varying boiling points potentially can be treated with this technology. For contaminants whose liquid phases have densities greater than water (dense non-aqueous phase liquids or DNAPLS), too high an initial concentration could result in downward migration of contamination when the liquid is concentrated *in situ* by the process. The suggested upper concentration limit depends on the specific compound and ranges from 200 to 1,000 mg/kg [1].

The primary contaminated matrix must be composed of soil; fractured rock or semisolid matrices cannot be treated by this technology. Highly impermeable clay materials also may not be suitable for SERP treatment. The technology is capable of treating soil with underground obstructions such as buried tanks, utility lines, and buried rocks or debris. The location of such obstructions should be determined to the greatest extent practical before treatment. Applying heat around underground objects such as utility lines could cause damage. Contaminated groundwater can be treated by the technology concurrently with the soil, or the treatment area may be dewatered before treatment.

The depth to the bottom of the treatment zone is not a significant limiting factor. The technology has been used at a depth of over 100 feet at another site (see Appendix A for more information). Applications of the technology in deeper soils may realize a significant cost advantage over excavation, due to the difficulty in removing soils at greater depths.

Applicable waste requirements for this *in situ* technology also include requirements for the site geology and geography. As described in Section 1.4, the site must have a lower confining layer and may need an upper confining layer to control the steam and contaminant flow. Sites with channels of permeable material (e.g., sand, utility trenches, loose debris) in a less permeable matrix may cause channeling of the steam and limit treatment of other areas. A minimum volume of contiguous waste is required for cost-effective operation. In general, this technology is not economical for areas smaller than 1,000 square feet or those with contamination extending to no more than 10 feet below the soil surface.

2.4 KEY FEATURES

The most obvious advantage to an *in situ* technology, such as SERP, is that little excavation is required to treat the soil. Since the soil is treated in place, the waste is not subject to any land disposal restrictions that might be applicable if excavation were required. This can reduce the costs of cleanup by reducing the need for transportation and disposal of hazardous substances. Additionally, because the soils are treated in place, the waste problem is not simply moved to another location.

The developer claims that SERP offers advantages over other *in situ* technologies such as vacuum extraction or soil flushing. High energy steam is used to treat the soil so that treatment can be much faster and more complete than with just air or cold water. Higher boiling point compounds can also be removed more readily using steam. Although the perched groundwater table at the Rainbow Disposal site was depressed during free product recovery prior to treatment with SERP, the developer claimed that contaminated groundwater could be treated concurrently with the soils in the treatment area. This claim was not evaluated.

The developer also claimed that SERP can effectively treat operating sites with minimal impact to site operations. At the Rainbow Disposal site, the ability to treat soils under and around existing structures was especially important to the site owners. On the active portion of the site, process and monitoring wells were installed below grade under metal plates so that truck traffic could continue unimpeded. Had large-scale excavation been required, the commercial activities on the site would have been suspended, which was not acceptable to the site owners or the serviced community.

2.5 AVAILABILITY/TRANSPORTABILITY

An expert in the field of SERP technology is required to design the system so that treatment theory can be properly applied to subsurface characteristics. Most of the process can then be constructed from off-the-shelf items. This allows the operator of the technology to estimate construction costs accurately. Some of the aboveground treatment processes (e.g., condensers and separators) must be sized and fabricated for the specific application. Temperature monitoring probes and accessories may also require custom fabrication.

Since the process operates in place, each application uses a different configuration tailored to the site size, geography, contaminant type, and other local factors. Key equipment includes well casings and materials, water conditioning equipment, boilers, vacuum pumps, and wastewater treatment equipment. The same aboveground equipment can be used to treat several sites in succession; however, transportability depends on the size of the equipment. Well materials and other below ground equipment such as temperature probes, however, are often not reusable once they have been installed.

One developer of a technology similar to SERP is designing a transportable system to be used with the technology. The transportable system will provide all the aboveground treatment processes required for application of the technology (steam generation, wastewater treatment, and vapor treatment). The size and other specifications of this transportable unit are not known at this time. Portable systems employing steam injection to treat shallow fuel contamination have been used in the Netherlands since 1985 [2]. These systems include re-usable steam lances instead of constructed injection wells.

2.6 MATERIALS HANDLING REQUIREMENTS

For SERP, materials handling equipment includes a variety of equipment required to install the wells and other process equipment; handle water conditioning chemicals, maintenance materials, and process wastes; and transport liquids and gases through the treatment system.

Boreholes for wells and for collecting soil samples are installed using a drill rig. Drilling services are generally subcontracted to a company which has both the required equipment (e.g., drill rigs, augers, samplers) and personnel trained in drilling operations and well construction. Drilling services are required at different times during the project, including pre-treatment sampling, process installation, and post-treatment sampling.

A forklift was used at the Rainbow Disposal site for transporting bags of salt or other chemicals to the water softeners; transporting drums containing drill cuttings, spent carbon or other wastes; and transporting equipment, such as piping, during process installation. Depending on site size and configuration, hand-powered equipment may be used exclusively or in addition to a forklift.

Pumps are used to transport the vapors and liquids away from the wells. Other pumps are used within the system to convey well water and water treatment chemicals to the boilers and to drive the wastewater through the treatment system. These pumps, especially the extraction well pumps, must be able to perform under harsh conditions, including elevated temperature, high solids content, and variable chemical concentrations. These factors should be taken into account during the selection of pumps and ancillary equipment, such as hoses and fittings.

2.7 SITE SUPPORT REQUIREMENTS

Access to utilities is required to use SERP on a site. Water is needed for producing steam. This water must be of high quality, containing no contaminants that might further contaminate the soil. Injectable water quality may be further determined by injection well permits. Approximately 20,000 gallons of water per day were required at the Rainbow Disposal site. Water usage is determined primarily by site size and volume of soil to be treated. SERP operators at the Rainbow Disposal site were able to discharge the treated wastewater directly to a storm sewer. Without a sewer connection, wastewater might need to be transported or piped to another location for disposal.

Electricity is required to run pumps, other process equipment, lights, monitoring equipment, and office equipment. At the Rainbow Disposal site, the boilers for steam production were fired by natural gas. A high capacity natural gas line was brought to the site. If a gas line is not available, other fuel may be substituted, depending on availability and air quality requirements.

Other support facilities for use of the technology would include concrete pads to support the boilers and other process equipment, a building or trailer for use as office space, and a storage building or trailer to store tools and equipment. A maintenance shop or area is also required. Outdoor lighting may be necessary for 24-hour operations.

A relatively accessible site with good roads is required to bring in process equipment and other heavy equipment, such as drill rigs and transport trucks. In addition, personnel must also be able to get to and from the site readily for daily process monitoring and control. The entire site, including all process wells, must be secured to prevent damage to the equipment and to minimize hazards to unknowing trespassers or visitors. A fence and a locked gate were used at the Rainbow Disposal site for security purposes. The Rainbow Disposal site also had 24-hour security to protect the active commercial facility, and this assisted in protecting the SERP equipment. Other sites may require a 24-hour guard depending on the application and site location.

2.8 RANGES OF SUITABLE SITE CHARACTERISTICS

Site characteristics which have not been included in Section 2.3, Applicable Waste, are discussed below. SERP is suitable for operation in moderate climates. It may be suitable for use in cold climates, but utilities or fuel consumption may be greater. Arid areas may also be prohibitive unless there is a large amount of water available for steam generation. System equipment can be designed or modified to use available fuels, and also to operate in colder climates by using insulation and shelter.

SERP is generally suitable for use in industrial areas and in areas with little habitation (such as military bases). While the technology can be operated with a low profile, the potentially long duration of treatment may not be acceptable in a residential setting since the process equipment may be noisy and unsightly. Investment in equipment which minimizes noise and other nuisance problems may allow use of this technology in almost any setting, although costs may be higher.

Because SERP is an *in situ* treatment technology, it may not be suitable for locations where there are fragile geological structures or ecosystems. Permits for constructing and operating injection wells may be difficult to obtain if there is any potential for negatively impacting usable water bodies above or below the soil surface. It may not be desirable to operate the technology at sites with certain toxic contaminants, such as dioxins, because of the chance of mobilizing these contaminants and the difficulty or cost of disposing of the wastewater and residuals generated from the process.

To treat shallow soils, an upper confining layer may be required so that steam does not exit through the surface. If an adequate layer does not already exist on the site, a temporary cap of asphalt could be placed on the site until treatment was completed.

2.9 LIMITATIONS OF THE TECHNOLOGY

The main limitation of the SERP technology, as shown by this full-scale Demonstration, is that it can be difficult to predict both how long the technology will need to be operated and how complete the treatment will be. An initial treatment time of eight months was planned for the Rainbow Disposal site, but the system was operated for two years (see Section 2.2, Operability). During treatment with SERP, the operators monitored certain operational parameters to determine the progress of treatment including soil and extraction well temperatures, and vapor stream contaminant concentrations. According to these indicators, the rate of removal of contamination from the soil was slow, thus extending the treatment time. The rate of removal of contamination might have been much greater if the process had been operated more continuously over the entire site.

Because the entire site is treated at once and in place, it is more difficult to test and adjust the technology while it is operating, unlike a flow-through process where the impact of operational changes can be determined more immediately. Additionally, plots of soil are generally not homogeneous in either contamination or geology. Some areas of a site may be completely treated while others are not, making it difficult to judge remediation progress. Proper monitoring of the treatment is crucial to the application and success of the technology. Even when treatment is effective, a certain amount of residual contamination is likely to remain in the soil.

The SERP equipment has a high capital cost. Some of the equipment is site-specific; it is difficult to reuse wells and temperature probes purchased to remediate a site. Operation of SERP requires trained personnel for operation of the boilers and for service and maintenance of the equipment. Labor costs were determined to be the most significant of the twelve cost categories investigated in the Economic Analysis found in Section 3 of this document.

After treatment with SERP is complete, the soil will remain at elevated temperatures for an extended period of time. Soil is an excellent thermal insulator, and a large mass of moist soil has a high capacity to retain heat. Data from models and from the application of SERP and similar technologies suggest that several years of cooling are required to bring the soil back to ambient temperatures. High soil temperatures can pose a hazard during digging or construction activities on the site and may delay any beneficial use of the site. The temperature of the soil may also inhibit natural biodegradation of the residual contamination. Continued vacuum extraction of the site long after the application of steam can potentially reduce the soil temperature much more rapidly than conductive cooling alone.

SECTION 3
ECONOMIC ANALYSIS

3.1 CONCLUSIONS OF THE ECONOMIC ANALYSIS

The results of the economic analysis are summarized in Table 3-1. The approximate total cost for use of the full-scale SERP technology at the Rainbow Disposal site was about $4,401,120 over the two-year period of operation. This results in a cost of approximately $46 per cubic yard for a site with 95,000 cubic yards of contaminated soil (see Section 3.3, Issues and Assumptions). Figure 3-1 is a graphical representation of the costs per cubic yard, broken out by cost category, for the actual case. Under ideal operating conditions, the remediation with SERP at the Rainbow Disposal site might have cost about $2,789,910, or approximately $29 per cubic yard. Based on available information, costs were also calculated for use of SERP at a similar site of the same size and contamination profile under what might be considered "typical" operating conditions. These costs were estimated to be about $3,375,910, or approximately $36 per cubic yard.

Labor is the largest cost for use of SERP, accounting for about one third of the total cost. Since labor costs are directly proportional to the duration of remediation, factors which would increase the remediation time would increase total costs the most significantly. Start-up costs and utilities are also significant for use of SERP, together accounting for another third of the total costs. The cost for natural gas accounted for more than ten percent of the total remediation costs. Cost details are discussed further in the following sections.

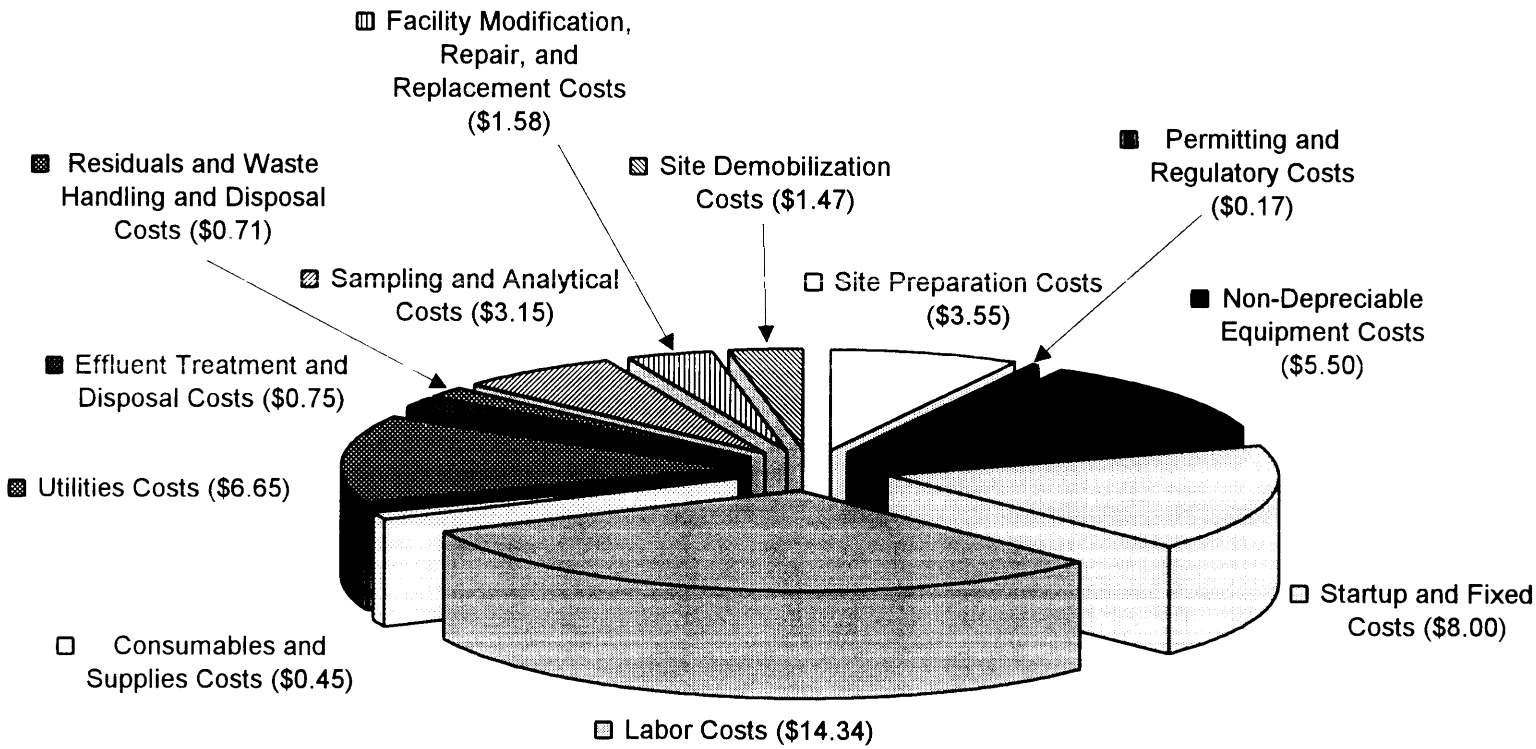
As discussed in the Executive Summary, and in more detail in Section 4 of this report, SERP did not meet the cleanup objectives set for the Rainbow Disposal site. At the time remediation at the site was stopped, the operator believed that the process had gone nearly to completion under the circumstances, and that little additional removal would have occurred if treatment had been continued. Continuing treatment would have increased the total cost and the cost per cubic yard for the site, but it is impossible to determine what these costs would have been. It is

Table 3-1. SUMMARY OF RESULTS OF THE ECONOMIC ANALYSIS *

	Approx. Actual Costs for Rainbow Disposal		Estimated Ideal Cost for Rainbow Disposal		Estimated Cost for a Typical Site of the Same Size	
	Total ($)	$/yd³ **	Total ($)	$/yd³ **	Total ($)	$/yd³ **
Time to Remediate (Days)	746		373		497	
Assumed On-Line Factor	50%		100%		75%	
Site size (yd³)	95,000					
Site Preparation Costs	$ 338,230	$ 3.56	$ 325,960	$ 3.43	$ 336,200	$ 3.54
Permitting and Regulatory Costs	$ 16,100	$ 0.17	$ 11,100	$ 0.12	$ 14,100	$ 0.15
Non-Depreciable Equipment Costs	$ 522,990	$ 5.51	$ 522,490	$ 5.50	$ 524,070	$ 5.52
Startup and Fixed Costs	$ 758,800	$ 7.99	$ 413,500	$ 4.35	$ 435,700	$ 4.59
Labor Costs	$ 1,362,000	$ 14.34	$ 775,600	$ 8.16	$ 1,033,600	$ 10.88
Consumables and Supplies Costs	$ 43,430	$ 0.46	$ 24,320	$ 0.26	$ 32,420	$ 0.34
Utilities Costs	$ 631,470	$ 6.65	$ 280,190	$ 2.95	$ 493,020	$ 5.19
Effluent Treatment and Disposal Costs	$ 71,100	$ 0.75	$ 35,600	$ 0.37	$ 47,400	$ 0.50
Residuals and Waste Handling and Disposal Costs	$ 67,200	$ 0.71	$ 49,250	$ 0.52	$ 61,400	$ 0.65
Sampling and Analytical Costs	$ 299,900	$ 3.16	$ 195,900	$ 2.06	$ 221,900	$ 2.34
Facility Modification, Repair, and Replacement Costs	$ 150,700	$ 1.59	$ 57,500	$ 0.61	$ 77,600	$ 0.82
Site Demobilization Costs	$ 139,200	$ 1.47	$ 98,500	$ 1.04	$ 98,500	$ 1.04
TOTAL COSTS	**$ 4,401,120**	**$ 46.33**	**$ 2,789,910**	**$ 29.37**	**$ 3,375,910**	**$ 35.54**

* This table presents a summary of the detailed costs itemized in Table 3-2.

** For each cost category, costs per cubic yard are reported to the nearest cent.



All costs in U.S. Dollars.
Total cost per cubic yard: $46.32

Figure 3-1. Cost Per Cubic Yard Treated During SITE Demonstration

possible that, had treatment been conducted with less downtime, the site would have been more completely remediated in less time.

3.2 BASIS OF THE ECONOMIC ANALYSIS

This economic analysis is designed to conform with the specifications for an order-of-magnitude estimate. This is a level of precision established by the American Association of Cost Engineers (AACE) for estimates having an expected accuracy within +50 percent and -30 percent. In the AACE definition, these estimates are generated without detailed engineering data. Suggested uses of these estimates are in feasibility studies or as aids in the selection of alternative processes [3]. Because the costs for use of SERP were derived from a post-mortem analysis of the treatment over the two-year period, the costs are probably more accurate than these specifications, especially for some cost categories. However, the applicability of these costs to other uses of SERP at other sites is limited by the highly site-specific nature of the process and the associated costs. Therefore, labeling these cost figures as "order-of-magnitude" estimates is appropriate.

3.2.1 Factors Affecting the Estimated Costs

The costs derived from the Rainbow Disposal SERP Demonstration are specific to this site only. A detailed cost estimate of SERP for another site would involve designing a treatment system to apply to that site, which is beyond the scope of this analysis.

Factors affecting the estimated costs include site soil type, site contamination characteristics, site location, and volume and area of the contaminated soil. The impact of any of these factors on the cost for using the technology can only be estimated based on available data. Soil type affects how quickly the steam can penetrate the soil and how rapidly the contamination can be removed. Less permeable soils, or areas of lower permeability within a more permeable matrix, can require longer treatment times and consequently exhibit higher costs. Different contaminant types or concentrations can influence the required treatment time; less volatile compounds are expected to require longer treatment for removal. The type of contamination may also influence the types and amounts of waste products generated, types of effluent treatment required, and waste disposal costs. Site location can affect the costs for labor, construction, utilities, and materials. Climate can also affect the costs, both in the energy required to heat the soil and the design of the necessary process and ancillary equipment. From examining costs for construction and operation, it appears that more cost-effective operation can be achieved when the volume of contaminated soil extends in depth as opposed to extending in surface area, since fewer wells would be required.

3.2.2 Cost Data Categories

Cost data associated with SERP have been assigned to the following 12 categories: (1) site preparation; (2) permitting and regulatory requirements; (3) capital equipment; (4) start-up and fixed costs; (5) labor; (6) consumables and supplies; (7) utilities; (8) effluent treatment and disposal; (9) residual waste shipping, handling, and disposal costs; (10) sampling and analytical services; (11) maintenance and modifications; and (12) demobilization.

3.2.3 Cost Sources

Cost data for this economic analysis were derived from several sources. The technology operator provided costs for equipment, labor, permitting, and demobilization. Other costs were derived from vendors of supplies and equipment and from utility companies. During operation, information on the use of utilities and supplies was collected, and operational logs were updated daily. These data were used to calculate and estimate the costs for supplies and maintenance as well as the on-line factor for the process. Costs for start-up, sampling and analysis, and demobilization were derived from process diagrams and construction drawings as well as information gathered by SAIC while conducting post-treatment sampling and analysis.

3.3 ISSUES AND ASSUMPTIONS

3.3.1 Type of Cost Analyses Performed

An economic analysis for the SERP technology was performed for three cases. The first case represents actual costs incurred at the Rainbow Disposal site over the two-year period of remediation. The second case examined potential costs for idealized conditions at the same site, while the third presents costs that could be expected at a site of the same size and contamination profile under "typical" operating conditions.

The first cost analysis, termed the actual case, represents the approximate actual costs incurred during the two-year remediation period (September 1991 to August 1993, a total of 746 calendar days) at the Rainbow Disposal site. This case uses actual cost data from the operator whenever available, utility rates and other cost information valid for Southern California during the period of remediation, and estimated costs where necessary. Significant equipment downtime occurred at the Rainbow Disposal site during remediation. For the actual case, an on-line factor of approximately 50 percent was calculated based on operational logs and observations of the process. For this cost case, monthly charges were based on a total of 25 months of operation, and weekly charges were based on a total of 107 weeks.

The second cost analysis, termed the ideal case, is a study of the costs of the technology at the Rainbow Disposal site for idealized conditions. These costs were based on use of the technology without major operational problems or equipment failures, and therefore assume an on-line factor of 100 percent. A remediation time of 373 (calendar) days was used for this cost case, half of the actual case, based on the assumption that the treatment rate is proportional to the total days of remediation only. This simplifying assumption was made although it is likely that, with a complex *in situ* process such as this one, there is not a proportional relationship between the percent of days that the equipment is in operation and the necessary duration of remediation. Further examination of the required length of treatment is beyond the scope of this investigation. The ideal case used the same cost rates as those incurred for the actual case at the Rainbow

Disposal site, and costs associated with Southern California utilities, labor rates, and other business factors. For this cost case, monthly charges were based on a total of 12 months of operation, and weekly charges were based on a total of 53 weeks. Because this case is based on the potentially unrealistic assumption that operation could occur without operational downtime, it represents the lowest cost, or "best case" that could be achieved for the technology at the Rainbow Disposal site and should therefore be considered a lower bound on the potential costs.

The third case suggests what costs would be incurred by using the technology at a site of the same size and similar contamination profile at a non-specified location. This typical case includes some equipment or process downtime, which might be expected during typical operations. This case assumed an on-line factor of 75 percent and therefore an operational time of approximately 75 percent of the duration of the actual case (for a total duration of 497 calendar days). This on-line factor was estimated based on knowledge of the process components and on lessons learned during operation that will prevent or minimize the impact of some potential operating problems. For this cost case, monthly charges were based on a total of 17 months of operation, and weekly charges were based on a total of 71 weeks.

The typical case differs from the actual and the ideal case in that calculations use rates for utilities, labor, and other cost factors that are based on a composite of those found in a selection of metropolitan areas around the country, (e.g., gas and water rates were derived from those currently charged in Boston, Massachusetts; Dallas, Texas; Miami, Florida; St. Louis, Missouri; and Seattle, Washington) instead of those for Southern California. Although this cost case is not directly comparable to the actual and the ideal cases, the application of the typical cost case allows discussion of the effect of site location and other factors on the total costs for SERP. Because the typical case utilized an on-line factor midway between those for the actual and ideal cases, it represents a likely set of costs for the technology application. The application of this case is explained more fully in subsections of Section 3.4.

Both the ideal case and the typical case assumed 24-hours-per-day operation, six days per week during operation. The actual operation began with a 16-hours-per-day operation for the first year of treatment. When 24-hours-per-day operation was started, system efficiency appeared to increase dramatically, with only moderate increases in costs. Less frequent shutdowns (weekly rather than daily) are also believed to reduce wear on boilers and other equipment due to cycling and thermal shock and to minimize blockage of process wells.

The three cost cases presented bracket a range of costs for similar sites over the expected range of on-line factors. The actual case is seen as a "worst case" for costs due to the large amount of operational downtime. Lessons learned from this application will assist in preventing excessive downtime in subsequent applications. Since the technology is extremely site-specific, actual costs will vary from these estimates. The effect of site size or contamination on the costs for SERP are not considered due to the complexity of the process, although both factors are expected to be important in both treatment effectiveness and total costs.

3.3.2 Other Assumptions

In addition to the assumptions described above, other general assumptions were used for each of the cost cases:

- Legal fees, legal searches, and access rights and roads are the responsibility of the site owner and are not included in remediation costs.
- Costs do not include profit.
- Extensive site characterization data, including the delineation of the size of the contamination plume, types of contaminants, and basic site geology (for all cases) were already available prior to the selection of SERP as the remedy. This limits the need for technology-specific site characterization.
- The site size for all cost cases is the same. The treatment zone is 2.3 acres (100,000 square feet) in area and encompasses a depth between 20 feet and 40 feet below the soil surface for a total volume of approximately 95,000 cubic yards (2,565,000 cubic feet). This volume is used to calculate the cost per cubic yard of soil treated.
- Costs for labor include wages, fringe benefits, and overhead charges.

- All personnel required for the remediation, except the project manager and any parent-company administration, are hired locally.
- High quality water is available for use with the technology.
- Clean drill cuttings from soil borings can be redeposited on the site rather than disposed of off-site.
- The level of health and safety protection needed is minimal (level D) during normal operations because the process occurs beneath the surface. Modified or full level C protection may only be needed during drilling and sampling operations. Higher levels of protection are not needed.

3.4 RESULTS OF THE ECONOMIC ANALYSIS

The detailed results of the economic analysis are shown in Table 3-2. Details on specific subcategories of costs and the derivation of costs for each category are found in the following text.

3.4.1 Site Preparation Costs

For use of an *in situ* technology such as SERP, a large proportion of the costs are incurred at the start with the planning and preparation of the site and equipment. A SERP process well system is built into the soil to be treated. Therefore, site preparation costs are a significant factor in the total treatment costs.

Site preparation costs include the costs for designing the system (site design and layout), as well as the aboveground systems to be installed. This was estimated, based on information supplied by the operator, as requiring 2,500 hours of engineering time at $100 per hour plus miscellaneous labor and other expenses ($20,000) for a total of $270,000. This cost was used for all three cases. It can be assumed that treatment systems for smaller sites, or those with less complex geology than at the Rainbow Disposal site, would be less costly to design.

Table 3-2. DETAILS OF THE ECONOMIC ANALYSIS

	Approximate Actual Costs for Rainbow Disposal		Estimated Ideal Cost for Rainbow Disposal		Estimated Cost for a Typical Site of the Same Size	
	Total ($)		Total ($)		Total ($)	
Time to Remediate (Days)	746		373		497	
Assumed On-Line Factor	50%		100%		75%	
Site size (yd^3)			95,000			
SITE PREPARATION COSTS						
Site Design and Layout	$	270,000	$	270,000	$	270,000
Site Survey and Investigation	$	39,100	$	39,100	$	39,100
Legal Searches			Not applicable[1]			
Access Rights and Roads			Not applicable[1]			
Preparation for Support Facilities	$	3,700	$	3,700	$	3,700
Auxiliary Buildings	$	8,930	$	4,660	$	14,900
Technology-Specific Requirements	$	16,500	$	8,500	$	8,500
Total Site Preparation Costs	**$**	**338,230**	**$**	**325,960**	**$**	**336,200**
PERMITTING AND REGULATORY COSTS						
NPDES and Other Permits	$	10,000	$	5,000	$	8,000
Development of Monitoring Protocols	$	6,100	$	6,100	$	6,100
Total Permitting and Regulatory Costs	**$**	**16,100**	**$**	**11,100**	**$**	**14,100**
EQUIPMENT COSTS						
Major Equipment[2]	$	402,000	$	402,000	$	402,000
Minor Equipment	$	519,000	$	519,000	$	519,000
Equipment Rental	$	3,990	$	3,490	$	5,070
Total Equipment Costs[2]	**$**	**924,990**	**$**	**924,490**	**$**	**926,070**
Total Non-Depreciable Equipment Costs	**$**	**522,990**	**$**	**522,490**	**$**	**524,070**
STARTUP AND FIXED COSTS						
Equipment Installation	$	249,000	$	249,000	$	249,000
Shakedown	$	52,800	$	52,800	$	52,800
Working Capital	$	30,000	$	30,000	$	30,000
Depreciation	$	362,000	$	41,700	$	55,600
Insurance and Taxes	$	50,000	$	25,000	$	33,300
Initiation of Monitoring Program	$	5,000	$	5,000	$	5,000
Contingency	$	10,000	$	10,000	$	10,000
Total Startup and Fixed Costs		**758,800.00**		**413,500.00**		**435,700.00**

Table 3-2. (Continued)

	Approximate Actual Costs for Rainbow Disposal	Estimated Ideal Cost for Rainbow Disposal	Estimated Cost for a Typical Site of the Same Size
	Total ($)	Total ($)	Total ($)
Time to Remediate (Days)	746	373	497
Assumed On-Line Factor	50%	100%	75%
Site size (yd^3)	95,000		
LABOR COSTS			
Project Direction	$ 107,000	$ 53,300	$ 71,000
Administration	$ 38,100	$ 16,000	$ 21,300
Engineering/Technical	$ 1,030,000	$ 613,000	$ 817,000
Maintenance	$ 79,900	$ 40,000	$ 53,300
Clerical Support	$ 107,000	$ 53,300	$ 71,000
Total Labor Costs	**$ 1,362,000**	**$ 775,600**	**$ 1,033,600**
CONSUMABLES AND SUPPLIES COSTS			
Water Softening Chemicals	$ 21,200	$ 13,200	$ 17,600
Filters and Activated Carbon	$ 8,600	$ 4,300	$ 5,730
Maint and Cleaning Materials	$ 3,380	$ 1,690	$ 2,250
Monitoring Supplies	$ 2,250	$ 1,130	$ 1,500
Health and Safety Supplies	$ 4,000	$ 2,000	$ 2,670
Paper/Office Supplies	$ 4,000	$ 2,000	$ 2,670
Total Consumables and Supplies Costs	**$ 43,430**	**$ 24,320**	**$ 32,420**
UTILITIES COSTS			
Natural Gas	$ 527,000	$ 228,000	$ 269,000
Well Water	$ -	$ -	$ 21,400
Electricity	$ 99,500	$ 49,700	$ 66,300
Phone	$ 4,970	$ 2,490	$ 3,320
Sewer	$ -	$ -	$ 133,000
Total Utilities Costs	**$ 631,470**	**$ 280,190**	**$ 493,020**
EFFLUENT TREATMENT AND DISPOSAL COSTS			
Treatment Equipment (See Equipment)	---	---	
Filter & Carbon Replacement (See Supplies)	---	---	
Sewer Discharge Costs (See Utilities)	---	---	
Monitoring and Reporting Requirements	$ 71,100	$ 35,600	$ 47,400
Total Effluent Treatment and Disposal Costs	**$ 71,100**	**$ 35,600**	**$ 47,400**

Table 3-2. (Continued)

	Approximate Actual Costs for Rainbow Disposal		Estimated Ideal Cost for Rainbow Disposal		Estimated Cost for a Typical Site of the Same Size	
	Total ($)		Total ($)		Total ($)	
Time to Remediate (Days)	746		373		497	
Assumed On-Line Factor	50%		100%		75%	
Site size (yd^3)			95,000			
RESIDUALS AND WASTE HANDLING AND DISPOSAL COSTS						
Drill Cuttings	$	42,600	$	33,200	$	36,300
Liquid Wastes (product, sludge)	$	7,500	$	7,500	$	7,500
Other Wastes	$	17,100	$	8,550	$	17,600
Total Residuals and Waste Handling and Disposal Costs	**$**	**67,200**	**$**	**49,250**	**$**	**61,400**
SAMPLING AND ANALYTICAL COSTS						
Operational Analyses (see Effluent Treatment)		---		---		---
Environmental Monitoring, initial	$	31,800	$	31,800	$	31,800
Environmental Monitoring, periodic	$	209,000	$	105,000	$	131,000
Environmental Monitoring, confirmation	$	59,100	$	59,100	$	59,100
Total Sampling and Analytical Costs	**$**	**299,900**	**$**	**195,900**	**$**	**221,900**
FACILITY MODIFICATION, REPAIR, AND REPLACEMENT COSTS						
Design Adjustments	$	56,500	$	20,600	$	27,400
Scheduled Maintenance	$	-	$	-	$	-
Equipment Replacement	$	94,200	$	36,900	$	50,200
Total Facility Modification, Repair, and Replacement Costs	**$**	**150,700**	**$**	**57,500**	**$**	**77,600**
SITE DEMOBILIZATION COSTS						
Site Restoration	$	92,000	$	92,000	$	92,000
Shutdown	$	47,200	$	3,500	$	3,500
Closure Permitting Costs			Not Applicable[1]			
Removal of Equipment	$	-	$	3,000	$	3,000
Total Site Demobilization Costs	**$**	**139,200**	**$**	**98,500**	**$**	**98,500**
TOTAL COSTS	**$**	**4,401,120**	**$**	**2,789,910**	**$**	**3,375,910**

1 Not applicable: This cost is the responsibility of the site owner and is not included in this analysis.

2 Major Equipment costs are taken into account under depreciation and are used to estimate factors such as repair and modification costs. They are not direct costs and are therefore excluded from the totals.

