Technology Application Analyses at Five Department of Energy Sites

May 1995

HAZARDOUS WASTE REMEDIAL ACTIONS PROGRAM

Environmental Management and Enrichment Facilities

Oak Ridge, Tennessee 37831-7606

managed by

LOCKHEED MARTIN ENERGY SYSTEMS, INC.

for the

U.S. DEPARTMENT OF ENERGY

under contract DE-AC05-84OR21400

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HAZARDOUS WASTE REMEDIAL ACTIONS PROGRAM

Leading the Way to Environmental Stewardship

Technology Application Analyses at Five Department of Energy Sites

May 1995

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U. S. Department of Energy
Oak Ridge Operations Office

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EXECUTIVE SUMMARY

The Hazardous Waste Remedial Actions Program (HAZWRAP), a division of Lockheed Martin Energy Systems, Inc., managing contractor for the Department of Energy (DOE) facilities in Oak Ridge, Tennessee, was tasked by the United States Air Force (USAF) through an Interagency Agreement between DOE and the USAF, to provide five Technology Application Analysis Reports to the USAF. These reports were to provide information about DOE sites that have volatile organic compounds contaminating soil or ground water and how the sites have been remediated. The sites were using either a pump-and-treat technology or an alternative to pump-and-treat.

The USAF was looking at the DOE sites for lessons learned that could be applied to Department of Defense (DoD) problems in an effort to communicate throughout the government system. The five reports were part of a larger project undertaken by the USAF to look at over 30 sites. Many of the sites were DoD sites, but some were in the private sector.

The five DOE projects selected to be reviewed came from three sites: the Savannah River Site (SRS), the Kansas City Site, and Lawrence Livermore National Laboratory (LLNL). SRS and LLNL provided two projects each. Both provided a standard pump-and-treat application as well as an innovative technology that is an alternative to pump-and-treat.

The five reports on these sites have previously been published separately. This volume combines them to give the reader an overview of the whole project.

TECHNOLOGY APPLICATION ANALYSIS

***Pump & Treat of Contaminated Groundwater
at***

U.S. Department of Energy

***Savannah River Site
Aiken, South Carolina***

prepared for

U.S. Air Force

May 1994 FINAL

TECHNOLOGY APPLICATION ANALYSIS

Page 1 of 12

SITE

U.S. Department of Energy
Savannah River Site
A/M Area
Aiken, South Carolina

TECHNOLOGY APPLICATION

This analysis covers an effort to **pump and treat groundwater** contaminated with volatile organic compounds (VOCs) by above ground **air stripping**. Full scale treatment began in September 1985 and is one component of an ongoing environmental restoration program. This analysis covers performance through December 1993.

SITE CHARACTERISTICS

Site History/Release Characteristics

- The Savannah River Site's historical mission has been to support national defense efforts through the production of nuclear materials. Production and associated research activities have resulted in the generation of hazardous waste byproducts now managed as 266 waste management units located throughout the 300 square mile facility.
- The A and M areas at Savannah River have been the site of administrative buildings and manufacturing operations respectively. The Savannah River Laboratory is also located within the A area. Specific manufacturing operations within the M area include aluminum forming and metal finishing.
- The M area operations resulted in the release of process wastewater containing an estimated 3.5 million pounds of solvents. From 1958 to 1985, 2.1 million pounds was sent to an unlined settling basin which is the main feature of the M-Area Hazardous Waste Management Facility (HWMF). The remaining 1.3 million pounds was discharged to Tims Branch, a nearby stream, during the years 1954 to 1982.
- Discovery of contamination beneath the settling basin in 1981 initiated a site assessment effort eventually involving approximately 250 monitoring wells over a broad area. A pilot groundwater remediation system began operation in February 1983. Full-scale groundwater treatment began in September 1985.

Contaminants of Concern

Contaminants of greatest concern in the groundwater are:

- 1,1,2-trichloroethylene (TCE)
- tetrachloroethylene (PCE)
- 1,1,1-trichloroethane (TCA)

Contaminant Properties

Properties of contaminants focused upon during remediation are:

Property at STP*	Units	TCE	PCE	TCA
Empirical Formula	-	C_2HCl_3	C_2Cl_4	C_2HCl_3
Density	g/cm ³	1.46	1.62	1.31
Vapor Pressure	mmHg	73	19	124
Henry's Law Constant	atm·m ³ /mole	9.9E-3	2.9E-3	1.6E-2
Water Solubility	mg/L	1000-1470	150-485	300-1334
Octanol-Water Partition Coefficient; K _{ow}	-	195	126	148

*STP = Standard Temperature and Pressure; 1 atm, 25 °C

Nature & Extent of Contamination

- Approximately 71% of the total mass of VOCs released to both the settling basin and Tims Branch was PCE, 28% was TCE and 1% was TCA.
- The dissolved organic solvents are estimated to be 75% TCE. A continued source for dissolved phase VOCs is contaminants sorbed to solids in the saturated zone or in the vadose zone.
- The area of VOC contaminated groundwater has an approximate thickness of 150 feet, covers about 1200 acres and contains contaminant concentrations as high as 223 ppm.
- Dense nonaqueous phase liquids (DNAPLs) were found in 1991 and present complications to long term remediation efforts.

U.S. Air Force

Contaminant Locations and Geologic Profiles

Data from hundreds of soil borings, groundwater monitoring wells and a variety of other investigative techniques has allowed the development of a three dimensional conceptual model of the site including groundwater behavior and contaminant concentration profiles for various geologic units. The following diagrams have been included here to provide a general understanding of site conditions. Data from the third quarter of 1985 is presented.

Site Layout

TCE Plume (Upper Lost Lake Aquifer Top View)

TCE Plume (Side View)

Groundwater monitoring data from the third quarter of 1985 along cross-section B-B' shown in top view

U.S. Air Force

Contaminant Locations and Geologic Profiles (Continued)

Hydrogeologic Units

Site Conditions

- The A/M-Area is approximately one mile inward from the northeast boundary of the 300 square mile Savannah River Site. Adjacent to the site boundary are rural and farming communities.
- The Savannah River Site includes a complex hydrogeology arising from heterogeneities in the multilayer aquifer system and discontinuous sand & clay layers.

Key Aquifer Characteristics

Aquifer parameters beneath the A/M-Area have been estimated as:

Unit	Hydraulic Conductivity	Transmissivity	Flow Direction
	[ft/day]	[gpd/day]	
Water Table Unit	9	175	Flow in the unconfined water table unit within the McBean Formation is complex but radial flow is expected outward from a plateau (at 244 MSL) surrounding most of the A/M-Area.
Lost Lake Aquifer	Avg. 40	Avg. 1750	Ranged from southwest to northeast near the A/M-Area in the Upper Lost Lake. Mainly east and south in the Lower Lost Lake during 1985-86.
Middle Sand Crouch Branch Confining Unit	29	1600	Mainly southeast during 1985-86.
Crouch Branch Aquifer	73	12,500	Mainly southeast during 1985-86.

- A wide range of values has been used to describe regional aquifer characteristics. Uncertainties stem from difficulties in aquifer testing and interpreting methods applied to the hydrogeological complexities noted above under Site Conditions.
- A moderate downward gradient appears to exist beneath the M-Area. Vertical flow rates have been estimated to be from 2 to 8 feet per year.
- Radial flow outward from a groundwater plateau surrounding most of the A/M-Area within the water table unit and Upper Lost Lake aquifer is approximately 15 to 100 ft/year.

U.S. Air Force

TREATMENT SYSTEM

Overall Process Schematic

Extraction Well Network

Air Stripper System Schematic

- In 1988, the original pall ring packing was replaced with cascade mini-rings to provide more surface area and less pressure drop across the system.
- In 1990, system in flow was upgraded from 400 gpm to 510 gpm.
- Drawing not to scale.

Extraction Well Close-Up

Typical Extraction Well
(Well Shown is #4)

Key Monitored Operating Parameters

- Water flows
 - Air flows
 - Pump discharge pressures
 - Groundwater levels
 - Contaminant concentrations in treatment plant influent & effluent
 - Contaminant concentrations in groundwater
- (to assess system operation)
- (to assess zone of capture)
- (to assess treatment effectiveness)
- (to assess achievement of remediation goals)

PERFORMANCE

Performance Objectives

- Achievement of Groundwater Protection Standards (GWPS) established as part of a RCRA permit for the M-Area. The GWPS are based on EPA's Maximum Contaminant Levels (MCLs) of 5 ppb for TCE and PCE and 200 ppb for TCA.
- Prevent migration of contaminated groundwater toward the Savannah River Site boundary and downward into the confined aquifer (Black Creek Formation).
- Achieve cleanup goals within 30 years.

Treatment Plan

The overall long-term environmental restoration strategy for the A/M-Areas involves an integrated approach containing three major elements. Only the larger A/M air stripping effort is fully detailed in this analysis:

- Operation of **pump-and-treat** systems to hydraulically contain contaminant plumes and remove contaminant mass from groundwater.
One 600 GPM capacity air stripper treats an average water flow of 510 GPM drawn from 11 extraction wells throughout the A/M area; a second stripper treating an average of 55 GPM from 1 extraction well near the Savannah River Laboratory in the A-Area.
- **Further characterization** of nature and extent of contamination with increasing focus on dense nonaqueous phase liquid (DNAPL) contamination.
The use of minimally invasive techniques, such as the cone penetrometer and geophysical techniques, are currently recommended for future use to fully characterize the extent of DNAPL contamination.
- Development, demonstration and implementation of technologies to supplement pump-and-treat efforts with increasing focus on **source area, DNAPL and vadose zone** remediation.
Soil vapor extraction, in situ air stripping, in situ heating, and surfactant flushing techniques are in various stages of implementation or demonstration.

Initial Process Optimization Efforts

Air stripper viability was tested through a succession of field programs:

Operational Performance

System Throughput

- For 1993, 243 million gallons of groundwater were pumped from 11 recovery wells to the production air stripper.
- Average water flow rate was 479 GPM and average air flow rate was 2,489 cfm through the air stripper during 1993.
- 19,500 lbs of VOCs were removed in 1993 which produced an average air emission rate of 2 lbs/hr.

System Downtime

- Average utility for 1993 was 96.4%. Cumulative average utility since 1985 is 95.3%.
- 1993 experienced 316 hours of downtime.
- Causes of downtime included scheduled maintenance, operator training, power outages, and equipment repair.

Hydrodynamic Performance

- Current estimates of the 30 year zone of capture of the pump and treat system have determined that portions of the existing plume will not be effectively controlled. Contaminated groundwater beneath the Savannah River Laboratory and southeast of the settling basin are beyond the anticipated capture zone. However, contaminated groundwater in the source areas and areas of highest VOC concentration is contained.
- The downward gradient across the Crouch Branch Confining Unit, and consequently the driving force for downward contaminant migration to the confined aquifer in the Crouch Branch Aquifer, has been reduced due to pumping effects.
- The groundwater recovery wells are screened in the more permeable areas of the shallow aquifer which increase hydraulic control yet limits access to silt and clay layers where retention of contaminants may be strongest.

Treatment Performance

Effects on Plume

- Reductions in contaminant plume size and concentration as a result of remediation are evident (the >100,000 ppb contaminant concentration zone has disappeared) but are generally limited to areas near recovery wells.
- Significant progress is evident in the Lost Lake Aquifer where initial contaminant concentration and hydraulic conductivity are highest.
- Downward migration of VOCs to the Crouch Branch Aquifer beneath the settling basin and north of the M-Area is evident. VOC concentrations have increased slightly in the confined aquifer since 1985.

TCE & PCE vs Time at Influent

- The concentration of TCE in extracted groundwater has varied widely over short (one year) time frames for individual wells. Some wells have shown short term increases in contaminant concentration, some decreases and others no clear trend.
- The trends may indicate plume redistribution and may also represent a decline in plume strength.
- There has been a clear reduction in overall contaminant concentrations sent to the air stripper.

Air Stripper Influent vs Effluent

- Average VOC removal efficiency >99.9%
- All VOCs treated below discharge criteria.

Compound	Average Concentration* [ppb] Influent	Average Concentration* [ppb] Effluent
TCE	15,006	<1.01
PCE	6,705	<1.0
Total	21,711	<1.12

*data from September 1985-1993

Total Pounds VOCs Removed

U.S. Air Force

COST

• The production air stripper was designed and constructed in 1984-1985. The major capital cost elements associated are provided below. Annual operating costs based upon data from 1985 through 1990 are also listed. All information is based on an analysis performed in 1990 and all costs are in 1990 dollars.

• During 1985 to 1990, the average volume of water treated by the air stripper was 198 million gallons per year. Using the operating costs detailed below (in 1990 dollars), the total cost of operation and maintenance is \$0.75 per 1000 gallons treated.

• An assessment of total cost and duration of operation for the pump and treat system to complete the cleanup is not possible due to the multi-phased approach to environmental restoration of the A/M Area. As detailed on page 6, the overall treatment plan for the site includes future identification and implementation of technologies to achieve cleanup goals. The extent to which the pump and treat system will be part of that effort has not yet been determined therefore projected costs to cleanup can not be estimated.

Operating Costs

Capital Costs

Design	\$420,000	Electrical Power (@ \$0.052/kwh)	\$26,000
Contracts (permitting, modeling, etc.)	368,000	Maintenance	13,500
Site Development	28,000	Labor (@ \$35/hr)	13,000
QA Engineering	18,000	Equipment repair & replacement	13,000
Control Building	21,000	Operation	45,700
Electrical	877,000	Operation & daily inspections	15,000
Instrumentation	466,000	Well sampling & lab analysts	36,000
Piping/Construction	925,000	Engineering support	15,000
Tower Installation	132,000		
Control System	230,000		
Erect/Test Tower	428,000		
Total	\$4,103,000	Total Annual Operating Cost	\$149,200

REGULATORY/INSTITUTIONAL ISSUES

- The production air stripper is part of the M-Area Hazardous Waste Management Facility which is permitted under the Resource Conservation and Recovery Act (RCRA). The air stripper unit is permitted as a waste water treatment facility requiring South Carolina certified Class-D physical/chemical operators. The air stripper unit is not regulated as a RCRA treatment, storage, disposal (TSD) facility.
- The air stripper has a South Carolina Bureau of Air Quality Control permit allowing the release of 34 tons/year (or 7.9 lbs/hr) of VOCs to the atmosphere.
- Recent Clean Air Act requirements mandate that industrial off gas systems be retrofitted with an off-gas treatment system. Catalytic oxidation has been demonstrated as an effective off-gas treatment and the M-Area air stripper is being retrofitted. The system will be installed by 1995, even though regulations for mitigation will not require retrofit until 2000.
- Treated water effluent from the stripper is released through an National Pollution Discharge Elimination System (NPDES) permitted outfall. The EPA Maximum Contaminant Levels (MCLs) listed under "Cleanup Criteria" below apply to this discharge.
- The facility's RCRA Part B permit requires periodic sampling at the recovery wells, air stripper and NPDES outfall.
- Eight production wells drawing from the Crouch Branch Confined Aquifer currently supply process and drinking water for A/M-Area Site operations.

