Case Study Abstract

Dynamic Underground Stripping Demonstrated at Lawrence Livermore National Laboratory Gasoline Spill Site, Livermore, California

Site Name:
Lawrence Livermore National Laboratory, Gasoline Spill Site

Location:
Livermore, California

Technical Information:
Roger Aines, Principal Investigator, LLNL (510) 423-7184
Robin Newmark, LLNL (510) 423-3644
Kent Udell, UC Berkeley (510) 642-2928

SIC Code:
5541 (Gasoline service station)

Waste Source:
Underground Storage Tanks

Contaminants:
Benzene, Toluene, Ethylbenzene, Total Xylenes (BTEX)
- Concentrations of fuel hydrocarbons (FHC) in saturated sediments indicates likely presence of free-phase gasoline
- Benzene levels in groundwater greater than 1 ppb found within 300 feet of release point
- Benzene levels in soil greater than 50 ppm

Technology:
Dynamic Underground Stripping (DUS)
- Combination of three technologies: steam injection at periphery of contaminated area to drive contaminants to centrally-located vacuum extraction locations; electrical heating of less permeable soils; and underground imaging to delineate heated areas
- Six steam injection/electrical heating wells approximately 145 feet deep, 4-inch diameter, screened in upper and lower steam zones
- Three electrical heating wells approximately 120 feet deep, 2-inch diameter
- Three groundwater and vapor extraction wells, approximately 155 feet deep, 8-inch diameter
- Extracted water processed through an air-cooled heat exchanger, oil/water separators, filters, UV/H_2O_2 treatment unit, air stripping, and GAC
- Extracted vapors processed through heat exchanger, demister, and internal combustion (IC) engines

Period of Operation:
November 1992 - December 1993

Cleanup Type:
Field demonstration (commercial-scale)

Cleanup Authority:
CERCLA and Other: Bay Area Air Quality Management District

Licensing Information:
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Purpose/Significance of Application:
Commercial-scale demonstration of dynamic underground stripping. Results compared to pump and treat, and pump and treat with vacuum extraction technologies.

Case Study Abstract

Dynamic Underground Stripping Demonstrated at Lawrence Livermore National Laboratory Gasoline Spill Site, Livermore, California (Continued)

Type/Quantity of Media Treated:
Soil and Groundwater
- 100,000 cubic yards heated to at least 200°F
- 4 hydrogeologic units and 7 hydrostratigraphic layers identified near gas pad
- Hydraulic conductivity ranged from <5 gpd/ft^2 (low permeability) to 1,070 gpd/ft^2 (very high to high permeability)
- Low groundwater velocities kept contamination confined to a relatively small area

Regulatory Requirements/Cleanup Goals:
- Groundwater cleanup levels established based on California MCLs: benzene 1 ppb; ethylbenzene 680 ppb; and xylenes 1,750 ppb
- Remediation was required until soil contaminant concentrations were identified as not adversely impacting groundwater
- Air permits were issued by the BAAQMD for the air stripper, GAC, IC engine, and for site-wide benzene

Results:
- Over 7,600 gallons of gasoline removed during demonstration effort
- Most of the gasoline was recovered in the vapor stream and not from extracted groundwater

Cost Factors:
- Overall program costs for the field demonstration, including all research and development costs, were $1,700,000 for before-treatment costs (project management, characterization and compliance monitoring), and $8,740,000 for treatment activities (process monitoring, subsurface wells, steam generation and electrical heating surface equipment, aboveground treatment systems, utilities, and labor and material costs)

Description:
The 800-acre Lawrence Livermore National Laboratory (LLNL) site was used as a flight training base and aircraft assembly and repair facility by the Navy beginning in 1942. In 1951, the Atomic Energy Commission converted the site into a weapons design and basic physics research laboratory. Initial releases of hazardous materials occurred in the mid- to late-1940s. Between 1952 and 1979, up to 17,000 gallons of leaded gasoline were released from underground storage tanks beneath a gasoline filling station in an area now designated as the Gasoline Spill Area (GSA). Soil and groundwater in the GSA were found to be contaminated with BTEX (benzene, toluene, ethylbenzene, and xylenes) and fuel hydrocarbons.