3 No direct maintenance costs have been used in this analysis. Costs for regular maintenance tasks are considered under labor and supplies.

Site surveying and investigation must be conducted to complete the design of the technology and to assist in designing the environmental monitoring program. The scope of these activities is very site-specific. The investigation at the Rainbow Disposal site included borehole drilling and logging, sample analysis, and data interpretation. Since preliminary site investigation and characterization occurred before the selection of SERP as a treatment technology, the cost for site surveying and investigation included drilling costs for only ten boreholes. It was assumed that thirty (30) soil and 30 groundwater samples from these boreholes were analyzed. Soil gas probes were also utilized to complete the plume delineation. The total site surveying and investigation costs were calculated to be approximately $39,100. Total costs for site design and layout, as well as site surveying and investigation, were assumed to be the same for all three cost cases.

Preparation for support facilities included grading, location of underground utility lines, connections for gas, electric, and water/sewer lines, and installation of auxiliary buildings. The total cost for these activities was calculated to be $3,700 for all cost cases. Construction of a concrete pad for the major equipment and associated grading requirements were considered technology-specific requirements and cost about $8,500. An additional concrete pad was built due to an error in specifications, which contributed an additional cost of $8,000 (for a total of $16,500) for the actual case that would not be incurred in the ideal or the typical cases.

Rental of the office trailer cost $342 per month, based on actual invoices. For the actual case (25 months of operation), office rental costs totaled $8,930 including delivery charges. A roll-off bin, borrowed at no cost from the Rainbow Disposal site, was used as an auxiliary storage and maintenance trailer. Costs for the buildings for the ideal case also included rental for the office trailer at a total cost of about $4,660 for 12 months of rental including delivery. A cost of about $14,900 for rental of both an office and a storage/maintenance trailer was calculated for the typical case based on a rental cost of $500 per month. Office and storage space requirements are site-specific and depend on climate, geographical location, and available space and buildings on the treatment site.

3.4.2 Permitting and Regulatory Costs

Several types of permits are required for installing and operating the SERP technology. Costs incurred include permit application fees and permit compliance fees. Costs were included for the following permits: permit to construct (SCAQMD), permit to operate (SCAQMD); NPDES permit for effluent discharge; well drilling permit (may not be required when less than 40 feet deep and no aquifers penetrated); and air permits for process equipment and the TOU. The NPDES permit was estimated to have cost $2,000 per year (for a total of $4,000 in the actual case). The cost for the remaining permits were estimated at $6,000 over the course of the project, for a total of $10,000. For the ideal case, a permitting cost of half the actual case was assumed ($5,000), since most permits are issued on an annual basis.

Also included in this category are costs for development and initiation of an appropriate environmental monitoring plan. These costs include engineering costs, reporting, and project management time to discuss these issues with the regulators. The cost for initiating the environmental monitoring program was estimated to be approximately $6,100. Regardless of how long the cleanup takes, this cost is incurred at the start of a project; therefore, this amount is the same for the actual and the ideal cases.

Permit costs are dependent on the local and regional conditions and environmental laws. California has rigorous environmental policies, and permit costs for this state are expected to be higher than the national average. Permit requirements and associated permitting costs can change rapidly, even over the course of a two-year project. For the typical case, permitting costs, including development of a monitoring program, were estimated to be about $14,100. However, depending on site-specific conditions, contaminants, and other factors (geological, ecological, and political), these costs could fluctuate significantly.

3.4.3 Equipment Costs

Costs for major and some minor equipment were received from the technology operator and based on actual invoice figures in 1991 dollars. The major equipment components are: two boilers, the thermal oxidizing unit, the ion exchange water softening unit, and the effluent treatment system (tanks and filters). The total cost for the major equipment was about $402,000. This cost was used to calculate the depreciation cost for use of the technology for all three cost cases (see Section 3.4.4). The items were sold at the end of remediation for $100,000 and were removed from the site by the purchaser.

Minor equipment includes items such as the following: tanks, well water collection systems, heat exchangers, an oil/water separator, well materials and headers, casings, well pumps, piping, metal trench plates, and miscellaneous monitoring equipment. This equipment was assumed to have been exempt from depreciation; the total cost for this equipment is included in the cost totals. The total cost for minor equipment, calculated from information received from the operator along with catalog pricing information [4,5], is about $519,000. Some of the minor equipment and associated materials may have salvage value at the end of the project. Well casings and *in situ* instrumentation were assumed to be non-reusable; however, they may have scrap value. If the costs for removing the materials is higher than the potential scrap value, and removal is not necessary for site restoration, these materials may be abandoned in place.

Rental equipment was used during the start-up phase of the project to assist in installation of process equipment. A forklift was rented for ten days at a daily cost of $45. A crane (with operator) was required to set up the boilers and other heavy equipment at a cost of $190/hour. The crane was assumed to have been rented for two eight-hour days. A forklift was borrowed from the site owners during treatment, so rental was not necessary. A pump was rented for approximately 10 days (at $50/day) to help clear some wells after heavy rains, but pumps were not assumed to be required for the ideal case or the typical case. For the typical cost case, where a forklift might not be readily available, use of a forklift for a total of 35 days (one day every two weeks) was added to the rental equipment costs.

3.4.4 Start-up and Fixed Costs

Start-up costs include installation of the process equipment, equipment shakedown, initiation of the monitoring program, working capital, depreciation, insurance, and contingency costs. Installation of the equipment for this *in situ* process included well drilling and installation ($191,000) and installing the aboveground process equipment and piping ($58,000). Well drilling costs were the same for all cases of this cost estimate and were based on available drilling rates and known time to drill and construct wells.

Shakedown costs were incurred over the two-week period when the system was tested. Treatment was initiated on a small area of the treatment zone to test the wells and all the aboveground equipment. Shakedown costs include the labor and materials for the shakedown. Eight-hour work days were assumed. The total costs for shakedown were the same for all cases of this cost estimate and were estimated to be about $52,800.

In this cost estimate, working capital was assumed to be the cash required to run the process for a period of one month. This figure included approximate costs for monthly utilities, supplies, rentals, and monthly monitoring requirements. Because Hughes Environmental Systems had a parent company responsible for direct payment of the employees involved during treatment at the Rainbow Disposal site, this cost did not include labor. Working capital was calculated to be $30,000.

Depreciation is the cost for use of all the major equipment over the course of the project. For the actual case, this included two years (746 days) worth of equipment use and also accounted for the resale value received for the equipment at the end of the project ($100,000). Therefore, an equipment life of two years was used to calculate the depreciation costs for the actual case.

The ideal and the typical cases either assume that a selling cost close to the book value could be achieved or that the technology operator had another use for the equipment after the remediation. Depreciation was calculated using a straight-line method with a ten-year equipment service life and the number of years (or fractions of years) of remediation.

Costs for insurance and taxes were estimated as approximately 2.5 percent of the total cost of the equipment per year. These factors were estimated to be approximately $50,000, $25,000, and $33,300 for the actual case, the ideal case, and the typical case, respectively.

Initiation of the monitoring program was also included in the start-up cost category. These costs typically include operator training required and collection of the first site or process samples used to establish a baseline for operations. The total cost for initiation of the monitoring program was estimated to be $5,000 for all cases.

Contingency represents the amount of money the operating company has available for unexpected needs. This was estimated to be $10,000 for all cost cases.

3.4.5 Labor Costs

The labor costs for the actual case were based on hourly wage figures and weekly schedules supplied by the technology operator. For approximately the first year of operation (61 weeks), the process was operated for 16 hours per day, 5 days per week. Full-time workers during two-shift-per-day operation included a site supervisor ($60/hour), site engineer ($75/hour), and two technicians/boiler operators ($40/hour each). The project director charged an average of ten hours each week to the project at $100/hour, and an administrative secretary ($40/hour) was employed for approximately 30 hours each week. Additional labor in the form of off-site company administration (ten hours per week at $50/hour) and additional maintenance personnel (15 hours per week, $50/hour) were assumed to have been required. The total weekly cost for two-shift-per-day operation was calculated to be $11,500.

When the 24-hours-per-day, six-days-per-week cycle of operation was started, labor costs were increased with the addition of another full-time technician. The secretarial position was split with another job, so only 25 hours per week were devoted to the SERP project. The total weekly costs for the three-shift per day operation were about $14,500 for over 45 weeks.

The weekly cost for the three-shift-per-day operation was also used to calculate the cost for the ideal case. The same weekly schedule was used for the typical case. Southern California labor rates are approximately 127% of the national average, so weekly labor costs used for the typical case have been adjusted. This figure was determined based on average regional labor cost data [3]. In the Northeast, labor rates are similar to those in Southern California, while other areas of the country have rates that average two-thirds of the Southern California rates.

In this cost estimate, the total labor costs calculated for the actual case were $1,362,000, of which 75 percent was for technical and engineering functions. The total costs calculated for the ideal and typical cases were approximately $775,600 and $1,033,600, respectively.

3.4.6 Consumables and Supplies Costs

The major consumables used during treatment with SERP were water softening salt and two water treatment chemicals used to protect the boilers from scaling and fouling. The water treatment chemicals were purchased from Blackhawk Engineering Company. Blackhawk 625 (BH625) is an oxygen scavenger used to control corrosion, while Blackhawk 689 (BH689) is a polymeric dispersant used to control boiler scale. A total of 30 tons of salt were used during treatment at a cost of $0.11 per pound. A total of 3,000 pounds of BH625 (at $2.05 per pound), and 650 gallons of BH689 (at $12.50 per gallon) were used. The total cost for these consumables was about $21,200.

For the ideal and typical cases, the amount of salt and chemicals used was calculated based on the average daily use of these chemicals during 24-hour-per-day-operation (100 pounds salt, 5 pounds BH625, and 1.1 gallons BH689), and the total assumed number of days of treatment. Costs for the ideal case were estimated to be approximately $13,200; costs for the typical case were estimated to be approximately $17,600. Costs for water softening and treatment are influenced by the quality of the water available, but this factor was not considered in the analysis.

Other supplies used during the project included filters and carbon for the water treatment system; maintenance and cleaning materials such as oil, detergent, and fuses; monitoring supplies such as strip chart paper and calibration gas; health and safety supplies such as disposable gloves; and office supplies. The rate of use of these supplies was based on operator log entries for the actual case and was assumed to be basically proportional to the number of days in operation for the ideal and typical cases. One full set of carbon and filters was included with the treatment system as installed. Supplies were calculated to cost a total of $22,230 for the actual case, $11,120 for the ideal case, and $14,820 for the typical case. The total cost for consumables and supplies was calculated for the actual, ideal, and typical cases to be approximately $43,430, $24,320 and $32,420, respectively.

3.4.7 Utilities Costs

The major utility required for treating the Rainbow Disposal site with SERP was the natural gas needed to fire the steam boilers. A total of approximately 800,000 therms (1 therm = 100,000 BTUs) of natural gas were used over the course of the project at a cost of $0.611/therm for the summer months (April through November) and $0.754/therm for the winter months, for a total cost of approximately $527,000. Based on this cost estimate, natural gas use alone was more than 10 percent of the total cost for use of SERP.

For the ideal case, the following factors were used to calculate the natural gas used: the average monthly natural gas usage during 24-hour operation (33,000 therms/month), twelve months of operation, and an average natural gas cost/therm of $0.654. The total natural gas cost was approximately $228,000.

For the typical cost case, the average monthly usage of 33,000 therms was used to determine the monthly gas costs using the monthly charges and gas rates for the cities investigated. Because different utility companies charge for natural gas using different combinations of monthly and usage charges, a monthly cost for gas was calculated for each locale and then the monthly costs were averaged. The average monthly charge for the natural gas was calculated to be $15,800, for a total of approximately $269,000. Natural gas rates vary by season and by region; the rates investigated for this analysis ranged from $10,000 to $20,000 for a month. In some locations, higher costs for natural gas and less stringent air quality regulations may make alternate fuels, such as diesel or gasoline, more attractive although this has not been figured into the cost calculations.

A large quantity of water, at least 12 million gallons, was used over the course of the project. At the Rainbow Disposal site, water was supplied by an on-site deep water well, formerly used by an ice company, and was available at no cost. Therefore, for the actual case, the cost for water was $0. The cost of the water used for the ideal case was also assumed to be $0. Costs for water discharged to the storm sewer were assessed only through the NPDES permit, with no additional charges based on actual gallons discharged. The same is assumed for the ideal case.

The totalizing meter used to record the amount of well water used in the process was calibrated at the conclusion of treatment according to procedures specified in the QAPP. At that time, the meter was found to be inaccurate at the typical flow rates used during treatment. Based on the field calibration and further calibration and testing performed by the meter manufacturer at the conclusion of the Demonstration, actual total flow was estimated to have been 110 to 130 percent of total meter reading. Since no charges were incurred for using water at the Rainbow Disposal site, this did not affect the costs for the actual or ideal cases. However, a correction factor of 1.2 was applied to the amount of water used presented here. This corrected value was used to calculate the cost of water for the typical case. Costs for water represent a small portion, less than one percent, of the total cost for use of SERP, so a small discrepancy in the actual amount of water used is negligible in the total calculated costs at the level of precision of these cost estimates.

For the typical case, an average cost for high-grade industrial or potable water was used in the calculation ($2/1,000 gallons), and water was assumed to be used at the same daily rate as the average during 24-hours-per-day operation at the Rainbow Disposal site (24,000 gallons, corrected). The total cost for process water for the typical case was calculated to be approximately $21,400. Sewer charges for the typical case were assumed to be charged on a per-gallon basis (at $0.10/gallon), based on the average daily water discharge for the actual remediation (2,500 gallons), and the number of days assumed for the typical case. This cost was estimated to be about $133,000. Sewer charges are expected to be highly site-specific.

Electricity service costs were based on an average monthly cost of $4,000 reported from invoices. Electricity use stayed fairly constant over the course of the project. A total cost of about $99,500 was calculated for the actual case, about $49,700 for the ideal case, and $66,300 for the typical case.

Phone service was calculated based on a monthly rate of $200, which included a three-line business system and a reasonable number of toll calls. The total cost for phone service was estimated to be about $4,970; $2,490; and $3,320 for the actual, ideal, and typical cases, respectively.

3.4.8 Effluent Treatment and Disposal Costs

The liquid effluent from the SERP process is composed mostly of oily water removed from the extraction wells. During the Demonstration, this water was treated in the aboveground system and released to the storm sewer. Costs for the treatment equipment were included with the equipment costs (Section 3.4.3), and the cost for filters and carbon was included with supplies and consumables costs (Section 3.4.6). Calculated sewer discharge costs (for the typical case) were included in the utilities category of this cost estimate (Section 3.4.7). Other costs for the disposal of the treated water were incurred during monitoring and reporting for the NPDES permit requirements. The monitoring included sample containers, analytical services, data interpretation, and report generation for the regulatory authorities. Samples were collected weekly during treatment and analyzed for total petroleum hydrocarbons (TPH) and benzene, toluene, ethylbenzene, and xylenes (BTEX). Calculated costs were based on collecting four samples per month for two parameters each with an approximate analytical cost of $1,760 per month, handling cost of $100 per month, and reporting cost of $1,000 per month. The total costs for the actual case were calculated to be about $71,100. Costs for the ideal and typical cases were based on the same frequency of monitoring over the shorter durations of treatment, and total approximately $35,600 and $47,400, respectively.

In some cases, discharge to a storm sewer would not be appropriate due to waste constituents or local water conditions. In these situations, wastewater would need to be handled in some other manner, such as secondary on-site treatment, discharge to a POTW, or off-site hazardous waste disposal. Costs for these other disposal options would probably be much higher than for NPDES discharge to a storm sewer.

3.4.9 Residual and Waste Handling and Disposal Costs

Several types of wastes are generated during treatment with the SERP process. These include drill cuttings from well installation and sampling boreholes, collected fuel product from the oil/water separator, spent carbon from the wastewater treatment system, oily sludge (bottoms) from the oil/water separator, and used disposable tools and protective clothing.

During the Demonstration, drill cuttings were placed into 55-gallon drums which were segregated by borehole number and drilling depth. Drums were purchased for approximately $30 each. Drill cuttings, which were determined to be uncontaminated based on analytical results, were redeposited on the site as fill at a negligible cost (about half of these drums could be reused). Approximately 137 drums of drill cuttings (out of approximately 460 drums collected) required off-site disposal at a certified landfill at a disposal cost per drum of $250. For this cost estimate, the ideal and typical case costs for drill cutting disposal were calculated based on the sum of the actual number of boreholes drilled before and after treatment and an estimated number of boreholes that would be required during interim sampling. Since interim sampling was performed quarterly, the number of interim sampling events was estimated based on the assumed treatment time for the ideal and typical cases. Two drums of drill cuttings were normally generated per borehole drilled. It was assumed that a total of 108 (out of 360), and 115 (out of 385) drums required disposal for the ideal and typical cases, respectively.

During the Demonstration, the contaminated activated carbon from the water treatment system was changed once during operation and once at the end of treatment. This generated 38 drums of contaminated carbon for disposal at a cost of $450 per drum. The same cost was assumed for the typical case. For the ideal case, only one change of carbon was assumed to be required, resulting in approximately 19 drums of spent carbon requiring disposal. Approximately ten drums of sludge from the oil/water separator were disposed of at a cost of $280 per drum; this cost included drum purchase price and was used for all cases.

Less liquid diesel was recovered during treatment with SERP than originally anticipated because most of the contamination was extracted in the vapor phase and could not be condensed to the liquid phase by the process. A total of approximately 4,700 gallons was collected over the course of the remediation, most of which was pumped from the extraction wells as free product on the water table. Recovered diesel can be recycled or disposed of, with a cost involved for either option. A cost of $1/gallon, or approximately $4,700, was calculated for disposal of the recovered diesel based on quotes from fuel blending and disposal companies. This same disposal cost was used for all three cases of this cost estimate.

Additional wastes requiring disposal included disposable equipment and other solid wastes. Since contact with the diesel only occurred during sampling activities, most of the disposable clothing and materials were disposed of with other solid wastes. Rainbow Disposal personnel collected non-hazardous solid wastes from the site during their normal operations, and no costs were incurred for this service. For the typical case, trash disposal might require a tipping fee which was estimated to be $500 total for the project. Well casings and other materials removed during demobilization also required cleaning, handling, and disposal, incurring an additional cost.

3.4.10 Sampling and Analytical Costs

Sampling and analytical services were required for soil, groundwater, and process liquid streams during the project. The cost for operational analysis for the wastewater treatment system was previously included under effluent treatment and disposal. Soil sampling was conducted at the beginning of the project, at quarterly intervals during treatment, and at the end of the project. Groundwater was sampled monthly during treatment.

The cost for analytical services was based on the number of samples collected, the analyses performed, and the reporting requirements for each analytical event. For pre-treatment sampling, 30 soil samples and 40 groundwater samples were collected and analyzed for BTEX, TPH, and semivolatile organic compounds (not all samples were analyzed for all parameters). Eight boreholes were directly attributed to pre-treatment sampling; other boreholes sampled were included as a part of process well installation. The cost of pre-treatment sampling used in this economic analysis was estimated to be approximately $31,800. This cost was used for the actual, ideal, and typical case.

Interim sampling for the actual case was estimated to have cost approximately $209,000 over the course of the project. This is based on the drilling of about 12 boreholes and collection of 30 groundwater and 30 soil samples per quarter for analysis for TPH and BTEX (actual quarterly sampling schemes and numbers of samples varied for each instance). Costs for interim sampling for the ideal and typical cases were based on the same sampling frequency over the shorter duration of treatment. Costs for interim sampling for the ideal and typical cases were estimated to be about $105,000 and $131,000, respectively.

Confirmation analyses for the Rainbow Disposal site, including drilling and sampling, were performed by the SITE Program. The confirmation analyses cost presented for the actual case was estimated based on the costs incurred by the SITE Program for these analyses, adjusted for the smaller number of samples that probably would have been collected if the operator conducted the confirmation sampling. Some sampling and analysis is required to determine whether the cleanup criteria have been met. The costs were based on drilling 20 boreholes and collecting and analyzing 50 samples for BTEX and TPH and include sampling, handling, and reporting costs. The total cost for confirmation sampling was estimated to be about $59,100 for all cost cases.

3.4.11 Maintenance, Repair, and Modification Costs

Maintenance and modification of the SERP system occurred almost continuously during treatment. Normal maintenance costs were included under the labor costs category (Section 3.4.5) and the consumables and supplies costs category (Section 3.4.6). Labor for repairs and modifications was also included in the labor rates described for labor costs. Maintenance and modification costs included in this section include costs for outside contracting for repairs, repair materials, and replacement parts. Specific design adjustments and modifications made during treatment included adding and abandoning injection and extraction wells (five were added during treatment); fabricating a condenser; hard piping the extraction wells after the hoses had started to deteriorate; and modifying parts of the TOU to resist corrosion. Design adjustments were estimated to have cost approximately $56,500 over the course of the project; the cost for replacement and repair was approximately $94,200.

The rate of both repair and modifications were assumed to increase as the process operates, since parts wear out. If the treatment at the Rainbow Disposal site had taken only the anticipated eight months, items such as well headers and extraction hoses would not have required replacement. Design adjustment and modification costs were assumed to be five percent of the major equipment cost (per year and fractions) for both the ideal and typical cases, estimated as approximately $20,600, and $27,400, respectively. Replacement costs were based on a percentage of the total equipment costs. Four percent of the total equipment cost (per year and fractions) was used to estimate the cost for replacement for the ideal and typical case, for costs of approximately $36,900, and $50,200, respectively. These costs are estimates only and depend on site and equipment-specific factors. Because the application of SERP at the Rainbow Disposal site was the first full-scale application of the technology, lessons were learned about process equipment requirements which can be used to reduce modification and repair costs for subsequent applications.

3.4.12 Demobilization Costs

Demobilization of *in situ* SERP is as site-specific as the installation and start-up. Depending on the site, demobilization might include removal of the aboveground process equipment, removal or abandonment of the process wells, site restoration, continued monitoring, or further treatment. At the Rainbow Disposal site, the process equipment (major equipment and some minor equipment) was purchased by an outside company for a total of $100,000. In return, the purchaser removed the equipment from the site. This resale figure was used in the calculations for depreciation over the life of the operation. It is likely that Rainbow Disposal realized some salvage value on items of equipment that could not be sold, since recycling and reclamation is part of its business. This savings is probably negligible, considering the extra labor that would be involved in preparing the equipment for salvage, and has not been included in the cost calculation.

The process wells were removed from the site according to Regional Water Quality Control Board specifications and well holes were filled with new grouting. Piping was removed from the trenches along with the gravel, and the trenches were filled with soil. The entire site was then covered with concrete, including the formerly bare "dirt lot" area as a part of the Rainbow Disposal operational expansion. The total cost for technology-specific removal and site restoration was estimated, based on information supplied by the operator, to be $92,000 for the actual case. This cost was also used for the ideal and typical cases because these costs are so site-specific. Since the Rainbow Disposal site is in an area zoned for industrial use and will remain covered by a concrete cap and in operation for at least the next seven years (the interval of the current disposal contract), little other site restoration was required. Costs at a site that requires restoration to a near-native state could be much higher due to additional costs for removal of concrete or asphalt capping, site grading and capping, and other requirements.

Other demobilization costs incurred at the Rainbow Disposal site included severance pay for laid-off workers ($43,700), excess inventory that had not been used by the end of the treatment ($1,000), return of rental offices and other equipment ($1,000), and miscellaneous expenses ($1,500). These are much higher in the actual case than would be expected for any subsequent application due to the sudden decision to stop work on the site. Severance pay was not included in the ideal or typical cost case estimates.

Because the SERP technology did not meet the regulatory cleanup criterion, Rainbow Disposal proposed performing groundwater monitoring on a frequent and regular basis to confirm that the potential for off-site migration of the contamination has been mitigated. Since the site will remain in operation and covered by concrete, there is no hazard to workers or the public from any contact with contaminated soils. The costs for long-term monitoring are the responsibility of the site owner and were not included in the cost estimates presented here.

The total estimated cost for demobilization at the Rainbow Disposal site was estimated to be about $139,200. Costs for the ideal and the typical case costs were estimated to be about $98,500 for both cases.

SECTION 4
TREATMENT EFFECTIVENESS

4.1 BACKGROUND

4.1.1 Site and Contamination

The Rainbow Disposal site is an active municipal trash transfer facility. Six days per week, trucks collect and deliver municipal trash to this site, where the trash is sorted and placed into other trucks for recycling or disposal. Rainbow Disposal currently is the sole company responsible for waste pickup from five cities in the Orange County, California area.

The site became contaminated in 1984 when an underground diesel fuel pipeline, used to supply fuel to the trucks, was punctured during digging operations. The leaking pipeline was not discovered for approximately 22 months, during which time a large quantity of diesel had leaked into the surrounding soil. Preliminary investigations showed that the soil under the Rainbow Disposal site had several distinct layers composed of alternating bands of permeable sand and low permeability clay. The layers influenced how the fuel became distributed in the soil. The fuel flowed downward under gravity through each sand layer. At each sand/clay interface, the fuel was forced to flow horizontally until breaks in the underlying clay allowed further downward flow. A perched aquifer located in a sand layer between 25 and 40 feet below the soil surface (known as the B-sand) prevented the fuel from flowing further downward while allowing for wide lateral spread. The contamination distribution that resulted included elevated levels of fuel compounds at all depths at the point of the spill and a zone of contamination, which extends for more than two acres laterally, in the sand layer between approximately 25 and 35 feet. Beneath the B-sand layer was a thick clay layer that protected a confined aquifer beneath from contamination. A perimeter designating where soil concentrations were above 1,000 mg/kg of total petroleum hydrocarbons (TPH) was drawn after further site investigation, as shown in Figure 4-1. This perimeter was used as the treatment area for SERP.

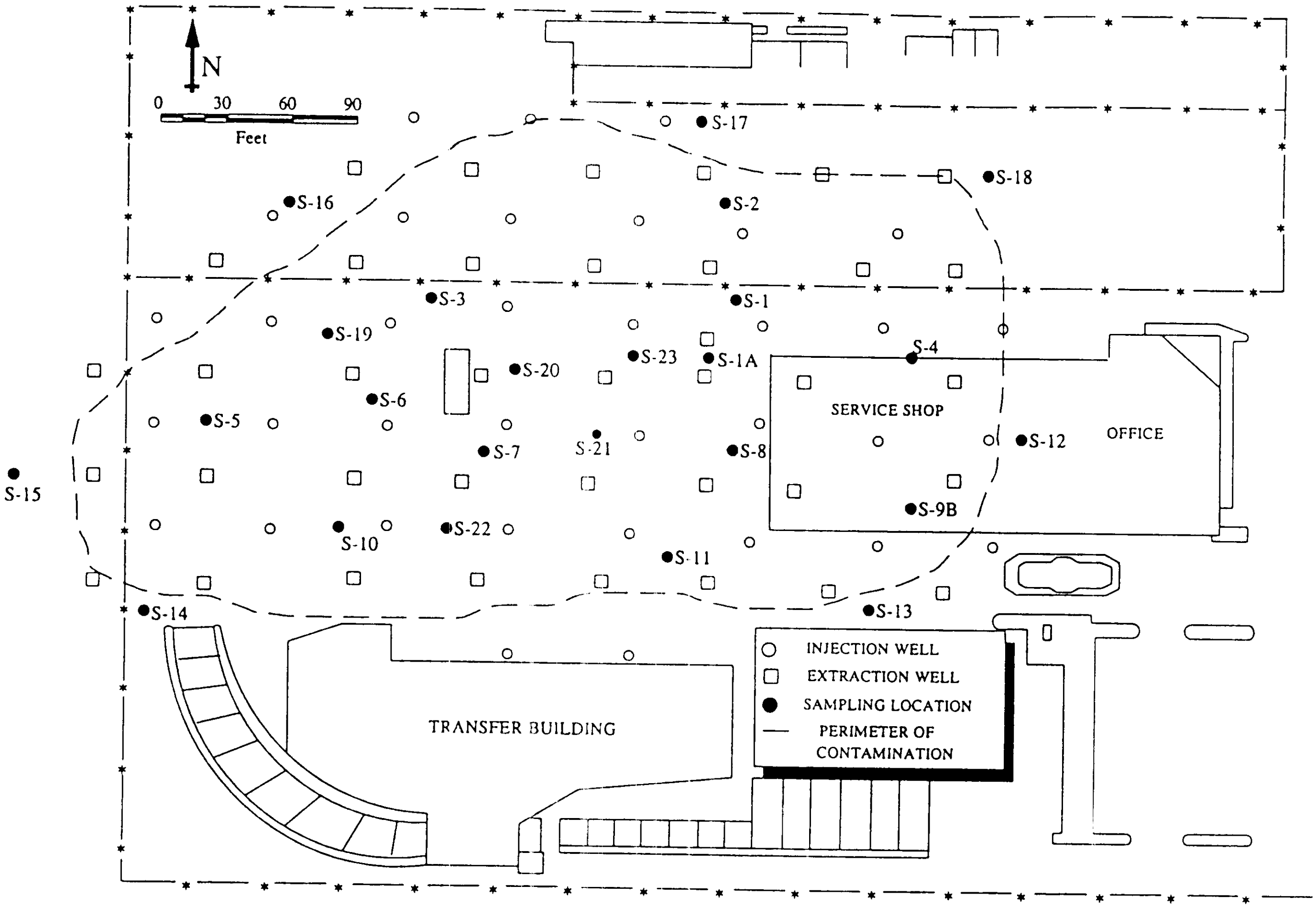


Figure 4-1. Pre- and Post-Treatment Sampling Locations at the Rainbow Disposal Site

It was originally estimated that between 70,000 and 135,000 gallons of No. 2 diesel were released into the site [7,8]. Free product was present in most monitoring wells screened above 40 feet in the zone of contamination. Approximately 4,000 gallons of free product were pumped from these wells, along with the groundwater from the perched aquifer, during well installation [7,8]. The perched aquifer remained drawn down throughout treatment with SERP.

Because the services provided by Rainbow Disposal were indispensable in the community, and operations could not be resumed at a different location, Rainbow Disposal required a remedial technique that could clean up the site without completely disrupting the ongoing operations. *In situ* SERP was selected because of the developer's claims that major excavation of soil would not be required and that the technology could be installed and operated below the soil surface.

The SITE Program became involved with the Rainbow Disposal site after most of the preliminary investigation had occurred and the remedy had been selected for the cleanup. The SITE Program was involved with an evaluation of steam injection technology at another site, and saw the concurrent evaluation of the full-scale SERP technology during the Rainbow Disposal site remediation as an excellent opportunity to gain additional knowledge of steam injection technology.

4.1.2 Treatment Objectives

The objectives for the cleanup at the Rainbow Disposal site were driven by the requirements of the lead regulatory agency, the Regional Water Quality Control Board (RWQCB). The soil cleanup level for the site was determined based on risk assessment, and was set at 1,000 mg/kg (ppm) of TPH as determined by the diesel fraction analysis of the California LUFT method. Additionally, the RWQCB required that the technology should not cause further spread of the diesel fuel into otherwise unimpacted areas adjacent to or below the contaminated strata.

There were two critical objectives for the SITE Program Demonstration of the SERP technology: (1) to evaluate the ability of the technology to meet the cleanup requirement set by the RWQCB for the site soil, based on soil sampling results; and (2) to perform a detailed economic analysis of this full-scale application of the technology.

Comparison of pre- and post-treatment soil data was performed only for informational purposes. The determination of contaminant removal efficiencies could not be designated as a critical objective because the SITE Program was not involved with the Rainbow Disposal site remediation at the beginning. Pre-treatment sampling was conducted at the site by the developer prior to the completion of a SITE Program Quality Assurance Project Plan (QAPP) for the Demonstration.

4.1.3 Treatment Approach

The technology was configured to treat the entire contaminated area (2.3 acres to a depth of approximately 40 feet) simultaneously. Since it was known that some portions of the site were much more contaminated than others, the technology could be and was adapted during treatment to try to focus the action of the steam and vacuum on portions of the site which required additional treatment, while shutting down the process in portions of the site presumed to be clean. Quarterly soil sampling and analysis was conducted by the operator and helped to guide the operation.

4.2 TESTING METHODOLOGY

The pre-treatment soil sampling borehole locations were selected and sampled by the technology developer with input from the SITE Program. Twelve boreholes were drilled within the treatment area. These are marked on Figure 4-1 as boreholes 1 through 12. Several sample borehole locations were selected in the area of the spill zone. Other borehole locations were selected based on the known distribution of site contamination and the configuration of the technology such as in areas that might be expected to have greater or lesser cleanup efficiency based on the anticipated steam flow pattern. Vertical sampling locations within each borehole were selected during sampling based on lithology and readings from a hand-held organic vapor analyzer; one to four samples were collected from each borehole for laboratory analysis. Samples were collected at discrete depths up to 40 feet below ground surface. One of the designated pre-treatment sample borehole locations was not sampled due to underground obstructions.

A total of 24 soil samples were collected during pre-treatment sampling. The soil samples for laboratory analysis were collected in brass tubes six inches in length and two inches in diameter. Pre-treatment soil samples were analyzed for total petroleum hydrocarbons (TPH—diesel fraction) and BTEX. A small number of samples were also analyzed for semivolatile organic compounds (SVOCs) to check for the presence of polynuclear aromatic compounds typically found in diesel.