Cleanup Criteria

- During initial remediation efforts in 1985, a cleanup goal of removal of 99% of VOCs over a 30 year period was used. A CERCLA baseline risk assessment was not developed or required.
- In 1990, groundwater protection standards based upon EPA MCLs were adopted during modifications of the facility's RCRA permit. The standards are:

<u>Compound</u>	<u>Criteria Level [ppb]</u>
TCE	5
PCE	5
TCA	200

SCHEDULE

A/M-Area Remediation Milestones

U.S. Air Force

LESSONS LEARNED

Implementation Considerations

- An integrated treatment program consisting of pump and treat for hydraulic control and dissolved plume mass removal combined with source/DNAPL targeted technologies has been determined to be the most effective long term remedial solution for the M-Area VOC plume at Savannah River.
- Technologies to supplement the pump and treat systems are in various stages of development, demonstration or implementation. These technologies focus on either the source area, DNAPL or vadose zone contamination and include soil vapor extraction, in situ air stripping, in situ bioremediation, in situ heating and surfactant flushing.
- There is a recognized need for supplemental site characterization efforts to redirect ongoing remediation activities at the site. Further characterization will focus on DNAPL contamination and will involve minimally invasive methods such as the cone penetrometer and geophysical techniques.
- Significant volumes of VOC-contaminated purge water are generated from sampling the extensive network of over 250 monitoring and compliance wells. Modifications to the air stripping system were implemented to treat this groundwater. The system changes include addition of a 10,000 gallon carbon steel receiving tank and associated piping.

Technology Limitations

- The presence of DNAPLs represents a significant long-term limitation to pump and treat due to residual DNAPL above and below the water table combined with mass removal limitations.
- Hydraulic factors, combined with the nature of contaminants, has inhibited the pump and treat system's ability to affect the fringes of the plume. However, the contaminated groundwater in the source areas and areas of highest VOC concentration is contained.
- Pump and treat is effective for plume restoration only where DNAPL source areas have been contained or removed.

Future Technology Selection Considerations

- Early M-Area remediation efforts did not address the long term prospect of removing residual levels of contamination. Future cleanups at sites with chlorinated solvents must carefully look for DNAPL during site characterization and address DNAPL and residual contamination removal as part of an overall remediation plan.
- The original aim of the pump and treat system in the M-area was for broad plume containment and destruction of 99% of the VOCs. This goal was later changed to achievement of EPA MCL based groundwater protection standards. Future pump and treat systems should consider the actual environmental and human risks, be highly designed, and address realistic elements of overall cleanup goals.
- Pump and treat for containment of dissolved contaminants is a viable tool for dissolved phase VOC removal and can be an element of presumptive remedies for such sites.
- A phased approach to site assessment and remediation is beneficial. Early actions to control plume migration and remove contaminant sources, when properly designed and implemented, can reduce risks posed by contaminated groundwater.

ANALYSIS PREPARATION

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Assistance was provided by the
WESTINGHOUSE SAVANNAH RIVER COMPANY
which supplied key information and reviewed report drafts.

for:

HAZARDOUS WASTE REMEDIAL ACTIONS PROGRAM
Environmental Restoration and Waste Management Programs
Oak Ridge, Tennessee 37831-7606

managed by
MARTIN MARIETTA ENERGY SYSTEMS
for the

U.S. Department of Energy
under Contract DE-AC05-84OR-21400

This analysis was funded by:

U.S. Air Force
Headquarters USAF/CEVR

CERTIFICATION

This analysis accurately reflects the performance and costs of the remediation:

x
C.L. Bergren

Westinghouse Savannah River Company
Environmental Restoration Department
Manager Northern Ground Water Facilities

x
G.E. Turner

Department of Energy
Savannah River Operations Office
Environmental Restoration Division
Environmental Specialist

U.S. Air Force

SOURCES

Major Sources For Each Section

Site Characteristics:	Source #s (from list below) 5,7,8 and 9
Treatment System:	Source #s 5,6 and 7
Performance:	Source #s 1,2,3,5 and 7
Cost:	Source # 5
Regulatory/Institutional Issues:	Source # 5
Schedule:	Source #s 1,5, and 7
Lessons Learned:	Source #s 1,3, and 4.

Chronological List of Sources and Additional References

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7. *Evaluation of Ground-water Extraction Remedies: Phase II EPA Publication 9355.4-05A, February 1992.*
8. *Evaluation of Ground-water Extraction Remedies, EPA/540/2-89-054, September 1989.*
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TECHNOLOGY APPLICATION ANALYSIS

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of Contaminated Groundwater
at***

U.S. Department of Energy

***Savannah River Site
Aiken, South Carolina***

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U.S. Air Force

June 1994 FINAL

TECHNOLOGY APPLICATION ANALYSIS

SITE

U.S. Department of Energy
Savannah River Site
A/M Area
Aiken, South Carolina

This analysis describes efforts to remediate soil and groundwater contaminated with volatile organic compounds (VOCs) using in situ air stripping with horizontal wells. The remediation activities were part of a field demonstration program involving other innovative technologies to provide information for long-term remediation efforts.

TECHNOLOGY APPLICATION

SITE CHARACTERISTICS

Site History/Release Characteristics

- The Savannah River Site's historical mission has been to support national defense efforts through the production of nuclear materials. Production and associated research activities have resulted in the generation of hazardous waste byproducts now managed as 266 waste management units located throughout the 300 square mile facility.
- The A and M areas at Savannah River have been the site of administrative buildings and manufacturing operations, respectively. The Savannah River Laboratory is also located within the A area. Specific manufacturing operations within the M area include aluminum forming and metal finishing.
- The M area operations resulted in the release of process wastewater containing an estimated 3.5 million pounds of solvents. From 1958 to 1985, 2.1 million pounds was sent to an unlined settling basin which is the main feature of the M-Area Hazardous Waste Management Facility (HWMF). The remaining 1.3 million pounds was discharged to Tim's Branch, a nearby stream, primarily during the years 1954 to 1982.
- Discovery of contamination beneath the settling basin in 1981 initiated a site assessment effort eventually involving approximately 250 monitoring wells over a broad area. A pilot groundwater remediation system began operation in February 1983. Full-scale groundwater treatment began in September 1985. These systems have removed over 300,000 lbs of solvents from the groundwater to date.
- High levels of residual solvent are found in the soil and groundwater near the original discharge locations. Technologies to augment the pump and treat effort, for example vacuum extraction, in situ air stripping, and bioremediation, have been tested and are being added to the permitted corrective action.
- This analysis focuses on the use of horizontal wells and in situ air stripping to remove solvents beneath the former process sewer line connecting the manufacturing area to the HWMF. Performance data are through September 1993.

Contaminants of Concern

Contaminants of greatest concern are:

1,1,2-trichloroethylene (TCE)
tetrachloroethylene (PCE)
1,1,1-trichloroethane (TCA)

Property at STP* Units	TCE	PCE	TCA
Empirical Formula	$C_2H_3Cl_3$	C_2Cl_4	CH_2Cl_3
Density	1.46 g/cm^3	1.62	1.31
Vapor Pressure	73 mmHg	19	124
Henry's Law Constant	$3.9E-3$	$2.9E-3$	$1.6E-2$
Water Solubility	1000-1470 mg/L	150-485	300-1334
Octanol-Water Partition Coefficient K_{ow}	-	195	148

*STP = Standard Temperature and Pressure: 1 atm, 25°C

Nature & Extent of Contamination

- Approximately 71% of the total mass of VOCs released to both the settling basin and Tim's Branch was PCE, 28% was TCE and 1% was TCA.
- The estimated amount of dissolved organic solvents in groundwater in concentrations greater than 10 ppb is between 260,000 and 450,000 pounds and is estimated to be 75% TCE. This estimate does not include contaminants sorbed to solids in the saturated zone or in the vadose zone. The area of VOC contaminated groundwater has an approximate thickness of 150 feet, covers about 1200 acres and contains contaminant concentrations as high as 223 ug/L.
- Dense nonaqueous phase liquids (DNAPLs), found in 1991, present challenges for long term remediation efforts.
- Vadose zone contamination is mainly limited to a linear zone associated with the leaking process sewer line, solvent storage tank area, settling basin, and the A-014 outfall at Tim's Branch.

Contaminant Locations and Geologic Profiles

Metal-degreasing solvent wastes were sent to the A-014 outfall and, via the process sewer, to the M-area settling basin. Data from hundreds of soil borings, groundwater monitoring wells, and a variety of other investigative techniques has established a well-documented VOC plume in both the vadose and saturated zones.

Site Layout

TCE Groundwater Plume (Top View)

Data from 15 feet below water table in the third quarter of 1990.

TCE Concentrations in Soil (West-East Cross-Section)

Concentration and lithology data from 1991 along an approximately 200 ft cross-section across the integrated demonstration site. Concentration contours of TCE in sediments are based on analysis of over 1000 sediment samples. Layering of contamination occurs in clay zones.

(figure modified from Reference 2)

Legend

soil concentrations in ug/L

U.S. Air Force

Contaminant Locations and Geologic Profiles (Continued)

Hydrogeologic Units

Aquifer Unit	Description	Thickness
Vadose Zone	Poorly sorted mix of sand, cobbles, silt & clay.	~57 ft
	Moderate to well sorted, fine to medium sand containing some pebbles; 13% silt & clay.	0-97 ft
	Moderately to well sorted medium sand; 18% silt & clay.	30-55 ft
Water Table Unit	Moderate to well sorted fine sand with some calcareous zones; 25% silt & clay; 14% silt and clay beds.	16-34 ft
Upper	Well sorted fine to medium sand; 16% silt & clay; 7% silt & clay beds.	14-60 ft
Lost Lake Aquifer	Discontinuous clay beds containing 70% silt & clay	
Lower	Moderate to well sorted medium sand; 17% silt & clay; 7% silt & clay beds.	4-44 ft
Crouch Branch Confining Unit	Clay, clayey silt, and poorly sorted fine to coarse, clayey sand; 62% silt & clay; contains 2 major clay layers the lower of which is 10-56 ft thick and is the principal confining unit for lower aquifer zones	32-95 ft
Crouch Branch Aquifer	Very poorly to well sorted, medium to coarse sands; 5% sand & clay beds; an important production zone for water supply wells in the M-Area.	152-180 ft

Site Conditions

- The A/M-Area is approximately one mile inward from the northeast boundary of the 300 square mile Savannah River Site. Adjacent to the site boundary are rural and farming communities.
- The horizontal well site is located in the southwestern corner of the M-Area and it encompasses the M-Area settling basin, the abandoned process sewer leading to the basin, and the outfall A-104.
- The Savannah River Site includes a complex hydrogeology arising from heterogeneities in the multilayer aquifer system and discontinuous sand & clay layers.

Vadose Zone and Upper Aquifer Characteristics

Schematic Diagram showing relationship between clay layers and hydraulic features.

- Sediments are composed of sand, clay and gravel.
- Clay layers are relatively thin and discontinuous, with the exception of the clay layers at 160 foot depth, and a thicker zone of interbedded clay and sand found at 90 foot depth.
- Water table is approximately 135 feet below grade.
- A moderate downward gradient appears to exist beneath the M-Area. Vertical flow rates have been estimated to be 2 to 8 feet per year.
- Radial flow outward from a groundwater plateau surrounding most at the A/M-Area exists. Flow is approximately 15 to 100 ft/year.

TREATMENT SYSTEM

Overall Process Schematic

- Air injected through lower horizontal well, below the water table.
- Air/contaminant mixture extracted from upper horizontal well, above water table.
- Off-gas treatment available for long-term remedial operation.
- Horizontal wells 1 and 2 used in the in situ air stripping demonstration.

(figure modified from Reference 2)

Horizontal Wells Layout

- Seven horizontal well have been installed using four different installation methods.
- Wells 1 & 2 and wells 3 & 4 are paired wells (subparallel in the subsurface, one in the vadoso zone and one in the saturated zone) targeting contaminated sands.
- Wells 6 & 7 are paired wells (parallel in the subsurface, both in the vadoso zone) targeting contaminated sands and clays beneath the closed disposal basin.
- Well 5 has surface well heads at both ends and is installed through contaminated clays.
- Wells 3 & 4 and wells 6 & 7 have not been used since installation

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Injection, Extraction, and Offgas Treatment

Injection

Offgas Treatment

Notes:

(F) = Flow Indicator, (M) = Methane Concentration Indicator, (P) = Pressure Sensor, (T) = Temperature Probe

1. A PID controller is used, calibrated based on % of LEL of methane.
2. Extraction system is limited by pumping capacity of extraction well to a maximum of 300 SCFM at 10" Hg.
3. Water trap removes debris and moisture from airstream. System includes a daytank to drain water from separator for ultimate treatment at M-Area air stripper.
4. Demonstration released VOCs directly to the atmosphere. Offgas treatment required for long-term remediation.

Generalized Horizontal Well

Well Installation Techniques

Four different well installation techniques were used during the demonstration:

1. **Petroleum Industry Technology.** A short-radius mud rotary technology. Vertical entry holes with a 35 foot radius for the curved section. Used non-rotating, curved drill guide, flexible drive pipe, an orientation assembly, and a stabilized straight-drilling assembly. Whip stocks used in curved section. Drilling fluids used. (wells 1&2)
2. **Hybrid Petroleum Industry/Utility Industry Technology.** Modified mud rotary system with bottom hole assembly comprised of a survey tool, steerable downhole motor, and an expandable wing drill bit. Drilling fluids used. (wells 3&4)
3. **Utility Industry Compaction System.** This technology yielded a well head at initial and terminal points of the bore hole. Downhole drill assembly consisted of a wedge-shaped drilling tool, a steering tool, and a flexible sub-assembly attached to the drill string. Advanced by compaction, forcing cuttings to the borehole wall. Reduced volumes of water introduced as cooling/drilling fluid. (well 5)
4. **Utility Industry River Crossing.** Based on mud rotary system used to drive a downhole drill assembly, including a drilling tool, hydraulic spud jet with a 2 degree bend to provide directional drilling. Steering system was a magnetic guidance tool. A guar gum-based drilling fluid used. (wells 6&7)

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PERFORMANCE

Performance Objectives

- Demonstrate proof of principle for air sparging using horizontal wells during a fixed, limited period of time permitted for the demonstration activity.
- Document substantial progress towards achievement of Groundwater Protection Standards (GWPS) established as part of a RCRA permit for the M-Area. The GWPS are based on EPA's Maximum Contaminant Levels (MCLs) of 5 ppb for TCE and PCE and 200 ppb for TCA.
- Reduce the contaminant concentrations in source areas so as to be able to achieve cleanup goals within 30 years.
- Demonstrate innovative characterization and monitoring technologies.
- Use of Integrated Demonstration Program site as an innovative technology education and training facility.
- Ensure that research, development, demonstration, and educational activities do not adversely impact remediation.

Treatment Plan

The M-Area HWMF RCRA Part B permit allows for ongoing and planned activities for vadose zone and groundwater remediation. Technology demonstrations at the IDP augment the M-Area HWMF program by addressing vadose zone contamination. Operation of one of the paired horizontal well systems will be part of full-scale M-Area remediation efforts.