A commercial-scale field demonstration of Dynamic Underground Stripping (DUS) was completed at the GSA from November 1992 to December 1993. DUS is a combination of three technologies: steam injection at the periphery of a contaminated area to drive contaminants to a centrally-located vacuum extraction location; electrical heating of less permeable soils; and underground imaging (primarily Electrical Resistance Tomography) to delineate heated areas. The DUS system used at the GSA employed 6 steam injection/electrical heating wells, 3 electrical heating wells, and 3 vacuum extraction wells, as well as above ground water and vapor treatment equipment.

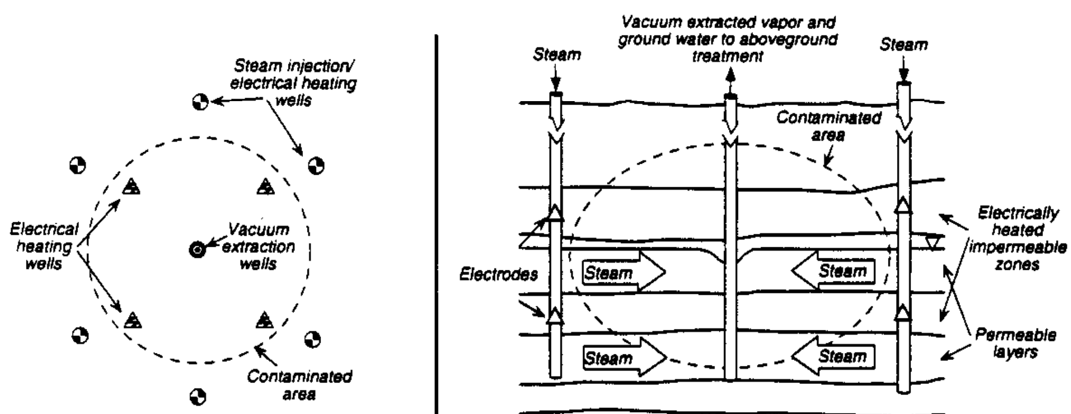
Over 7,600 gallons of gasoline were removed by the DUS system in the demonstration effort. Most of the gasoline was recovered in the vapor stream and not from the extracted groundwater. Potential cost savings of $4,000,000 were identified for applying DUS at the same site in the future (taking into account the benefits of the lessons learned and without research-oriented activities).

SECTION 1
SUMMARY

Technology Description

Dynamic Underground Stripping (DUS) is a combination of several technologies targeted to remediate soil and ground water contaminated with organic compounds. DUS is effective both above and below the water table and is especially well suited for sites with interbedded sand and clay layers. The main technologies which comprise DUS are:

- ***steam injection*** at the periphery of a contaminated area to heat permeable subsurface areas, vaporize volatile compounds bound to the soil, and drive contaminants to centrally located ***vacuum extraction*** wells;
- ***electrical heating*** of less permeable clays and fine-grained sediments to vaporize contaminants and drive them into the steam zone; and
- ***underground imaging***, primarily Electrical Resistance Tomography (ERT), which delineates heated areas to ensure total cleanup and process control.



Plan View **Cross-Sectional View**

Technology Status

A full-scale demonstration was conducted at:
Lawrence Livermore
National Laboratory (LLNL)
Gasoline Spill Site: GSA
Livermore, California
November 1992 through December 1993

Before application of DUS, the site contained an estimated 6,500 gallons of fuel hydrocarbons (FHCs) both above and below the water table at depths up to 150 ft. The site is underlain by complexly interbedded high and low permeability sediments.