The sampling and analysis plan for post-treatment soil sampling was designed based on pre-treatment soil sampling data and other site characterization information. The number of borehole locations and samples were determined based on a geostatistical analysis of pre-treatment data. Geostatistical methods were also used to evaluate post-treatment soil sample data. A total of 72 samples from 24 boreholes were collected after treatment. Twelve of these boreholes were located adjacent to the 12 pre-treatment borehole locations, including the borehole location that was not sampled. These paired boreholes were within three to four feet of each other. Samples from the paired post-treatment boreholes were collected from the same depths as those for pre-treatment, and also from additional depths. Within the perimeter of contamination, primary samples were collected at two to four discrete depths up to 40 feet below ground surface.

Seven of the post-treatment boreholes (numbered 12 through 18 on Figure 4-1) were located outside of the established perimeter of contamination in areas that were known to be clean or had levels of contamination less than 200 mg/kg of TPH. Two samples with depths between 25 and 40 feet were collected from each of these boreholes in order to detect any lateral off-site migration of contaminants during treatment.

The remaining five post-treatment borehole locations were in areas of the site that were determined to be under-represented in the pre-treatment sampling. The locations of the post-treatment boreholes in relation to landmarks on the site and the contamination perimeter are shown in Figure 4-1. On the scale of this drawing, the pre-treatment boreholes correspond directly to those for post-treatment with the same numbers.

Because in-place soil contamination can be highly variable, triplicate sampling was performed to assess the contaminant variability over short distances. To accomplish this, duplicate and triplicate samples were collected at six primary sample locations. The specific locations for triplicate sampling were selected randomly prior to treatment. The triplicate samples were collected vertically within an 18-inch split spoon sampler in separate brass sleeves. Six three-inch-long sleeves were used in the split spoon to collect the soil. The first, third, and fifth sleeves were used for TPH and TRPH analysis, while the remaining sleeves were used for BTEX analysis. Each sample was analyzed separately to allow the variability inherent in the soil matrix to be statistically determined.

Samples collected after treatment were analyzed for TPH, total recoverable petroleum hydrocarbons (TRPH), and BTEX. The analysis of TRPH was conducted in addition to TPH because TRPH is an approved EPA method, while TPH, though widely used, is a California state method and is not an approved EPA method. The TPH method (modified SW-846 Method 8015) analyzed extractable petroleum hydrocarbons by Gas Chromatograph/Flame Ionization Detector. Methylene chloride is used in this method to extract the sample. The TRPH method (EPA Method 418.1) used an infrared instrument to analyze petroleum hydrocarbons. Fluorocarbon-113 is used in this method to extract the sample. The analysis of BTEX was required by the RWQCB even though BTEX compounds were only present in a few of the pre-treatment soil samples.

SVOCs were not positively identified in the pre-treatment samples due to their low levels in the soil and to matrix interferences from the high levels of TPH. Therefore, analysis for SVOCs was not performed for post-treatment samples, and no conclusions can be drawn about their removal by the technology.

Quality assurance and quality control samples, including equipment blanks and trip blanks were also collected and analyzed during the post-treatment sampling event to ensure that the data was of good and known quality. Matrix spike and matrix spike duplicate samples were analyzed for all three analytical parameters. Quality control standards were also analyzed.

Groundwater conditions were beyond the scope of the SITE Program SERP technology evaluation, and groundwater samples were not collected for this purpose. Due to regulatory requirements, the technology operator performed routine monitoring of the confined groundwater aquifer. According to the operator, this routine monitoring detected no degradation of groundwater quality during use of the SERP technology.

4.3 PERFORMANCE DATA

4.3.1 Soil Sample Analyses

Table 4-1 presents the post-treatment soil sampling results for TPH and TRPH. Based on analysis of the post-treatment TPH and TRPH data, removal of contamination by the SERP technology was less complete than expected. Forty-five percent of the post-treatment soil sample results inside the treatment area were above the cleanup criterion of 1,000 mg/kg TPH. Seven percent of soil samples had TPH concentrations in excess of 10,000 mg/kg.

No BTEX was detected in any of the post-treatment samples. The analytical detection limit was 6 μg/kg. This may be an indication that the SERP technology was effective in removing these compounds because BTEX compounds were found at low mg/kg levels in a few pre-treatment soil samples. However, this finding is not conclusive. There were no cleanup criteria established for BTEX compounds in soil.

Results of the analysis of triplicate samples were highly variable, showing that the site contamination was heterogeneous even over small vertical distances (approximately three inches). Table 4-2 presents the triplicate sample results and associated statistics.

A geostatistical analysis of the post-treatment soil data was conducted using a "nearest neighbor" approach on a computerized model to assess the spatial variability of soil contamination and to determine a weighted average of the soil results. The use of this geostatistical approach results in the calculation of a more "unbiased" estimate of the true average level of contamination for the site as a whole. This is particularly true when there is no pattern of spatial correlation such as low spatial variability at short distances and high spatial variability at longer distances for soil contamination, as was determined to be the case at the Rainbow Disposal site [9]. Based on the

Table 4-1. TPH AND TRPH RESULTS FOR POST-TREATMENT SOIL

Boring	Depth (ft)	TPH (mg/kg)	TRPH (mg/kg)	Boring	Depth (ft)	TPH (mg/kg)	TRPH (mg/kg)
1	16.5	21	60	19	28	41	214
1	26.5	31,800	12,500	19	32	351	686
1	30	5,640	1,430	19	38	232	232
1	35	3,500	1,100	20	30	1,880	1,610
1A	15	4.3	<24	20	34	21,600	1,690
1A	25	344	108	20	41	2.8	307
1A	30	6,090	5,570	21	30	10,900	25,400
1A	35	2,270	4,570	21	35	9,080	9,740
2	32	670*	187*	21	40	1,020	952
2	35	960	376	22	31	14	151
3	32	392	190	22	37	177	96
3	38	4.2	<27	22	42	628	291
4	30	6,800*	2,000*	23	20	5.5	<20
4	38	1,800	604	23	30	6,100*	6,100*
5	30	11	<26	23	38	438	770
5	35	5,160	113	Outside Treatment Area			
5	38	7,910	8,110	12	33	3.6	<20
6	32	1,080	542	12	39	4.2	82
6	40	1,700*	1,400*	13	32	7.8*	<40*
7	25	8.3	<22	13	38	4.8	<20
7	35	9,330	12,900	14	30	4.2	<20
8	31	3,360	2,000	14	40	4.4	<20
8	43	15	164	15	31	35	<20
9B	25	2.6	43	15	36	369	228
9B	32	3.4	<20	16	35	6.3*	<42*
9B	37	8.5	<20	16	39	4.3	<20
10	30	69*	<55*	17	31	3.2	<20
10	37	1,360	762	17	36	3.3	<20
10	40	3,260	592	18	30	4.1	<20
11	30	1,880	348	18	35	6.2	74
11	35	807	141				

* Average of Triplicate Results   < Not detected at detection limit shown

Table 4-2. RESULTS OF TRIPLICATE ANALYSES FOR TPH AND TRPH

Borehole Number	Depth (ft) and designation	TPH Results (mg/kg)	TRPH Results (mg/kg)	Standard Deviation of TPH Results (mg/kg)	Standard Deviation of TRPH Results (mg/kg)
2	32 primary	674	80	230	100
	duplicate	120	161		
	triplicate	312	321		
4	30 primary	12,400	1,450	5,000	2,400
	duplicate	239	259		
	triplicate	7,710	5,820		
6	40 primary	590	1,150	1,400	770
	duplicate	3,680	2,460		
	triplicate	863	638		
10	30 primary	82	<20	47	>50*
	duplicate	5.6	<20		
	triplicate	118	127		
13	32 primary	3.3	<20	4.6	>29*
	duplicate	14	81		
	triplicate	5.9	20		
16	35 primary	5.3	<20	2.1	>30*
	duplicate	9.2	85		
	triplicate	4.5	<20		
23	30 primary	5,090	5,830	1,300	190
	duplicate	5,320	6,230		
	triplicate	8,010	6,230		

< Not detected at the detection limit shown

* Calculated using non-detect results at the detection limit. Actual standard deviations may be slightly higher.

geostatistical analysis, the post-treatment weighted average soil TPH concentration is 2,290 mg/kg, with a standard error of 784 mg/kg. Based on an approximate normal distribution for the weighted average, the 90 percent confidence interval for TPH concentration is 996 mg/kg to 3,570 mg/kg. This large interval is because of the variability of site soil sampling results due to the heterogeneity of the *in situ* soil; analytical variability was within established quality control limits and contributed little to overall data variability. According to this analysis, at 90 percent confidence, the true average may be below the cleanup criterion of 1,000 mg/kg, but this represents a small probability. Therefore, with almost 90 percent confidence, the average concentration of the site soil after treatment with SERP is above the cleanup criterion.

The geostatistical analysis results for TRPH yielded a weighted average concentration of 1,680 mg/kg, with a standard error of 608 mg/kg. The 90 percent confidence interval for the weighted average for TRPH is 676 mg/kg to 2,680 mg/kg. The calculated weighted average and confidence interval for TRPH are lower in magnitude than for TPH. No TRPH cleanup criteria were set for the Rainbow Disposal site.

Samples collected from areas outside the perimeter of contamination (those numbered 12 through 18) were analyzed for TPH, TRPH, and BTEX. Only one of the 12 samples collected had TPH levels higher than 200 mg/kg, the limit used to determine whether lateral migration of contamination due to treatment with SERP had occurred. Since this one sample was less than twice the limit, and the variability found in samples from the site was so great, this result is not felt to indicate that any significant lateral migration had occurred. Additionally, of the remaining perimeter samples, only two contained greater than 10 mg/kg TPH and many contained levels less than 5 mg/kg, which was the achieved detection limit during the original site survey. TRPH results for samples collected outside the perimeter of contamination were similar to TPH results. BTEX compounds were not detected above the 6 μg/kg detection limit.

4.3.2 Comparison of Pre- and Post-Treatment Conditions

A secondary (non-critical) objective of the Demonstration was to determine a removal efficiency (or percent removal) by comparing pre- and post-treatment sample analysis data. Percent removal was calculated for TPH only, since no pre-treatment TRPH data exists, and only three of the pre-treatment samples contained detectable amounts of BTEX. Percent removals calculated for each set of paired boreholes are shown in Table 4-3. Percent removal was calculated as:

$$\frac{\text{Pre-treatment Concentration} - \text{Post-treatment Concentration}}{\text{Pre-Treatment Concentration}} \times 100$$

Direct comparison of the paired borehole sample TPH results shows great variability for the data set. This pairing analysis is of limited value because of the high spatial variability associated with the *in situ* soil contamination. Samples from paired boreholes were located within three to four feet of each other laterally and at the same depth; however, triplicate sample results over much shorter distances (18-inches) showed variability as high as those between the pre- and post-treatment paired boreholes. Some areas seem to show good or moderate reduction in contamination, while other areas show increases in contamination, some of them rather large. These results are supported by Figure 4-2 which presents the pre- and post-treatment data sets in a histogram showing the percent of samples in incremental concentration ranges.

Due to the high spatial variability of the *in situ* soil contamination at this site, a more valid approach to determine a removal efficiency is to pool pre- and post-treatment data sets for comparison. To accomplish this, weighted average concentrations of TPH in the soil before and after treatment were compared. A weighted average TPH concentration in the soil before treatment was calculated using geostatistical modeling (nearest neighbor approach) as was done for the post-treatment data. The weighted average pre-treatment concentration was calculated to be 3,790 mg/kg with a standard error of 2,340 mg/kg. Since the distribution of the pre-treatment weighted average did not conform to a normal distribution, the confidence interval on this

Table 4-3. PERCENT REMOVAL FROM BOREHOLE PAIRS

Borehole	Depth (ft)	Pre-Treatment TPH Concentration (mg/kg)	Post-Treatment TPH Concentration (mg/kg)	Percent Removal (%)
1	15	3,480	20.5[a]	99
1	25	11,300	31,800[b]	0
1	30	4,870	5,640	0
2	35	1.3	3,500	0
3	32	728	392	46
4	30	3,860	6,800[c]	0
5	30	2,240	11.4	99
5	35	325	5,160	0
5	38	312	7,910	0
6	32	2,800	1,080	61
7	25	10.6	8.3	22
7	35	39,100	9,330	76
8	43	469	12.3	97
10	30	472	69[c]	85
10	37	3.2	1,360	0
10	40	72	3,260	0
11	30	165	1,880	0
11	35	810	807	0
1A	15	1.2	4.3	0
1A	25	4,180	344	92
1A	30	4,160	6,090	0
1A	35	1,380	2,270	0
AVERAGES		3,670	3,190[d]	13

[a] Post-treatment sample was collected at 16.5 feet
[b] Post-treatment sample was collected at 26.5 feet
[c] Average of triplicate sample results
[d] Average for post-treatment was calculated using all the post-treatment data in the treatment area, including data from boreholes which were not sampled before treatment.

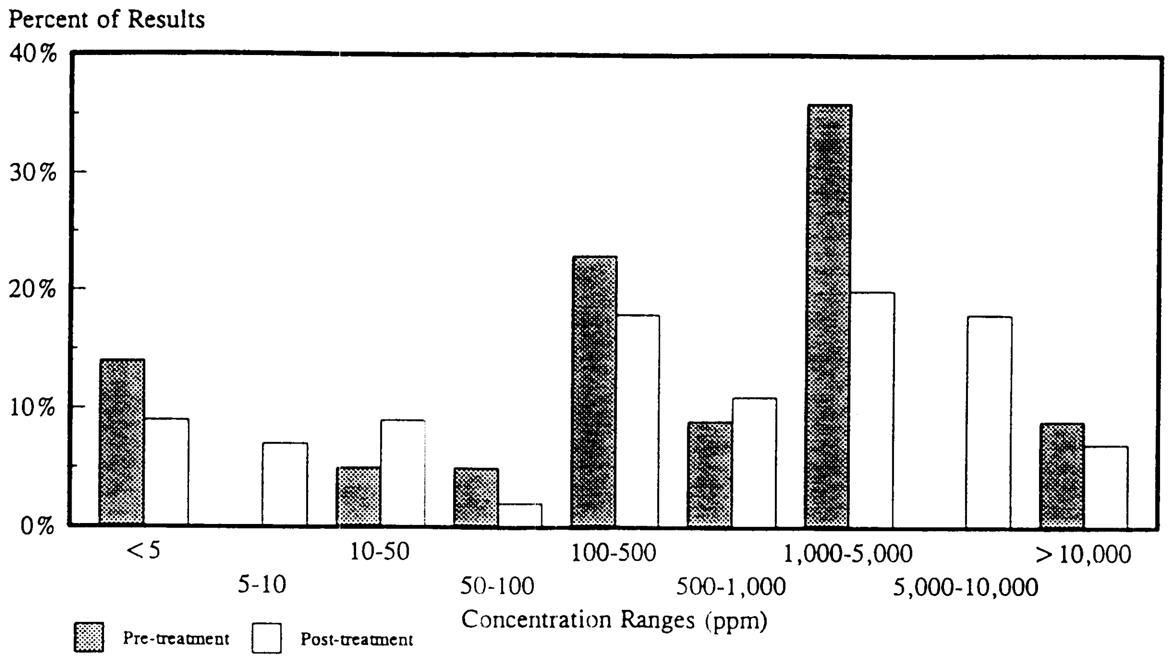


Figure 4-2. Histogram of Pre- and Post-Treatment TPH Concentration Data

average was calculated using a computerized "resampling" technique. This technique is often used to more accurately estimate confidence intervals for statistics with non-standard and non-normal distributions [10]. At 90 percent confidence, the calculated interval on this weighted average is 1,390 mg/kg to 7,290 mg/kg. This large range is due to the smaller number of pre-treatment samples collected and to the variability in the data set.

Comparing the pre-treatment soil TPH weighted average to the post-treatment soil TPH weighted average, the overall removal efficiency was calculated to be about 40 percent. Using the resampling technique to calculate the confidence interval, at 90 percent confidence, the percent removal could be significantly higher or lower. This large uncertainty about the exact removal efficiency is due primarily to the lack of sufficient pre-treatment sample measurements, and the resultant data set variability. (Pre-treatment data were collected by the developer before the preparation of the SITE Program QAPP.) According to process data, however, it is known that some diesel contamination was removed from the soil during treatment.

The amount of diesel recovered in the storage tank during treatment was measured and totaled approximately 700 gallons at the end of the project. This is much less than the amount anticipated to be collected when the system was designed and installed. Partly, this was due to the poor effectiveness of the process at treating the site soil. However, this was also due to design factors of the technology application including inadequate vapor stream condenser design. More diesel was removed through the vapor treatment system and oxidized in the TOU than was collected in the storage tank. Vapor concentration measurements taken at the inlet of the TOU over the course of treatment by the flame ionization detector (and the LEL meter before the FID was on line), along with the flow rate and inlet temperature, were used to estimate the amount of diesel which was removed in vapor form.

Based on these data, it was calculated that approximately 15,400 gallons of diesel were treated by the TOU. Therefore, a combined total of approximately 16,000 gallons of diesel were removed during treatment with SERP. This volume, compared with the initial estimate of the amount of fuel released (70,000 to 135,000 gallons [7,8]), less 4,000 gallons recovered prior to treatment with SERP, suggests that between 12 and 24 percent of the original spill volume was removed from the soil and treated above ground. This removal efficiency, based on diesel recovered and treated, although lower than the removal efficiency based on the soil data, is within the percent removal confidence interval for the soil data. It should be noted that vapor stream system measurements were not critical measurements for this Demonstration.

4.3.3 Soil Temperature Data

Twenty temperature monitoring wells in and around the treatment area were used to measure the soil temperature, determine the progress of the steam through the soil within the treatment area, and ensure that the steam flow stayed within the treatment area. The locations of all these wells are shown in Figure 4-3. Plots of the temperatures over time in selected wells are presented with a discussion of what these temperature plots may indicate about the operation of the process in different locations of the site.

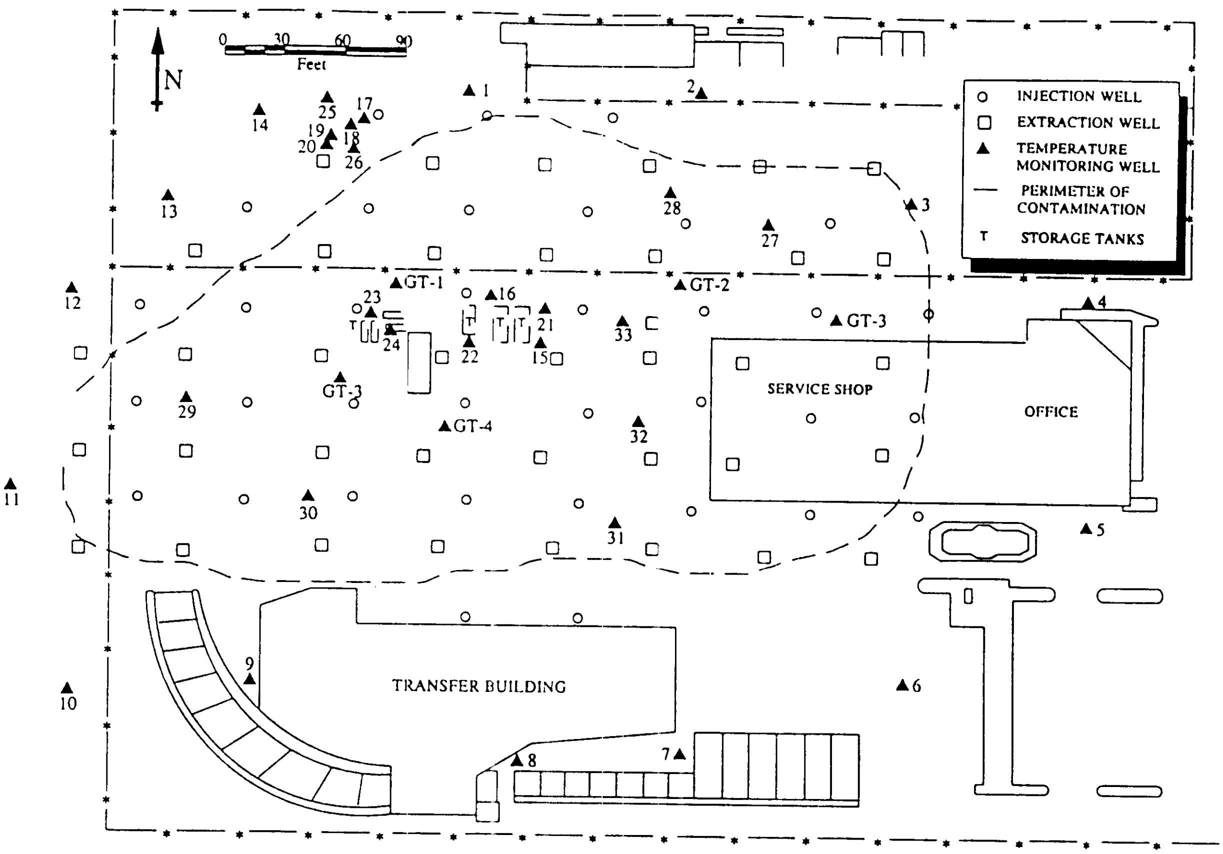


Figure 4-3. Temperature Monitoring Well Locations

Figure 4-4 is a plot of the temperature versus time at Well 15. This figure shows little heating of this area of the site at all depths. Since this well was close to underground tanks on the site, the injection and extraction wells in this area were not turned on until late in the remediation, at which time the area began to heat. Only the 30-foot depth appears to have reached the steam temperature, and only for a period of a few weeks. However, temperatures recorded at 20- and 40-foot depths were increasing during this time.

Figure 4-5 is a plot of the temperature versus time at Well 23, and Figure 4-6 is a plot of the temperature versus time at Well 24. As can be seen on the site map (Figure 4-3), Wells 23 and 24 are in a line between an injection well and an extraction well, with Well 23 being closer to the injection well. As would be expected from the process, the two figures seem to indicate a steam or heat front moving from the injection well towards the extraction well, since Well 23 heated up sooner than Well 24. No heating was seen at Well 23 until April 1992, which was

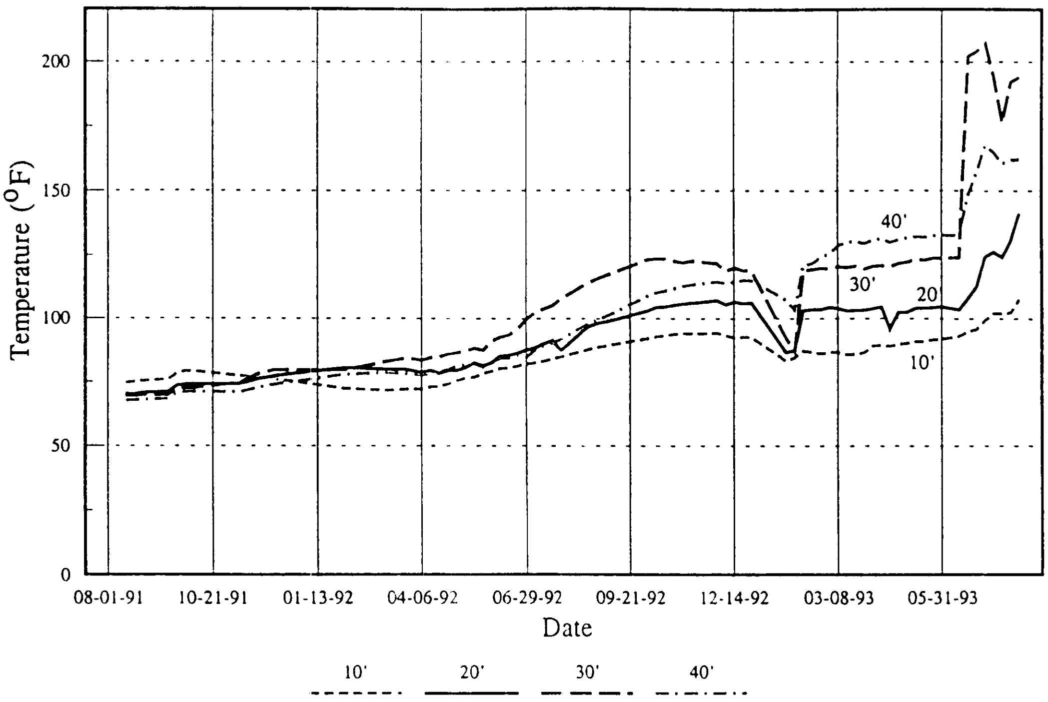


Figure 4-4. Soil Temperature Plot for Well Location 15

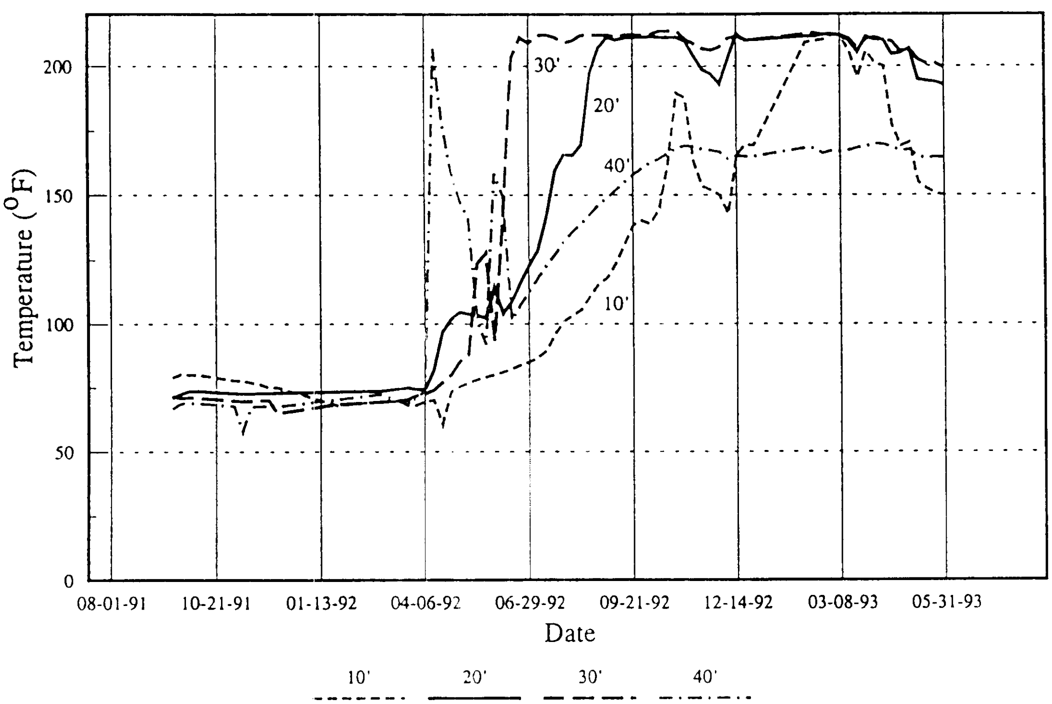


Figure 4-5. Soil Temperature Plot for Well Location 23

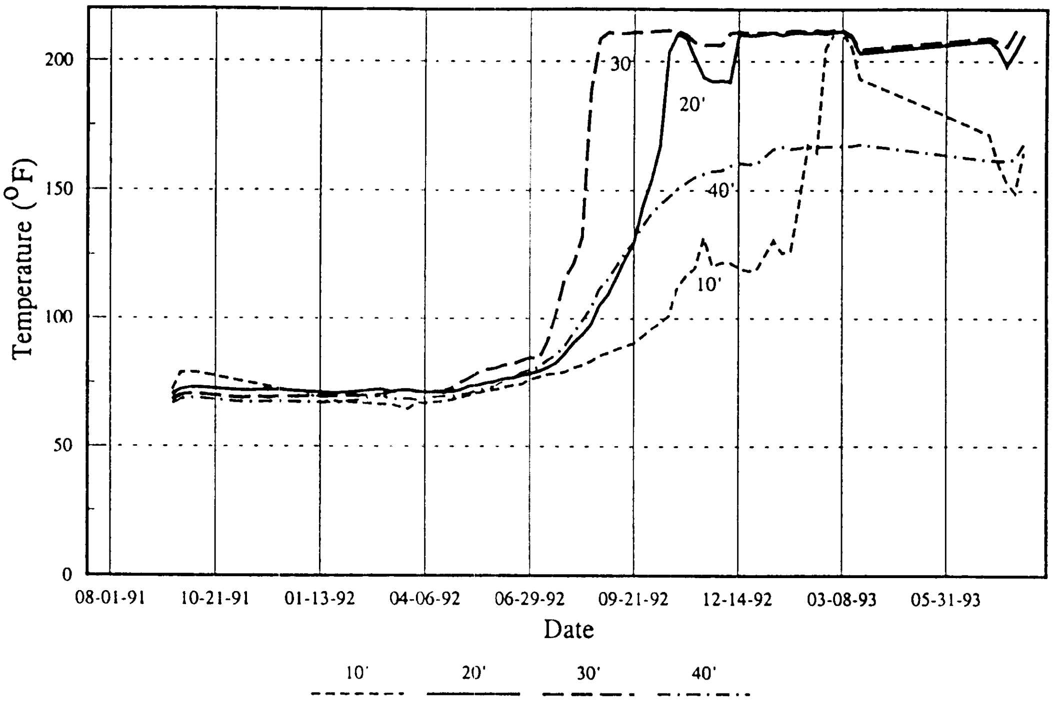


Figure 4-6. Soil Temperature Plot for Well Location 24

after the boilers had been recommissioned after lengthy downtime; Well 24 began heating in June 1992. In both these wells, as in many of the other monitoring wells, the 30-foot depth heated more effectively than the 20-foot depth or other depths. This indicates that the expected steam flow pattern was established, from the injection interval (30 to 40 feet) to the higher extraction interval (10 to 35 feet). Slower and more gradual heating at the 40-foot depth may be due to the upward flow pattern developed, the influence of the cooler soil below, or to the change in soil type near the bottom of the treatment zone.

Figure 4-7 shows the temperature profile for Well 27. Temperature probes were placed at different depths in this well than in many of the other wells, showing more detail in the middle depths. This graph shows a similar pattern of heating to that of Well 23, indicating that many parts of the site started heating to steam temperature at the same time (April 1992). The steam front reached this location at the same time for depths between 15 and 27 feet and slightly later

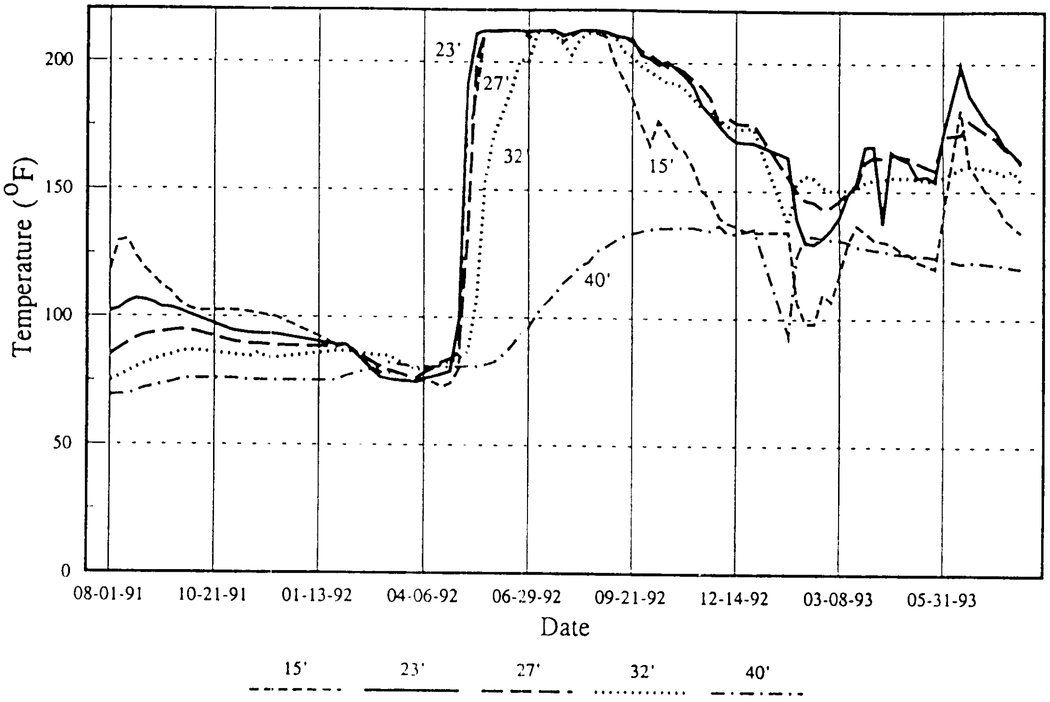


Figure 4-7. Soil Temperature Plot for Well Location 27

for the 32-foot depth. The shallower depth of the initial steam front shown in this well could have been caused by many factors, including soil types. Another reason for a different flow path at this location is that this temperature well is located between pairs of the same type of process well, rather than between an injection/extraction well pair as was the case for Wells 23 and 24.