The overall long-term environmental restoration strategy for the A/M-Areas involves an integrated approach containing three major elements. Only the larger A/M air stripping effort is fully detailed in this analysis:

- **Operation of pump-and-treat systems to hydraulically contain contaminant plumes and remove contaminant mass from groundwater.**
One 600 GPM capacity air stripper treats an average water flow of 510 GPM drawn from 11 extraction well throughout the A/M area; a second stripper treating an average of 55 GPM from 1 extraction well near the Savannah River Laboratory in the A-Area.
- **Further characterization of nature and extent of contamination with increasing focus on dense nonaqueous phase liquid (DNAPL) contamination.**
Characterization and monitoring emphasized: minimally invasive techniques; real-time, in situ sample analysis; optimization of data from a single borehole; and to use new physical/chemical processes to improve sample analysis. Monitoring technologies included downhole flow and temperature sensor, cone penetrometer systems, geophysical systems, multilevel samplers, and real-time field analytical instruments.
- **Development, demonstration and implementation of technologies to supplement pump-and-treat efforts with increasing focus on source area, DNAPL and vadose zone remediation.**
Technology demonstrations at the site have included characterization and monitoring, directional drilling, in situ air stripping, in situ bioremediation, in situ soil heating, and off-gas treatment. Off-gas treatment technologies have included portable catalytic system used to treat VOC-contaminated off-gas streams, as well as thermal desorption and recycle/recovery systems used, recovering contaminants from carbon filters in off-gas treatment.

Initial Process Optimization Efforts

In Situ Air Stripping

- Initial phase consisted of vacuum extraction of vadose zone gases, followed by air sparging, simultaneous air injection into the saturated zone and vadose zone extraction.
- Horizontal wells 1 and 2 were used for the in situ air stripping demonstration.
- Parametric studies of air injection rates and temperatures were conducted between July and December, 1990.
- Helium tracer was used to determine injected air mass balance.

In Situ Bioremediation

- Nutrient injection and concurrent vadose zone extraction carried out in horizontal wells 1 and 2.
- Designed to enhance air stripping methods, resulting in decreased contaminant concentration in groundwater and enhancing remediation of fine-grained sediments
- Based on stimulation of indigenous organisms to biodegrade TCE, producing water and carbon dioxide.
- Demonstration included steady and pulsed injection of air/methane blend (1-4% methane).
- Nitrous oxide and triethyl phosphate added for biodegradation optimization.

Operational Performance

- In Situ Air Stripping Demonstration showed five fold increase in VOC removal efficiency compared to the use of vertical injection and extraction wells.
- Air injection into Well 1 varied from at 65, 170, and 270 scfm.
- Vacuum extraction from Well 2 ranged from 550 to 600 scfm at 10 to 11 inches Hg.
- Removal capabilities - 16,000 pounds of VOCs removed from vadose zone and groundwater over the 139-day duration of the in situ air stripper demonstration.
- System operated at 90% utility with shutdowns for repairs and maintenance less than 10% of the time.

Treatment Performance

Effects on Vadose Zone Contaminants

- Substantial changes in groundwater VOC concentrations measured during demonstration.
- Most monitoring wells at site exhibited lower concentrations of contaminants and increases in microbial numbers and metabolic activity during the air injection period.
- Post-demonstration sediment data indicates that almost all contaminants in sediment in the vadose zone were removed primarily due to microbial activity during later phases of remediation.

Removal Data

- 139 day demonstration removed nearly 16,000 lbs of VOCs.
- Soil vapor extraction (without air injection) removed contaminants at a rate of 109 lbs/day.
- Combined injection and extraction increased the removal rate to 130 lbs/day.

(figure modified from Reference 6)

In Situ Air Stripping VOC Extraction Rates

- Contaminant removal rate ranged between 100 and 140 lbs/day over most of the 139 days.
- Vacuum extraction removed an estimated 109 lbs/day while air injection resulted in an additional 20 lbs/day of VOC removal.

(figure modified from Reference 6)

COST

• A cost study (Reference 4) was conducted that compared in situ air stripping with horizontal wells against the conventional cleanup technologies of combined pump and treat and soil extraction. A comparison of costs indicated that in situ air stripping can remove VOCs for approximately 60 % of the cost of conventional methods. Detailed capital and operating costs taken from the study for the in situ air stripping application are presented below.

Capital and Operating Costs

Equipment Costs

Design and engineering (100 hrs @ \$50/hr)	\$5,000
Mobile Equipment (pickup truck)	15,000
Capital : Well Installation (subcontracted)	
Air Injection Well (165 ft deep, 300 ft long)	93,323
Air Extraction Well (75 ft deep, 175 ft long)	76,762
Subtotal: Well Installation	170,085
Other Equipment	
Air injection system(300 cfm blower)	3,500
Air extraction system (600 cfm blower)	5,000
Vapor air separator (c/s 1@600 cfm)	2,750
Carbon adsorption unit (2@600 cfm canister)	10,000
Duct Heater (2,000 btu propane fired)	3,250
Water treatment unit (12 gph recirculation unit)	4,000
Monitoring equipment	17,000
Temporary storage (metal shed)	1,500
Portable generator (25 kva)	3,500
Fuel storage (fuel oil and propane)	1,500
Piping and installation (10% of equipment cost)	5,200
Electrical (12% of equipment cost)	6,240
Subtotal: Other Equipment	63,440
Total Equipment costs	\$253,525

Site Costs

Site Costs (set up and level area)	\$5,000
Total Site Costs	\$5,000

Labor Cost

Mobilize/demobilize (based on 200 hrs set up & tear down)	
Technician --2	12,000
Laborers --2	10,000
Oversight engineer --1	12,000
Per diem	3,600
Monitoring/maintenance crew (139 days @ 2 hrs/day)	
Technician -- 1	8,340
Oversight engineer --1	16,680
Total Annual Labor Costs	\$62,620

Consumable Costs

Carbon recharge (2.23 lb carbon/lb VOC)	101,688
Fuel oil - diesel @ 10 gph	35,362
Lubricants	6,950
Deionized water	3,336
Chemical additives	6,950
Maintenance supplies	3,475
Total Annual Consumable Costs	\$157,761

Notes:

1. Consumable supplies: Recycled carbon, \$2.85/lb.; Diesel fuel, \$1.06/gal; Lubricants, \$50/day; Deionized water, \$0.10/gal; Chemical additives, \$50/day; Maintenance supplies, \$25/day.
2. Offgas treatment costs assume conventional carbon adsorption. However, demonstration did not include offgas treatment. Costs may be reduced more by installation of a higher efficiency offgas treatment system.

Cost Analysis for In Situ Air Stripping

• A study of cost effectiveness of in situ air stripping (Ref. #4) illustrated that equipment costs drop to a smaller percentage of total system costs when capital costs are annualized over 10 years as shown in the pie chart. Based upon an annual extraction rate of 33,612 lbs VOCs and a total VOC quantity of 16,000 lbs, total costs per pound of VOC removed were calculated at Savannah River as follows:

Cost/Lb of VOC Removed

Equipment	\$1.51
Site	\$0.31
Labor	\$3.91
Consumables	<u>\$9.86</u>

Total **\$15.59**

• For the same cost study, carbon adsorption was included for offgas treatment. However, a more highly engineered offgas treatment system can be expected to reduce the annual costs substantially.

Cost Analysis for Horizontal Well Installation

- Costs for installation of horizontal wells is much higher than costs for installation of vertical wells (approximately 10 times greater using the petroleum industry, 35 foot radius top-drive technique; approximately \$360 per foot).
- Some horizontal drilling techniques can be expected to be far less expensive, particularly at shallower depths.
- The 40 to 50 foot depth indicated a critical distinction between drilling technologies for horizontal wells.
- Shallower than 40 to 50, feet the utility industry compaction or river crossing techniques may be used with a cost as low as \$50 per foot.
- For depths greater than 40 to 50 feet, the petroleum industry technology and its hybrid petroleum/utility river crossing technology can be used. Costs for the deeper horizontal wells range from \$360 per foot up to \$700 per foot.
- As drilling companies gain experience with horizontal wells, the costs are expected to decrease.
- Despite the high drilling costs, if carbon adsorption is used as the off-gas treatment, it contributes the largest part to the total remedial system cost.

REGULATORY/INSTITUTIONAL ISSUES

- The M-Area settling basin and excavated sections of the process sewer line were remediated through a RCRA closure completed in 1990, and certified by the State of South Carolina in 1991.
- Permitting for the demonstrations, including the South Carolina Department of Health and Environmental Control (SCDHEC) Air Quality Control (AQC) permit waiver and Underground Injection Control (UIC) permits, had expired as of September, 1993.
- Future remediation and demonstration activities will require National Environmental Policy Act (NEPA) review and appropriate SCDHEC permits.
- For remedial activities, the M-Area HWMF RCRA Part B Permit must be reviewed to determine if a permit modification is necessary.
- Any future vacuum extraction will not require UIC permitting, however, if either in situ air stripping or in situ bioremediation is conducted, UIC issues need to be addressed. UIC permits are issued by South Carolina Board of Drinking Water Protection under the Safe Drinking Water Act.
- If future remedial activities involve bringing contaminated groundwater to the surface, a wastewater permit may be required from SCDHEC. If treated groundwater is discharged to a surface water, an NPDES permit or permit modification will be required.
- An AQC permit was not required for the demonstrations, but will be required for full scale remediation.

SCHEDULE

A/M-Area Remediation Milestones

LESSONS LEARNED

Implementation Considerations

- During installation of horizontal well 1, the drill string became stuck, and was abandoned downhole (approximately the bottom 360 feet of the well). To salvage the hole, a perforated steel tube was threaded into the borehole to act as the screen zone of the well. The result was loss of a considerable length of well screen for use in remedial efforts.
- Six pressure sensors have been installed along horizontal wells 1 and 2 to measure the efficiency of each well along its length. The measurements were spaced at approximately 60 foot intervals. Measurements indicated active extraction/injection along the entire length of the borehole. This type of monitoring is inexpensive and recommended.
- Drilling fluids, containing (at various times) bentonite, polymer, and lignosulfonate in fresh water were used to maintain borehole stability. Significant amounts of drilling fluids were lost to the formations. Methods to reduce fluid loss during horizontal drilling were investigated.
- The filter pack on all these horizontal wells is made up of natural formation solids, principally due to collapse around the borehole. This may diminish well efficiencies.
- During installation of horizontal well 5, the well with two wellheads, two attempts were made to install the well screen. On the final attempt, fiberglass casing and 3.5 inch diameter and 0.010 inch slotted fiberglass well screen was used to alleviate polyvinyl chloride (PVC) screen failure during pull back.
- To lesson fluid loss in permeable zones observed during installation of 6, an attempt was made to advance the washover pipe. However, the string broke when an attempt was made to retract the pipe. The abandoned washover string reduced the effective screen length from 400 feet to 230 feet.
- During well development at two of the horizontal wells, sand trapped in the borehole terminus reduced the effective screen length; one well was reduced by 5 feet, the second well was reduced by 15 feet.
- Horizontal vacuum extraction wells extract water from the vadose zone during operation -- the vertical trajectory of the well must be planned to avoid plugging.

Technology Limitations

- Clay layers, because of their low permeability, are troublesome. However, these zones have significant levels of contamination. Heterogeneities in the subsurface, either due to stratigraphy or fractures, can result in preferential air flow pathways, resulting in less effective contact and remediation.
- By inducing water flow, in situ air stripping can accelerate a lateral or downward migration of contaminants in certain geologic settings. If clay layers or other geologic features constrict vertical flow, it may be necessary to use in situ air stripping in conjunction with a pump and treat system for hydraulic control.
- Due to the high cost of installing horizontal wells, the selection of the location of the well becomes more important than for vertical wells.

Future Technology Selection Considerations

- Directional drilling of horizontal wells was demonstrated to assess its role in improving the efficiency of a remediation project. Remediation efficiency may be enhanced by increased surface area for reaction, similarity of borehole and contaminant plume geometry, borehole access to areas beneath existing facilities, and the ability to drill areas along facility boundaries to control plume migration. Direct comparison of vertical and horizontal vacuum extraction during the program confirmed the improvements from using horizontal wells.
- Successful in situ air stripping requires good contact between injected air and contaminated soils and groundwater. An optimal geologic setting would have moderate to high saturated soil permeability, a homogenous saturated zone, and sufficient saturated thickness. Vadose zone characteristics would be high permeability and homogeneity. Air stripping would be more effective in coarse-grained soil.

Future Technology Selection Considerations (Continued)

- For in situ air stripping to be effective, the contaminants of concern must be strippable, that is mobile in and between all phases. Contaminants must have a dimensionless Henry's Law Constants greater than 0.01, vapor pressures greater than 70.1 mmHg (at 25°C), and soil/water partition coefficients (K_{od}) less than 1000 to be physically removable. Most light hydrocarbons and chlorinated solvents satisfy these conditions.
- Horizontal wells may provide for better contact with linearly-shaped contaminant plumes. In situ air stripping may be more effective with relatively thin plumes of contaminants.

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which supplied key information and reviewed report drafts.

for:

HAZARDOUS WASTE REMEDIAL ACTIONS PROGRAM
Environmental Restoration and Waste Management Programs
Oak Ridge, Tennessee 37831-7606
managed by
MARTIN MARIETTA ENERGY SYSTEMS
for the
U.S. Department of Energy
under Contract DE-AC05-84OR-21400

This analysis was funded by:

U.S. Air Force
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CERTIFICATION

This analysis accurately reflects the performance and costs of the remediation:

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SOURCES

Major Sources For Each Section

Site Characteristics:	Source #s (from list below) 2, 3, 7 and 8
Treatment System:	Source #s 1, 2, 6 and 7
Performance:	Source #s 2 and 4
Cost:	Source # 4
Regulatory/Institutional Issues:	Source # 2 and 4
Schedule:	Source #s 2, 4 and 8
Lessons Learned:	Source #s 2, 4 and 5

Chronological List of Sources and Additional References

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TECHNOLOGY APPLICATION ANALYSIS

***Pump and Treat of Contaminated Groundwater
at***

U.S. Department of Energy

***Kansas City Plant
Kansas City, Missouri***

prepared for

U.S. Air Force

October 1994 FINAL

TECHNOLOGY APPLICATION ANALYSIS

Page 1 of 13

SITE

U.S. Department of Energy
Kansas City Plant (KCP)
A RCRA Corrective Action Site
Kansas City, Missouri

TECHNOLOGY APPLICATION

This analysis covers an effort to pump and treat groundwater contaminated with volatile organic compounds (VOCs) by above ground advanced oxidation processes (AOPs). The treatment began in May 1988 and is currently ongoing. This analysis covers performance through February 1994.

SITE CHARACTERISTICS

Site History/Release Characteristics

- The KCP is located within the Bannister Federal Complex approximately 13 miles south of downtown Kansas City, Missouri. The complex is bordered on the east by the Blue River and on the south by Indian Creek.
- Constructed in 1942 as an aircraft engine manufacturing facility, the KCP is part of the U.S. Department of Energy's (DOE) Albuquerque Operations Office. The Atomic Energy Commission, predecessor to the DOE, began production of components for nuclear weapons at the KCP in 1949. Subsequent defense related research and manufacturing operations resulted in the release of contaminants to the subsurface.
- A series of hydrogeologic investigations initiated in the early/mid 1980s revealed elevated contaminant concentrations (primarily chlorinated VOCs) in soil and groundwater.
- A groundwater pump and treat system, the subject of this report, started operation in May 1988. That system was designed as an interim remedial measure to prevent further migration of VOC-contaminated groundwater while additional RCRA Facility Investigation (RFI) and Corrective Measures Study (CMS) efforts to define final site remedial measures were being performed. A low intensity Ultraviolet (UV)/Ozone (O_3)/Hydrogen Peroxide (H_2O_2) treatment system operated until May 1993 when it was replaced by a high intensity UV/ H_2O_2 system. The initial system was a demonstration of first-generation AOP technology; the replacement system is considered second-generation technology.

Contaminants of Concern

Contaminants identified as being of greatest concern in groundwater at the KCP are:

Tetrachloroethene (PCE)
Trichloroethene (TCE)
1,2-dichloroethenes (1,2-DCEs)
Vinyl chloride

Other contaminants detected in soil or groundwater include aromatic and halogenated VOCs, petroleum hydrocarbons, PCBs and selected metals.

Arsenic, present at concentrations higher than drinking water standards, was determined to be the result of natural geochemical processes.

Contaminant Properties

Properties of contaminants focused upon during remediation are:

Properties*	Units	PCE	TCE	1,2-DCEs**	Vinyl Chloride
Density	-	1.62	1.46	1.25/1.27	0.91
Vapor Pressure	mm Hg	952	28.1	7	245
Henry's Law Constant	atm·m ³ /mole	0.0259	0.0091	0.0066/ 0.0076	0.0144
Water Solubility	mg/l	150	1,100	2,250/3,3500	2,670
Octanol-Water Partition Coefficient; K_{OW}	-	398	240	3/5	24
Organic Carbon Partition Coefficient; K_{OC}	-	364	126	49/59	57

* Properties at 20 °C. ** Data presented for both cis and trans-isomers.

Nature & Extent of Contamination

- Characterization of the nature and extent of contamination at the KCP evolved over a number of years of investigation and interim remediation. Thirty-seven solid waste management units were found to have contributed to three primary areas of groundwater contamination known as: the TCE Still Area, the Underground Tank Farm Area, and the Northeast Area/Outfall 001 Area.
- Groundwater contamination is largely confined within the KCP limits. However, chlorinated VOCs have migrated with groundwater along a backfilled stream channel to the Blue River northeast of the KCP.
- The vertical distribution and concentrations of VOCs in soil and groundwater suggest the potential presence of dense non-aqueous phase liquid (DNAPL) in several areas which contribute to groundwater contamination.
- The presence of numerous subsurface utilities/utility trenches, including building footing tile drains, have a significant impact on contaminant migration at the KCP site. These utilities act as sources of recharge water, preferential migration pathways, and collectors for contaminated groundwater.

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Contaminant Locations and Geologic Profiles

Site Layout (Plan View)

Remedial investigation field activities at the site have included:

- Borings and subsurface soil sampling
- Monitoring well installation and groundwater sampling
- Groundwater elevation measurements
- Geophysical testing
- Water source/sink assessment
- Hydraulic tests
- Borehole packer testing
- Surface water sampling and elevation measurements
- Groundwater modeling

Data from ~200 soil borings and ~190 monitoring/extraction wells were used to develop an understanding of subsurface conditions, including contaminant migration. Selected data from site studies have been used in this report to depict site conditions.

Horizontal Distribution of VOCs in Groundwater - Generalized Representation (Plan View)

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Contaminant Locations and Geologic Profiles (Continued)

Vertical Distribution of VOCs in Groundwater

• In general, concentrations of prime contaminants of concern in groundwater increase with depth in overburden soils at the KCP site. Dense non-aqueous -phase liquid(s) (DNAPL) may be present in some areas. The figure below, illustrating TCE concentrations in groundwater at one of the 3 primary contamination areas (the TCE Still Area), is representative of the vertical distribution of chlorinated VOCs at the KCP site.

• Alluvial deposits at the KCP site are underlain by bedrock consisting of alternating layers of sandstone and shale. A thin layer of sandstone (< 10 feet thick) immediately beneath the alluvium pinches out beneath the site. Packer testing performed on the shale indicated it was relatively impermeable. No bedrock migration of VOCs has been observed.

• Because the bedrock surface dips in the opposite direction as alluvial groundwater flow, additional monitoring wells were completed within the shallow sandstone at the request of EPA to monitor for the potential migration of VOCs. No VOCs or dissolved-phase contamination have been detected in these wells. Additionally, contaminant transport modeling predicted that VOCs (if present) would migrate at an average rate of < 1 foot per year under worst-case conditions in the sandstone.

Schematic Cross-Section of Bedrock and Alluvium at KCP

Notes: Cross section is not to scale.
Cross section location shown on site map (page 2).

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Location of Old Blue River Channel (Plan View)

The former Blue River channel, now filled, has a hydraulic conductivity an order of magnitude greater than the surrounding soil. This former river channel is serving as a preferential pathway for migration of contaminated groundwater from the Northeast Area/001 Outfall to the current location of the Blue River.

Groundwater Sinks and Sources

Several site structures (in addition to the extraction wells and interceptor trench) serve as sinks/collectors for groundwater on the KCP site and impact contaminant migration. Groundwater drains include: the 001 Outfall Interceptor system (~6,000 gallons per day (GPD)), which is a collection system to prevent groundwater infiltration into an NPDES storm sewer, a sump for the building southwest of the former South Lagoon, building footer drains, and possibly the plant sewer lines. Building drains control the surface of the water table in the vicinity of the Main Manufacturing Building.

In addition to recharge due to infiltrating precipitation, it is believed that leaking underground water and steam lines could be serving as a source of water to the subsurface. The KCP has initiated a study to quantify artificial sinks and sources of water in the subsurface at the KCP site.

Site Conditions

- The KCP is situated in the Blue River Valley about 800 feet above Mean Sea Level (MSL) and is in the 100-year flood plain of the both the Blue River and Indian Creek. However, a 500 year event floodwall protects the site.
- Approximately 46% of the site is covered by grass or gravel and is available for recharge. The site receives ~ 34 inches of precipitation per year.
- The topography of the complex is flat-lying except where it drops ~ 30 feet along the Blue River and Indian Creek and where it rises ~ 50 feet north of the KCP site.
- The Pennsylvanian bedrock (shales) in the vicinity of the KCP is noted for its uniformity. There are no structural features such as faults, that affect the KCP site. No fractures were observed in bedrock (shale) cores performed at the KCP site.
- The surface of the bedrock at the KCP site slopes to the east, reflecting surface topography. However, the slope or dip of individual layers (sandstones and shales) is to the west. Site lithologic logs indicate the presence of ~1 to 3 feet variation in the elevation of the bedrock surface.
- Groundwater flow at the KCP site is primarily to the east and discharges to the Blue River and Indian Creek. A portion of the KCP site groundwater flow is to the south.

Key Aquifer Properties

Aquifer parameters for the alluvial deposits at the KCP site have been estimated as:

Property	Units	Tank Farm	South Lagoon	Northeast Area
Porosity	%	20	20	20
Hydraulic Gradient	ft/ft	0.002	0.008	0.007 to 0.02
Horizontal Hydraulic Conductivity*	ft/day	2.3	1.1	1.5
Groundwater Velocity	ft/yr	8.4	16	19 to 55
Storage Coefficient**	-	0.002	0.0005	0.002

* Based on pumping test data. Conductivities calculated from bail and slug test data were ~ one order of magnitude lower.

** Low values are reflective of the fine-grained nature of the aquifer materials.

The horizontal hydraulic conductivity of the shallow (knobtown) sandstone is 0.04 to 0.005 ft/day. The underlying shale is impermeable to water.

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REMEDIATION SYSTEM

Overall Process Schematic

Fourteen extraction wells and one trench installed in three phases (1987, 1988, and 1989).

Acidification to solubilize inorganic metals, bag filtration, (UV/peroxide) oxidation of organic contaminants in one of two reactors, and subsequent neutralization.

Discharge treated water to municipal wastewater treatment plant.

Extraction Well Network

Legend

- Extraction Well
 - Well Identification Number
 - Bottom Depth of Screened Interval (Screened Lengths Vary from 10 to 11 feet)
 - Flow Rate in Gallons per Minute (GPM)
- The design flow for each of the wells was 2 gpm, however slight fluctuations occurred.

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Extraction Well Detail

Typical extraction well (KC89-112)

NOTES: 1.) Some extraction wells completed with subsurface vaults
2.) Submersible pumps with stainless steel impellers in each well

Interceptor Trench Schematic

Key Design Criteria

- Hydraulic containment of VOC-contaminated groundwater
- Handle range of flow rates to allow for operational flexibility
- Destruction of organic contaminants in extracted groundwater rather than transfer to another media
- Redundant treatment capability to maintain hydraulic containment in the event of unanticipated breakdown, and to provide for treating increased flow rates during future-final site remediation

Key Monitored Operating Parameters

- Groundwater elevations
 - Groundwater VOC concentrations
 - Water flow rates
 - Temperature, pressure, and pH
 - UV and H_2O_2 dosage
 - Filter pressures
 - Influent/effluent contaminant concentrations
- (to assess containment system performance)
- (to assess treatment system operation and effectiveness)

Treatment System Schematic

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PERFORMANCE

Performance Objectives

- Prevent further migration of VOC-contaminated groundwater from 3 areas of identified contamination
- Design and operate treatment system to decrease VOC concentrations in extracted groundwater to below sewer discharge limits

Remedial Action History/Plan

Remediation at the KCP site is being implemented in a phased manner. The following groundwater-related interim remedial actions have been performed to date:

1988 Initiated pumping of groundwater (6 GPM) from Underground Tank Farm Area and treatment with UV/O₃/H₂O₂ system as interim measure and to demonstrate treatment technology

1990 Treatment of additional 14 GPM from TCE Still Area and 13 GPM from Northeast Area/001 Outfall using the same treatment system with additional Aqueous-Phase Granular Activated Carbon (GAC) polishing

1993/1994 Second-generation UV/H₂O₂ treatment system installed to provide capacity for treating an additional 30 GPM (approximate) of groundwater from the 001 Outfall Area, and to provide additional operational and environmental benefits

Overall Performance Summary

Conclusions drawn after 5 (plus) years of operating the interim pump and treat system are summarized below:

- The extraction system appears to have been effective in substantially containing VOC-contaminated groundwater emanating from the KCP site. The KCP expects to begin extracting up to an additional 30 GPM of VOC-contaminated groundwater to prevent its infiltration into the 001 Outfall storm sewer line during 1994.
- The concentrations of VOCs in groundwater and the extent of contamination has not changed considerably in the TCE Still Area, Underground Tank Farm Area or the Northeast Area/001 Outfall since initiating the Interim Remedial Action.
- While the initial AOP treatment system met discharge limits, ozone leaks, the need to treat air emissions and significant downtime required for maintenance contributed to the decision to change to the high-intensity UV/H₂O₂ AOP. The new AOP system has also operated within discharge limits.

Operational Performance

Volume and Rate of Water Pumped/Treated

- During 1993, a total of approximately 11.2 million gallons of groundwater water was extracted and treated by the interim system. Of this total, ~2.2 million gallons was extracted from the Underground Tank Farm Area ~4.5 million gallons from the TCE Still Area and ~4.5 million gallons from the Northeast Area/001 Outfall.
- The average daily flow rate for the entire interim system in 1993 varied from a high of 32 GPM in January to < 2 GPM in July, during treatment unit replacement.

System Downtime

- Numerous equipment malfunctions and a significant amount of downtime occurred during the first 15 months (May 1988 - July 1989) of continuous operation of the UV/O₃/H₂O₂ system. The system operated > 65% of the time in 1988 except during September when it was shut down for equipment modifications. The interim system operated 61% of the time in 1989 except during June when it was down for servicing modifications by the manufacturer. Except during downtime periods for construction, equipment, modifications and frozen pipes, and the UV/O₃/H₂O₂ system operated > 90% of the time from 1990 until May 1993 when it was replaced by the high intensity UV/H₂O₂ system.
- The replacement UV/H₂O₂ system commenced continuous operation in August/September 1993. This treatment system has operated > 95% of the time. Much of the maintenance that required the prior treatment system to be shut down can now be performed while the replacement system remains operational.

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Hydrodynamic Performance

- A modeling evaluation performed in May 1992 concluded that the extraction system was substantially containing the three primary groundwater VOC plumes at the KCP site. The planned addition of supplemental extraction wells near Outfall 001 is intended to decrease infiltration of contaminated groundwater into storm sewer lines to comply with NPDES permit effluent standards.

Effect on In Situ Contaminant Concentrations

While the pump and treat system has removed a substantial mass of VOCs from the subsurface, statistically significant changes of in situ groundwater VOC concentrations have not occurred.

Treatment System Performance

- The original UV/O₃/H₂O₂ treatment system was replaced with the high intensity UV/H₂O₂ in May 1993 to provide capacity to treat an additional 30 GPM from the 001 Outfall Area. Despite the on-going maintenance problems, the UV/O₃/H₂O₂ treatment system routinely met permit discharge limits at a flow rate ~ 6 GPM from 1988 until 1990. The sewer discharge limit for total organic halogens was exceeded on 2 occasions in 1990 as a result of the adding of ~ 27 GPM of groundwater extracted from the TCE Still Area and the Outfall 001/Northeast Area. The original system was designed to handle only 25 GPM of water containing VOCs at concentrations higher than predicted by an Interim Corrective Measure Study. Aqueous-phase granular activated carbon (GAC) polishing of the UV/O₃/H₂O Unit effluent was added in the late 1990 to remove residual organics prior to discharge. An in-line filter was installed and backwashing instituted to extend the life of the GAC by removing iron and manganese that precipitated following oxidation in the AOP reactor.
- Following successful completion of a rigorous acceptance testing program of the replacement UV/H₂O₂ system during late 1992, the system was placed into operation during May 1993. As illustrated in the following graph, total VOC concentrations in the replacement system effluent have been well below the sewer discharge limit. The on-going maintenance problems experienced with the initial system have been eliminated.

UV/Peroxide Treatment System Performance

- The initial UV/O₃/H₂O₂ system destroyed ~ 94.6% VOCs; ~3.7% were emitted to ambient air and ~ 1.7% were discharged to the sanitary sewer system. The replacement UV/H₂O₂ system destroyed > 99.95% VOCs; ~< 0.05% are discharged to the sanitary sewer system and there are no emissions.

- The system is designed to treat up to 30,000 ug/l. Influent averaged approximately 25,000 ug/l.
- Up to 0.3 ug/l PCBs have been detected in the UV/H₂O₂ treatment system influent. PCBs have not been detected in the treated groundwater discharged to the sanitary sewer.

Legend
 ■ Influent VOC Concentration ● Effluent VOC Concentration

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COST

- Although advanced oxidation was more expensive than other alternatives such as air stripping/GAC, it was selected because of its waste minimization benefits. With advanced oxidation the contaminants are destroyed, and not transferred to another media.
- The selection of the high intensity UV/H₂O₂ treatment to replace the UV/H₂O₂ was due in part to cost savings associated with: eliminating GAC polishing, eliminating the need to treat air emissions, and reduced operation and maintenance labor and expenses.
- Capital and operating costs for the replacement UV/H₂O₂ system is presented below. Operating costs for treatment (including replacement parts, laboratory analysis, utilities, labor, and raw materials) calculated by Oak Ridge National Laboratory were \$15.51/1,000 gallons for the first-generation UV/O₃/H₂O₂ demonstration unit and are projected to be \$13.80/1,000 gallons for the second-generation UV/H₂O₂ replacement units once the additional 001 Outfall extraction system commences operation. The costs presented below are based on actual costs spent from fiscal years 1987 to 1994; the cost figures are not in constant dollars.