Figure 4-8 is a temperature plot of Well 30, which is located further away from the spill zone than the wells discussed previously. This plot shows a slightly different pattern of heating. In October 1991, this location had nearly reached the steam temperature for all but the 10-foot depth. Then the soil began to cool off, coinciding with the extended boiler problems experienced in the winter of 1991/1992. Reheating in this location began in April 1992. However, the second time the soil was heated, the temperature increased less rapidly. It is possible that the initial steam front changed the soil (e.g., porosity or moisture content) which then retarded reheating of the soil. If this is true of treatment with SERP, then intermittent operation could be very

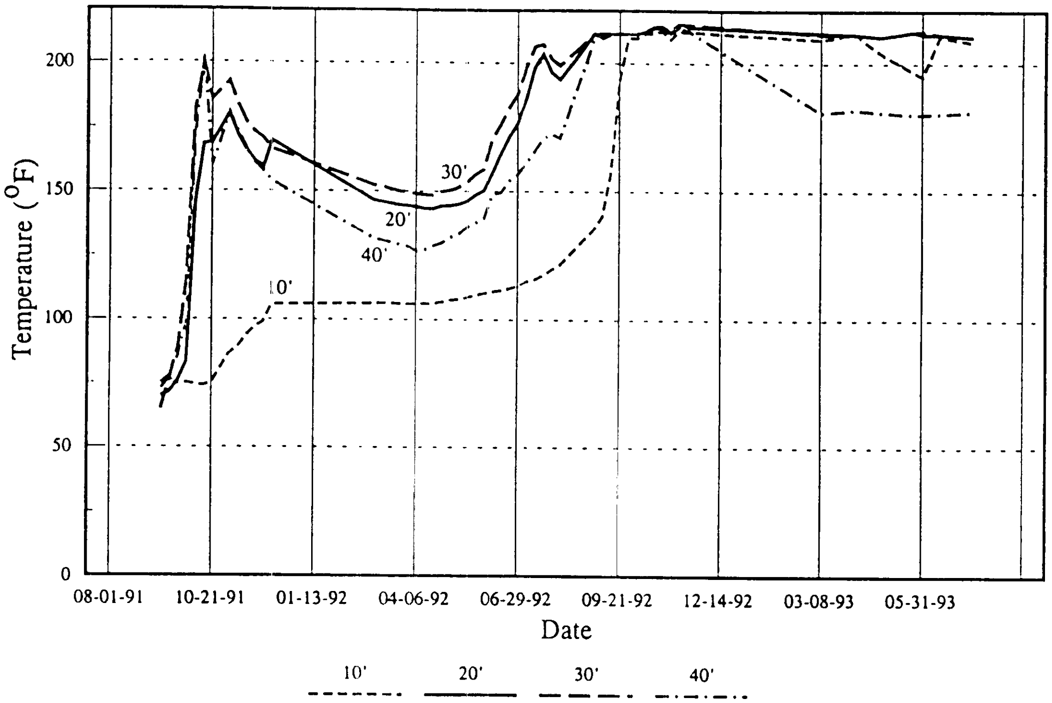


Figure 4-8. Soil Temperature Plot for Well Location 30

inefficient, and reduction of downtime critical to effective operation. However, this area of the site did stay heated after the steam temperature was reached again.

Figure 4-9 is a plot of the temperature at Well 33, which is near Well 15 and the location of the initial diesel spill. The heating in this area was slow initially, and then intermittent for the rest of treatment. A significant increase in temperature in this location was not seen until late June 1992. Well 33 is near two extraction wells, and began heating about the same time as well 24 which was also near an extraction well. This again seems to demonstrate the movement of a steam front from injection to extraction well areas. The temperature fluctuated in Well 33 until the fall of 1992 when it reached the steam temperature. The fluctuating temperature pattern may have occurred because a nearby injection well was turned off for much of the treatment time to protect the underground tanks. Also, since this temperature well is near two extraction wells, the operation of the vacuum may have caused the soil to cool. The poor heating of this area,

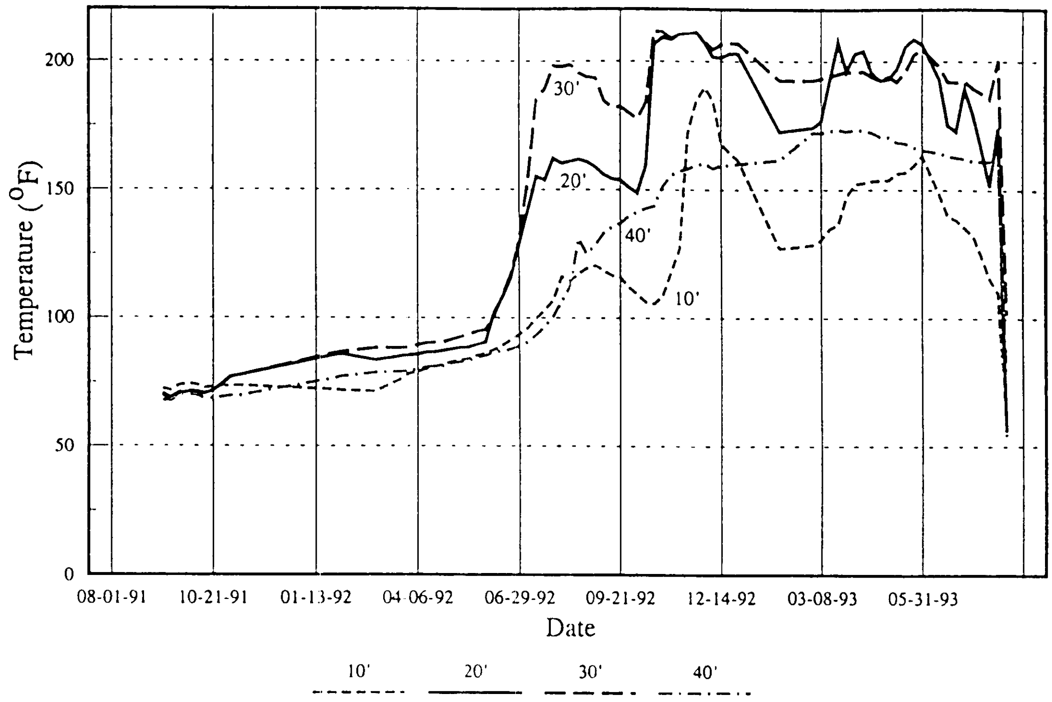


Figure 4-9. Soil Temperature Plot for Well Location 33

especially at the lower and higher depths (10 feet and 40 feet) may have led to poor treatment; two nearby sample locations (S-1A and S-23) showed high levels of contamination after treatment. However, the variability in soil concentration data limits this conclusion.

The last temperature graph shown here, Figure 4-10, is the temperature profile for Well 20. This plot is also representative of Wells 17, 18, 19, 25 and 26 since they are located close together. These wells were installed in a test plot used during shakedown testing of the process and equipment. The wells in this location reached high temperatures sooner than other wells because this area was treated much earlier and more intensely than the rest of the treatment area. The temperatures recorded at Well 20, especially at the 20- and 30-foot depths, approximately parallel to the operation of the process. Major downtime, which occurred over the winter of 1991/1992 and in the fall of 1992, is seen on the plot where the soil starts to cool. Injection wells near this location were shut off in early 1993 to focus the operation elsewhere, which can also be seen in the cooling of the soil near the end of treatment.

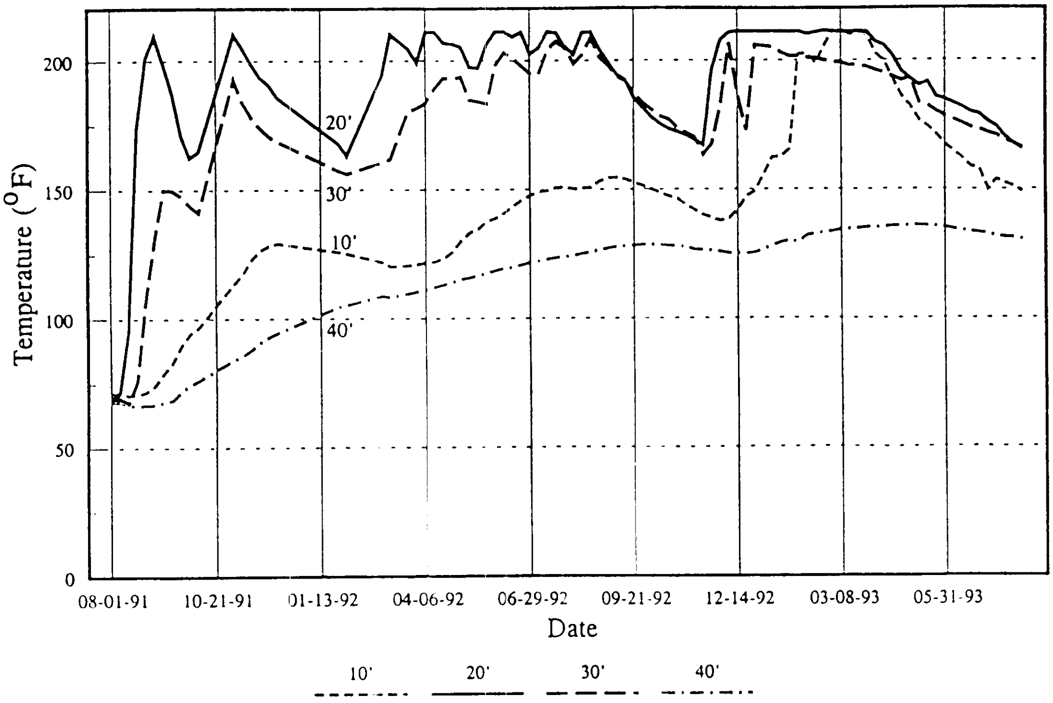


Figure 4-10. Soil Temperature Plot for Well Location 20

From the examination of the soil temperature profiles, several general conclusions can be drawn about the operation of SERP at the Rainbow Disposal site. Heating of the soil took much longer than originally anticipated, and high soil temperatures needed to effect contaminant removal were not maintained in many areas. This may have been due to the way the process was operated initially and to excessive operational downtime. The steam flow patterns expected to occur in the soil did seem to occur, including the development of a steam front which moved from injection wells to extraction wells and from the injection depth upward towards the extraction depth. Inspection of the temperature data collected also suggests that additional temperature monitoring wells over the entire treatment area would have been useful in monitoring and operating the process, which could have improved the remediation overall.

4.3.4 Additional Process Data

Figure 4-11 is a graph of the monthly water use, based on flow totalizer readings, and monthly diesel extracted from the soil in the vapor phase, calculated from FID and LEL readings of the inlet vapor to the TOU. FID readings are only available from June 1992; LEL readings were used for months before that. These two process measurements help to describe the operation of the process. For example, the water used in a month indicates the amount of time the boilers were operating that month and is therefore representative of the energy input to the soil in the form of steam. Major equipment downtime occurred in the winter of 1991/1992, and in the spring of 1993, which is shown by decreases in water use in this graph.

The calculated volumes of diesel recovered show the removal of hydrocarbons from the soil by the technology, since most of the contaminant removed remained in the vapor phase. The volume of diesel removed per month was dependent on several process factors including the temperature of the treated soil, the amount of vacuum drawn on the soil, the number of extraction wells in operation, and the number of hours in operation. It can be seen from the

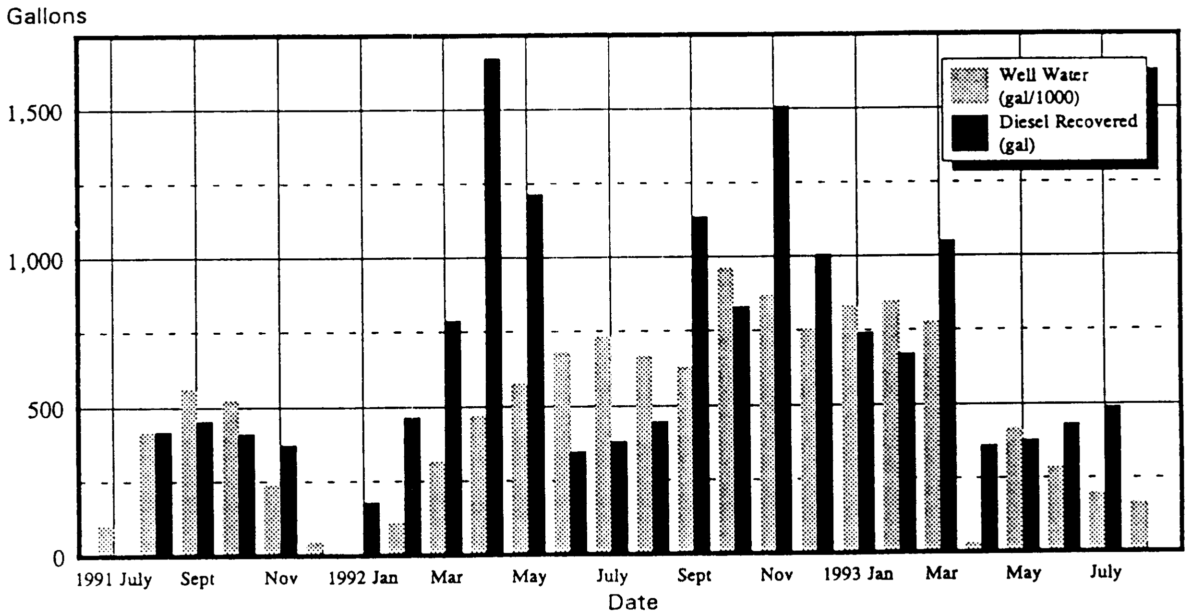


Figure 4-11. Well Water Usage and Diesel Recovered at the Rainbow Disposal Site

graph that a rapid increase in the diesel recovery occurred in April of 1992. Temperature monitoring well graphs showed that the site was near or at steam temperature at this time after the lengthy process downtime. Diesel recovery is lower after May of 1992, probably due in part to intermittent TOU problems. Another reason for the decrease in removal may be because an initial front of easily mobilized contaminant had been removed in April and May, leaving more tightly bound contamination in the soil.

In October and November 1992, shortly after process operation was changed to a 24-hour per day cycle, another peak hydrocarbon removal was reached. The removal remained high for several months. When the removal dropped off, the operator felt this indicated that parts of the site were becoming clean, and therefore started to turn off some of the injection wells in order to concentrate the treatment on areas known to be more contaminated.

Each time a group of wells were shut off, this resulted in a small increase (peak) in removals due to the effect of concentrating the steam and vacuum on a smaller, more contaminated area. These smaller peaks, which cannot be distinguished on the monthly diesel recovery graph, taper off more quickly than the original peak in October.

4.3.5 Reliability

The SERP system experienced many operational problems during the two-year treatment period. The actual on-line efficiency during this period was determined to be about 50 percent based on operational logs. Both of the boilers had operational downtime, frequently simultaneously, which delayed the heating of the soil. The boiler downtime was due to structural, mechanical, and electrical problems, and in approximately a half-dozen instances resulted in downtime of several weeks or more during repairs. Intermittent operation of the boilers probably contributed to these problems. The change from 16-hour- to 24-hour-per-day operation lessened the thermal shock on the boilers from frequent starting and stopping and helped to prevent further problems. Some boiler problems could be traced to emission reduction devices required by regional air quality regulations. These devices may not need to be used on sites in other areas.

The TOU also experienced several operational failures and significant amounts of downtime over the course of the project. Because of the high operating temperatures inside the unit, several days were required to cool the unit before repair work could be performed, and then at least 24 hours of heating were required to bring it up to operating temperature. Internal components of the TOU failed in part due to the high humidity in the vapor stream being oxidized. A more effective vapor condensing system in front of the TOU might have helped to prevent or minimize these problems. Alternately, a vapor treatment technology less sensitive to moisture could have been selected for use with the technology.

Other reliability and maintenance problems occurred over the course of the project, including breakage or malfunction of well headers, hoses, and valves. At the Rainbow Disposal site, two factors were significant in increasing the amount of system maintenance and repair required. The installation of all the process wells below grade on the active portion of the facility made it more difficult to locate problems until they had become significant. Also, the remediation took almost three times as long as originally planned, so many of the parts had reached the end of their useful service life before the end of the project.

Because this was the first full-scale application of the technology, it is believed that more operational problems occurred here than would occur after additional experience has been gained with the technology. Lessons learned from this application will also assist in minimizing equipment and operational problems with subsequent systems.

4.4 RESIDUALS

Residuals from the SERP treatment which required disposal or further handling are described in this section. Drill cuttings were produced every time a borehole was drilled for installation of process wells or for a sampling event. On the average, two 55-gallon drums of drill cuttings were generated for each 40-foot borehole drilled using an eight-inch auger. Some sampling events were conducted with smaller augers, generating fewer drill cuttings. Samples were collected from each borehole to determine whether the drill cuttings contained detectable levels of diesel fuel. Uncontaminated drill cuttings were redeposited on the site as fill. Approximately 230 drums of drill cuttings were generated during the technology mobilization, treatment, and post-treatment sampling. An estimated 40 percent of these drums (92) were considered contaminated and required off-site disposal.

The effluent from the process wastewater treatment system can also be considered a residual from the process. Approximately 1.6 million gallons of water were treated by the wastewater treatment system and discharged to the storm sewer. At a site with some highly regulated or difficult to treat contaminants, the use of a storm sewer for the discharge of the process wastewater might not be appropriate. For this case, discharge to a POTW might be an option. More rigorous on-site treatment, or off-site disposal, might also be necessary for disposing of the wastewater effluent.

The SERP wastewater treatment system at the Rainbow Disposal site included 5-micron filters and activated carbon beds, which needed to be replaced when blinded or exhausted. The filters and carbon were another source of residuals from the system. One change of the carbon beds was required during treatment, and another at the end of treatment. A total of nineteen 55-gallon drums of spent carbon were generated from the beds when they were replaced. The used carbon was sent off-site to be regenerated or landfilled. Regeneration might be the more economical option, depending on the amount and types of contaminants that the carbon had been removing from the water. The 5-micron filters were mostly used to remove particulates and colloids from the water. Depending on the composition of the waste, these filters may or may not be considered a hazardous waste. The filters would then be disposed of accordingly in a municipal or hazardous waste landfill.

The SERP technology is designed to remove the contaminants from the soil and concentrate them for more efficient treatment or disposal. The effluent treatment system includes a gravimetric oil/water separator to remove most of the diesel from the extraction well liquids. The diesel was then collected in a storage tank. For this treatment about 4,700 gallons of diesel were collected. The recovered diesel was sent off-site for disposal or recycling. At other sites, the type of contamination present in the soil would determine the disposal options for the recovered liquid, which in some cases could be burned on-site as fuel. The recovered diesel could not be burned as a fuel at the Rainbow Disposal site due to air regulation requirements.

The oil/water separator also produced small amounts of sludge. This material was periodically removed, placed into 55-gallon drums, and sent off-site for disposal. Approximately ten drums of this material were generated during treatment.

The contaminated vapor from the extraction wells was oxidized in the TOU, which was designed to effect at least 99.99 percent destruction of the organic compounds. The resultant gas stream contained water vapor and carbon dioxide. This gas was released to the atmosphere through a stack. A site contaminated with other compounds, especially those containing sulfur or chlorine, might require further gas treatment.

Solid waste residuals produced from SERP treatment include used protective clothing and disposable tools. Depending on the contact these items have had with the waste materials, they can be disposed of as non-hazardous trash, decontaminated, or packaged in drums and sent to a hazardous waste landfill. At the Rainbow Disposal site, non-hazardous trash could be readily disposed of by the site owners. Potentially hazardous trash could be disposed of in the same manner as the contaminated drill cuttings. If it is necessary to remove well casings from the ground, these materials may also be disposed of as non-hazardous waste if they can be decontaminated, or as hazardous waste if they cannot be decontaminated.

SECTION 5
OTHER TECHNOLOGY REQUIREMENTS

5.1 ENVIRONMENTAL REGULATION REQUIREMENTS

Federal, state, and local regulatory agencies may require permits prior to construction and operation of the SERP technology. Most federal permits will be issued by the authorized state agency. Federal and state requirements may include obtaining a hazardous waste treatment permit or modifying an existing permit. Air emission permits may be required for any unit that could emit a hazardous substance. The Air Quality Control Region may also have restrictions on the types of process units and fuels that would be used. Local agencies may have permitting requirements for grading, well installation and abandonment, and health and safety. In addition, if wastewater is disposed of to the sanitary sewer, then the local water district would have effluent limitations and sampling requirements. Finally, state or local regulatory agencies may also establish cleanup standards for the remediation.

At the Rainbow Disposal site, federal and state permits included an air permit obtained from the South Coast Air Quality Management District for the construction and operation of the thermal oxidation system. The South Coast Air Quality Management District also placed restrictions on the model of boiler used for steam generation and the type of fuel allowed (natural gas). A NPDES permit was obtained from the Santa Ana RWQCB for discharge of the treated groundwater to the storm sewer system, and a Class V Underground Injection permit was obtained from the USEPA for injection of the steam. No hazardous waste treatment permit was required since the remediation involved spilled diesel product which is not considered a hazardous waste.

Local permits included various construction and operation permits from the Huntington Beach Department of Building and Safety, and permission to operate granted by the local Fire Department. The Orange County Health Care Agency required permits for the construction and abandonment of the groundwater monitoring, extraction, and injection wells. They also requested to be kept informed about the operations during the remediation activities.

5.2 PERSONNEL ISSUES

Full-scale application of a SERP system will probably necessitate 24-hour per day operation. At the Rainbow Disposal site, three technicians, a full-time site engineer, and a full-time site supervisor were required each week during 24-hour per day operation. At least one technician must be on hand at all times during operation to supervise the function of the boilers and other equipment. These technicians must be certified in boiler operation by the state in which they are operating. The technicians and other personnel must also be skilled in maintenance of machinery (such as pumps and blowers). Training in duties specific to the operation of SERP, such as collecting temperature data, will need to be performed during process operation.

A part-time secretary was required to order supplies, produce required reports, and handle other secretarial and administrative tasks. For SERP, Hughes Environmental had a parent company to which certain administrative duties were directed, and from which came administrative requirements for items like timecards and purchasing; additional administrative staff may have otherwise been needed.

During sampling events, a geologist and a sampling assistant were required to direct the drilling, collect the samples, and log the boreholes. Personnel present during drilling on a hazardous waste site must have current OSHA health and safety certification. Other personnel working on the site may also need this training, depending on the job description, site layout, and type of contamination. Personnel who work with hazardous substances or waste must also be enrolled in a medical monitoring program in accordance with OSHA regulations.

At the Rainbow Disposal site, the contamination was present below the soil surface. During typical operations, no contact was made with the contaminated material. Personal protective equipment for normal work functions included a hard hat and work boots for any personnel required to enter the equipment area or the active portion of the Rainbow Disposal site (required by Rainbow Disposal's Health and Safety policies). During drilling, digging, residuals handling, or other activities where contaminated or hazardous materials might be encountered, other equipment such as chemical resistant gloves and disposable coveralls were sometimes required. For other sites, the type and use of protective clothing would depend on job function, and contaminant characteristics and toxicity.

5.3 COMMUNITY ACCEPTANCE

A Visitor's Day meeting was held in March 1992 to distribute information to the public on the remediation project and on the SITE Program Demonstration of the SERP technology. The meeting included presentations by the developer and the EPA SITE project manager, and a brief tour of the site and technology. Participants in the Visitor's Day included regulatory personnel, remediation contractors, and members of the public. The turnout at the Visitor's Day was high, indicating strong interest in the SERP technology and its application for remediation at the Rainbow Disposal site.

The SERP technology works mainly underground, and contaminated soil excavation activities are minimized. This process limits the potential for human exposure to the contaminants in the soil, which may make the technology more acceptable to the local community. If the process is designed and applied properly, the contaminants will be kept within the treatment zone and will not migrate off-site or vaporize to the atmosphere. The technology is designed to operate more rapidly than other *in situ* technologies, thus limiting the duration of the disturbance to site neighbors. The ability to operate a commercial facility aboveground while the process is operating belowground can be very important, as was the case at the Rainbow Disposal site.

The process equipment used for SERP, including boilers and compressors, has the potential to be noisy. This can be somewhat mitigated through choices of equipment and appropriate installation. Drilling activities required for soil sampling and process well installation can produce both noise and dust. These disturbances are for a short duration and can be mitigated as appropriate to the situation.

Increases in traffic in the area are temporary and would include mobilization and demobilization of heavy equipment at the start and end of the project, and periodic mobilization of drill rigs. The technology requires a small crew of personnel for operation, so increases in daily traffic would be minimal. At the Rainbow Disposal site, the increases in traffic, dust, and noise were all negligible in comparison with the ongoing trash transfer activities at the site.

SECTION 6
TECHNOLOGY STATUS

6.1 PREVIOUS/OTHER EXPERIENCE

Technologies similar to *in situ* SERP have been investigated on a field-scale level at other contaminated sites. Most notably, a portion of a site contaminated by gasoline to a depth of about 135 feet was recently remediated with Dynamic Underground (steam) Stripping at the Lawrence Livermore National Laboratory in Livermore, California. The technology was successful in removing and recovering a significant portion of the gasoline contamination from more permeable unsaturated and saturated soil in the test area. Innovative techniques were applied to monitor the steam zone and control the process. Appendix A to this ITER presents a case study of the Dynamic Underground Stripping Process.

Since 1985, several small gasoline and diesel spill sites in the Netherlands have been treated using similar steam stripping methods [2]. Due to the shallow groundwater in that area, portable systems utilizing steam lances were used instead of permanent process wells.

At this time, other tests of steam injection technology are planned at sites contaminated with dense non-aqueous phase liquids such as trichloroethene. The ability of the technology to remediate sites contaminated with these denser-than-water compounds, without causing downward or off-site migration, will be a key evaluation objective for these tests.

6.2 SCALING CAPABILITIES

The SERP technology can be designed, within engineering constraints, to treat a large area to significant depths. Based on results from the full-scale application of SERP technology at the Rainbow Disposal site, the critical factor in scale-up from pilot- or field-scale to full-scale site remediation seems to be maintaining control of the *in situ* process. Insufficient subsurface temperature monitoring capability over the large treatment area (2.3 acres) and excessive equipment downtime contributed to inadequate process control and operation and incomplete remediation at the Rainbow Disposal site. To reduce downtime, major process equipment must be sized correctly for the full-scale application and must be designed to withstand the corrosion and wear from long-term treatment.

6.3 OTHER INFORMATION

Hughes Environmental Systems, Inc. operated the SERP technology at the Rainbow Disposal site; however, they are not vending the technology for use at other sites because they are no longer in the environmental remediation business. Since SERP uses commonly available process equipment, the technology can be designed and operated by other consultants knowledgeable in design and operation of the process. Similar *in situ* steam technologies may have patented process or monitoring equipment available only through the developers.

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APPENDIX A: Case Study

Dynamic Underground Stripping Process at Lawrence Livermore National Laboratory

The Dynamic Underground Stripping process, similar to the Steam Enhanced Recovery Process (SERP), was developed and operated by Lawrence Livermore National Laboratory (LLNL) in conjunction with the College of Engineering at the University of California, Berkeley. This process was used to recover gasoline contamination from an underground spill at LLNL. The process uses steam injection, vacuum extraction, and electrical heating to effect contaminant removal from soil and groundwater. In addition, underground imaging is used to monitor the process.

This case study is included here because it presents another application of a technology similar to SERP with different contamination and geologic conditions. The Demonstration of Dynamic Underground Stripping at LLNL was conducted and evaluated by LLNL personnel, with limited participation by the EPA SITE Program. Therefore, this study is only included in this report as an appendix.

The test site at LLNL was contaminated with leaded gasoline. Gasoline, being more volatile than diesel, is more readily removed by vapor extraction. Gasoline contamination existed in the vadose and saturated zones, and in permeable and low permeability soils, at the LLNL site. The geology of the LLNL test site is alluvial, and is highly variable from location to location.

A full-scale Dynamic Underground Stripping process was used at LLNL. Treatment was conducted with six injection wells encircling three extraction wells. These wells along with the EPA SITE Program post-treatment sampling borehole locations are shown in Figure A-1. An area of roughly 2,000 yd^2 down to approximately 135 feet was treated by the process. The treatment area was significantly smaller than at the Rainbow Disposal site, but the depth of treatment was much greater. Electrical heating was used to enhance the removal of contaminants from low permeability zones.

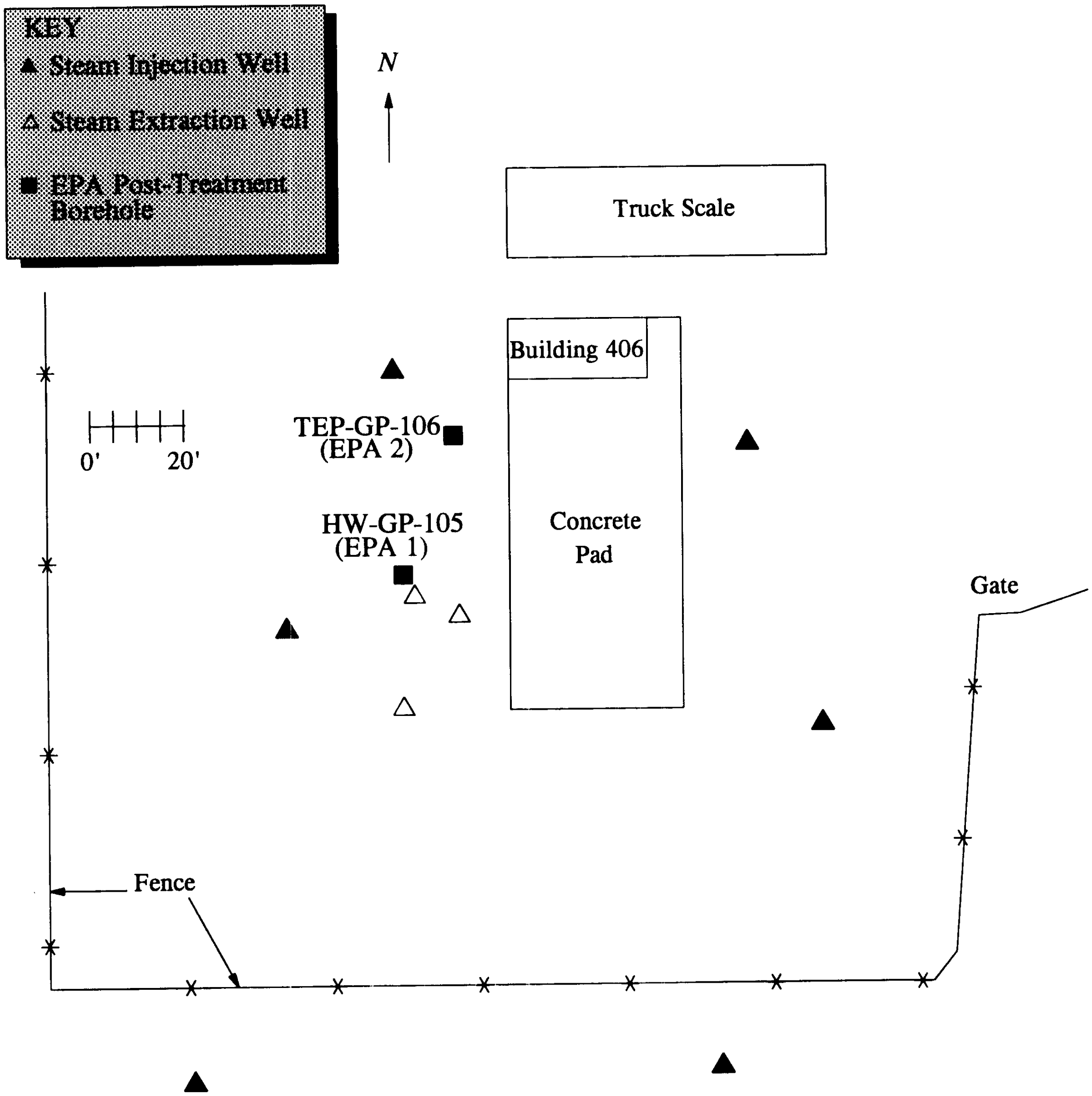

Figure A-1. Locations of Process Wells and Sampling Boreholes at the LLNL Site

The maximum total concentration of benzene, toluene, ethylbenzene, and xylenes (BTEX) recorded in the unsaturated zone before treatment was 4,800 ppm. The volume of soil with contamination in excess of one ppm of BTEX existed in an approximate cylinder, 60 feet in diameter, extending down to almost 135 feet.

Tables A-1 and A-2 present the results for the soil samples collected and analyzed by the EPA SITE Program after treatment with steam and electrical heating was completed. Soil samples from borehole #105 showed BTEX and Total Petroleum Hydrocarbons (TPH) contamination below the water table (100 feet). This borehole was located near the original spill point. Additional contamination was removed by vapor extraction after this sampling episode. Soil samples from borehole #106 had non-detectable values for BTEX and TPH. This borehole was located further from the original spill point.

The following document, "Summary of the LLNL Gasoline Spill Demonstration—Dynamic Underground Stripping Project" presents the LLNL results of the study. These results indicate that Dynamic Underground Stripping was very effective in removing gasoline contamination from groundwater and soil in the test zone. As indicated by the EPA SITE Program data above, this report shows that the process mobilized the contamination toward the center of the test site and significantly reduced the concentrations of contaminants overall.

There were several reasons why Dynamic Underground Stripping was more successful than SERP: the contamination had more volatile components, LLNL enhanced the treatment with electrical heating, LLNL used improved operational procedures, and LLNL used more effective monitoring of the steam zone for operational control.