Capital Costs

Extraction Wells, Vaults, Pumps, Piping, Trenching, Electrical Conduit, & Utilities	\$1,213,900
Bag Filter Units (2)	4,500
Tanks (3)	1,700
Treatment Buildings (site preparation, construction, and engineering), 3 original extraction wells	126,000
Control Systems	2,300
Equipment Installation	20,000
Startup (including acceptance testing)	15,000
Total Capital Cost	\$ 1,383,400

Operating Costs

Electrical Power	\$ 25,300
Maintenance	
Labor	52,200
Equipment Repair and Replacements ^a	3,300
Engineering Support and Project Management	44,200
Laboratory Analysis (Influent/Effluent)	78,000
Monitoring Well Analysis	110,000
Consumables	
Hydrogen Peroxide 3,600 gallons/year @ \$4.00/gallon	14,400
Sulfuric Acid 3,600 gallons/year @ \$1.09/gallon	3,900
Caustic 7,200 gallons/year @ \$1.91/gallon	13,800
Bag Filters	700
Extraction Pump and Motor Assembly Replacement (2/year)	1,200
Transport and Disposal of Spent Filters and Personal Protective Equipment	500
Extraction Well Rehabilitations	
Chemical Treatment	5,300
Redevelopment	2,400
Total Annual Operating Cost	\$ 355,200

^a Average annual cost of equipment repair and replacement costs from 1983 to 1994, including costs associated with system start-up and the purchase of spare parts.

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REGULATORY/INSTITUTIONAL ISSUES

• The KCP Site investigation is being performed in accordance with a U.S. Environmental Protection Agency RCRA 3008 (h) Administrative Consent Order in 1989. Initial investigation efforts, and the extraction and treatment of groundwater from the Underground Tank Farm Area were performed as voluntary actions in 1988 with EPA cognizance.

• Treatment of extracted groundwater using UV/O₃/H₂O₂ was initiated in 1988 as a demonstration of one of the first full-scale operating AOP systems. A rigorous program of pilot testing and long term performance monitoring was implemented to assure regulators of the effectiveness of this treatment technique and to develop data on long-term reliability and operation and maintenance costs. The second generation UV/H₂O₂ that replace the UV/O₃/H₂O₂ system in 1992 also underwent rigorous prove-in testing in accordance with a Startup Plan approved by EPA and the City of Kansas City, MO.

• Treated water is discharged to the municipal sanitary sewer system under the provisions of a wastewater discharge permit issued by the Kansas City Water and Pollution Control Department in February 1988. Discharge limits are summarized below:

Parameter	Concentration (mg/L)	Parameter	Concentration (mg/L)
Cadmium	0.69	Arsenic	0.250
Chromium	2.77	Total Organic Halogen	0.16
Copper	3.38	Sulfides	10.0
Lead	0.69	Oil and Grease	100
Nickel	3.98	Total Cyanide	2.0
Zinc	2.61		
Iron	100.00		
Manganese	20.00		
Boron	1.00		

• Final cleanup goals have not yet been established for the site. Cleanup goals will be set subsequent to completing RFI/CMS activities.

SCHEDULE

Major Milestones

◆ Completed Activities

◇ Future Activities

• Extraction and treatment of groundwater from near the 001 Outfall will be initiated following NEPA review and obtaining approval from a railroad to a pipe groundwater beneath an active rail line that crosses the KCP site.

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LESSONS LEARNED

Implementation Considerations

- An understanding of the extent of contamination at this site has evolved over a decade of investigation, monitoring, and remediation. Defining the extent of contamination has focused on determining the need for remediation in specific areas of the site, selecting and designing remedies, and evaluating the effectiveness of implemented remedial actions.
- Monitoring data and modeling results suggest that predicting the rate of aquifer restoration may be complicated due to hydrogeologic variability caused by leaking underground utilities, building footing tile drains and other anthropogenic factors and the likely presence of DNAPL(s) in a number of areas of the site.
- Initiating an interim remedial action provided for hydraulic containment of VOCs dissolved in groundwater while the full extent of contamination and supplemental remedial actions are defined.
- Extraction flow rates must be manually adjusted at the individual well heads. The ability to control flows from the central treatment system building would eliminate difficulty in performing this task.
- Substantial and frequent fouling of the extraction system wells with bacterial slime and oxides of naturally-occurring iron and manganese have resulted in the need for frequent chemical treatment and redevelopment of wells, and repair/replacement pumps, pump motors and water level probes.
- Vaults and pipe conduits allow oxygenated rainwater to drain into extraction wells through vent tubes, contributing to the growth of bacterial slime and need for more frequent well treatment/redevelopment. Modifications made to minimize this concern have included installation of berms and drainage systems around selected well vaults. Measures to epoxy seal openings in the piping conduit are being investigated.
- The initial UV/O₃/H₂O₂ treatment system was not designed to adequately handle the flow rate and VOC concentrations realized with the interim containment system. The replacement UV/H₂O₂ treatment system was designed to handle a wider range of flow rates and concentrations to provide operational flexibility.
- The initial UV/O₃/H₂O₂ treatment system experienced significant downtime for acid cleaning of filters, ozone sparger tubes and UV lamp sheathes, and GAC backwashing/changeout. The replacement system provides for pH adjustment prior to UV/H₂O₂ treatment to minimize fouling caused in part by oxidation of inorganics.

Technology Limitations

- The initial UV/O₃/H₂O₂ treatment system was a first-generation AOP technology installed and operated at the KCP for demonstration purposes. The second-generation (replacement) AOP treatment system, operational since May 1993, has performed well at a lower cost and without the on-going maintenance problems experienced with the initial demonstration system.
- The saturated hydrocarbons present at the KCP site were readily treated by both the initial UV/O₃/H₂O₂ and the second-generation/replacement UV/H₂O₂ systems. AOP manufacturers' literature indicates that treatment efficiencies for unsaturated hydrocarbons are much lower.
- UV/H₂O₂ was selected instead of a second-generation UV/O₃/H₂O₂ AOP to replace the initial treatment system because systems that employ ozone: require more maintenance (e.g., the ozone generator and delivery system), residual ozone in the headspace of the reaction chamber is corrosive to the chamber, and catalytic oxidation is required to destroy ozone in the air discharge.

Future Technology Selection Considerations

- Greater attention should be paid to the design of extraction well systems that minimize operation and maintenance problems.
- AOP systems can destroy saturated hydrocarbons in extracted groundwater. However, designs must consider the potential for fouling with oxidized inorganics and the implementation of pretreatment measures when appropriate to ensure satisfactory performance and manageable maintenance.

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for:

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Environmental Restoration and Waste Management Programs
Oak Ridge, Tennessee 37831-7606

managed by
MARTIN MARIETTA ENERGY SYSTEMS
for the

U.S. Department of Energy
under Contract DE-AC05-84OR-21400

This analysis was funded by:

U.S. Air Force
Headquarters USAF/CEVR

CERTIFICATION

This analysis accurately reflects the performance and costs of the remediation:

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U.S. Air Force

SOURCES

Major Sources For Each Section

Site Characteristics:	Source #s (from list below) 3, 4, 6, 7, 8, 9, and 10
Remediation System:	Source #s 1, 2, 3, 4, 5, 7, 8, 9, and 10
Performance:	Source #s 1, 2, 3, 4, 6, 7, 8, 9, 10, and 11
Cost:	Source #s 1, 2, 8, and 11
Regulatory/Institutional Issues:	Source #s 1, 3, 4, 5, 6, 9, and 11
Schedule:	Source #s 1, 2, 4, 5, 6, 7, and 10
Lessons Learned:	Source #s 1, 2, 4, 6, 7, 10, and 11

Chronological List of Sources and Additional References

1. *Kansas City Plant Groundwater Treatment System Overview*, prepared by AlliedSignal, Inc., Undated.
2. *Kansas City Plant Ultraviolet/Ozone/Hydrogen Peroxide Groundwater Treatment System Overview*, prepared by M.E. Stites, Environment, Safety and Health Department AlliedSignal, Inc., and R.F. Hughes, Energy and Environmental Systems Division, Oak Ridge Associated Universities, Undated.
3. *Tank Farm Interceptor System Evaluation and Treatment Unit Corrective Action Plan - Rev 1*, April 1991.
4. *Groundwater Interceptor System Evaluation, Kansas City Plant*, prepared by Department of Energy, Albuquerque Operations Office, Environmental and Health Division, Environmental Programs Branch, May 1992.
5. *Groundwater Treatment System Interim Measures Plan, U.S. DOE Kansas City Plant*, revised August 1993.
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TECHNOLOGY APPLICATION ANALYSIS

**Extraction and Treatment of
Contaminated Groundwater**

**at
U.S. Department of Energy**

**Lawrence Livermore National Laboratory
Livermore Site
Livermore, California**

prepared for

U.S. Air Force

February 1995 FINAL

TECHNOLOGY APPLICATION ANALYSIS

Page 1 of 17

SITE

Lawrence Livermore
National Laboratory (LLNL)
Livermore Site
Livermore, California

TECHNOLOGY APPLICATION

This analysis reports the use of optimized hydraulic control, source removal and advanced technologies to clean up groundwater contaminated with volatile organic compounds (VOCs), fuel hydrocarbons (FHCs) and chromium by a network of treatment facilities employing ultraviolet (UV)/oxidation, air stripping, ion exchange and granular activated carbon (GAC) technologies. Initial treatment began in 1989 and additional capacity is being phased in through an ongoing evaluation process. Vadose zone remediation efforts are not addressed in this analysis.

SITE CHARACTERISTICS

Site History/Release Characteristics

- The 800-acre LLNL site was converted from agricultural use into a flight training base and aircraft assembly and repair facility by the Navy in 1942. In 1951, the Atomic Energy Commission converted the site into a weapons design and basic physics research laboratory. Later site missions have included programs in biomedicine, energy, lasers, magnetic fusion energy, and environmental science.
- Initial releases of hazardous materials occurred in the mid to late 1940s. There is also evidence that subsequent localized spills, leaking tanks and impoundments, process cooling water and landfills released VOCs, FHCs, chromium and tritium to sediments and groundwater, primarily from 14 major areas of concern.
- In 1983, VOCs were detected by LLNL in a domestic water supply well west of the site. A regulatory order to investigate groundwater quality was issued by the state in 1984 and ultimately lead to investigation of over 350 potential release sites.
- Bottled drinking water was supplied to nearby residents beginning in 1983 and all affected supply wells were permanently sealed between 1985 and 1989 by LLNL. Selected waste pits and a landfill were excavated and backfilled in 1982/83 and 1984, respectively. The LLNL site was added to the National Priorities List in 1987.

Contaminants of Concern

Contaminant Properties

VOCs:
Trichloroethylene (TCE)
Perchloroethylene (PCE)
1,1 & 1,2-Dichloroethylene (DCE)
1,1 & 1,2-Dichloroethane (DCA)
Carbon tetrachloride (CCl₄)
1,1,1-Trichloroethane (TCA)
Chloroform
FHCs:
Benzene (B)
Toluene (T)
Ethylbenzene (E)
Xylenes (X)
Ethylene dibromide (EDB)
Metals:
Chromium (Cr)
Trivalent chromium (Cr³⁺)
Hexavalent Chromium (Cr⁶⁺)
Radiological Parameters:
Tritium (³H)

Properties*	TCE	PCE	1,1-DCE	Chloroform	CCl ₄	Benzene
Density (g/cm ³)	1.47	1.63	1.22	1.50	1.58	0.87
Vapor Pressure (mm Hg)	57.9	17.8	600	151	90.0	95.2
Henry's Law Constant (atm-m ³ /mole)	0.0091	0.0259	0.0340	0.0029	0.0241	0.0056
Water Solubility (mg/l)	1,100	150	2,250	8,200	757	1,750
Octanol-Water Partition Coefficient (K _{OW})	240	398	69.2	93.3	437	132
Organic Carbon Partition Coefficient (K _{OC})	126	364	65.0	47.0	439	83.0

*Properties at 20°C, 1 atm

Site Conditions

- The ground surface slopes gently to the northwest changing in elevation from 670 ft above mean sea level (MSL) to 570 ft above MSL from the southeast to northwest corners. Two intermittent streams, the Arroyo Seco and the Arroyo Las Positas, traverse the area.
- Climate is semiarid with annual precipitation around 14 inches/year.
- Land north and south of the site is zoned for industrial use, high-density urban areas are west of the site, and east of the site is primarily agricultural land.
- Municipal water supply wells in downtown Livermore approximately 1.6 miles away from the contaminant plume are the primary drinking water source for over 10,000 of Livermore's 50,000 plus residents.

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Nature and Extent of Contamination

Data below taken from Reference 9 except where noted.

VOCs: • VOCs underlie approximately 85% of the LLNL site over an area of about 1.4 square miles. The VOC plume thickness varies between 30 and 100 ft and rarely exceeds 200 ft in depth.

• TCE and PCE are the predominant VOCs with maximum concentrations of 4800 and 1100 parts per million (ppm) respectively. TCE, PCE and chloroform account for 91% of the total quantity of dissolved VOCs. VOCs exceed 1000 parts per billion (ppb) in groundwater at only 10 of 300 monitoring wells.

• The vadose zone generally contains low residual VOC concentrations (less than 100 ppb) except near a pair of release sources in the southeastern part of the site where up to 6000 ppb have been found.

FHCs: • FHCs ranging in concentration from about 1 to 16,000 ppb in groundwater are almost exclusively found near the site of a previous gasoline leak. Horizontal migration has been limited to about 500 ft due to low groundwater velocities. Significant vadose zone contamination in the area, up to 11,000,000 ppb FHCs have been detected in the vadose zone. Demonstration of Dynamic Underground Stripping has removed an estimated 10,000 gallons of FHCs from November 1992 to January 1994 (References 1 and 4).

Metals: • Metals from both natural conditions and facility activities have exceeded drinking water standards in sparse locations. Chromium, naturally occurring or perhaps from use as a corrosion inhibitor in cooling towers, is found in concentrations up to 160 ppb in groundwater. No consistent plume or migration pathways have been identified for metal contaminants.

Radiological Parameters: • Groundwater in the few wells where tritium is of concern would be expected to decay below federal and state drinking water standards before the water migrates offsite if no remediation was conducted.

Contaminant Locations and Hydrogeologic Profiles

Remedial investigation activities at LLNL involved review of over 350 potential release sites which were ultimately incorporated within 14 areas of concern. The source investigation methodology involved review of historical information, sample collection and drilling of over 800 subsurface borings. The site hydrogeology was characterized from:

- field boring logs
- borehole geophysical logs
- hydraulic test data (over 300 tests were conducted over a 4 year investigation period)
- sediment and water chemistry
- subsurface data from other investigations, including seismic and soil vapor surveys

Site Layout (Plan View)

Shaded areas indicate identified source areas of contamination.

Topography

All elevations in ft above MSL.

Groundwater Elevations

All elevations in ft above MSL (March 1989).

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Contaminant Locations and Hydrogeologic Profiles (Continued)

Distribution of VOCs in Groundwater

Isoconcentration contour map of total VOCs in groundwater integrated over 0-100 ft depth

Isoconcentration contour map of total VOCs in groundwater integrated over 100-200 ft depth

Maximum Pre-Remediation Concentrations for Selected VOCs

All data are expressed in ppb and were obtained between 3/90 and 3/91

TCE	PCE	1,1-DCE	Chloroform	CCl ₄	B	T	E	X	Total VOCs
4800	1050	370	<270	91	4600	4200	610	3700	5808

Legend

All concentrations in ppb

- 1 to 10 ppb
- 10 to 100 ppb
- 100 to 1,000 ppb
- >1,000 ppb

Cross-Section Indicating Areas of VOC Contamination

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Site Characterization Methodology

Initial remedial investigation efforts at LLNL using a depth-sampling technique led to an understanding of subsurface conditions and contaminant locations. Geologic cross-sections (see page 3) showing locations of contaminants were constructed using these data. More recent site characterization activities have focused upon the development of a comprehensive hydrostratigraphic characterization of the site through application of a systematic methodology. This methodology entails:

1 Evaluating Independent Data Sets

- hydraulic test results & water levels
- geophysical well logs
- geologic core descriptions
- chemical analyses of soil & groundwater
- high resolution seismic reflection

Overall, 4 lithologic units (not shown below) and 7 hydrostratigraphic units (shown below) have been identified.

2 Defining Hydrostratigraphy

3 Generating Information Displays

- hydrostratigraphic cross-sections
- hydraulic communication maps
- structure surface maps
- isopach maps
- potentiometric surface maps
- isoconcentration maps

This methodology provides information for optimizing the location of extraction wells to:

- maximize mass removal rates, and
- hydraulically control plumes.

4 Development of a Conceptual Model for 3-D Fate and Transport Simulations

Portion of a Typical Hydrostratigraphic Cross-Section

Key Soil/Aquifer Characteristics

- The site is underlain by several hundred feet of complexly interbedded alluvial and lacustrine sediments. A shallow groundwater system of predominantly heterogeneous alluvial deposits and a deeper groundwater system of fluvial and lacustrine sediments are separated by a regional confining aquitard.
- Depth to groundwater varies from about 120 ft in the southeast corner to about 25 ft in the northwest corner. Rainfall only appears to penetrate to the water table along the arroyo channels and other surface drainage features.
- Groundwater gradients vary from relatively steep (0.02 ft/ft) in the northeast corner of LLNL to fairly flat (0.001 ft/ft) toward the west. Average groundwater velocity without pumping is about 70 ft/year.
- Regional groundwater flow is generally westward, locally stratified and primarily horizontal, but flowpaths deepen west of the site.
- Pumping tests and the distribution of VOCs indicate a high degree of horizontal subsurface communication. Lesser communication in the vertical direction and the layered alluvium prevent significant downward migration of VOCs.
- Pumping tests also revealed a wide range (spanning nearly four orders of magnitude) of hydraulic conductivities. This is typical of heterogeneous alluvial sediments.

Area-specific aquifer parameters were estimated as:

Area	Number of data points	Geometric Mean Hydraulic Conductivity [ft/d]	Hydraulic Gradient	Velocity [ft/y]
A	64	5.6	0.002	14
B	24	3.2	0.001	4
C	15	3.1	0.005	19
D	12	4.4	0.005	27
E	48	2.4	0.012	35

- Velocities are calculated based upon a porosity of 0.30 and are applicable only to the area specified. When considering conductivity and velocity over larger areas at LLNL, considerably higher values are appropriate.

REMEDIATION SYSTEM**Overall Process Schematic** **Extraction Well Network & Treatment Plant Locations**

TREATMENT FACILITY	A	B	C	D	E	F	G	Trailer 5475
# of Extraction Locations	7	3	4	3	2	2	2	TBD
# of Extraction Wells	22	7	9	12	17	9	TBD	TBD
# of Piezometers/Monitoring Wells	68	21	30	36	41	20	TBD	TBD

Note: TBD = to be determined

Legend

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Extraction Well Designs

An extraction well design decision making process was instituted at LLNL. Decisions were based upon a systematic consideration of:

- the suitability of existing wells for extraction,
- contaminant concentration levels in groundwater and intervening fine-grained sediments, and
- order-of-magnitude differences in VOC concentrations among adjacent permeable zones.

Either existing wells are used for extraction or one or more single screen or multiple screen extraction wells are installed.

The objectives are to:

- pump permeable zones selectively and/or at different flow rates,
- assess flow and contaminant mass removal rates for individual zones, and
- avoid clogging well screens and treatment systems with fine-grained sediment in water pumped from screened silt and clay.

Treatment System Overview

- Treatment Facility G, scheduled for initial operation in 1996, will likely be installed as 2 separate portable facilities to treat VOC contaminated groundwater at a total rate of 60 gpm by air stripping followed by GAC treatment of offgases.
- The Trailer 5475 facility is scheduled for detailed design in 1997 or 1999.

Legend

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Treatment System Schematics

TFB

- Similar configuration to Treatment Facility A but scaled down for lower flow rates
- Discharge to a drainage ditch leading to Arroyo Las Positas

TFD

- Similar configuration to Treatment Facility C.
- A series/parallel air stripping tank arrangement involving three units was selected:

TFE

- Similar configuration to Treatment Facility A
- Potential need for add-on ion exchange treatment unit for chromium removal
- Two polishing diffuse aeration air strippers in series
- Discharge to drainage retention basin

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Treatment System Schematics (continued)

- Treatment Facility F has an accompanying soil vapor extraction system and is also the site of a technology demonstration program for Dynamic Underground Stripping (utilizing steam injection to remove gasoline).

- Treatment facilities A, B, C and D are enclosed in buildings and set atop concrete pads.
- Safety features for the facilities include automatic shutdown interlock control systems to prevent spills or discharging.
- Inorganic chemistry was major design consideration, particularly for Treatment Facilities C, D, E and F; scaling will be controlled through routine maintenance or the addition of polyphosphates.
- The initial seven treatment facility locations were selected to minimize piping requirements and provide efficient discharge routes.
- Spent GAC with VOCs is shipped offsite for regeneration or disposal. Sodium chloride solution with chromium is disposed as hazardous waste.

PERFORMANCE

Performance Criteria

The LLNL Groundwater Project is designed to satisfy numerous chemical-specific, location-specific and action-specific requirements. However, the driving force for determination of cleanup are Federal and California Maximum Contaminant Levels (MCLs) for drinking water. The primary contaminants, PCE and TCE, have MCLs of 5 ppb. The project is also designed to:

- Prevent migration of contaminated groundwater to nearby offsite water supply wells.
- Cleanup offsite plume components.
- Achieve cleanup goals in 50 years or less.

Remediation History

The LLNL groundwater treatment program is in the early stages of implementation. Treatment facilities A,B,C and F have operated with some of the planned extraction wells since their startup. Treatment facility D (TFD) began operation in October 1994. More detailed performance information is becoming available. The general remediation strategy employed and preliminary data gathered to date are presented in the following "Performance" subsections.

Remediation Plan

The overall long-term environmental remediation strategy for the LLNL Livermore Site uses ground water extraction and treatment that is based on an hydraulic control philosophy including:

- ✓ detailed characterization,
- ✓ validated modeling
- ✓ phased implementation of remediation,
- ✓ directed extraction & injection, and
- ✓ adaptive time-managed pumping.

This unique approach will:

- ➡ enable testing and optimization of extraction, injection and treatment system designs, efficiencies, and extents of hydraulic and contaminant capture prior to full-scale or widespread use;
- ➡ employ dynamic management of wellfields and optimization of cleanup through field monitoring and modeling; and
- ➡ ensure continued regulatory and community acceptance.

Dynamic management of the wellfield involves operation of individual wells either continuously, intermittently, or not at all depending upon the results of field monitoring and the estimates of models and optimization routines:

Operational Performance

System Throughput

- TFA treated approximately 87.3 million gal from Sept 1989 to Oct 1994 and 4.2 million gal during the 3rd quarter of 1994.
- TFB treated approximately 21.2 million gal from Oct 1990 to Oct 1994.
- TFC treated approximately 1.7 million gal from Oct 1993 to Oct 1994.
- TFD treated approximately 71.1 thousand gal from Sept 1994 to Oct 1994.
- TFF treated approximately 15 million gal groundwater from Feb 1993 to Oct 1994 and 2.8 million ft³ of vapor during 3rd quarter 1994.

System Downtime

- TFA has operated almost full time since Sept 1989 to Jan 1993; TFA was shut down in May 1991 to upgrade the system from 100 to 150 gpm.
- In Jan 1992, 20 ppb Cr⁶⁺ was found in TFB effluent (discharge limit is 11 ppb). The system was shut down and the chromium source was determined to be a combination of naturally occurring levels in groundwater and leaching from paints coating the aeration tank.

Hydrodynamic Performance

TFA and TFB are expected to establish hydraulic control of the offsite portion of the VOC plume. Modeling efforts anticipate the creation of hydraulic capture zones shown at right when all treatment facilities are fully operational.

Treatment Performance

Influent vs Effluent

UV/Oxidation Unit Treatment Efficiency

Performance results, comparing influent vs. effluent concentrations for the UV/Oxidation unit at TFA (4/92 data) and TFB (3/91 data).

	TFA		TFB	
	In	Out	In	Out
TCE	4	<0.5	120	<0.5
PCE	110	<0.5	na	na
1,1-DCE	10	<0.5	2.5	<0.5
Chloroform	4	4.1	2	1.3
CCl ₄	<0.5	0.8	5.5	4.8

NOTE: All concentrations in ppb; na = not available

Treatment Facility Destruction Efficiency

	Design Average Influent Concentrations [ppb]								Treated Effluent Discharge Limits [ppb]		
	TFA	TFB	TFC	TFD	TFE	TFF	TFG-1	TFG-2	NPDES	WDO	LWRP
TCE	7	300	20	875	860	200	38	17	-	-	-
PCE	280	40	5	28	60	10	13	22	4	-	-
1,1-DCE	12	10	2	11	20	10	11	1	-	-	-
1,2-DCE (cis&trans)	4	3	-	1	1	-	-	2	-	-	-
1,1,1-TCA	5	1	-	-	-	3	3	-	-	-	-
1,1-DCA	5	5	-	1	-	-	-	-	-	-	-
1,2-DCA	-	1	-	20	2	130	-	-	-	-	-
Chloroform	10	10	3	5	9	20	15	4	-	-	-
CCl ₄	-	2	-	20	3	10	7	3	-	-	-
Freon 113	5	10	100	1	8	10	7	3	-	-	-
Freon 11	-	-	-	148	-	-	-	-	-	-	-
EDB	-	-	-	-	-	10	-	-	0.02	-	-
Benzene	-	-	-	-	-	20,000	-	-	0.7	-	-
BTEX	-	-	-	-	-	65,000	-	-	-	-	250
Total VOCs	328	382	130	1,110	963	403	99	50	5	5	1000
Lead	-	-	-	-	-	30	-	-	5.6	500	200
Cr ⁶⁺	-	20	30	11	4	-	21	9	11	500	-
Total Cr	-	20	30	11	4	-	21	9	50	1,700,000	620

NOTE: "-" = not part of design basis; negligible anticipated influent; NPDES = National Pollution Discharge Elimination System permit; WDO = state Waste Discharge Order Requirement; LWRP = Livermore Water Reclamation Plant requirement.

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Treatment Performance (continued)

Effects on Plume

Current agreements specify that all treatment facilities will be operated until in situ VOC concentrations are below MCLs for 2 years. Final closure will be described in the future Compliance Monitoring Plan.

Contaminant Concentrations vs Time at Influent

At TFA, influent PCE concentrations have been reduced from 900 ppb to 150 ppb since startup.

Contaminant Mass Removal

Information on the total volume of VOCs removed by each treatment facility has only recently been collected as the facilities have become more fully operational. From start of operation through September 1994 mass removal data were:

<i>Treatment Facility</i>	<i>VOC Mass Removed</i>	<i>Ave. Extraction Rate as of Sept 1994</i>
TFA	44.4 kg	150 gpm
TFB	8.5 kg	20 gpm
TFC	0.9 kg	22 gpm
TFD	0.04 kg	8 gpm
TFF	10,200 gal of liquid equivalent gasoline	50 gpm

COST

- Remedial design reports were issued in 1993 and 1994 for Treatment Facilities (TF) A, B, C, D, E and F. The cost data below are from these reports. The data reflect actual costs for design and construction of TFA and TFB and represent projected costs in 1993 dollars for TFC, TFD, TFE and TFF.
- Technology evaluations, preliminary designs, final designs and most of the construction effort for the LLNL groundwater treatment project were performed by LLNL personnel. When necessary, subcontractors were competitively procured for specialized construction assignments. The costs below reflect the internal costs of design and construction activities performed by LLNL staff.

Capital Costs

TFA (1)

Building (including piping & power)	\$472,500
Recharge basin, access road & fence	116,500
Polishing tank & installation	20,000
UV unit for 100 GPM rate (60 kw)	63,000
UV unit for 150 GPM rate (120 kw)	150,000
UV upgrade design & installation	73,700
	<u>\$895,700</u>

TFB (1)

Building (including design & inspection)	\$3,500
Piping & power to well heads	5,000
60 kw UV/Oxidation unit	80,000
Electrical modification	9,200
Influent pipeline modifications	23,200
	<u>\$446,400</u>

TFC (2)

Building (including design, construction, piping & power)	\$1,080,000
Air stripper & associated equipment	130,000
Ion-exchange unit & equipment	162,000
Activation cost	40,000
Material procurement charge (9.7%)	28,324
	<u>\$1,440,324</u>

TFD (2)

Building (including design, construction, piping & power)	\$1,000,000
Process equipment	170,000
Ion-exchange unit & equipment	180,000
Activation cost	40,000
Material procurement charge (9.7%)	16,500
	<u>\$1,406,500</u>

TFE (2)

Building (including design, construction, piping & power)	\$1,000,000
60 kw UV/Oxidation unit	140,000
Process equipment	75,000
Ion-exchange unit	60,000
Activation cost	40,000
Material procurement charge (9.7%)	26,700
	<u>\$1,341,700</u>

TFF (2)

TFF piping & power	\$1,511,700
Process equipment	400,000
Vapor modification (for steam underground stripping demonstration)	159,900
Discharge pipeline	87,000
Activation (construction support only)	80,000
	<u>\$2,238,600</u>

Operating Costs

	TFA (1)	TFB (1)	TFC (2)	TFD (2)	TFE (2)	TFF (2)
Labor	\$80,000	\$80,000	\$610,000	\$610,000	\$590,000	\$700,000
Materials	50,000	50,000	210,000	210,000	210,000	100,000
Maintenance Contract	34,000	20,000	-	-	-	-
LLNL Overhead	-	-	110,000	110,000	100,000	100,000
Total	\$164,000	\$150,000	\$930,000	\$930,000	\$900,000	\$900,000

NOTES (1) • TFA & TFB capital and operating costs were determined prior to current project management system and are not inclusive of all costs.

(2) • The TFC, TFD, TFE and TFF cost accounting methods attempt to include all internal LLNL costs associated with operation and maintenance.

• Labor cost estimates for TFC through TFF include hydrogeologists, chemists, engineers, technicians, analysts, LLNL hazardous waste management specialists and plant engineering support. This labor requirement is expected to steadily decrease over the 53-year projected time of operation (83% effort for years 6-10, 67% for years 11-15 and 50% effort for years 15-53).