Table A-1. POST-TREATMENT ANALYTICAL RESULTS FOR BOREHOLE #105

Depth (ft)	TPH (mg/kg)	Benzene (mg/kg)	Toluene (mg/kg)	Ethylbenzene (mg/kg)	Xylenes (mg/kg)
76.25	ND	ND	ND	ND	ND
82.00	ND	ND	ND	ND	ND
84.25	ND	ND	ND	ND	ND[X]
91.75	ND	ND	ND	ND	ND[X]
96.10	ND	ND	ND	ND	ND[X]
101.55	ND	ND	ND	ND	ND[X]
104.65	ND	ND	ND	ND	ND[X]
109.35	21	0.8	2.9	0.34	2.3[X]
112.05	120	2.8	12	2.3	13[X]
116.95	1,400	13	81	24	140[X]
122.30	23	1.4	4.2	ND	3.2[X]
125.30	9	0.27	0.92	0.18	0.91[X]
130.75	ND	ND	0.015	ND	0.014[X]
135.00	ND	ND	ND	ND	0.028[X]

ND - Not detected at or above detection limit.
Detection Limits: TPH-1.0 mg/kg; Benzene-0.0005 mg/kg; Toluene-0.0005 mg/kg; Ethylbenzene-0.0005 mg/kg; Xylenes-0.0010 mg/kg.
X - Estimated value; Continuing calibration values for xylenes failed QC criteria.

Table A-2. POST-TREATMENT ANALYTICAL RESULTS FOR BOREHOLE #106

Depth (ft)	TPH (mg/kg)	Benzene (mg/kg)	Toluene (mg/kg)	Ethylbenzene (mg/kg)	Xylenes (mg/kg)
76.25	ND	ND	ND	ND	ND
81.75	ND	ND	ND	ND	ND
87.30	ND	ND	ND	ND	ND
93.85	ND	ND	ND	ND	ND
95.85	ND	ND	ND	ND	ND
100.25	ND	ND	ND	ND	ND
103.80	ND	ND	ND	ND	ND
106.75	ND	ND	ND	ND	ND
109.35	ND	ND	ND	ND	ND
115.35	ND	ND	ND	ND	ND
128.80	ND	ND	ND	ND	ND
130.75	ND	ND	ND	ND	ND
135.00	ND	ND	ND	ND	ND

ND - Not detected at or above detection limit.
Detection Limits: TPH-1.0 mg/kg; Benzene-0.0005 mg/kg; Toluene-0.0005 mg/kg; Ethylbenzene-0.0005 mg/kg; Xylenes-0.0010 mg/kg.
X - Estimated value; Continuing calibration values for xylenes failed QC criteria.

UCRL-ID-120416

Summary of the LLNL Gasoline Spill Demonstration—Dynamic Underground Stripping Project

R. L. Newmark and R. D. Aines

April 3, 1995

Lawrence Livermore National Laboratory

Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

Environmental Technologies Program

Dynamic Underground Stripping

Lawrence Livermore National Laboratory
University of California

Berkeley Environmental Restoration Center

Summary of the LLNL Gasoline Spill Demonstration—Dynamic Underground Stripping Project

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Environmental Technologies Program

UCRL-ID-120416

Preface

This report summarizes the four volumes of *Dynamic Underground Stripping Project: LLNL Gasoline Spill Demonstration Report* (Newmark, 1994a), which compiles the final reports for all the component activities of the Dynamic Underground Stripping demonstration at the LLNL gasoline spill site. The demonstration and cleanup efforts at that site from 1992 to early 1994 were funded jointly by the Department of Energy's Office of Technology Development and Office of Environmental Restoration. The full report combines those efforts into sections that reflect the major technical aspects of the project: Summary, Characterization, Operations, Monitoring, Predictive Modeling, and the Accelerated Removal and Validation (ARV) Project.

The Dynamic Underground Stripping demonstration at the LLNL gasoline spill site was extremely successful, and all of the project goals were met or exceeded. All aspects of this project reflect the integration of complementary technologies and process engineering. Some applications are obvious, such as the use of electrical heating and steam injection to heat the whole range of soil types. Others are not so obvious, such as the need to electrically isolate diagnostic and monitoring systems from the tremendous currents intentionally applied to the ground. The technical challenges in merely fielding these methods in a safe and effective manner at an operating industrial site were great. Safety in operation was a prime design parameter; our excellent safety record is one of the most satisfying accomplishments of this project. The combined achievements are greater than the sum of each individual component; this satisfies the requirements of true integration of method and application.

Acknowledgments

The full report, like the demonstration project itself, represents collaboration among investigators from many organizations, both between LLNL and other agencies and between organizations within LLNL. In particular, we acknowledge the contributions of Professor Kent Udell and the team members from the Environmental Restoration Center of the University of California at Berkeley, and the close collaboration between these individuals and LLNL researchers. The success of this project was largely due to the unique field-scale collaboration that utilized the complementary interests and research abilities of University and Laboratory researchers.

The successful demonstration of Dynamic Underground Stripping at the LLNL gasoline spill site was made possible through the combined efforts of a great many people, with a broad range of expertise. We acknowledge the efforts of the mechanical and environmental technicians, procurement, construction and plant engineering personnel, and other staff without whose contributions (often in difficult conditions and inclement weather) this project would not have been possible. Students from the Environmental Center at University of California–Berkeley also provided essential support.

We gratefully acknowledge the support of the U.S. Department of Energy's Office of Environmental Management for this demonstration. The demonstration of innovative technologies requires that both experimental and compliance-driven cleanup operations needs be addressed. The efforts of the U.S. Department of Energy's representatives to reconcile often conflicting requirements made this project possible. In particular, we acknowledge the efforts of Clyde Frank, Pat Whitfield, Tom Crandall, Tom Anderson, Katie Hain, John Mathur, Kathy Angleberger, John Lehr, J. T. Davis, Richard Scott, Mike Brown and Bill Holman. Over its three-year history, this project utilized the resources of many, if not most, of the organizations at LLNL. In particular, we acknowledge the support of Jesse Yow, John Ziagos, Lee Younker, Bob Schock, J. I. Davis, Ann Heywood, Jay C. Davis, Alan Levy, Walt Sooy, Dennis Fisher, Harry Galles, Jens Mahler, and Bill McConachie.

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Summary of the LLNL Gasoline Spill Demonstration— Dynamic Underground Stripping Project

Introduction

Underground spills of volatile hydrocarbons (solvents or fuels) can be difficult to clean up when the hydrocarbons are present both above and below the water table and are found in relatively impermeable clays (Figure 1). Years of groundwater pumping may not completely remove the contamination. Researchers at Lawrence Livermore National Laboratory (LLNL) and the College of Engineering at the University of California at Berkeley (UCB) have collaborated to develop a technique called Dynamic Underground Stripping to remove localized underground spills in a relatively short time. The U.S. Department of Energy's Office of Environmental Restoration and Waste Management has sponsored a full-scale demonstration of this technique at the LLNL gasoline spill site.

Although it has been known for years that accumulations of separate-phase organics represent the most serious cause of groundwater pollution (National Research Council, 1994; MacDonald and Kavanaugh, 1994), their very low solubility in water has made them very hard to remove by the classic method of pumping out groundwater and treating it at the surface. Similarly, the principal natural mechanism for groundwater restoration, biological metabolism of the contaminant, usually will not work in very concentrated contaminant because of the toxic nature of the organic. (Bacteria typically metabolize organics dissolved in water, not free organic liquids.)

When highly concentrated contamination is found above the standing water table, vacuum extraction has been very effective at both removing the contaminant and enhancing biological remediation through the addition of oxygen. Below the water table, however, these advantages cannot be obtained. For such sites where the contamination is too deep for excavation, there are currently no widely applicable cleanup methods.

Dynamic Underground Stripping removes separate-phase organic contaminants below the water table by heating the subsurface above the boiling point of water, and then removing both contaminant and water by vacuum extraction. The high temperatures both convert the organic to vapor and enhance other removal paths by increasing diffusion and eliminating sorption. Because this method uses rapid, high-energy techniques in cleaning the soil, it requires an integrated system of underground monitoring and imaging methods to control and evaluate the process in real time.

Results of First Full-Scale Test

We conducted the initial testing of the combined thermal and monitoring/imaging methods of Dynamic Underground Stripping at the site of a gasoline spill at the Lawrence Livermore National Laboratory. This site was chosen because several thousand gallons of gasoline were trapped up to 30 feet below the water table (Figure 2), mimicking the behavior of heavy solvents such as trichloroethylene (TCE).

This first full-scale test of Dynamic Underground Stripping at the LLNL gasoline site was extremely successful. Results completed in December 1993 indicate that the process is more than 60 times as effective as the conventional pump-and-treat process now being used at 300 designated Superfund Sites to treat contamination below the water table, and is 15 times as effective as vacuum extraction in the vadose zone (above the water table) (Figure 3). The LLNL site was previously under treatment by vacuum extraction from a central extraction well (Nicholls et al., 1988; Thorpe et al., 1990; Cook et al., 1991). From August 1988 to December 1991, more than 1900 gallons of gasoline were removed from the vadose zone. However, the extraction rate had dropped to about 2 gallons per day by 1991. No large groundwater removal actions were undertaken at that point; but because of the low solubility of gasoline in water (about 10,000-ppb total hydrocarbons were observed in the groundwater), a pumping rate of 50 gallons/minute would have only removed about 0.5 gallon of gasoline per day. To continue the cleanup, the vacuum venting operation was halted, and replaced by the Dynamic Underground Stripping technique.

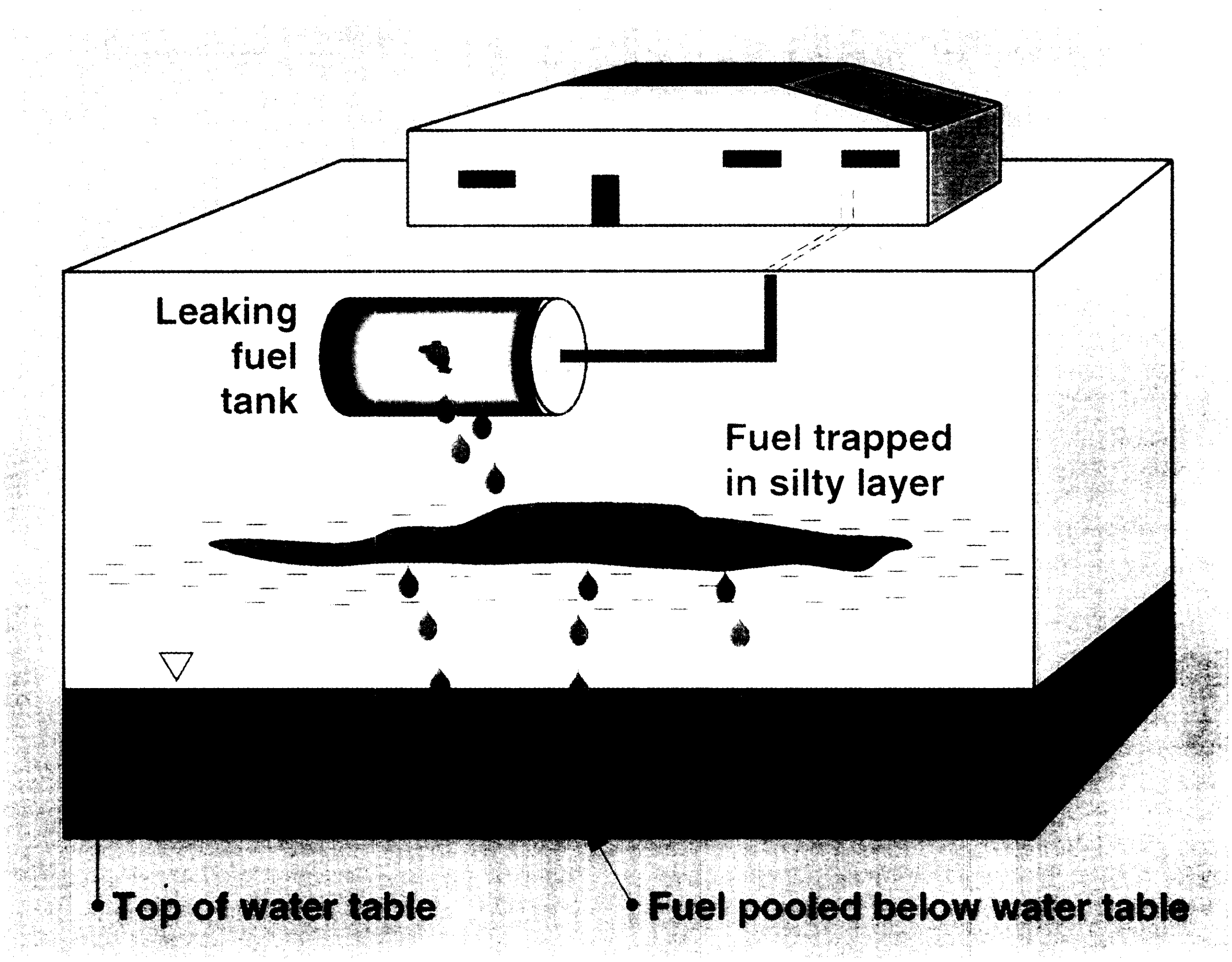

Figure 1. A plume of organic liquid forming beneath a leaking underground storage tank. This behavior is typical of a heavy organic solvent such as trichloroethylene (TCE). Some of the liquid may be trapped in layers of low-permeability soil above the water table. The remainder will form a pool below the water table, as shown here. Lighter contaminants such as gasoline can be trapped below water by movement of the water table.

During the 21 weeks of operation over the course of one year, Dynamic Underground Stripping removed more than 7600 gallons of gasoline trapped in soil (significantly more than the 6200 gallons estimated to be present), both above and below the water table, with separate-phase contamination extending to >120 ft deep. The maximum removal rate was 250 gallons of gasoline a day. The process was limited only by the ability to treat the contaminated substance at the surface. Actual field experience indicates that the process costs $60–$70 a cubic yard. Approximately 100,000 yd^3 were cleaned.

Based on Three Technologies

Dynamic Underground Stripping relies on three integrated technologies; steam injection, electrical heating, and underground imaging (Figure 4).

Steam Injection

Steam is pumped into injection wells, heating the contaminated earth to 100°C. Steam drives contaminated water toward the extraction wells where it is pumped to the surface. When the steam front encounters contamination, volatile organic compounds are distilled from the hot soil and are moved to the steam/groundwater interface, where they condense. Vacuum extraction after full steaming of the contaminated zone continues to remove residual contaminants. The steam injection/vacuum extraction technique was developed at UCB (Udell and Stewart, 1989, 1990; Udell et al., 1991; Udell, 1994d). The steam system and operational design used here are described in Siegel (1994) and Udell (1994c). Predictive

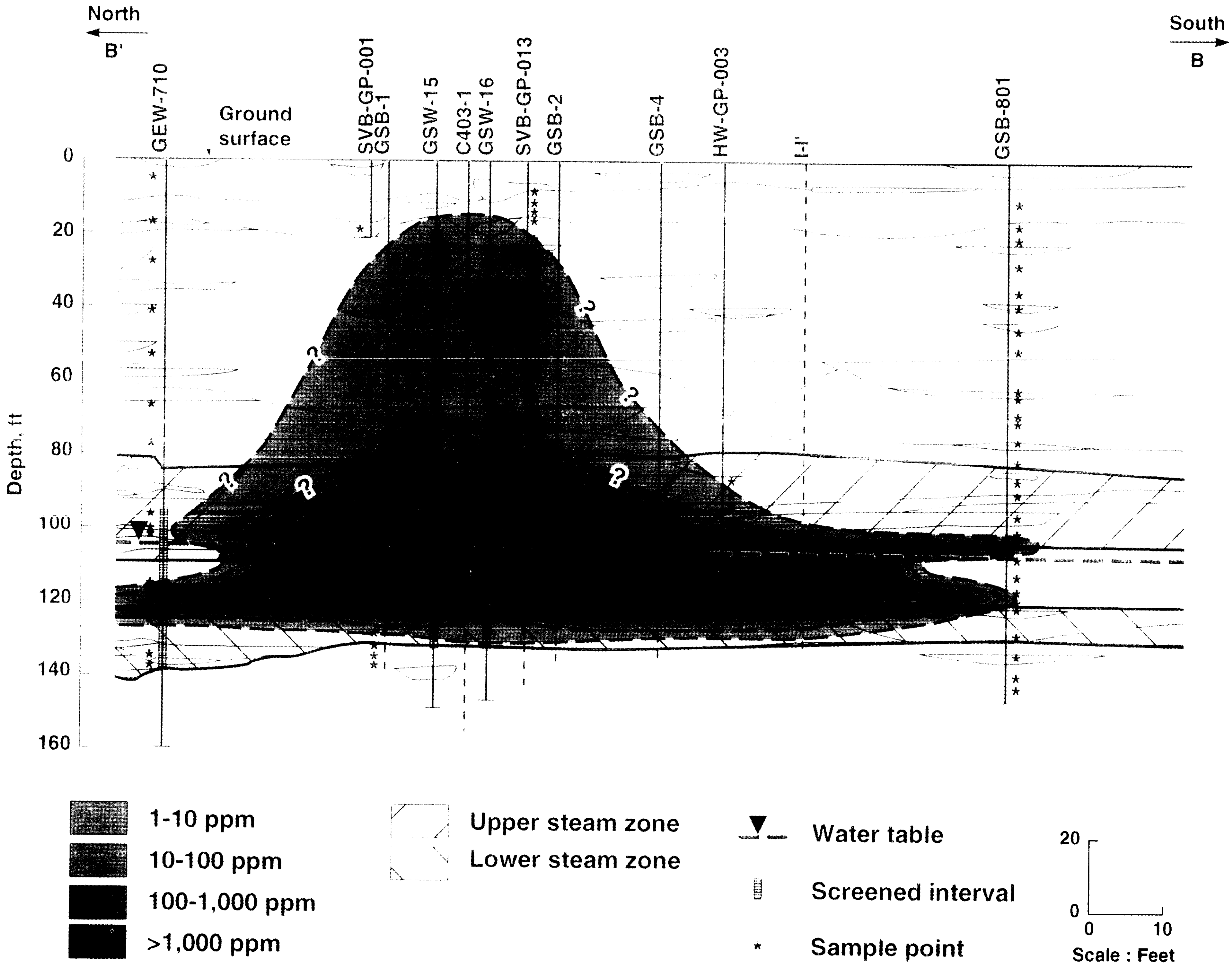

Figure 2. Cross section showing an approximation of the gasoline contamination at the treatment site before Dynamic Underground Stripping began. The darker areas represent higher concentrations; the darkest indicates free-product gasoline. The dashed line denotes the level of the water table. (From Bishop et al., 1994).

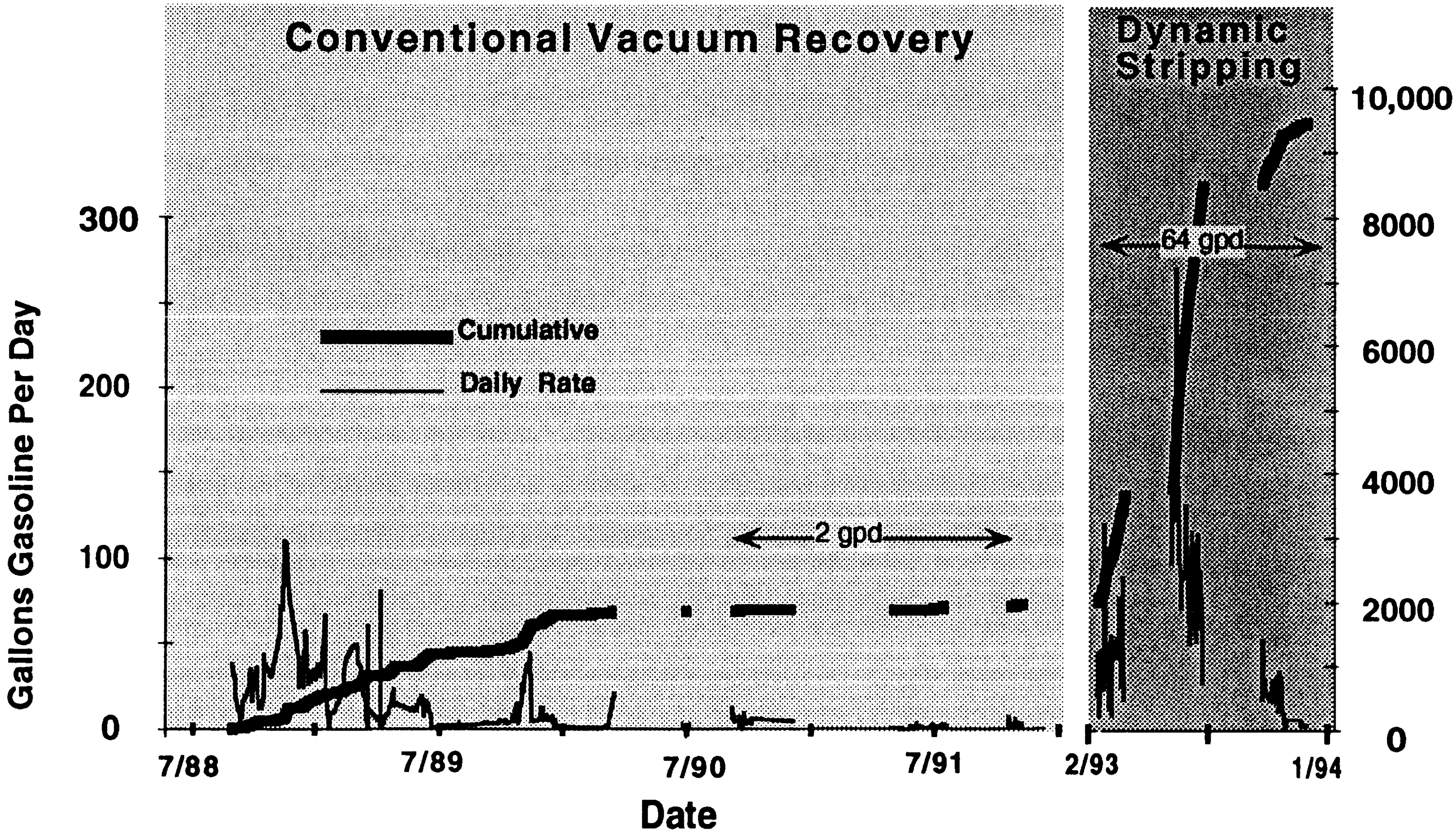

Figure 3. Recovery rates during Dynamic Underground Stripping compared to conventional methods fielded at the LLNL gasoline spill site. Vacuum extraction, begun in late 1988, stabilized at a recovery rate of 2 gallons of gasoline per day after an initially higher rate (Cook et al., 1991). Conventional pump and treat combined with vacuum extraction, tested just before the start of Dynamic Underground Stripping (not shown), showed an initial additional recovery rate of 0.5 gal/day gasoline in pumped water, for a total conventional recovery of 2.5 gal/day. Dynamic Underground Stripping averaged 64 gal/day during the year in which the 21 weeks of operations were conducted. Dynamic Underground Stripping removed vadose zone contamination at about 15 times the rate of conventional methods, and groundwater contamination at greater than 60 times the conventional rate.

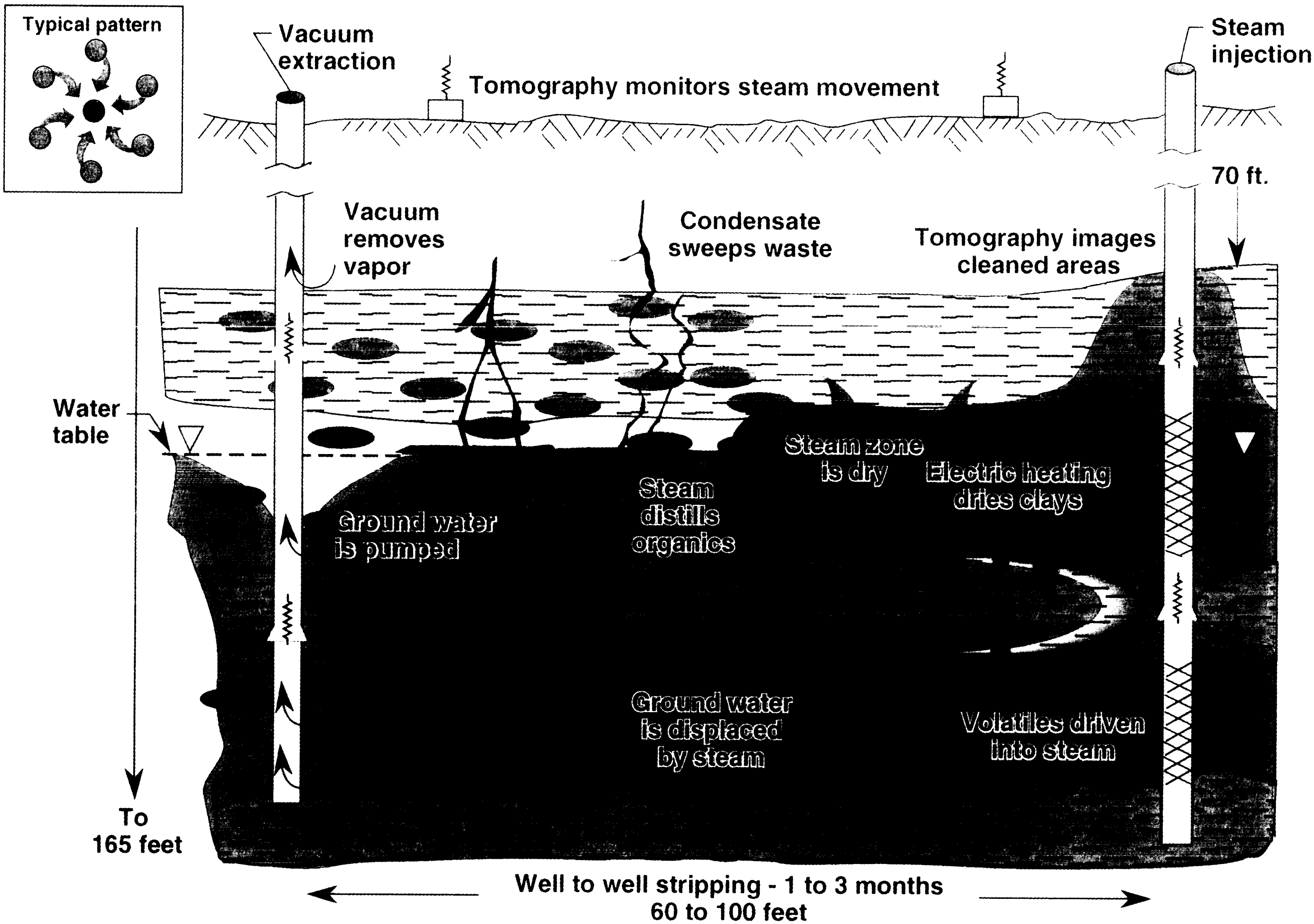

Figure 4. The Dynamic Underground Stripping process. Steam drives contaminated groundwater toward extraction wells and then heats the soil to distill organics. Electrical heating dries and distills impermeable clays that the steam cannot readily penetrate. Geophysical techniques monitor the process. The process operates both above and below the water table (dashed line) and is particularly economically attractive for free-product removal (solid green).

calculations of the operational characteristics and recovery efficiency of steam injection as applied at the LLNL gasoline spill site are given by Udell (1994b), Kenneally (1994), Adenekan and Patzek (1994), and Lee (1994).

Electrical Heating

This technique heats clay and fine-grained sediments and causes water and contaminants trapped within the soils to vaporize and be forced into the steam-swept zones, where vacuum extraction removes them. Electrical heating is ideally suited for tight, clay-rich soil and/or near-surface (less than 20 feet) cleanups. It is an effective complement to steam injection, because it cleans the thick, less permeable zones that the steam does not penetrate well.

Electrical heating has been used in a number of configurations in enhanced petroleum recovery (*e.g.*, Chute et al., 1987; Chute and Vermeulen, 1988); the three-phase system used here was designed at LLNL (Buettner and Daily, 1994a; McGee et al., 1994). Details of the electrical heating construction and operational design used here are given by Siegel (1994), and the results of the preheat phase are found in Buettner and Daily (1994b). Our predictive and diagnostic modeling capability for electrical heating is presented by Carrigan and Nitao (1994). Sweeney et al. (1994) give details of the post-steam electrical heating process conducted during this experiment.

Underground Imaging

To monitor the Dynamic Underground Stripping process, we used geophysical imaging methods to map the boundary between the heated zones and the cooler surrounding areas. Electrical resistance tomography (ERT) has proven to be the best imaging technique for near-real-time images of the heated zones (Newmark, 1992, 1994c; Ramirez et al., 1993; Vaughn et al., 1993). This technique is necessary for controlling the thermal process and for monitoring the water movement. Details of the use of ERT at the gasoline spill site are given by Newmark (1994b), and Ramirez et al. (1994). Tiltmeters provided additional information regarding the shape of the steamed zone (Hunter and Reinke, 1994), while detailed temperature and geophysical logs provided extremely accurate assessments of the degree of penetration and the complex heating of the numerous heterogeneous formation layers (Newmark, 1994b; Goldman and Udell, 1994; Boyd et al., 1994).

The LLNL Gasoline Spill Site

We conducted an experimental application of the Dynamic Underground Stripping technique during 1993 at the LLNL gasoline spill site. This is the former site of the Laboratory's filling station; fueling operations at this location date back to the 1940s, when the LLNL site was a U.S. Naval air station. It is located in the center of an industrial area—the Laboratory's shipping and receiving yard. A county road runs along the south side, and major underground utility lines run through the site.

Previous characterization results were combined with an extensive set of measurements taken during the installation of 22 process and monitoring boreholes at the site. Details of the site characterization are given in Bishop et al. (1994). This characterization showed that an estimated 6200 gallons of gasoline were present within our target treatment area (both above and below the water table) (Figure 2). Gasoline was trapped up to 30 ft below the water table because of a rise in the water table after the spill occurred, with the gasoline held below water by capillary forces in the soil. The soils at the site are alluvial, ranging from very fine silt/clay layers to extremely coarse gravels, with unit permeabilities ranging over several orders of magnitude. There are two principal permeable zones, one above and one below the water table, which is located at 100 ft. In between the permeable zones, straddling the water table, is a 10–15-ft-thick silty/clay layer of low permeability, which was also heavily contaminated (Nelson-Lee, 1994).

The targeted volume was intended to include all of the free-phase gasoline at the site, and was a distorted cylinder about 120 ft in diameter and 80 ft high, extending from a depth of 60 ft to a depth of 140 ft (Figure 5). Later results indicated that two small areas of gasoline probably existed outside the treatment area, possibly from separate spills.

Six steam injection/electric-heating wells were placed to surround the free product in an irregular circle determined by the shape of the free product; three additional electric heating wells were placed near the center of the spill. These were not part of the original design, but

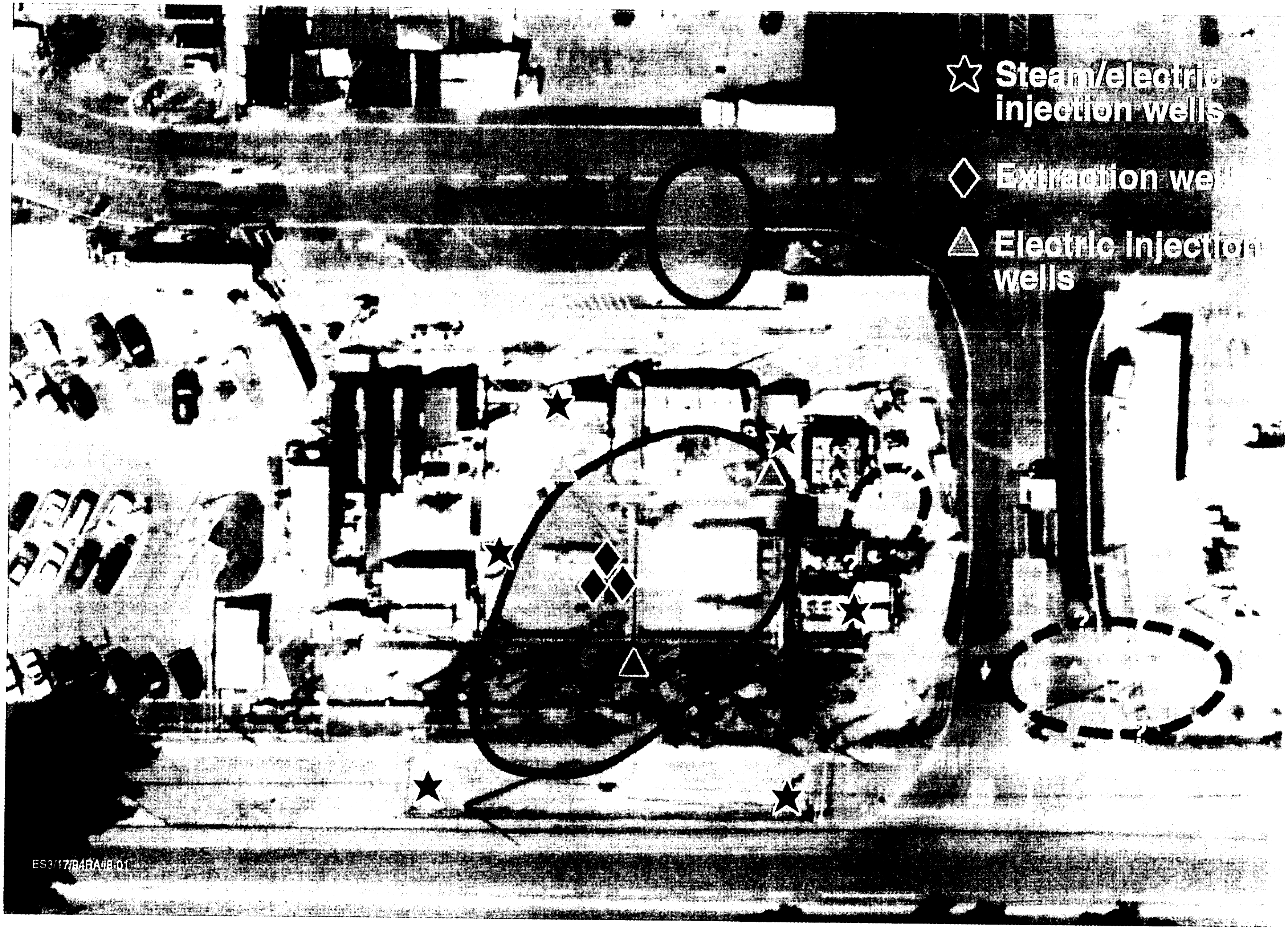

Figure 5. Aerial view of the LLNL gasoline spill area, showing regions of known or suspected free-product gasoline contamination (circled). The area is within the LLNL shipping and receiving yard. East Avenue, a county road, is seen on the south edge of the photograph. Injection wells were sited to encircle the central plume of free product to ensure that the gasoline would be moved toward the extraction well cluster at the center.

were required when the free-product zone was discovered to be larger than anticipated during the drilling of the injection wells. Each injection well was initially center-punched with a small-diameter hole for characterization. The discovery of unexpected free product in two of them had minimal impact; the holes were completed as monitoring locations, and new injection wells were drilled farther from the spill center. We placed eleven monitoring/imaging wells within and outside the target area to provide control of the heating processes (Figure 6).