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REGULATORY/INSTITUTIONAL ISSUES

- All facilities comply with the Bay Area Air Quality Management District standards for VOC release. Groundwater discharges to the storm sewer are also controlled by National Pollutant Discharge Elimination System (NPDES) requirements (currently TFB, TFC and TFD). Groundwater discharges to the recharge basin are controlled by the San Francisco Bay Regional Water Quality Control Board (RWQCB) Waste Discharge Order Requirements (currently TFA). Groundwater discharge to the sanitary sewer is controlled by Livermore Water Reclamation Plant (LWRP) requirements (currently TFF).
- An active and ongoing public involvement program has served to coordinate discussions and commentary from an interested and concerned local population.
- An extensive and detailed quantitative risk assessment involving fate and transport modeling of contaminants was performed for the LLNL Livermore Site. The best estimate of noncarcinogenic risk produced a Hazard Index (HI) of $1.6E-3$ indicating little potential for chronic health effects. However, an EPA health conservative (worst case) risk assessment method produced cancer risks as high as $1E-3$ and HI's equalling 1 which exceeds EPA's acceptable cancer risk range at Superfund sites of $1E-4$ to $1E-6$ and indicate the potential for chronic health effects. The best estimate of the maximum incremental risk of developing cancer was $2E-7$ from a lifetime exposure to VOCs in downtown Livermore well water. No members of the public are currently exposed to VOCs from the use of wells near LLNL.

Cleanup Criteria

Currently, treatment systems will be operated until groundwater concentrations of target contaminants are below MCLs for two years. Final closure will be discussed in the Future Compliance Monitoring Plan.

SCHEDULE

Major Milestones

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LESSONS LEARNED

Implementation Considerations

- Comprehensive subsurface site characterization efforts have provided significant project benefits. They have allowed for optimal placement of extraction wells to maximize contaminant removal rates and provide hydraulic control of plumes. The methodology is cost-effective in light of the high cost of misplaced wells.
- Conducting pilot-scale or field treatability tests for standard groundwater treatment unit operations proved useful in design and construction of treatment systems. Air stripping VOCs also removes carbon dioxide which causes calcium carbonate scaling and a rise in pH. Measures to prevent or reduce scaling were tested for effectiveness prior to full-scale implementation. Addition of carbon dioxide slowed scaling. However, addition of polyphosphate eliminated scaling at TFF. Polyphosphate will be used at the other facilities as needed.
- Transparent piping at the ion-exchange resin treatment units for Cr^{6+} removal were a design upgrade that allowed for easier verification of system conditions during operation.
- Phased implementation of treatment system capacity was compatible with the need for maintaining operability. Integration of geologic and engineering design for facilities and pipelines is essential to construct high performance systems cost-effectively.

Technology Limitations

- To maintain high UV VOC destruction efficiency, UV lamps must be cleaned to prevent buildup of mineral coatings from inorganic groundwater components.
- H_2O_2 concentration at TFB was increased from 30 to 100 ppm to reduce Cr^{6+} which has a low discharge limit, to Cr^{3+} , which has a higher discharge limit. Residual levels of H_2O_2 exiting the UV/Oxidation unit at TFB may be the cause of low fish survivability tests of TFB effluent. Liquid-phase GAC treatment to keep H_2O_2 levels below 10 ppm was successfully bench-tested and will be installed after the UV/Oxidation unit.
- Current projections of cleanup duration exceed 50 years. Even with anticipated reductions in project staffing requirements, long-term operation and maintenance costs dominate project economics.

Future Technology Selection Considerations

- Treatment configurations can be employed to treat mixtures of chlorinated alkanes and alkenes, FHCs, and metals. UV/Oxidation treatment is effective on alkenes but ineffective on alkanes. Followup treatment with an air stripping process removes residual alkanes. Simple air stripping, while not a destruction technology, may be preferable in some instances. Ion-exchange resin treatment as a final polishing effort to remove metals was a straightforward addition to other treatment trains.
- The open and ongoing dialog with regulators and the local community has greatly contributed to the project's progress. LLNL personnel share all data and discuss work-in-progress with regulators during monthly and quarterly scheduled meetings as well as at seminars and workshops convened on an as-needed basis. The approach has secured early concurrence from regulators during ongoing technology-related decision making.
- A rigid Record of Decision (ROD) may have created obstacles to ongoing remediation strategy planning efforts in some instances. A more flexible ROD might allow improvements in the remediation approach which arise during the long project time frame to be implemented more easily. Flexibility was an important issue in maintaining consistency with anticipated funding levels and project priorities.
- Flexibility of remedial strategy and technology selection was especially important in light of shifts in project priorities. Over time, greater emphasis has been placed on offsite plume margin control compared to onsite source control/cleanup to meet budget requirements and to address community concerns.

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for:

HAZARDOUS WASTE REMEDIAL ACTIONS PROGRAM
Environmental Restoration and Waste Management Programs
Oak Ridge, Tennessee 37831-7606

managed by
MARTIN MARIETTA ENERGY SYSTEMS
for the

U.S. Department of Energy
under Contract DE-AC05-84OR-21400

This analysis was funded by:

U.S. Air Force
Headquarters USAF/CEVR

CERTIFICATION

This analysis accurately reflects the performance and costs of the remediation:

x Michael Brown

Michael Brown
Environmental Restoration
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U.S. Air Force

SOURCES

Major Sources For Each Section

Site Characteristics:	Source #s (from list below) 1, 3, 9, 11 and 12
Treatment System:	Source #s 5, 6, 7, 8 and 9
Performance:	Source #s 4, 5, 6 and 7
Cost:	Source #s 5, 6 and 7
Regulatory/Institutional Issues:	Source #s 1, 4 and 8
Schedule:	Source # 8
Lessons Learned:	Source #s 1, 2, 3 and 4

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TECHNOLOGY APPLICATION ANALYSIS

**Dynamic Underground Stripping
of Contaminated Soil & Groundwater
at**

U.S. Department of Energy

**Lawrence Livermore National Laboratory
LLNL Gasoline Spill Site
Livermore, California**

prepared for

U.S. Air Force

March 1995 FINAL

TECHNOLOGY APPLICATION ANALYSIS

Page 1 of 16

SITE

Lawrence Livermore
National Laboratory (LLNL)
LLNL Gasoline Spill Site
Livermore, California

TECHNOLOGY APPLICATION

This analysis reports on the use of **Dynamic Underground Stripping (DUS)** technology to remediate soil and groundwater above and below the water table contaminated with **fuel hydrocarbons (FHCs)** from a former gasoline spill. DUS employs a combination of **steam injection** with vacuum extraction, **electrical heating**, and **underground imaging**.

SITE CHARACTERISTICS

Site History/Release Characteristics

- The 800 acre LLNL site was converted from agricultural use into a flight training base and aircraft assembly and repair facility by the Navy in 1942. In 1951, the Atomic Energy Commission converted the site into a weapons design and basic physics research laboratory. Later site missions have included programs in biomedicine, energy, lasers, magnetic fusion energy, and environmental science.
- Initial releases of hazardous materials occurred in the mid to late 1940s. There is also evidence that subsequent localized spills, leaking tanks and impoundments, process cooling water and landfills released VOCs, FHCs, lead, chromium and tritium to sediments and groundwater primarily from 14 major areas of concern.
- Between 1952 and 1979, based upon inventory records, as much as 17,000 gallons of **leaded gasoline** was released from underground storage tanks (USTs) in an area now designated the Gasoline Spill Area (GSA).
- Corrective actions taken since 1988 at the GSA have included the removal and sand filling of four USTs, installation of a gas skimmer which removed 100-150 gal of gasoline, soil vapor extraction of about 1900 gal, and intermittent use of a groundwater pump & treat system using UV/H₂O₂ treatment. A large subsurface microbiological population indicates that indigenous microbes have metabolized additional gasoline constituents.

Contaminants of Concern

Contaminants of concern focused on during the remediation are:

Benzene
Toluene
Ethylbenzene
Xylene
1,2-Dichloroethane

Low levels of other chlorinated solvents are also present in the GSA but were not specifically targeted by DUS remediation efforts.

Contaminant Properties

Property at STP* Units	B	T	E	X***	
Empirical Formula	-	C ₆ H ₆	C ₆ H ₅ C ₂ H ₅	C ₆ H ₅ CH ₃	C ₆ H ₄ (CH ₃) _{2m}
Density	g/cm ³	0.87	0.87	0.87	~0.87
Vapor Pressure	mmHg	75	29	7	10
Henry's Law Constant	atm·m ³ /mole	5.6E-3	6.5E-3	8.4E-3	2.5E-1
Water Solubility	mg/L	1,780	534	161	178
Octanol-Water Partition Coefficient; K _{ow}	-	132	490	1,413	1,830
Organic Carbon Partition Coefficient; K _{oc}	-	50	339	565	255

*STP = Standard Temperature and Pressure; 1 atm, 25°C
** Properties at 20°C ***Mixture of m,o and p-xylenes

Site Conditions

- The GSA occupies an approximately 1 1/4 acre level area at the southern edge of LLNL. The site was formerly a gasoline filling station for use by LLNL vehicles.
- Climate is semiarid with annual precipitation around 14 inches/year.
- Land north and south of the site is zoned for industrial use, high-density urban areas are west of the site and the east side is primarily agricultural. Immediately south of the GSA are facilities owned and operated by Sandia National Laboratory.

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Nature and Extent of Contamination

- The mass of FHC as gasoline prior to any remediation efforts was estimated based upon soil and groundwater sampling to be approximately 16,000-17,000 gal: 6,000 in the vadose zone, 10,000-11,000 in saturated sediments and 100 dissolved in groundwater. Mass volume estimates made immediately prior to application of DUS identified approximately 6,500 gal of gasoline within the treatment zone.
- Concentrations of gasoline were as high as 5,100 ppm in saturated sediments near the center of the vadose zone indicating the likelihood of free phase gasoline. The free phase was trapped within low-permeability sediments by a groundwater table that has risen 10 to 30 ft since the time of the main portion of the release (1979).
- FHC concentrations exceed 10 ppm only in the immediate vicinity of the release point with concentrations decreasing to 1 ppm and 100 ppb at 35-40 ft and 40-45 ft respectively. Benzene levels above 1 ppb (California Maximum Contaminant Level (MCL) is now 0.5 ppb) are found within 300 ft. FHCs are not present below a depth of 150 ft.
- Fuel was trapped below the water table by a 20 ft rise in groundwater elevations in the late 1970's from cessation of agricultural pumping.

Contaminant Locations and Hydrogeologic Profiles

The GSA has been extensively studied since 1984. Over 70 subsurface borings and monitoring wells revealing the areas geologic, physical and chemical characteristics have been completed. Short & long term drawdown, injection and extraction tests were conducted to assess hydraulic properties. Pneumatic data derived from soil vapor extraction efforts has also been collected.

Site Layout (Plan View)

Cross-Sectional View

4 Hydrogeologic units and 7 hydrostratigraphic layers have been identified along cross-section B-B' shown in the plan view above. A FHC concentration profile along this same cross-section is provided in the "Performance" section on p. 9.

Hydrogeologic Unit Characterization

#	Hydraulic Conductivity Range [gpd/ft ²]	Interpreted Permeability
1	15 to 1070	Very high to high (mean=280)
2	13 to 1000	High to moderate (mean=154)
3	16 to 170	Moderate to low (mean=116)
4	<5 to 18	Low (mean=11)

Hydrostratigraphic Layer Characterization

- 1 5-15 ft thick interval of coarse-grained high-permeability sandy gravels and gravelly sands
- 2 30 ft thick, laterally continuous interval of clayey silts to silty clays
- 3 very heterogeneous zone of elongated lenses of channel sands and gravels interbedded with intervals of silty clays and clayey silts from 50 to 80 ft depth; forms aquitard over USZ
- 4 partially saturated water-bearing zone composed of a heterogeneous mix of high to low permeability sandy to clayey gravels and gravelly to silty sands, 80 to 100 ft depth
- 5 low-permeability silty clays and clayey silts; forms barrier between the USZ and LSZ
- 6 high-permeability laterally continuous gravelly sands and sandy gravels; ave 11 ft thick
- 7 laterally continuous sequence of silty clays to clayey silts at least 15 ft below base of LSZ

NOTE: The 2 steam zones appear to be hydraulically isolated from adjacent aquifers, are relatively permeable and contain the most elevated FHC concentrations.

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Contaminant Locations and Geologic Profiles (Continued)

Areal Extent of Benzene Contamination

Key Soil/Aquifer Characteristics

- The site is underlain by several hundred feet of complexly interbedded alluvial and lacustrine sediments. A shallow groundwater system of predominantly heterogeneous alluvial deposits and a deeper groundwater system of fluvial and lacustrine sediments are divided by a confining aquitard.
- Depth to groundwater varies from about 120 ft in the southeast corner of LLNL to about 25 ft in the northwest corner. Depth to groundwater in the GSA is approximately 100 to 120 ft.
- Regional groundwater flow is generally westward, locally stratified and primarily horizontal.
- Pumping tests and the distribution of contaminants at LLNL indicate a high degree of horizontal subsurface communication. Minimal observed communication in the vertical direction and the layered alluvium prevent significant downward migration of contaminants.

- Physical parameters measured on sediment cores from 60 to 150 ft depths within the center of the GSA were:

Bulk Density	1.44-1.87	Particle Density	2.50-2.94	Organic Carbon [%]	<0.01-0.46
pH	7.01-7.91	Sorption constant, Kd	0.03-0.58	Cation Exchange Capacity [meq/100g]	4.0-19.0
Porosity	0.29-0.45				

- In addition to GSA hydrogeologic unit data presented on p.2, aquifer parameters for other areas at LLNL have been estimated as:

Area	Number of data points	Hydraulic Conductivity [ft/d]	Hydraulic Gradient	Velocity [ft/y]
A	64	5.6	0.002	14
B	24	3.2	0.001	4
C	15	3.1	0.005	19
D	12	4.4	0.005	27
E	48	2.4	0.012	35

• Velocities are calculated based upon a porosity of 0.30 and are applicable only to the area specified. When considering conductivity and velocity over larger areas at LLNL, considerably higher values are appropriate.

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REMEDIATION SYSTEM

Overall Process Schematic

System Configuration

NOTE: 21 Tiltmeters (not shown) were also utilized. Additional subsurface borings & groundwater monitoring wells are present from initial & ongoing characterization activities.

Legend

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Well Close-Ups

Thermal Enhancement

Extraction

Monitoring

Geophysical Monitoring

Tiltmeter

Thermocouples (not shown) are present in the monitoring, steam injection and electric heating wells

All drawings not to scale

U.S. Air Force

- The configuration shown above was used for the 2nd DUS steam pass. The most significant difference from the 1st pass was the installation of the internal combustion engines to replace a regenerable carbon adsorption unit which could not handle the higher than anticipated vapor flow rates and hydrocarbon concentrations.

PERFORMANCE

Performance Objectives

- Satisfying research objectives of each DUS technology demonstration phase
- Avoiding uncontrolled mobilization of contamination
- Removing as much gasoline as possible from the treatment zone [achievement of site cleanup goals (including an MCL of 0.5 ppb for benzene) were not specified objectives]

Demonstration Overview

DUS activities at LLNL occurred in a series of demonstration efforts:

PHASE	OBJECTIVES/APPROACH	KEY RESULTS
Clean Site Demonstration	<ul style="list-style-type: none"> • To field test the DUS process on an uncontaminated site with well characterized geology 	<ul style="list-style-type: none"> • Determination of steam injections, electric heating & monitoring well design improvements • Identification of improved operating strategy of electric heating prior to steaming • Soil layers raised from 70°F to 160°F
DUS Demonstration <i>Electrical Heating Phase</i>	<ul style="list-style-type: none"> • To heat less permeable contaminated zones 	<ul style="list-style-type: none"> • Over 1700 gal of gasoline removed
DUS Demonstration <i>1st Pass Steaming Phase</i>	<ul style="list-style-type: none"> • Continuously steam treatment zone over a 5 week period to remove gasoline 	<ul style="list-style-type: none"> • Over 4900 gal of gasoline removed • Most soils within treatment zone exceed 212°F; residual contamination (estimated at 750 gal) and an unsteamed area ("cold spot", 170°F, remained)
DUS Demonstration <i>2nd Pass Steaming Phase</i>	<ul style="list-style-type: none"> • Intermittently steam and vacuum extract treatment zone over 6 weeks to remove gasoline 	
Accelerated Removal & Validation (ARV) Project	<ul style="list-style-type: none"> • Operate continuously to remove residual contamination • Test process modifications such as altering injection/extraction locations & air sparging • Reheat electrically • Allow for simultaneous electrical heating & process monitoring with installation of fiber-optic transmission system 	<ul style="list-style-type: none"> • Remainder of free product removed • Over 1000 gal of gasoline removed • Improved understanding of electrical heating process - less effective with groundwater pumping and recharge • Sparging tests demonstrated value of modeling & use of tracer gases

Treatment Plan

A generalized approach to implementing DUS includes

Operational Performance

- A significant percentage of the field activities occurred in a shutdown mode where various processes were debugged and optimized. In addition, distinct demonstration phases used different equipment configurations. Therefore, long-term routine operational performance data is not available.
- Operational difficulties encountered included biofouling especially from microorganisms destroyed by steaming, scaling and deposits on sensors, clogging from fines brought to the surface and difficulties in maintaining the cycling, pressure varying, high temperature process.

In Situ Heating Performance

- At total of 100,000 yd³ was heated at least to 200°F (boiling point at applied vacuum).
- The growth of the hot zone was monitored by electrical resistance tomography (ERT) and a network of temperature probes and tiltmeters.
- A variety of data was used to prepare multiple representations of heating effects:

Temperature Profiles Along Individual Wells

- More permeable layers heat first.
- Heating ultimately effective throughout treatment zone.

Tiltmeter Plots

- Tiltmeter data allows generation of vector-based representations of steam from growth on a given day from 2 injection wells
- Data is useful for tracking any steam heading outside of the treatment zone

Electrical Resistance Tomography Imaging

- ERT images provide a continuous representation of steam passage between 2 electrode-equipped boreholes.
- The process allows identification of "cold spots" and provides data on efforts to provide uniform heating.

In Situ Heating Performance (Continued)

Temperature Profiles Along Individual Wells

- Impermeable layers maintained temperature increases
- Permeable layers were cooled by groundwater pumping especially at peripheral wells due to infiltration of groundwater from outside the treatment zone

Hydrodynamic Performance

- The GSA was an ideal spot for demonstration of DUS due to its low groundwater velocities. This kept contamination confined to a relatively small area. The plots at right illustrate that BTEX concentrations at locations at the periphery of the treatment zone declined during the demonstration.

Effects on Site Physical/Chemical/Biological Characteristics

- No unanticipated bulk changes in physical or chemical soil and groundwater parameters were observed.
- Biological characterizations before and after DUS revealed that viable (although different) microbial populations capable of degrading gasoline were present; the treatment zone was not sterilized.

Treatment Performance

Effects on Plume

Estimated Total Fuel Hydrocarbon concentrations before and after the second steam pass of DUS are shown below:

- No spreading observed; contamination drawn to center of treatment zone.
- Continued operation removed an additional 1000 gallons.
- The ability of DUS to remove contaminants sorbed to soils was illustrated by a marked rise in benzene and total gasoline concentrations in groundwater during DUS. At one groundwater monitoring well in the treatment zone, concentrations of C6 to C12 hydrocarbons were below 30 ppm since 1987, but during DUS these concentrations rose to nearly 150 ppm before dropping to levels below those found before DUS.

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Treatment Performance (Continued)

Contaminant Mass Removal

- During the DUS 1st steam pass, 74% of the 1683 gallons removed were collected by the vapor stream GAC unit. An additional 17% condensed in the vapor stream and the remaining 9% was dissolved in groundwater.

- During the 2nd steam pass, 77% was burned by the internal combustion engines, 21% was condensed and 1% was dissolved.

Above Ground Treatment Plant Performance

UV/H₂O₂ Unit

- Destruction efficiencies during the last half of the 1st steam pass were less than 40% but adjustments maintained an efficiency over 90% during the last half of the second steam pass.
- Free gasoline product was found in the unit after the 1st steam pass.

GAC/ICE Units

- The GAC unit was undersized for the vapor flows encountered.*
- The ICE unit could also have been larger but nevertheless performed successfully. Dilution air was necessary since hydrocarbon concentrations were above the explosive limit.

• Majority of contaminant was removed in the vapor phase.

COST

Project costs were obtained from LLNL from a variety of sources. The cost sections below detail costs based upon overall funding received from the Department of Energy, program management planning documents, capital costs for individual equipment components, and actual operating costs incurred during the 2nd steam pass (which is most representative of operating costs for future applications). In addition, LLNL has prepared an estimate of potential cost savings if DUS were applied at the same site in the future with the benefit of lessons learned and without research-oriented activities. A summary of that estimate is also presented.

DUS costs were compared to estimated costs of applying alternative technologies at the GSA:

DUS	\$10-11M	(clean up in 9 months)
DUS with lessons learned (see next page)	6M	(clean up in 6 months)
Soil excavation & removal	30M	(clean up in 1 year)
Pump & treat with soil vapor extraction	25M	(clean up over 30 years)

Overall Program Costs

Construction through 1st Steam Pass	\$7.240M
2nd Steam Pass	2.200M
ARV Phase	<u>1.000M</u>
Total	\$10.440M

Note: Costs include all research & development costs associated with the demonstration

Program Costs Through 1st Steam Pass & Selected Capital Cost Components

Program Costs: The following program elements were taken from planning documents. Actual costs were approximately 5% lower:

Project Management

Management	\$225,000
Post analysis & report writing	335,000
Review & write safety plans	70,000
Permitting	65,000
Equipment design	<u>200,000</u>
	\$896,000

Characterization & Compliance Monitoring

Drilling phase sampling	\$315,000
Pre-electrical heating sampling	35,000
Pre-steam sampling	20,000
Post-steam sampling (4 new wells)	50,000
Compliance monitoring	10,000
During experiment sampling	<u>25,000</u>
	\$455,000

Process Monitoring

Design	\$50,000
ERT & thermal	270,000
Tiltmeter	70,000
Hydraulic testing	<u>55,000</u>
	\$445,000

Selected Component Costs: The following capital cost items include overlaps with the program cost elements shown above:

Subsurface Wells

Note: Costs due not include design and installation labor

Steam injection/vapor extraction (8 wells at approx. \$32,000 each with ave depth of 145 ft)	\$256,000
ERT-Temperature monitoring (11 wells at approx. \$10,000 each with ave depth of 165 ft)	\$110,000
Electrical heating (3 wells at approx. \$10,000 each with ave depth of 120 ft)	\$30,000

Electrical Heating Surface Equipment

Note: Costs due not include design and engineering

Installation labor	\$129,000
Transformer	50,000
Circuit breaker/switch panel	40,000
Cable	18,000
Miscellaneous materials	67,000
Other direct costs	<u>63,000</u>
	\$367,000

Steam Generation Surface Equipment

Note: Boiler leased for \$17,300/month; design costs not included

Installation labor	\$174,000
Boiler utility set-up	100,000
Miscellaneous materials	42,000
Other direct costs	<u>79,000</u>
	\$395,000

Extracted Groundwater & Vapor Surface

Treatment Systems - Treatment Facility F

Note: Costs do not include design and engineering; facility originally designed for 30 year pump & treat mission

Piping & power	\$1,512,000
Process equipment	400,000
Vapor modifications for DUS	160,000
Discharge pipeline	87,000
Activation	80,000
Other direct costs	<u>291,000</u>
	\$2,530,000

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Operating Costs

Utility Consumption

Boiler natural gas (3.8E10 cu.ft @ \$0.39/100,000 cu.ft.)	\$149,000	} \$1.50 per cubic yard treated
Boiler water (3.6E6 gal @ \$1.25/100 cu.ft.)	\$6,000	
Boiler electricity (40,000 kWh @ \$0.06/kWh)	\$2,400	

Electricity for electrical heating (200,000 kWh @ \$0.06/kWh) \$12,000

Labor & Material Costs for 2nd Steam Pass (all values in thousands of dollars)

Note: Costs represent 6 weeks of 24 hr operations and continuously monitored experimental conditions

	Scientists & Engineers	Technicians	External Analysis	Materials	TOTALS
Phase 1: Planning	44	-	-	-	44
Phase 2: Maintenance & Modification	2	31	-	27	60
Phase 3: Operations					
Steam Injection Operations					
Periods of steam injection	27	51	-	167	245
Periods of no steam injection	14	5	-	-	19
ERT Monitoring	13	22	-	-	35
Additional UC Berkeley support	-	50	-	-	50
Effluent Treatment Operations					
Effluent treatment	35	203	-	91	329
Sampling & analysis	50	17	18	-	85
Phase 4: Post Steaming Characterization					
Sampling	41	36	-	-	77
Soil Analysis	-	-	83	-	83
Drill Rig	-	26	-	9	35
Phase 5: Reporting & Technology Transfer	400	-	-	-	400
Phase 6: Dismantling (conservative estimate)					181
Contingencies					228
	Grand Total				\$1,870

Estimated Cost Savings for Reapplication/Cost Sensitivities

LLNL has prepared an estimate of potential cost savings if DUS were applied at the same site in the future with the benefit of lessons learned and without research-oriented activities. The estimated savings would be derived from:

- reduction in design effort by over 50% (-\$206K)
- elimination of discharge lines & transformer modifications (-855K)
- use of temporary steam generation equipment (-355K)
- reduced site characterization (-210K)
- replacement of UV unit with air stripper (-500K)
- elimination of modification designs for 2nd pass steam and ARV phases (-604K)
- reduced management effort (-100K)
- reduced science & engineering staff requirements (-166K)
- reduced operations staff requirements (-505K)
- reduced reporting and safety documentation preparation (-470K)

Resultant total savings would be approximately \$4,000,000

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REGULATORY/INSTITUTIONAL ISSUES

- The timetable for the DUS demonstration was dictated by the air permits issued for the project. The system was shut down while it was still removing 50 gal/day of gasoline and an unheated region remained because the air discharge allowances had been consumed.
- The boiler for steam generation utilized Best Available Control Technology (BACT) consisting of a low NOx burner design and flue gas recirculation to control NOx emission to 40 ppm. The Bay Area Air Quality Management District (BAAQMD) granted a research exemption for the project rather than requiring LLNL to purchase an emission allotment of 2,200 lbs (1.6 lbs/h) of NOx.
- The BAAQMD issued permits for the following:

<i>DISCHARGE</i>	<i>COMPOUND</i>	<i>SAMPLING FREQUENCY</i>	<i>DISCHARGE LIMIT</i>
Air stripper	Total Hydrocarbons	5/wk	10 ppm
GAC	Total Hydrocarbons	5/wk	10 ppm
IC Engine	Total Hydrocarbons	5/wk	Destruction > 98.5%
Sitewide benzene	Benzene	Monthly	1.815 lb/day

- National Pollution Discharge Elimination System (NPDES) water discharge limits issued by the Bay Area Regional Water Quality Control Board (RWQCB) mandated MCLs for effluents. The system was designed to satisfy the limits, however, during upset conditions, effluent was sampled and sent to a sanitary sewer regulated by the Livermore Water Reclamation Plant.

SCHEDULE

Major Milestones

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LESSONS LEARNED

Design Issues

- The DUS demonstration made use of an existing groundwater treatment unit designed to treat gasoline and low levels of chlorinated solvents over a long period of time using oil/water separation, UV/H₂O₂, and GAC for the liquid phase and GAC for the vapor phase. This design was not optimal for DUS conditions. The large vapor flows loaded with fuel hydrocarbons required installation of an internal combustion engine to replace the GAC. The high temperature process created conditions unfavorable to UV treatment (increased carbonates and silicates in the extracted liquids would come out of solution when cooled in the UV unit. Packed tower air stripping may be more appropriate for similar applications in the future
- The success of the DUS process is dependent upon boiling the subsurface environment. The process must be designed not only to bring soil and groundwater to steam temperature but to impart a large amount of energy to create a complete steam zone.
- Above ground equipment must be able to handle large peak extraction rates and rapid changes in rate.
- Most of the recovered gasoline is in the vapor phase rather than separated out of the extracted groundwater. Vapor recovery systems must be sized accordingly.
- Above ground treatment units should be configured not to interfere with access to the subsurface treatment zone.

Implementation Considerations

- Effective removal of contaminants from the subsurface requires alternating steam-injection and vacuum extraction phases. The pressure changes created by this oscillatory approach distills contaminants from pore spaces in both saturated and unsaturated sediments.
- Extraction rates can vary greatly depending upon the amount of steam injected, the total vacuum applied and cycle times.
- Permitting of air discharges both from the above ground treatment units as well as from equipment used to supply steam energy is an issue requiring early attention.
- DUS is a labor intensive process requiring significant field expertise to implement.
- Electrical Resistance Tomography (ERT) proved to be the most effective method for monitoring the DUS process in real time. Alternative geophysical techniques could be used for other applications.

Technology Limitations

- Data on long-term routine operating experience with DUS is not yet available.
- Future development needs currently identified for DUS include demonstrating the process for removing chlorinated solvents, automating monitoring techniques and further refining system design and operating techniques.

Future Technology Selection Considerations

- DUS was effective at quickly removing concentrated free product contaminants including materials sorbed to saturated sediments without mobilizing contaminants outside of the treatment zone.
- Steam injection is effective at heating impermeable zones and repeated steam passes can heat adjacent impermeable areas.
- Electrical heating is effective on clay zones, however, power requirements increase when extracting hot fluids from the treatment zone.
- DUS is compatible with long-term efforts to bioremediate residual contamination following steam injection. At LLNL, viable microbial populations continued to degrade gasoline at the site at temperatures above 158°F after application of DUS.
- DUS can compare favorably in terms of speed, effectiveness and cost with alternative technologies for deep subsurface plumes. At LLNL, significant cost savings were realized from DUS as opposed to installation of soil vapor extraction/pump & treat systems or excavation of contaminated areas. Further reductions in DUS cost are anticipated as experience is gained optimizing subsequent applications.

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for:

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managed by
MARTIN MARIETTA ENERGY SYSTEMS
for the

U.S. Department of Energy
under Contract DE-AC05-84OR-21400

This analysis was funded by:

U.S. Air Force
Headquarters USAF/CEVR

CERTIFICATION

This analysis accurately reflects the performance and costs of the remediation:

x Richard Abbott 3/17/95
[DOE representative]

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SOURCES

Major Sources For Each Section

Site Characteristics:	Source #s (from list below) 1 and 13
Treatment System:	Source #s 1, 3, 4, 5, 6, 7, 8, and 9
Performance:	Source #s 1, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12 and 14
Cost:	Source #s 1 and 2
Regulatory/Institutional Issues:	Source #s 1, 4 and 8
Schedule:	Source # 4, 6, 8, 10 and 11
Lessons Learned:	Source #s 1, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12 and 14

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