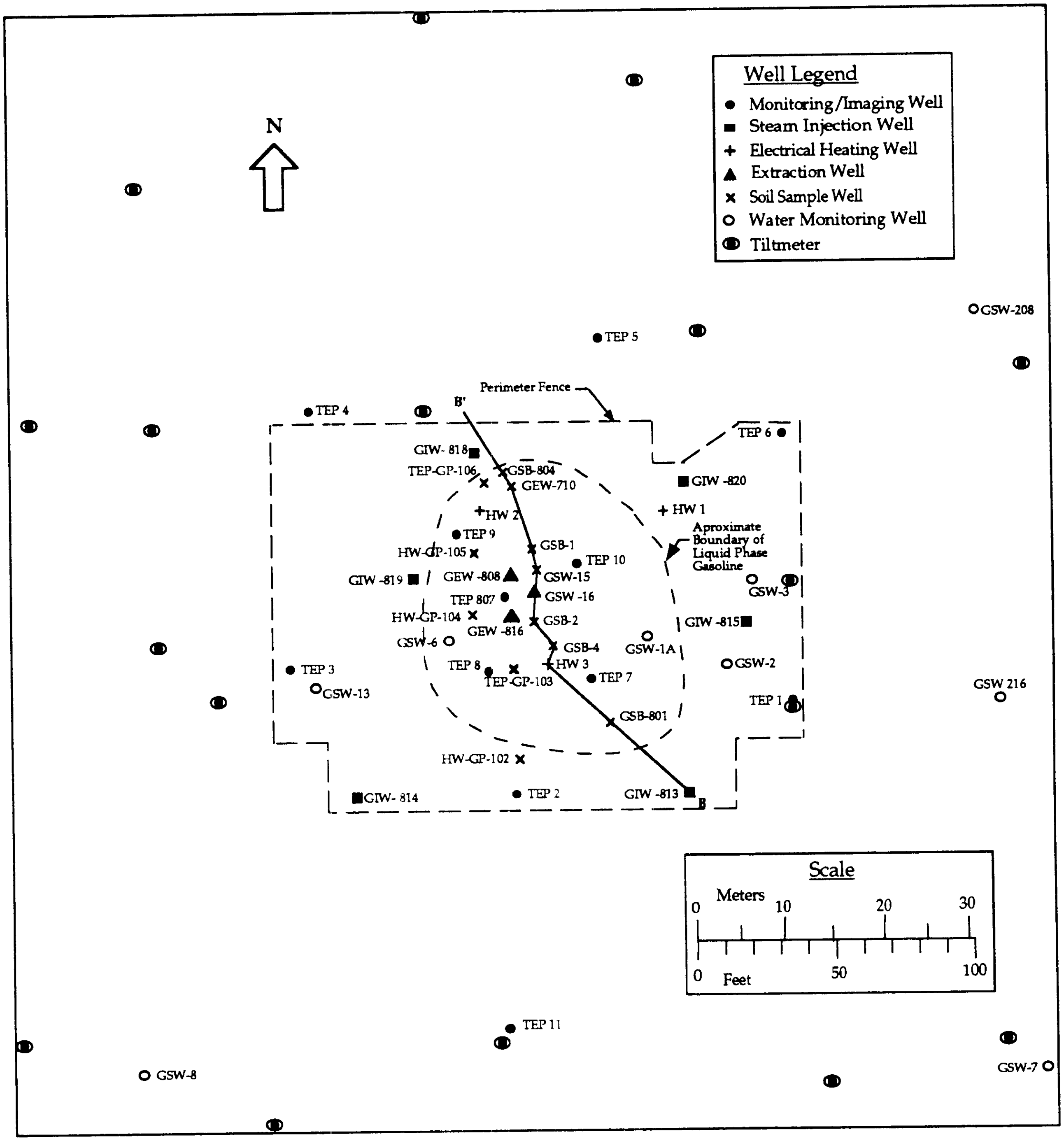

Figure 6. Map of the LLNL gasoline spill site, showing the location of wells referred to in this summary. The location of cross section B-B' (Figure 2) is shown. (Not all pre-Dynamic Underground Stripping well and boring locations are shown.) This map shows a slightly larger area than Figure 5.

Cleanup Operations

Goals of the Experiment

Dynamic Underground Stripping was originally designed for the removal of separate-phase organic liquids from highly contaminated areas both above and particularly below the water table. The goals of the first application of the method were:

1. To determine the effectiveness of the process in removing free product.
2. To evaluate the effectiveness of the monitoring methods for controlling heat input and mapping heated zones.
3. To examine whether any deleterious effects (such as dispersal of contaminant) might occur.
4. To demonstrate the necessary engineering and operational practices required for effective and safe operation of this high-energy technique.

All goals were met and the site and process were turned over to the Laboratory's site remediation team (funded by DOE's EM 40) for final site cleanup (Sweeney et al., 1994).

Experimental Operations

Operations at the site were conducted in four distinct phases:

(1) Electric Preheating: November and December 1992
(2) First Steam Pass: February 1993
(3) Second Steam Pass: May–July 1993 (drill-back characterization followed)
(4) Polishing Operations (accelerated removal and validation): October–December 1993
Table 1 summarizes the project history.

The electrical preheat of the site began in November 1992, before the treatment facility was completed. No extraction data are therefore available from this phase. The electrical preheat phase is described in detail by Buettner and Daily (1994b). The 1-MW electrical system operated at a maximum power output of about 800 kW. The chief monitoring methods used during the electrical preheating were temperature measurements and ERT. Temperatures were measured using both fixed thermocouples in individual boreholes and, for continuous logs, an infrared-sensor system in the 11 2-in.-diameter fiberglass monitoring/imaging wells (Newmark, 1994b; Goldman and Udell, 1994).

The goal of an average 20°C temperature rise in the clay zones was achieved; some of the clay layers were heated to a maximum of 70°C (Figure 7). The effects of this phase on the extraction of gasoline were not tested, but several of the groundwater monitoring wells on the site showed increases in the concentration of gasoline components, indicating that free-phase gasoline was being mobilized in the vicinity (Figure 8). Gasoline concentrations in these wells had been decreasing previously, apparently due to localized bioremediation or venting resulting from the increased air circulation to the borehole area.

Steam injection began in early February 1993 into the lower of two steam zones (permeable layers) using a 24,000 lb/hr (50 gallons water/minute, energy approximately 8 MW) natural-gas-fired, skid-mounted boiler (Figure 9). Siegel (1994) describes the steam operations in detail. Steam injection rapidly heated the permeable zones to above the boiling point of water, and initial steam breakthrough to the extraction wells occurred in 12 days (Figure 10). During the first steam pass, it was learned that, although a bank of cold, free-product gasoline may precede the steam front to the extraction wells, it contains only a small fraction of the recovered gasoline (Jovanovich et al., 1994; Aines et al., 1994) (Figure 11). None of the 1700 gallons recovered during the first steam pass could unambiguously be associated with the liquid front ahead of the steam. The great majority of the gasoline came out after a steam zone was fully established, and the extraction continued without further steam injection. The reduced vapor pressure forces residual pore fluids and contaminants to boil. At this point, the forced boiling generated large amounts of water and gasoline in the vapor stream, and our potential removal rates greatly exceeded our dual-bed activated-carbon trailer's design limit of about 25 gallons/day. During the planned shutdown following the first steam pass, the vapor treatment system was redesigned to increase capacity (Sorensen and Siegel, 1994).

The monitoring and imaging systems utilized at the gasoline spill site provided excellent control of the steam injection process (Newmark, 1994b; Goldman and Udell, 1994; Ramirez et al., 1994; Boyd et al., 1994). Initial steam breakthrough to the extraction wells occurred in only 12 days; each subsequent breakthrough occurred sooner as

Table 1. Project history of the Dynamic Underground Stripping project LLNL gasoline spill site cleanup.

Phase	Dates	Objectives	Accomplishments
Vacuum Extraction, Vadose Zone EM 40 Operations	9/88 to 12/91	> Extract vadose gasoline contamination. > Evaluate extraction effectiveness.	> Pilot Test permitting received. > 2000 gallons removed > Biological activity confirmed
Clean Site Engineering Test EM 50	2/91 to 9/91	> Demonstrate establishment of steam zone below water table. > Evaluate and optimize monitoring, imaging systems. > Optimize resistance heating electrode design. > Evaluate personnel and environmental safety.	> 10,000 yd^3 steam zone established below water table with no steam rise. > ERT, thermal logging, and tiltmeters demonstrated, chosen for gas pad use. > Individual electrode capacity raised from 20 kW to 200 kW. > Safe procedures established for personnel; no detrimental environmental effects .
Electrical Pre-Heat **EM50 operations, EM 40 Treatment Facility F construction**	11/92 to 1/93	> Raise temperature of clay/silt layers 20°C so conductivity always above steam-temperature gravel zones. > Test electrical safety at high current in industrial area. > Optimize electrical heating methods.	> Clay pre-heating accomplished. > Maximum heating to 70°C in clay layer. > Safety measures and procedures adequate. > 850 kW continuous power achieved. > Nighttime operations with daylight construction of treatment facility.
1st Steam Pass **Joint EM40/EM50 operations**	2/93 to 3/93	> Heat target zones to steam temperature. > Optimize monitoring/control methods. > Evaluate treatment procedures and facility. > Quantify possible deleterious effects (such as contaminant spreading). > Demonstrate safe handling of steam and hot gasoline effluent.	> Upper and Lower steam zones heated to boiling point. > ERT established as control system with 12 hr turnaround on 10 planes/day. > Non-contact thermal logger demonstrated with no hysteresis, 100°C/2 ft gradients. > Gasoline found to be mainly recovered in vapor phase, greatly exceeding capacity. No liquid phase free-product recovered. > No spreading of contaminant to outer monitoring wells/ > Safe handling of steam and hot gasoline. > 1700 gallons gasoline removed.

Table 1. (Continued.)

2nd Steam Pass **Joint EM40/EM50 operations**	5/93 to 7/93	> Operate re-designed vapor treatment system with 10x capacity of first pass. > Optimize steaming/recovery technique to maximize vacuum recovery. > Heat zones which were insufficiently heated in first pass. > Accurately measure gasoline flux in vapor and condensate paths, reduce uncertainty in total recovery rate, continuously monitor gasoline flux.	> 100,000 yd^3 heated to boiling point. > Recovery rates in excess of 250 gal/day achieved. > Tiltmeters used for imaging of horizontal extent of steam zones from individual wells. > Most cool zones from 1st pass fully heated to steam temperature (one "cold spot" remained at 80°C). > Fluxes measured to ±10 % accuracy, continuous monitoring systems demonstrated. > 4600 gallons gasoline removed.
Post-Test Drill-Back Characterization **EM 50**	7/93 to 9/93	> Measure soil concentration changes along six-hole cross-section > Ascertain from soil concentrations whether spreading had occurred (outside original contamination) > Evaluate process effectiveness. > Examine possible changes to soil. > Examine effects on existing microbial gasoline-degrading ecosystem.	> Soil concentrations reduced dramatically. > No spreading of contaminant; only inward motion seen. > Vadose zone completely clean (<1ppm) > Saturated zone contaminant remained around extraction cluster only. > No significant soil changes. > Active microbial ecosystems at all locations and soil temperatures up to 90°C, makeup varies by soil temperature.
Accelerated Recovery and Validation (ARV) **EM 40 Operations**	10/93 to 1/94	> Remove remaining free product, especially in cool zone. > Make use of existing heat and high extraction rates to continue removal. > Electrically heat clay/silt zones to enhance removal. > Test sparging, injection well extraction.	> Remaining free-product gasoline removed (1000 gallons). > Ground water concentrations of 5 of 6 regulated compounds reduced to MCL. > Benzene down to 100 ppb in ground water. > Sparging monitored with noble-gas tracers. > Electrical heating maintained site soil temperatures during extraction.

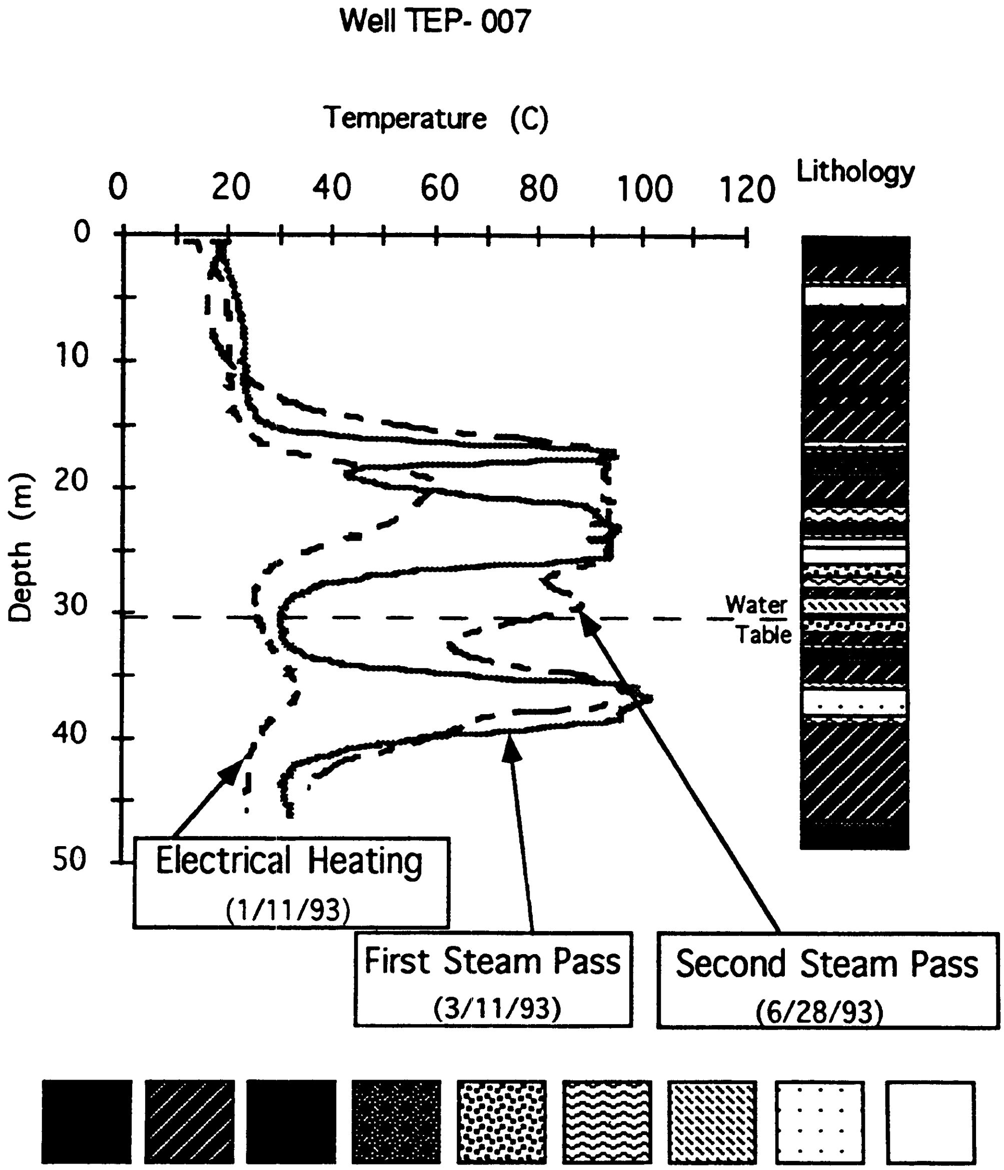

Figure 7. Temperature logs from a monitoring well inside the ring of injection wells, along with the lithology. These logs show electrical heating of the clay-rich layers during the electrical preheat, steam passing through the most permeable layers during the first steam pass, and conductive heating of and later penetration by steam into less permeable layers during the second steam pass. (From Newmark, 1994b).

the formation gained heat. This made the day-to-day process monitoring critical in order to ensure that the correct amount of steam was injected to drive contaminant to the center without adding excessive amounts of steam outside the pattern. Each of the twelve injection ports (two each in six wells) would inject a different amount of steam at a given pressure, ranging from 600 lb/hr to one well that would apparently have taken the entire output of the boiler had we so permitted. This range is expected in such a heterogeneous site, but it requires that the location and size of the steam zones be measured *in situ*, not merely calculated from injection volumes.

Temperature measurements made both with fixed thermocouples in the field and with the

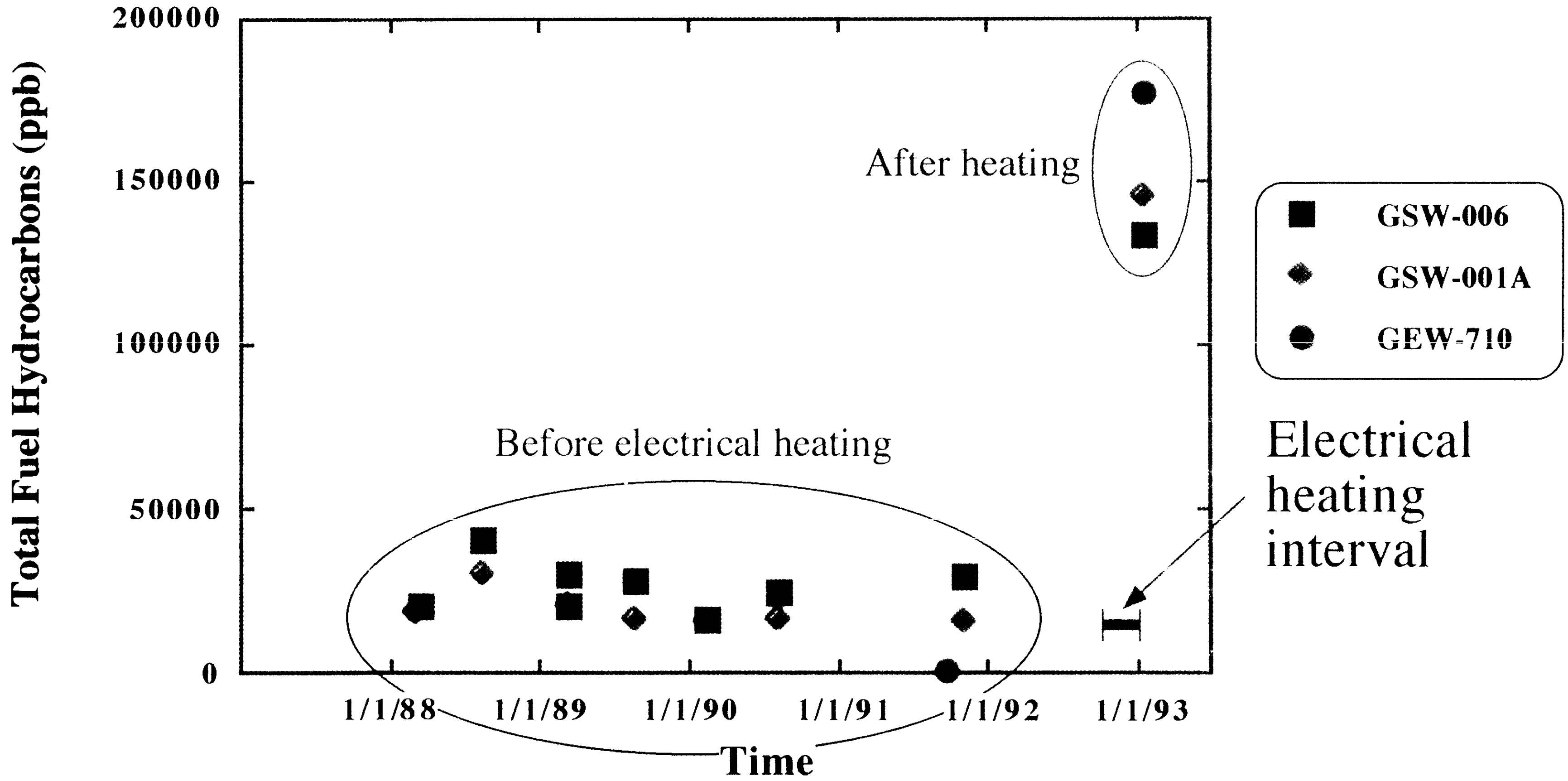

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Figure 8. Chemical signatures of groundwater in monitoring wells in the central gasoline spill area. Before electrical heating, total fuel hydrocarbon concentrations (TFH) were below 50,000 ppb and generally decreasing, most probably due to localized enhanced bioremediation in the vicinity of the boreholes. After electrical heating, high TFH concentrations were found, indicating contact with free-product gasoline (Buettner and Daily, 1994b).

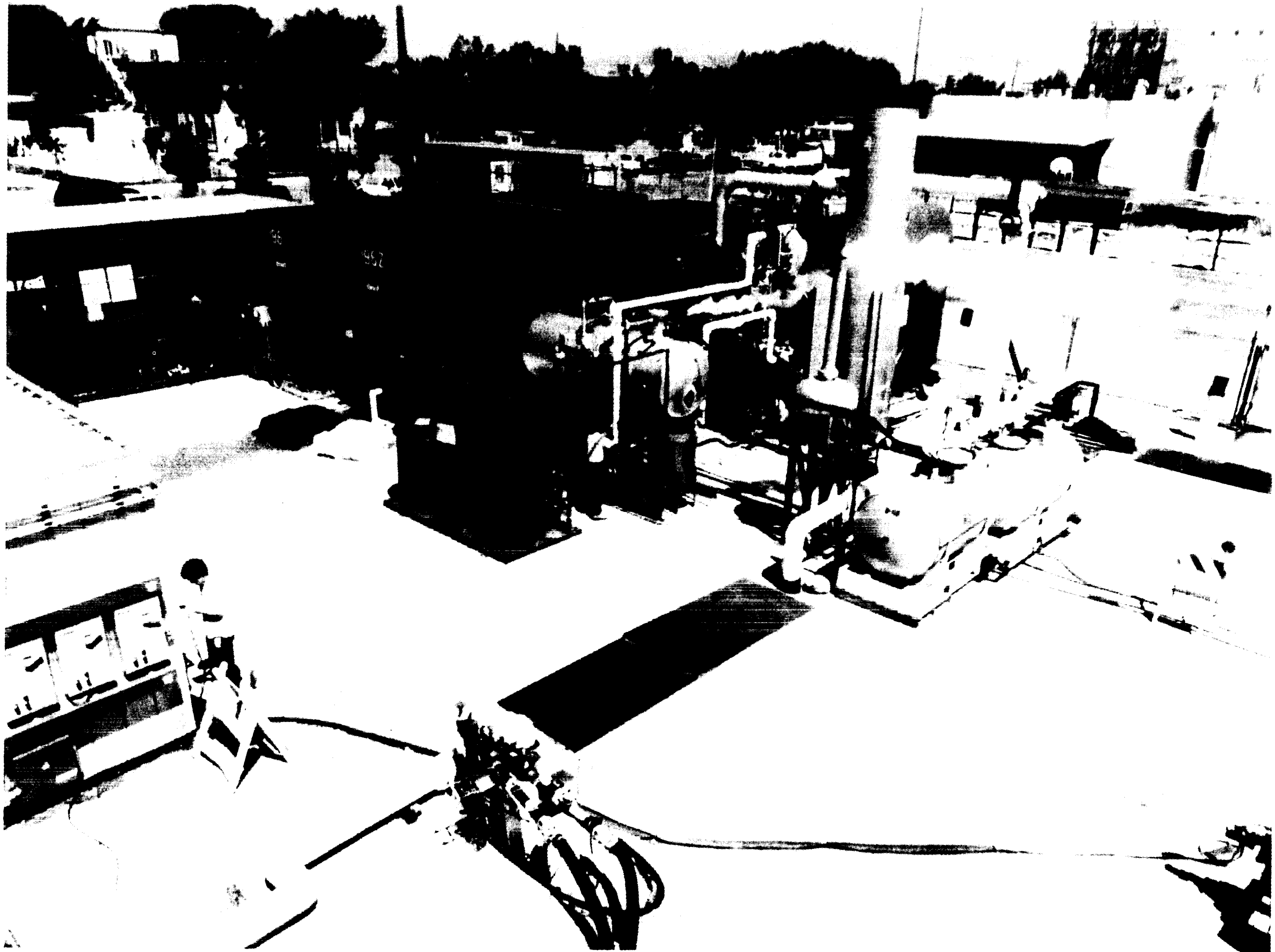


Figure 9. Portable steam plant used for the Dynamic Underground Stripping demonstration at the LLNL gasoline spill area. The 24,000 -lb/hr boiler is skid-mounted; this particular unit was leased by the month. A steam injection/electrical heating well can be seen in the foreground. Steam is distributed to the injection wells via flexible rubber hoses. The boiler is fired by natural gas and fed by Laboratory drinking water, both from Laboratory utility lines. An injection well is seen in the foreground, with two injection lines (one for each steam zone). Steam is piped to the wells using flexible reinforced-rubber steam lines.

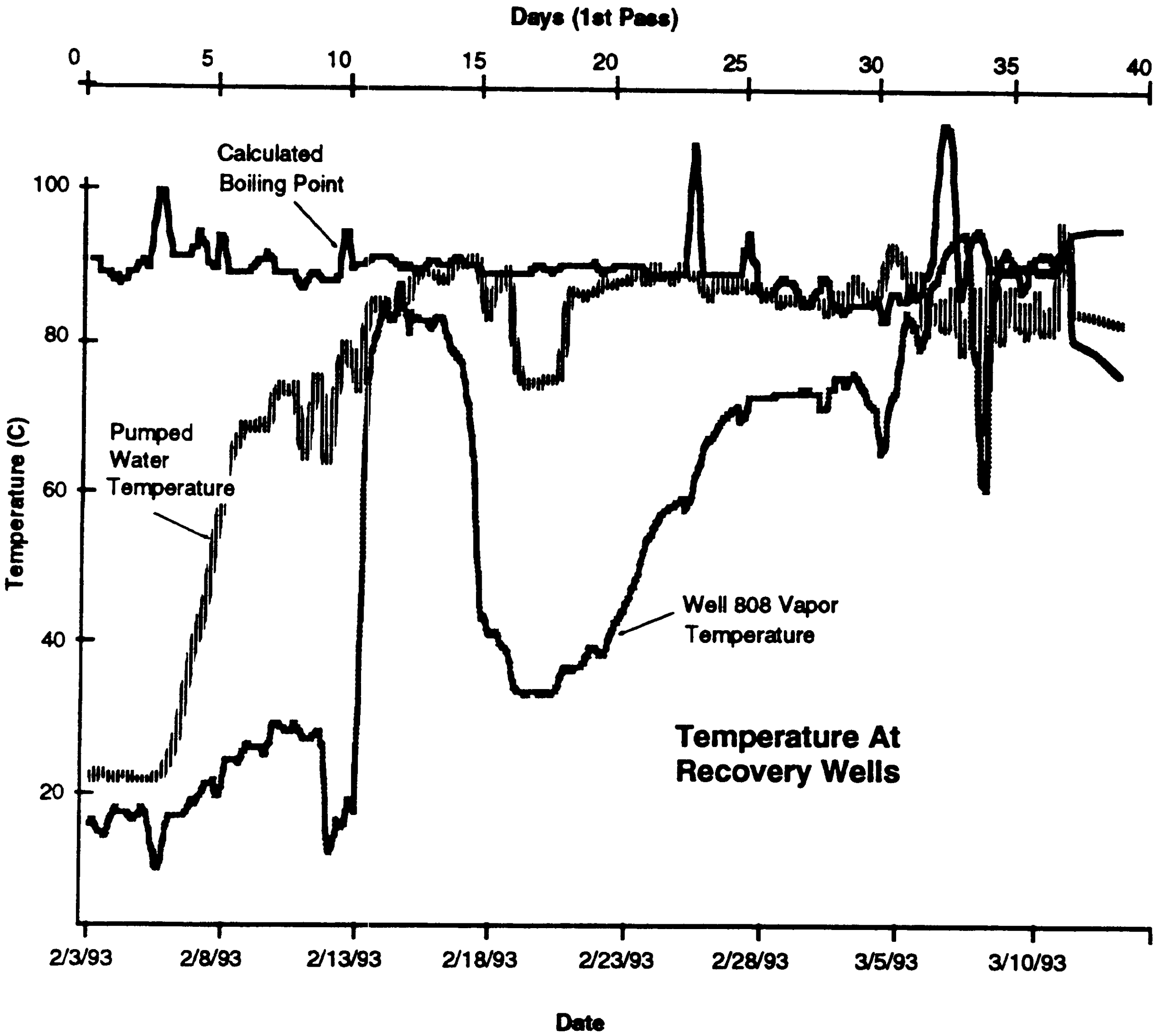


Figure 10. Extraction well temperatures during the first steam pass. Steam breakthrough to the extraction wells occurred about 12 days after steam injection began in the lower steam zone. Calculated boiling point based on the vacuum applied to the well. (After Aines et al., 1994).

continuous temperature loggers showed a rapid temperature rise in the more permeable zones (Figures 6 and 12). The temperature logs revealed thermal gradients of up to 100°C over just a few feet depth during initial steam injection, and provided the most accurate measurements of the vertical distribution of the steam at the 11 locations (Newmark, 1994b; Kenneally, 1994).

Between the wells, ERT proved to be a rapid and accurate way to map steam progress at 1–2-m resolution, providing actual images of the heated zones by comparing the electrical resistance distribution before heating to that afterwards (Ramirez et al., 1994) (Figure 13). Daily ERT images showed the vertical extent of the steam zones and the lateral movement between imaging wells. They revealed a number of areas where steam was moving vertically in the formation that were not detected by the temperature logs in individual wells. The total cycle time to obtain and process the data for each image was about an hour. This made ERT the principal control method, and decisions on steam injection rates made at the morning operations meetings were based principally on ERT images from the previous day. Coupled with the temperature profiles from the continuous temperature loggers, steam

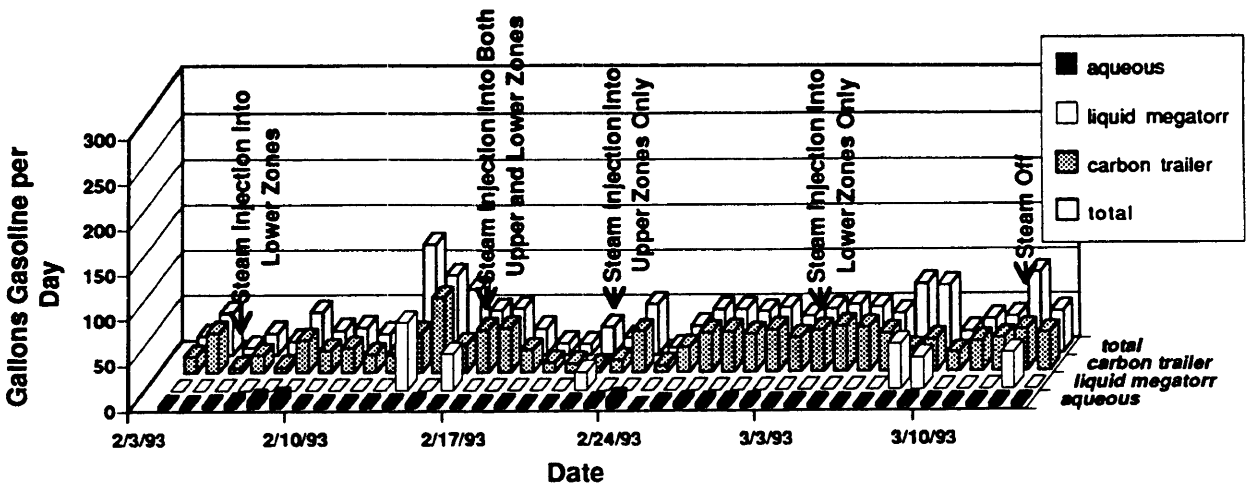


Figure 11. Daily average gasoline recovery rates during the first steam pass. (From Udell, 1994a,c).

progression through the formation was seen to occur in multiple horizontal permeable zones, with significant vertical motion occurring in some areas. The combined ERT/temperature 2-in. fiberglass wells were placed to allow optimal monitoring of the interior of the treated zone (extending about 30 ft outside the ring defined by the steam injection wells) and lower-resolution monitoring of the surrounding area. Induction logs run in the monitoring wells revealed the changes in the electrical properties of the heated soils in detail. These results were used to calculate fluid saturation in the steamed zones (Boyd et al., 1994) (Figure 14).

An array of tiltmeters was installed near-surface in a double ring surrounding the site to monitor the lateral extent of the steam zone outside the treated area (Hunter and Reinke, 1994). The array was used in two modes: passive and active.

In the passive mode, tiltmeters measure the small deformations in the ground surface that result from a subsurface pressure transient in terms of tilt. As the steam front moving in the subsurface approaches a tiltmeter, it produces a pressure transient and causes the ground to deform. If the signal is sufficiently large, the tiltmeter will detect the slight tilt resulting from that pressure transient. Using this method, we mapped the outer extent of the steamed region during steam injection.

In a more active mode, the tiltmeter array was used to measure the slight deformation in the ground surface resulting from a pressure transient induced into the steam zone by shutting off an injection well for a fixed time. Maps of the areal extent of the steam zone emanating from each well could then be obtained, particularly for the lower steam zone (located below the pre-steam water table). This technique was extremely effective in mapping the lateral spread of steam and the development of any preferential steam pathways.

During the first steam pass, tiltmeters were primarily relied upon to delineate the outer extent of the steam front. We tested and validated the processing technique whereby the individual steam zones could be mapped during this pass, where the subsurface monitoring network of temperature measurements and ERT image planes could provide ground truth.

The second steam pass was begun after a 3-month hiatus to redesign the effluent treatment capacity, establish better analytical control on the effluent stream based on our new knowledge of the comparative flows in vapor and water, and evaluate the cost-effectiveness of the process. In this pass, we optimized the amount of time the formation was kept under vacuum (no steam injection) and greatly increased the extraction rate, hitting a contaminant recovery peak of more than 250 gallons/day and routinely removing more than 100 gallons/day (Figures 15 and 3).

The focus of the various monitoring activities was somewhat different during this pass, where steam was being injected into previously heated soil. Although the ERT images continued to provide valuable information, interpretation was

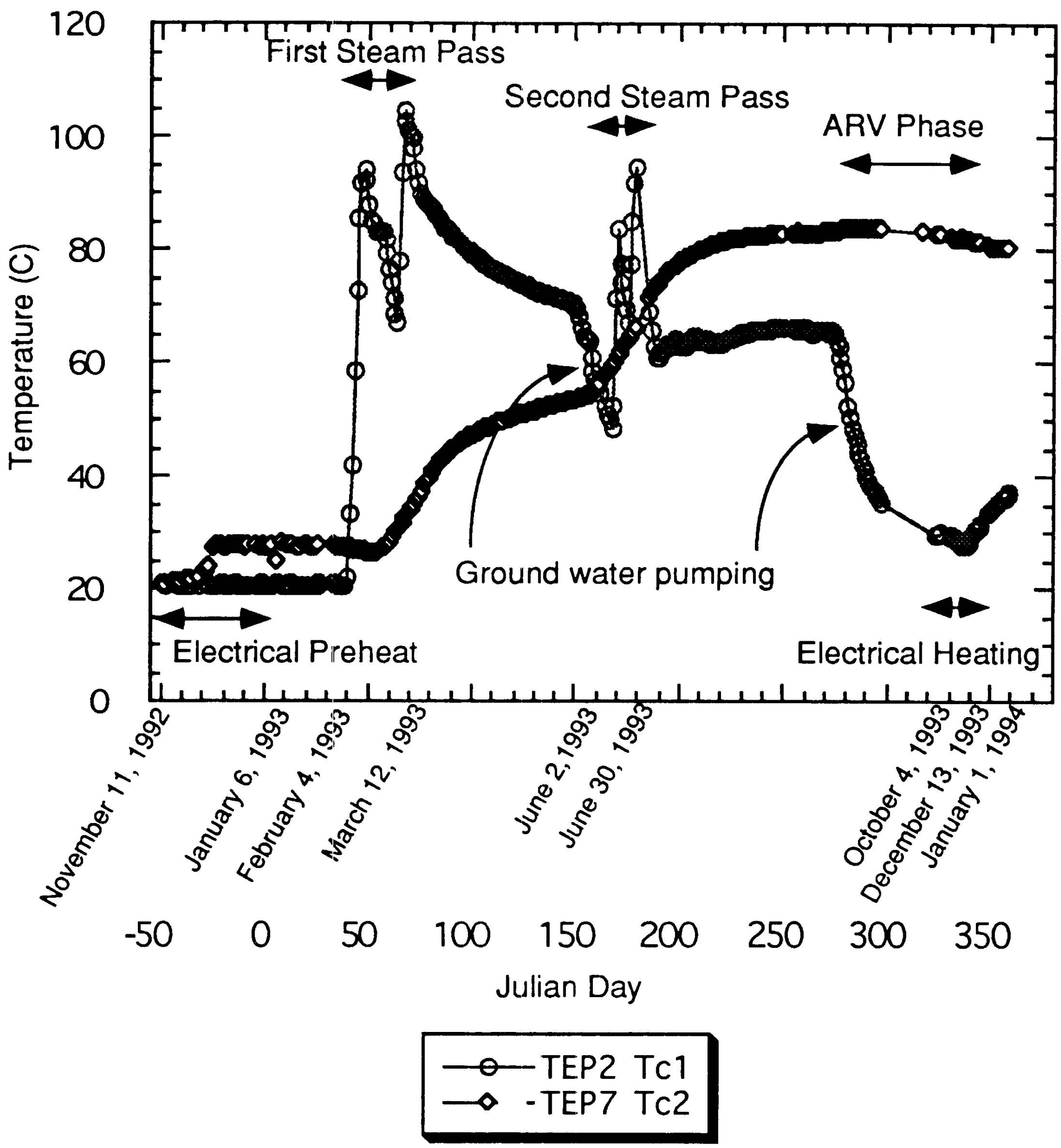


Figure 12. Individual thermocouples reveal the thermal history of different soil types at fixed locations in the field. A temperature record of a thermocouple positioned at about 40-m depth in a permeable gravel unit in the lower steam zone in well TEP 2 shows rapid temperature increases during steam injection. During groundwater pumping, cool fluids are drawn across this location from outside the steamed area, causing temperatures to decrease. By contrast, a thermocouple positioned at about 34-m depth in a clay-rich unit in well TEP 7 shows gradual temperature increases resulting from electrical heating and steam injection. Both fixed thermocouples lie below the standing water table. (After Newmark, 1994b).

more difficult, as the contrast between steam and hot soil was diminished by nearly an order of magnitude. Temperature measurements were similarly more difficult to interpret, as the relative temperature changes in the treatment area grew smaller.

The tiltmeter array was used to determine the horizontal dimensions of the steam zone, and we relied more heavily on the tiltmeter maps of individual steam zones (Figure 16). This was particularly important during the second steam pass, when steam was alternately injected into selected wells to target the remaining cooler zones. Using the tiltmeter maps and temperature logs for guidance, we injected steam into two or three wells at a time to selectively heat portions of the pattern

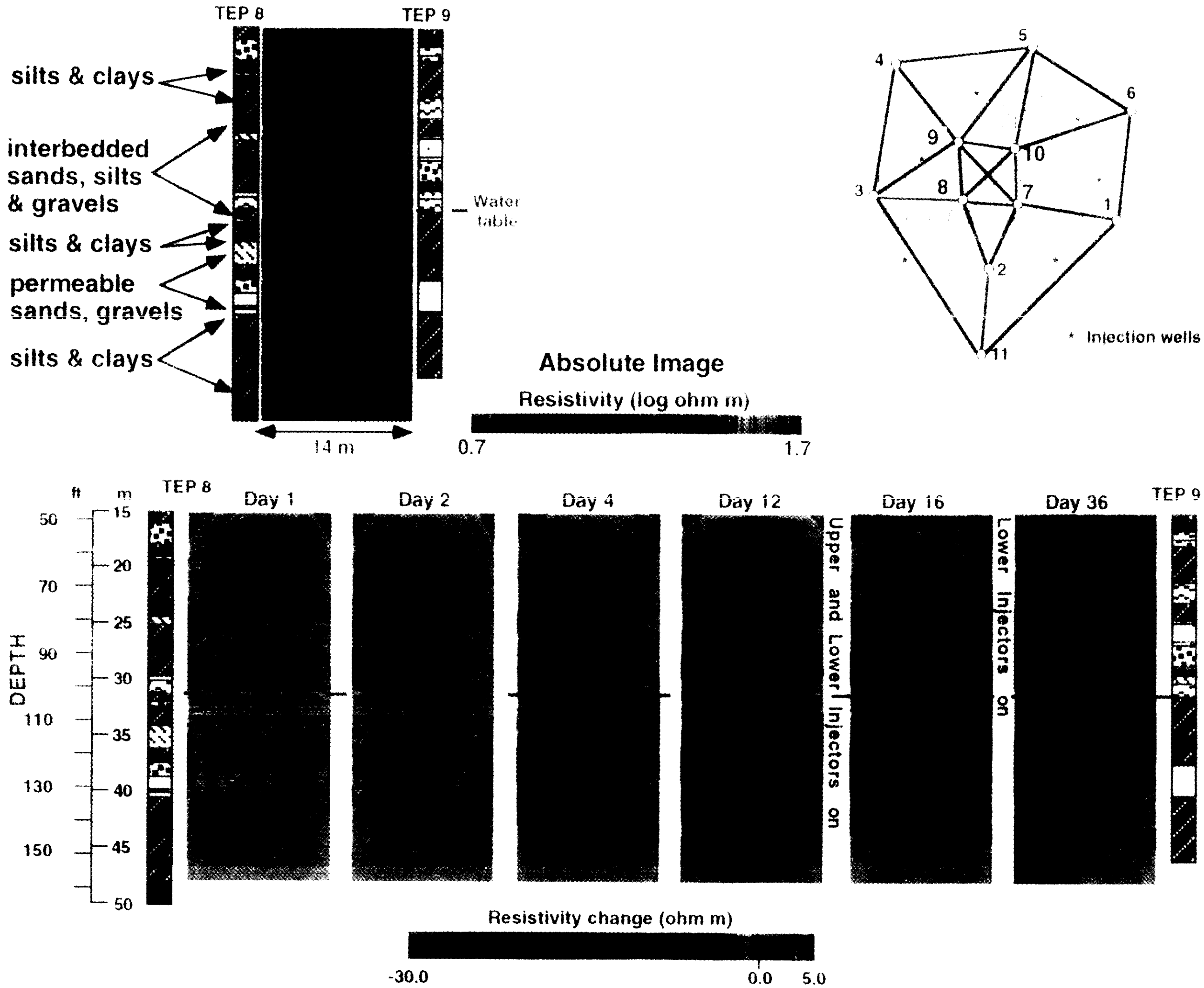


Figure 13. Electrical Resistance Tomography (ERT) images. Top: ERT absolute images reveal the continuity of soil units across image planes. The resistive units correspond to the more permeable sand and gravel zones; the conductive units correspond to the clay-rich intervals. (The apparent pinching-out of units in the center of the image is due to the increase in resolution radius toward the center of each image). Bottom: ERT difference images show the progress of the steam fronts across the image plane, starting from the first day of steam injection. This image plane (between wells TEP 8 and TEP 9) is located approximately 6 m from the nearest injection well, and is oriented nearly perpendicular to a line linking it and the extraction wells. Small decreases in electrical resistivity are observed within hours of the start of steam injection. Although steam was initially injected into only the lower steam zone (centered at about 35-m depth), steam leaked into the upper steam zone (centered at about 25-m depth) through the well completion in the nearby injection well; this is evidenced by the resistivity decreases in both zones in these images. By the end of the first steam pass (Day 36), both the upper and lower steam zones were at or near steam temperature, with conductive heating occurring in the neighboring clay-rich units. The preferential steam paths closely follow the more resistive units seen in the absolute images. (From Newmark, 1994b).

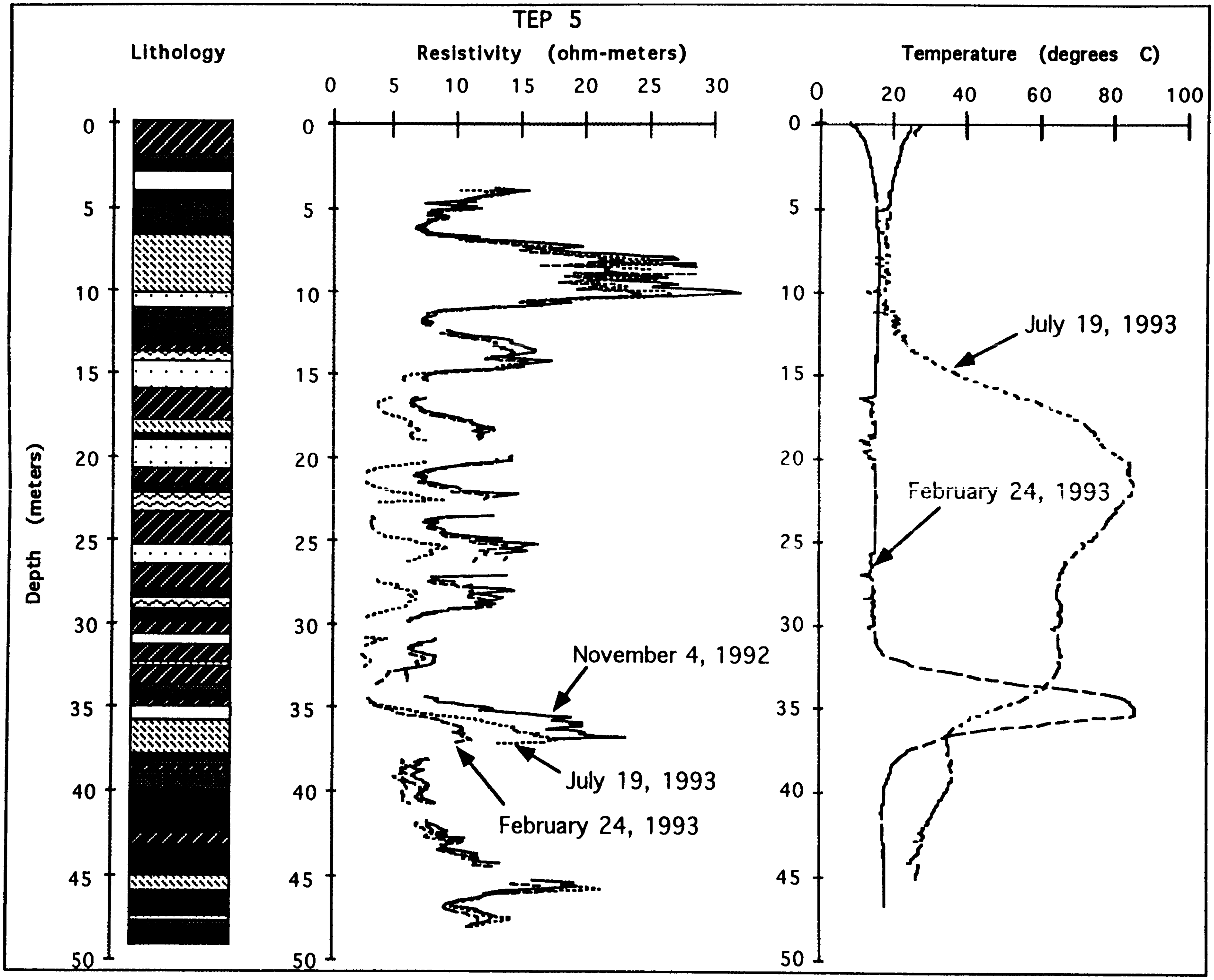


Figure 14. Induction logs such as these obtained in well TEP 5 reveal the changes in soil electrical properties in detail. In the baseline log (11/4/92, solid curve), the permeable zones have high resistivity. During the first steam pass (2/24/93, dashed), the narrow heated zone at about 35 m displays lowered resistivity. After the second steam pass (7/19/93, dotted), a broad zone from about 15-40 m exhibits both elevated temperatures and diminished resistivity. The narrow aquifer at 35 m has experienced groundwater recharge; hence, its resistivity is indicative of heated saturated conditions compared to the hot, dryer conditions existing during the first steam pass. (From Boyd et al., 1994; Newmark, 1994b).

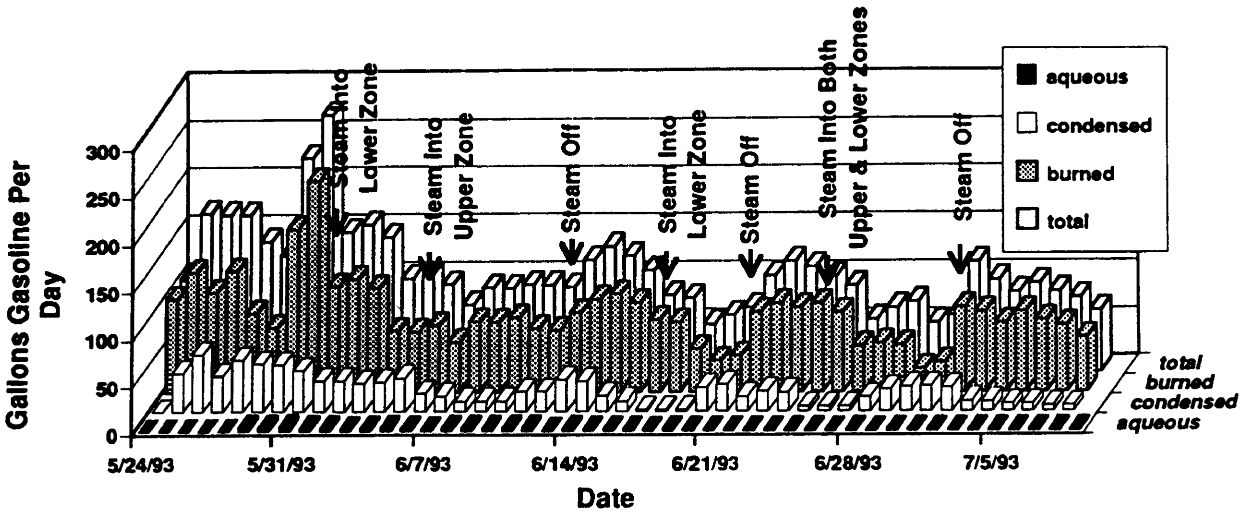


Figure 15. Daily average gasoline recovery rates during the second steam pass. (From Udell, 1994a,c).

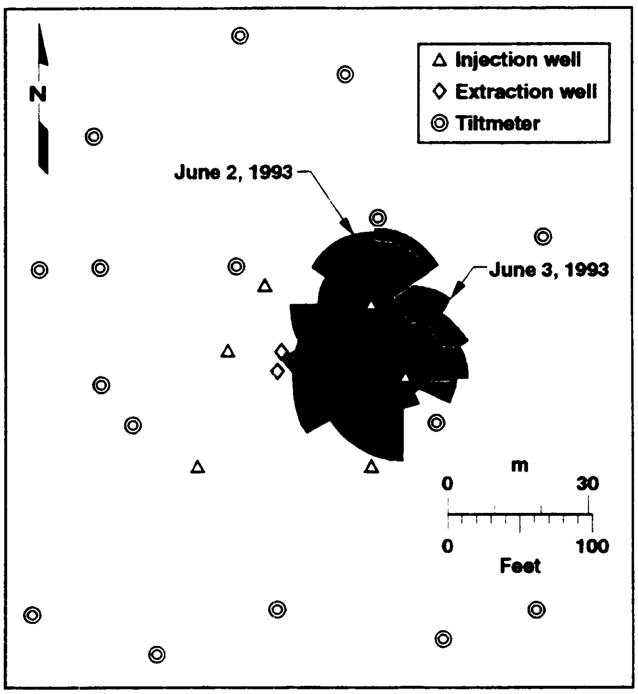


Figure 16. Tiltmeter maps show the growth of the team fronts emanating from two injections wells on consecutive days. At this time, steam was being injected into only two wells, below the water table. Steam broke through to the extraction wells the third day. (From Hunter and Reinke, 1994).

and "sweep" the steam across the remaining cool areas. The pulsed mode of operation, alternating steam and vacuum-only on a 5–6-day cycle, was very effective at maximizing contaminant removal. We terminated this phase on schedule on July 9, 1993, while the extraction rates still ranged between 50 and 100 gallons/day.

Evaluation of the gasoline concentration in the effluent from the extraction well proved difficult in the first pass, but was significantly improved in the second pass (Jovanovich et al., 1994; Aines et al., 1994). Most of the gasoline was removed in the vapor phase, and much of that was condensed along with a large amount of water in the heat exchanger (Aines et al., 1994). The second-pass addition of an oil-water separator on this part of the effluent stream allowed an accurate determination of the condensed part of the flux by simple volume measurement (Sorensen and Siegel, 1994). The remaining dried, cooled vapor was burned in two internal combustion engines; the flux of gasoline in this stream was highly variable, as a function of the amount of steam in the injection wells, total vacuum applied, and time of day (temperature of the heat exchanger).

Because of the cost and hazards associated with sampling and analysis, off-line vapor samples were collected only once or twice daily. This sampling frequency provides somewhat limited insight into the Dynamic Underground Stripping process, and cannot provide sufficient data for detecting short-term fluctuations in system performance or for real-time optimization and control of the system.

We employed a series of continuous in-line chemical sensing systems to measure this flux and to allow the same level of control for the chemical extraction rate as was obtained for the thermal injection systems. These included a standard Fourier-transform–infrared (FT–IR) spectrometer equipped with a gas sample cell, an automated gas chromatograph (with photoionization detector), and the experimental Differential Ultraviolet Absorption Spectroscopy (DUVAS) system. The trends indicated by the in-line sensors were in agreement with standard off-line laboratory analyses, and were obtained continuously in near or real-time (Figure 17a).

Continuous monitoring allowed transient events and mid- to long-term trends in the extraction process to be measured. For example, the DUVAS data showed significant diurnal fluctuations in the absorption of total aromatic compounds; these fluctuations corresponded with recorded variations in ambient temperature and changes in the pressure and flow rates within the vapor extraction system (Barber et al., 1994a,b) (Figure 17b). The correlation between ambient temperature and sensor response led to an analysis of the vapor system's efficiency. The fluctuations appear to be caused by changes in condensation efficiency resulting from variations in ambient temperatures (higher condensation rates during the cooler nighttime temperatures.) This explanation also resolved the apparent scatter between the contaminant concentrations measured in the morning and afternoon vapor samples. (The morning values showed significantly lower concentrations than the afternoon samples.) Thus, the in-line sensors, due to their high sample frequency, revealed trends that occurred between samples and provided a context in which to interpret the analytical results.

During the second steam pass, about 5000 gallons of gasoline were recovered. Extraction rates were extraordinarily high at the beginning of the second pass because of the 3-month heat soak of the formation and the accompanying release and volatilization of gasoline (Aines et al., 1994).

By the end of the two steam injection phases, most of the soil within the treatment volume was heated to the boiling point of water. Only the thick clay layer at 95 to 110 ft in depth did not reach this value, in places reaching only 80°C. It was within this "cold spot" that the largest concentrations of gasoline remained (Figure 18).

Drill-back characterization utilizing six boreholes in a line across the spill site after these first two phases indicated that, as expected, there was still free-product gasoline in the vicinity of the extraction wells but that it was now restricted to a small area just below the water table (Figure 19). Based on the observed soil concentrations, it was estimated that about 750 gallons remained in the clay unit. Gasoline had been substantially removed from the edges of the spill and from the vadose zone.

Of significant importance to this experimental application of Dynamic Underground Stripping was the finding that gasoline concentrations were not increased in the soil outside the treatment volume. However, groundwater and vapor gasoline concentrations were still very high.

At this point, operational control of cleanup activities at the gasoline spill site was transferred

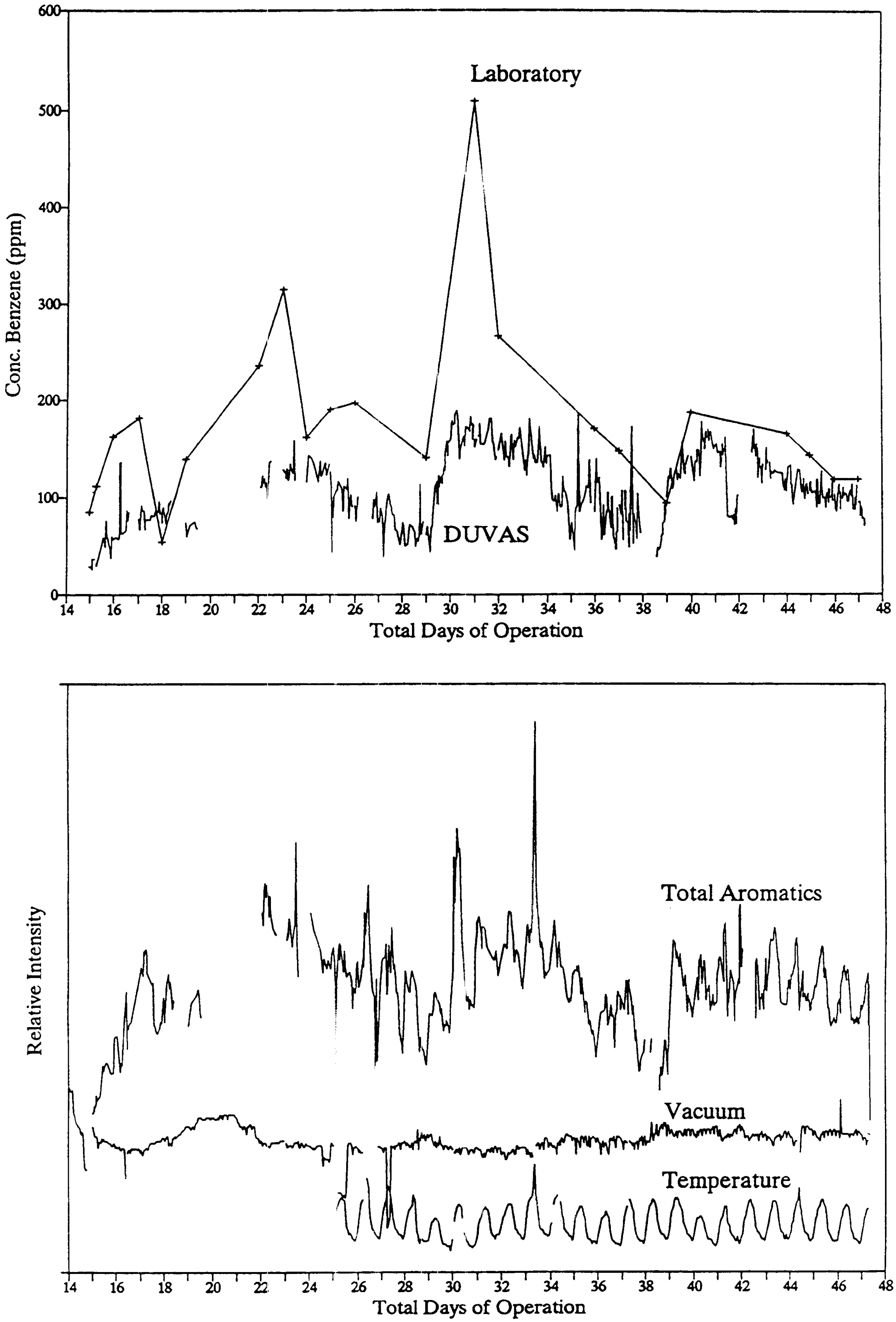


Figure 17. (a) Comparison of the benzene concentration measured by DUVAS and off-line laboratory analyses, (b) Observed variations of relative total aromatic concentration from DUVAS, extraction line vacuum, and vapor temperature. (From Barber et al., 1994a).

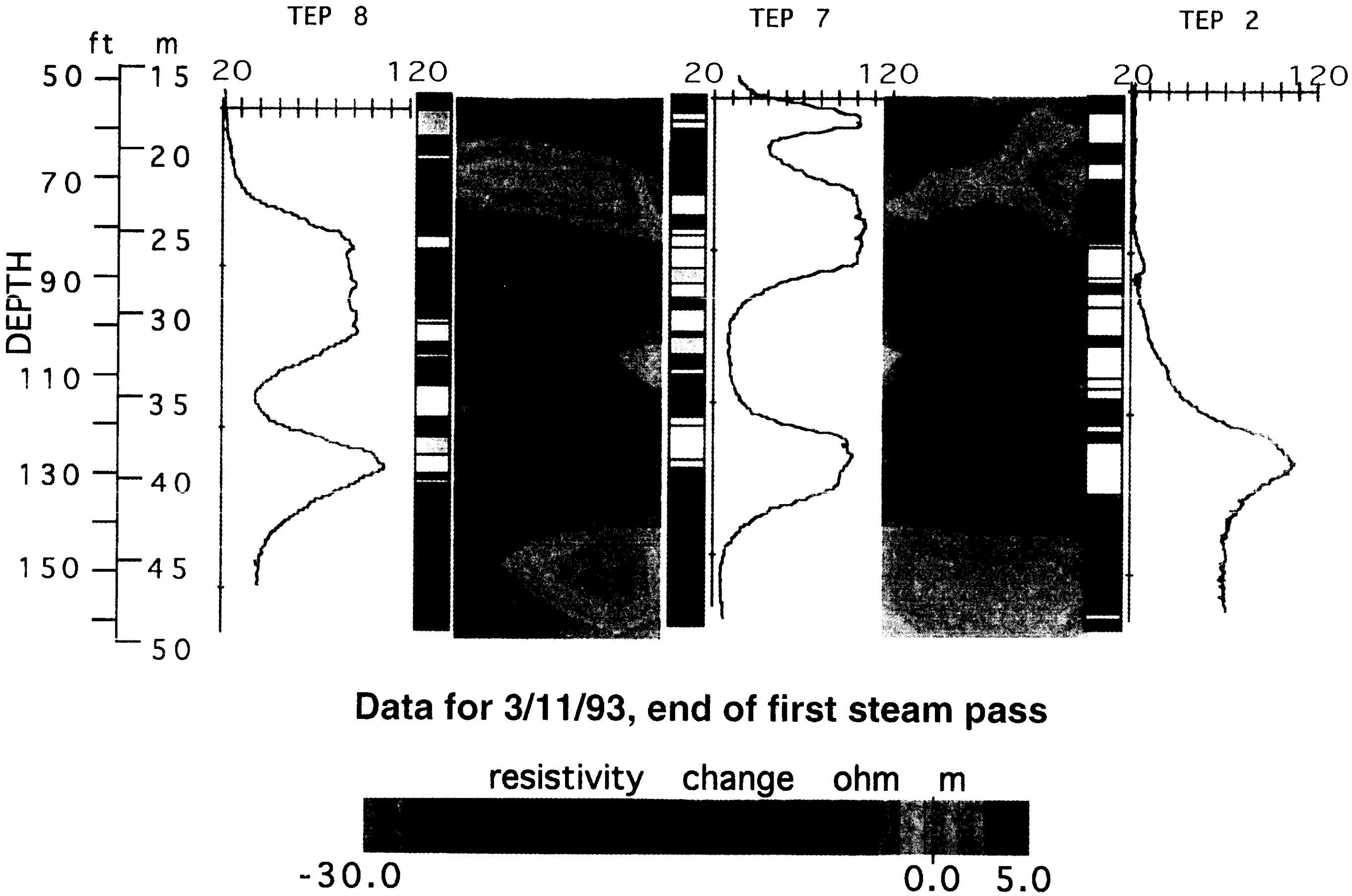


Figure 18. ERT and temperature surveys detected a "cold spot" after the first steam pass. Data from March 11, 1993, at the end of the first steam pass, reveal a zone between about 32 m and 37 m where temperatures have not risen much above ambient. The ERT images indicate the lateral continuity of this zone between wells in which temperatures can be measured.

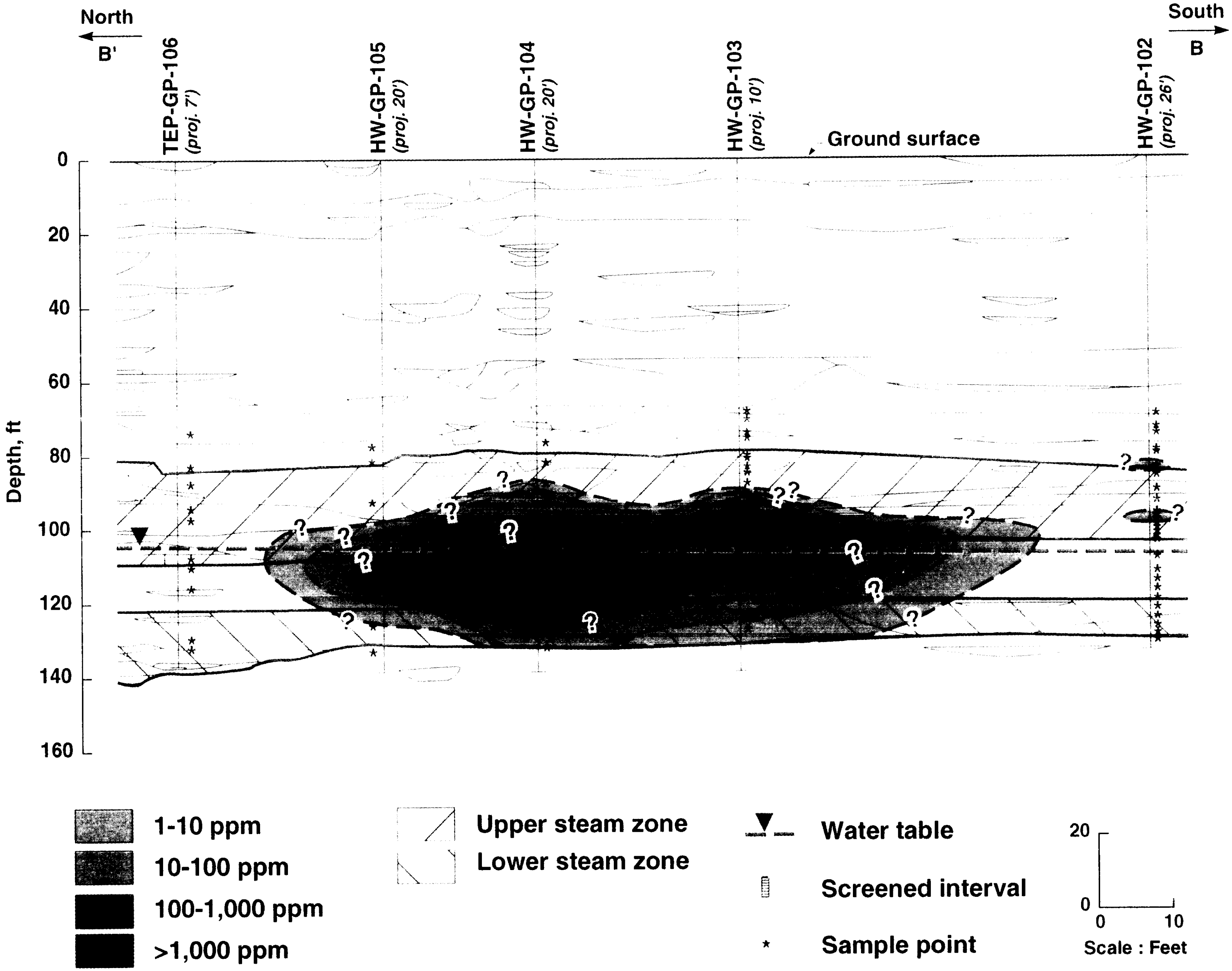


Figure 19. Approximate cross section of the treatment site from the characterization drill-back after the two steam passes (compare with Figure 2). The area of gasoline contamination has contracted greatly, and there are no indications of free product remaining in the treated area outside the volume immediately around the extraction wells. No gasoline has been dispersed outside the treated volume. (From Bishop et al., 1994).

from the more experimental Dynamic Underground Stripping demonstration team to the LLNL site cleanup organization. Subsequent activities focused on the final cleanup of the site.

Extraction of groundwater and vapor resumed as part of the Accelerated Recovery and Validation (ARV) project (Sweeney et al., 1994) in October 1993; the spike in initial extraction rates was smaller than observed after the first pass (Figures 20 and 3). Electric heating was applied to the system in November. Approximately 1000 gallons were removed during this phase, with the concentrations and extraction rates falling dramatically. Electric heating raised the overall temperature of the treated zone only slightly, apparently because the extraction systems were removing large amounts of heat (50 to 100 kW) at the high temperatures prevailing at the time.

When the extraction systems were turned off, temperatures in the clay zones began rising (Figure 21). The electric heating was terminated on December 16, and the system was shut down for the holidays. At this point, at least 7600 gallons of gasoline had been removed from the site. The discrepancy between this and the 6200 gallons estimated to be present is not surprising due to the extreme heterogeneity of the site and the difficulty in characterizing gasoline trapped in soil capillaries. Historically, very few measurements of total hydrocarbons were made at the site, since measurements of BTEX (benzene, toluene, ethylbenzene, and xylenes) were sufficient to delineate the contamination and quantify the regulated contaminants (Dresen et al., 1986). The error in converting the BTEX measurements to total gasoline is therefore fairly large, and the estimated total volume of gasoline subject to an error of several thousand gallons (Devaney, 1994; Aines et al., 1994).

In January 1994, groundwater pumping and vapor extraction resumed. During the 1-month shutdown during the 1993–1994 year-end-break, concentrations in the vapor increased only slightly, and water concentrations decreased. Benzene concentrations in the extraction wells continued their downward trend, now at less than 200 ppb from a peak of 7000 ppb before the start of steam injection. At a groundwater monitoring well within the pattern, benzene concentrations have decreased dramatically, from several thousand parts per billion before Dynamic Underground Stripping to less than 30 ppb in January 1994. Other wells show similar decreases. These factors indicate that there is no significant free-phase gasoline remaining in the treatment volume, although significant contamination may still lie outside the treatment volume.

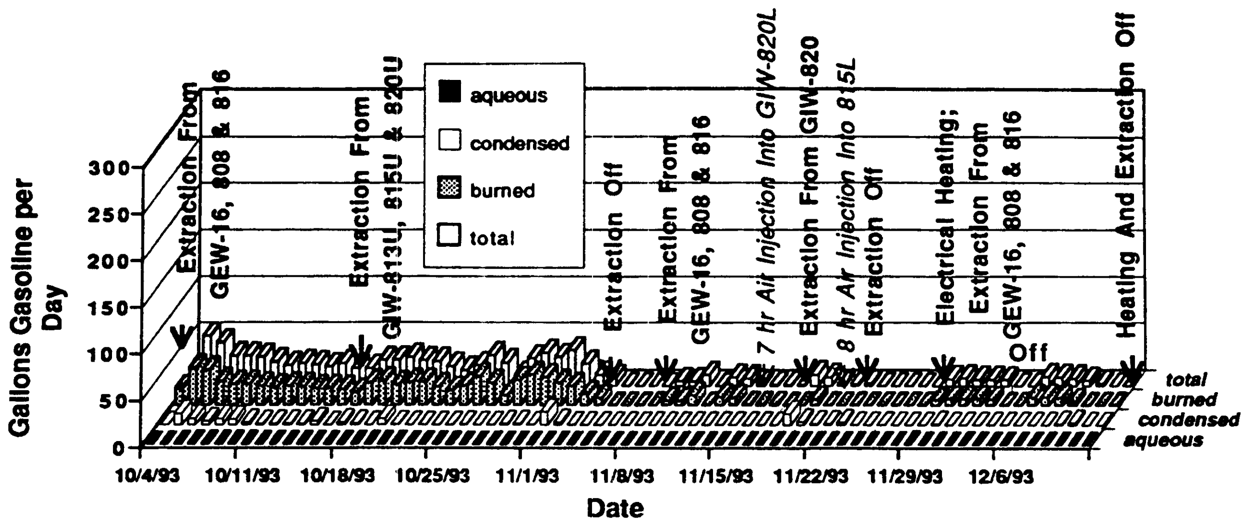


Figure 20. Daily average gasoline recovery rates during the ARV phase. (From Udell, 1994a,c).

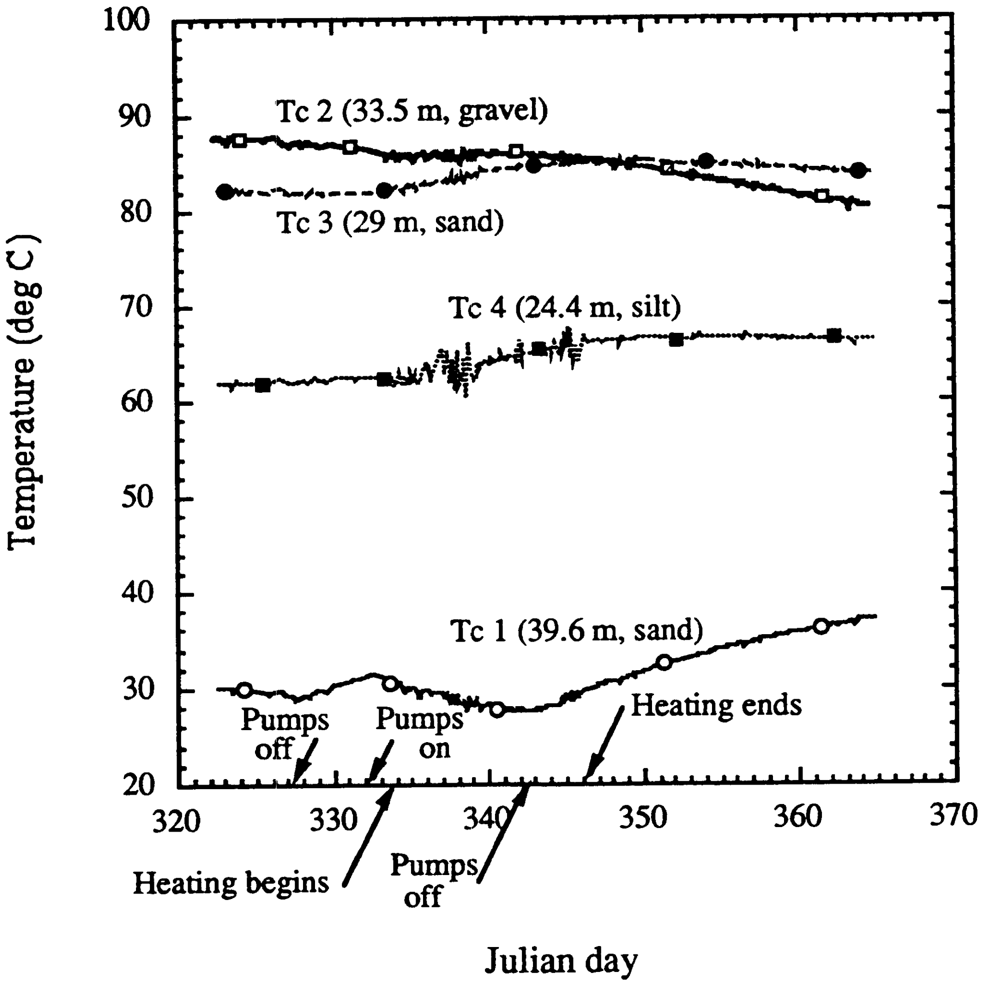


Figure 21. Fixed thermocouples in well TEP 2 show different responses to electrical heating during the ARV phase. Slight temperature rises occur in sandy or silty zones, even while the extraction systems were removing heat from the system. The two lower thermocouples (Tc 1 and 2, open symbols) are located below the standing water table. The two thermocouples above the water table (Tc 3 and 4, closed symbols) show temperature rise throughout electrical heating. (After Sweeney et al., 1994).

Cleanup Results

Free-Product Removal

Free-product gasoline has been removed from the treated area at the LLNL gasoline spill site, thus accomplishing the goal of Dynamic Underground Stripping; approximately 7600 gallons of gasoline were removed from above and below the water table. This conclusion deserves careful scrutiny because of the previous great difficulty in accomplishing this goal experienced by other cleanup methods.

The bases for this conclusion are:

1. 6200 gallons of gasoline were estimated to be in the treatment zone, and 7600 have been removed. After the August 1993 drill-back, soil concentrations indicated that 750 gallons remained (if the distribution was symmetric). Over 1000 gallons have since been removed. Extraction rates fell to nearly zero (11 gallons per month) in January 1994 and have remained low.

2. Groundwater concentrations in the extraction wells and in the two available monitoring wells inside the pattern (GEW 710 and GSW 1A) are lower than the apparent solubility of the most recently extracted gasoline. Although the solubility of gasoline can vary greatly depending on its composition, by measuring the concentration in the water in the oil-water separator where raw

gasoline is known to be in contact with groundwater (Jovanovich et al., 1994; Sweeney et al., 1994), an accurate estimate under site conditions can be obtained. The equilibrium concentrations currently are >35,000 ppb at 20°C; groundwater samples from the extraction and monitoring wells are less than 10,000 ppb at elevated temperatures (>50°C). These are well below the initially observed values for water in contact with free product when wells were drilled (40,000–70,000 ppb), and an order of magnitude below the values observed in the monitoring wells after electrical heating mobilized gasoline (120,000—180,0000 ppb).

3. Vapor and liquid concentrations did not rise significantly after the December 1993–January 1994 shutdown period. Previous shutdowns with hot ground resulted in large increases in concentration when the treatment system was turned on again. Presumably, this was due to the mobilization and/or vaporization of free-product gasoline. The absence of such a pulse after ARV indicates that there was no free product remaining.

4. Groundwater concentrations of BTEX at the central extractors are at lower values than the initial groundwater concentrations just outside the injection ring (e.g., GSW 2, 3, 13), and are at comparable concentrations to many of the distal wells (see below).

The limitations to the conclusion that we have removed all the free product are:

1. Our ability to resolve the presence of free-product pockets by chemical means is limited by the degree of contact with flowing air or water. This is difficult to quantify.

At the start of ARV, the remaining gasoline left a chemical signature of 20,000 ppb total petroleum hydrocarbons (TPH) in groundwater, which dropped to 10,000 ppb by the end of the ARV phase (Sweeney et al., 1994). During ARV, about 1000 gallons of gasoline were removed. This places an upper limit on the free product remaining in the treated area today, based on groundwater analysis alone of 1000 gallons.

There are approximately 1 million gallons of groundwater in the near vicinity of the extraction wells. Given the observed concentrations of TPH during the ARV phase, this places a lower limit of 10-20 gallons (dissolved in groundwater). This indicates that there are much less than 1000, but possibly on the order of tens, of gallons of gasoline remaining (99.9% removal would correspond to about 10 gallons remaining). Any pocket of free product near the extraction wells would have to be extremely well isolated from the permeable parts of the formation to have survived.

2. Free product may remain in the area outside and east of the treated area (e.g., near GSW 216). The vapor concentrations in the easternmost injection well (GIW 815) are still fairly high (Sweeney et al., 1994). This may be due to either free product in the area or from the vapor being pulled in from the area to the east. It is more likely that this results from vapor being pulled in from the east; if there were free products in the area, we would have seen this in the GSW-001A results. In addition, there was a pocket of free product under the receiving yard to the north of the treatment area before Dynamic Underground Stripping was begun. This was sampled during the drilling of TEP 5 (Bishop et al., 1994).

Groundwater Cleanup

Cleanup of groundwater is the goal of any remediation effort, so the results of the LLNL demonstration must be measured principally in terms of the resulting contaminant concentrations in the water beneath the site even though the goals of the project were strictly limited to free-product removal. The regulated contaminants 1,2 dichloroethane (DCA), xylene, and toluene are at or near their allowed Maximum Contaminant Limit (MCL) in the groundwater of the treated area. Benzene has been reduced dramatically, although it is still well above the MCL (Table 2, Figure 22).

Table 2 gives average values for the major regulated contaminants in the central region of the gas pad; this requires the use of data from several wells, as noted. Dynamic Underground Stripping went far beyond free-product removal; it lowered the benzene concentrations inside the central region to levels below those observed outside the treated area (the so-called bathtub ring of untreated but slightly contaminated water) (Figure 23).

Concentrations of 1,2 DCA have dropped to below detection limits in the treated area, and are significantly reduced in the surrounding region.

Xylene concentrations are diminished in the treated area. The increase in xylene concentration in GSW 216 (east of the treated area) probably reflects the local mobilization of gasoline components through increased solubility and decreased sorption due to heating (Figure 8).

Table 2. Average level of contaminant in central extractors.

Date	Benzene 1.0 ppb		Toluene 100 ppb		Xylenes (1750 ppb)		1,2 DCA (1.0 ppb)		Ethylbenzene (680 ppb)	
	ppb	ratio to mcl -1	ppb	ratio to mcl -1	ppb	ratio to mcl -1	ppb	ratio to mcl -1	ppb	ratio to mcl -1
1987	6400	*6399*	4900	*48.0*	2800	*0.6*	*200*	*399*	*360*	*-0.5*
1988	4600	*4599*	4220	*41.2*	2940	*0.7*	118	*235*	360	*-0.5*
1990	1705	*1704*	1500	*14.0*	1643	*-0.1*	188	*375*	305	*-0.6*
1992 (Pre-DUS)	3646	*3645*	2187	*20.9*	2935	*0.7*	117	*233*	838	*0.2*
1993 (Average DUS)	2081	*2080*	4143	*40.4*	3810	*1.2*	0	*-1*	684	*0.0*
12/93 (Post-DUS)	286	*285*	804	*7.0*	1725	*0.0*	0	*-1*	88	*-0.9*
1/94	170	*169*	683	*5.8*	1866	*0.1*	0	*-1*	36	*-0.9*
3/94	125	*124*	150	*0.5*	846	*-0.5*	0	*-1*	7.7	*-1.0*
6/94	157	*156*	257	*1.6*	327	*-0.8*	0	*-1*	26	*-1.0*
8/94	172	*171*	177	*0.8*	530	*-0.7*	0	*-1*	2	*-1.0*
9/1/1994	209	*208*	189	*0.9*	448	*-0.7*	0	*-1*	6	*-1.0*
Average of wells outside treated area, 1992 *	385	*384*	3	*-1.0*	6	*-1.0*	72	*143*	5	*-1.0*

*Notes: 1987 GSW 15 value from 12/15/87

1988 average of values from GSW-015 in 1988

1990 average of tests of GSW 16 11/6 - 12/14/90

Data for GSW 001A for DCA only, 1990

1992 Average of GEW 816 tests, about 8/15/92

1993 Average of all values observed at SEPI port during second pass operations (from Jovanovich et al., 1994)

12/93 LLNL Lab data sampled 12/6/93 , GO-018. UVI port (although SEPI is consistently about 20% higher)

1/94 Data from LLNL ERD GM-071 sampled 1/19/94, data from UVI port (uncorrected for SEPI/UVI differences if any)

3/94 LLNL lab data GO-091 sampled 3/10/94, UVI port

6/94 LLNL data GP-037 sampled 6/14/94, UVI port. After about 1 month of total shut down.

8/94 LLNL data GP-096 sampled 8/1/94, UVI port.

LLNL data GP-125 sampled 9/1/94, UVI port.

Outside wells: Average of 1992 values for GSW 8,10,208,216 (wells well outside the treated area that had gasoline contaminant)

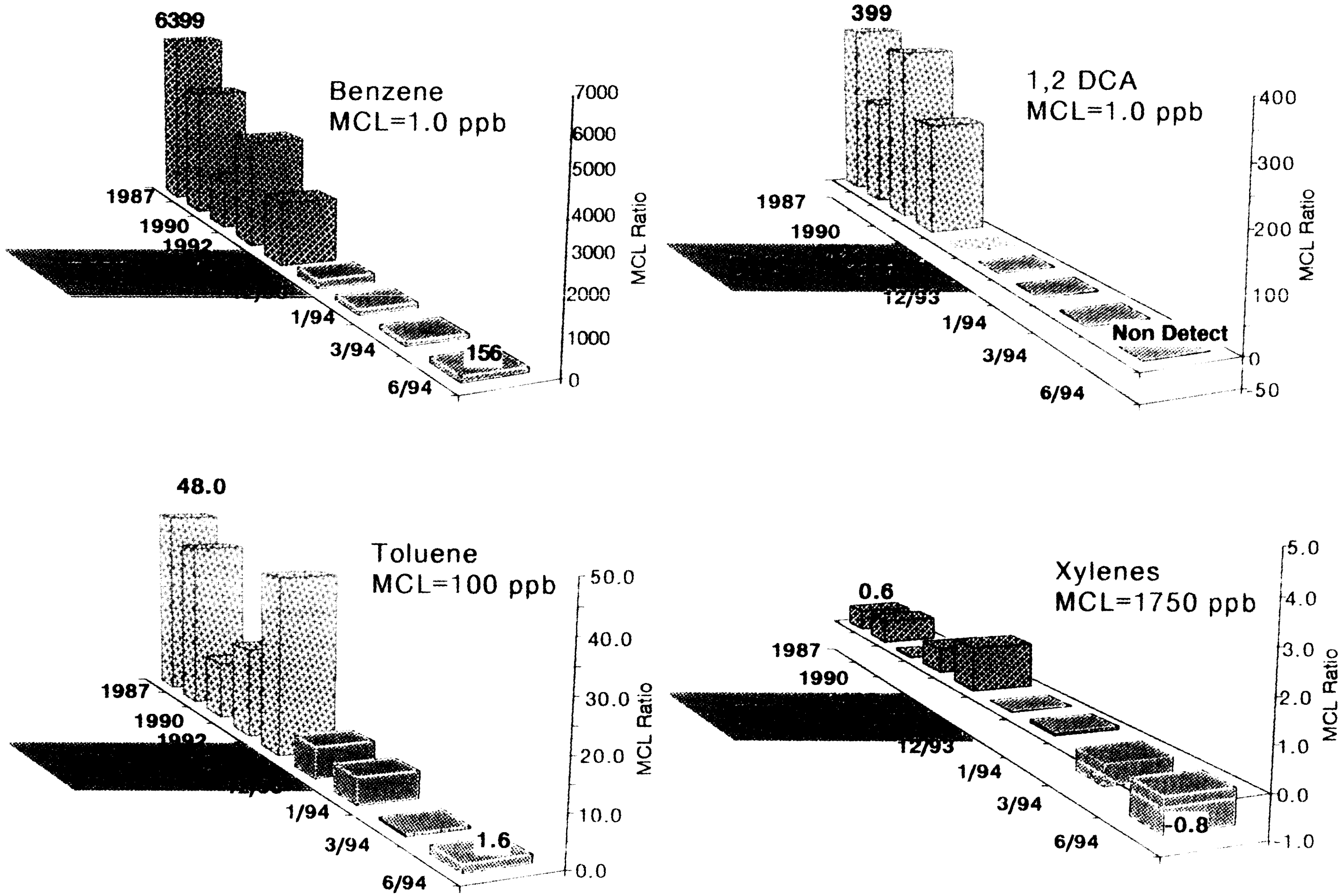
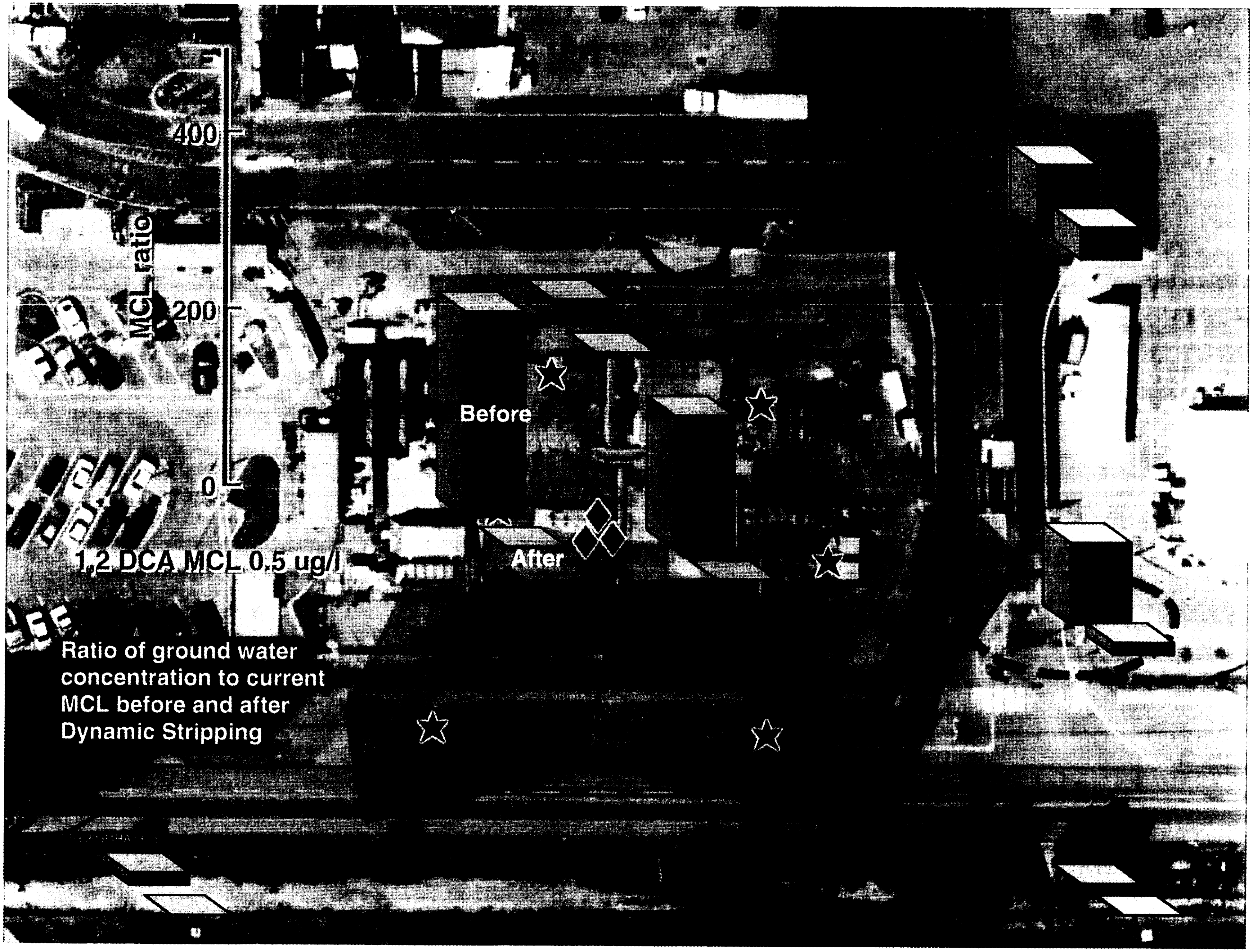
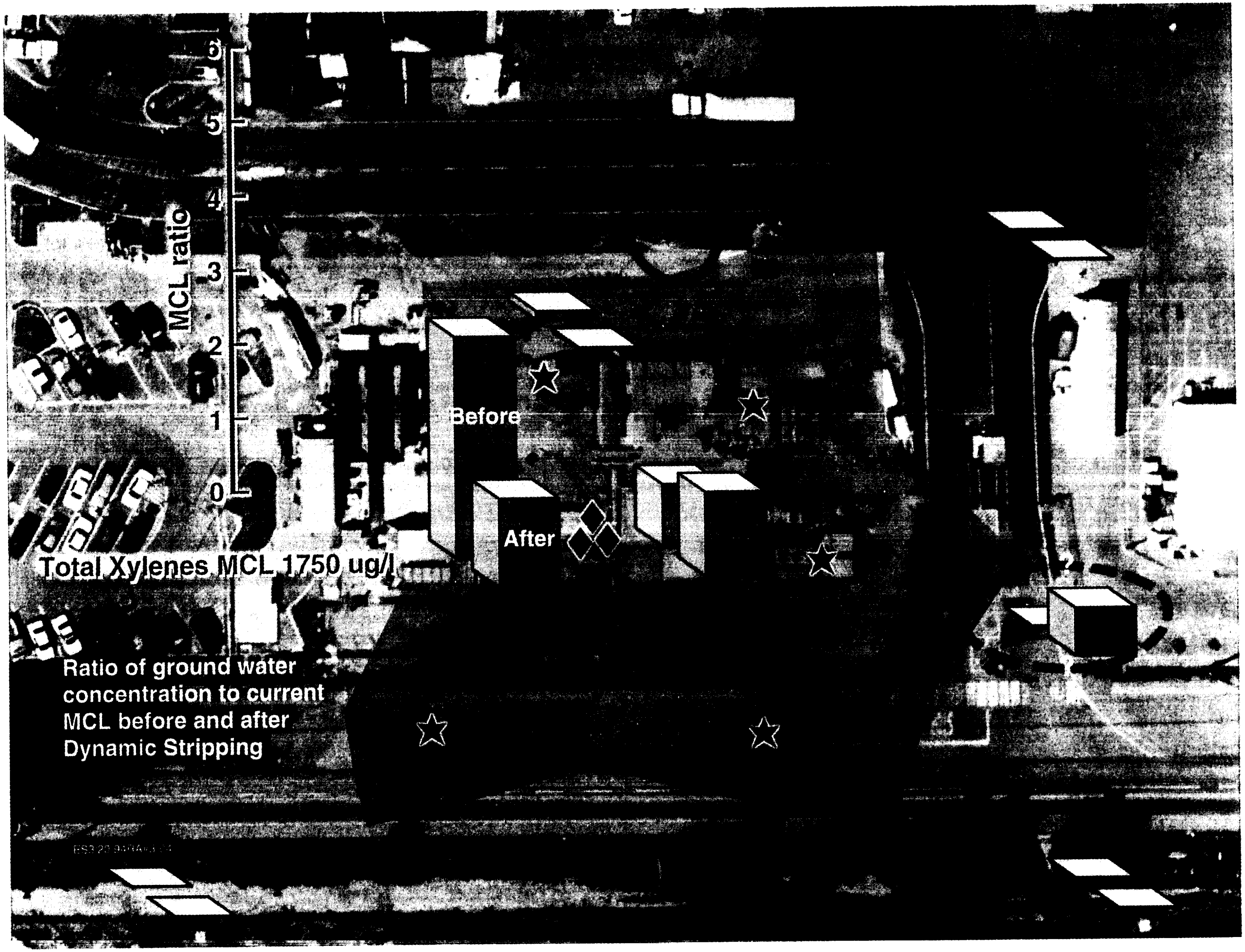


Figure 22. Dissolved groundwater contaminants at the gasoline spill site through June 1994. MCL ratio is expressed as [(contaminant concentration (ppb))/(MCL (ppb))] – 1. The ratio is zero when the MCL is reached, and drops to negative values (as shown for xylene) when the MCL is exceeded. Values are given for the central extraction wells (GSW 15, 16 and GEW 808, 816). Starting and ending ratios are noted. In June, 1,2 DCA and total xylenes were below MCL, as were ethylbenzene and ethylene dibromide (not shown). Toluene was at 1.6 above its MCL, and benzene was 156 times its MCL. Data from Table 2.

Figure 23. Comparison of MCL ratios observed at seven monitoring or extraction wells before Dynamic Underground Stripping (1992 average values) and after the ARV phase (January 1994). Clockwise from the central extraction wells (GEW 808 and 816) are GEW 710, GSW 208, GSW 216, GSW 7, GSW 8, and GSW 1 (at center of photo) (Figure 6). Free-product gasoline was observed in GSW 216 when it was drilled in 1986 (Dresen et al., 1986). (a) Benzene.


MCL ratio
400
200
0
Before
After
1,2 DCA MCL 0.5 ug/l
Ratio of ground water concentration to current MCL before and after Dynamic Stripping

(b) 1,2 DCA.



(c) Total xylenes.

Concentrations in GSW 1 appear higher in the treated area; this value roughly matches the levels seen in the extraction wells, and reflects the same mobilization mechanisms. Ethylbenzene and ethylene dibromide are below the MCL as well.

Contaminant concentrations in the central extraction wells appear to approach the outside well values, indicating that water in the treated area is equilibrating with the untreated water as the extraction system draws water in.

The ability of Dynamic Underground Stripping to remove contaminants to such low levels in groundwater is probably indicative of the boil-off distillation mechanism described by Udell (1994a). Because volatile components are generally removed from boiling water at a mass-removal rate exceeding that of the water, boiling of a small percentage of the pore water can dramatically reduce aqueous concentrations.

Udell examines the effect as a function of boiling rate, solubility, and Henry's law constants; unfortunately, solubility and Henry's law constants are not known at high temperatures for most groundwater contaminants (see data for xylene obtained as part of the ARV activities, Sweeney et al., 1994). This mechanism may be responsible for the almost instantaneous removal of 1,2 DCA from the gasoline spill site groundwater by Dynamic Underground Stripping and the dramatic decrease seen in benzene relative to xylene.

Ongoing Bioremediation

Before Dynamic Underground Stripping treatment of the gasoline spill area, a wide variety of microorganisms were actively degrading the BTEX components of the gasoline. These organisms included the dominant genus *Pseudomonas* originally, and after a campaign of vacuum venting in 1990–92, the genus *Flavobactor* was dominant. The largest populations existed in areas where gasoline was present at low concentrations. In the capillary fringe zone (up to 5 ft above the water table) where gasoline concentrations were highest, there were low numbers of culturable organisms. In the central area of the spill, below the water table, oxygen concentrations were very low, and microbial activity was effectively zero.

Extensive characterization of the microbial population was conducted before heating the area, with the expectation that the soils would be sterilized and the population rebound of microorganisms in the area could be studied. Post-test drill-back in August 1993 included collection of extensive soil samples that were cultured for microorganisms both at room temperature and at 50°C.

Although the gram-negative bacteria that had been the dominant BTEX degraders were gone, extensive microbial communities were flourishing in all samples, including those in which the soil was collected at temperatures greater than 90°C. The dominant species were no longer bacteria, but yeasts and related organisms (*Rhodotorula, Streptomyces*), which had been observed in small numbers before heating. Thermophiles previously identified from environments such as the hot springs at Yellowstone National Park are important members of the new community, as well as a number of other organisms apparently representing previously unidentified species.

The rates at which this new biological community are degrading gasoline components has not yet been quantified, but it is clear that BTEX degraders (e.g., *Rhodotorula*) have survived and can rapidly undertake the final removal of contaminants from the groundwater. At this point, the addition of trace nutrients to the system is being considered to enhance this activity. It is hoped that final reduction of benzene levels to below the MCL of 1.0 ppb can be accomplished through a combination of continued intermittent operation of the groundwater and vapor extraction systems to provide oxygen, and proper encouragement of the microbial ecosystem.

Conclusions from the Gasoline Spill Site Demonstration

- Separate-phase gasoline has been removed from the treated area.
- A stable steam zone can be established below the water table.
- Steam injection is effective for heating permeable zones, and repeated steam passes can effectively heat small impermeable layers between.
- Dynamic Underground Stripping can reduce groundwater contamination to very low levels.
- Electrical heating is effective for heating clay zones, but higher power levels are required when extraction of hot fluids is removing heat from the formation.
- Establishing a complete steam zone in very permeable materials requires large amounts of steam; the more the better.
- Electrical resistance tomography is extremely sensitive to heating of soil and gives rapid images of steam movement between wells.
- Tiltmeters accurately mapped the outer extent of the steam fronts both above and below the water table, and the footprint of steam zones emanating from individual injectors in the lower steam zone.
- Steam did not displace much liquid contaminant in a piston flow.
- Vapor recovery is the major contaminant removal mechanism.
- Gasoline is locally mobilized in heated areas and may show higher groundwater concentrations outside the treatment area even though it is not being transported.
- Treatment systems must be robust to handle the large peak extraction rates and the rapid changes in rate.

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