Key results included:

- The system removed over 7,000 gallons of gasoline (more than the original estimate of contamination) during 10 weeks of operation conducted in phases over a 1-year period. The maximum extraction rate was 250 gallons per day.
- DUS removed the localized underground spill at LLNL more rapidly and cost-effectively than the estimated effectiveness of competing baseline technologies of pump-and-treat or pump-and-treat with vacuum extraction.
- DUS is projected to cost between $11 and $37 per cu yd of contaminated soil and is projected to remediate a site in six to nine months as opposed to thirty years for the baseline technology of pump and treat.

Technology Status (continued)

Over a dozen patents covering the major aspects of DUS are either pending or have already been granted to DOE and the University of California. DUS is licensable from the University of California Office of Technology Transfer, and licensing discussions are currently in progress. The results of the LLNL demonstration illustrating the effectiveness of subsurface heating are corroborated by the results of field-scale demonstrations of other in situ thermal treatment processes conducted through other EPA, DOD, and DOE programs. Conceptual designs, cost estimates, and detailed designs have been prepared for applying DUS at other sites. Future development efforts will focus upon applying the technology at sites contaminated with dense nonaqueous phase liquids (DNAPLs) and at sites with fractured subsurface media.

Contacts

Technical

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Licensing Information

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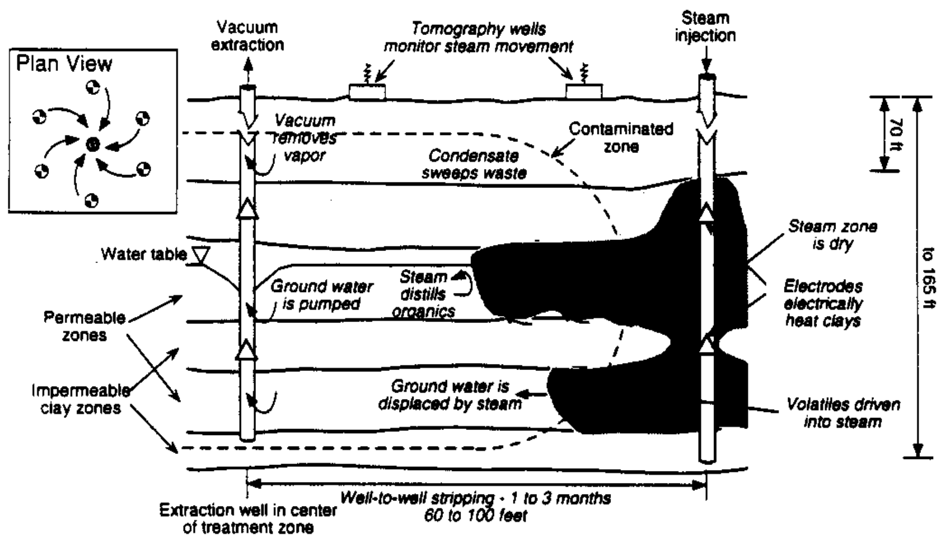
Overall Process Schematic

DUS combines steam injection, electrical resistance heating, and underground imaging and monitoring techniques to mobilize and recover contaminants from the subsurface. The figure below is a conceptual illustration of the process for relatively simple subsurface conditions. Appendix B provides detailed information about the process including close-ups of subsurface wells and descriptions of surface treatment equipment.



Major elements of the technology are:

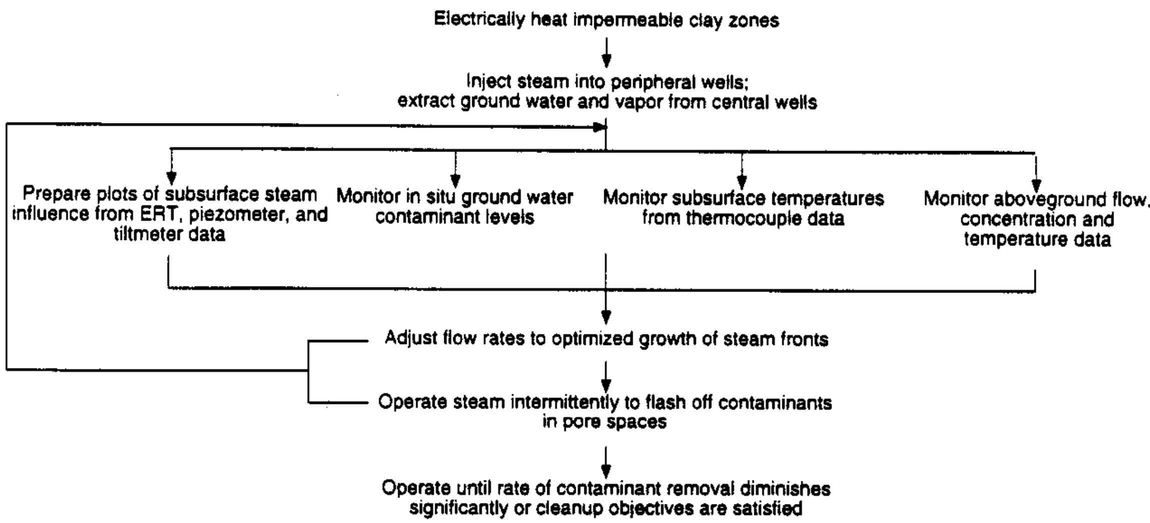
Steam Injection and Vacuum Extraction - Injection wells drilled around an area of concentrated contamination supply steam and electric current. Vacuum extraction wells in the center of the contaminated area remove contaminants. A steam front develops in the subsurface as permeable soils are heated to the boiling point of water and volatile organic contaminants are vaporized from the hot soil. The steam moves from the injection to the extraction wells.

Electrical Resistance Heating - Electric current is used to heat impermeable soils. Water and contaminants trapped in these relatively conductive regions are vaporized and forced into the steam zone for vacuum extraction.

Underground Imaging and Monitoring - Several geophysical techniques used to monitor the underground movement of steam and the progress of heating include temperature measurements (taken from monitoring wells throughout the treatment area), ERT (which relates measurement of electrical conductivity to the progress of the steam front in the heated zone, and tiltmeters (which detect small subsurface pressure changes created by the movement of the steam front).

Generalized Treatment Plan

A generalized approach to implementing DUS developed as a result of the demonstration includes:



Demonstration Operations and Results Overview

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

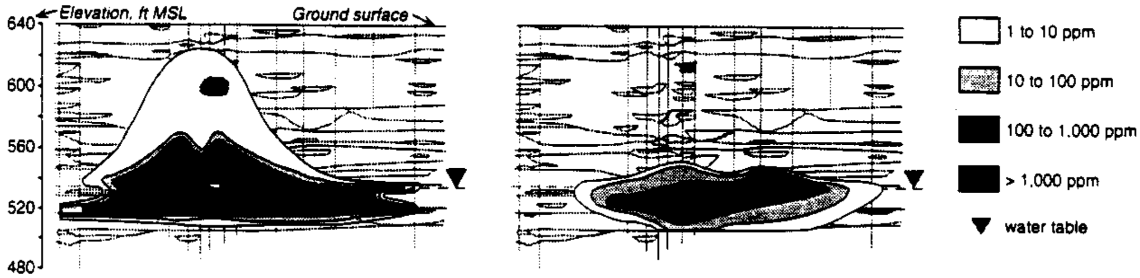
PHASE	OBJECTIVES/APPROACH	KEY RESULTS
Clean Site Demonstration	To field test the DUS process on an uncontaminated site with well-characterized geology	Steam injections, electric heating, and monitoring well design improvements were identified Identification of improved operating strategy of electric heating before steaming
DUS Demonstration *Electrical Heating Phase*	To heat less permeable contaminated clay zones	Temperature of clay layers raised from 70°F to 160°F
DUS Demonstration *1st Pass Steaming Phase*	Continuous steam injection over a 5-week period to vaporize and remove gasoline	Over 1700 gal of gasoline removed
DUS Demonstration *2nd Pass Steaming Phase*	Intermittent steam injection and vacuum extraction over a 6-week period	Over 4900 gal of gasoline removed Temperature of most soils within treatment zone exceeds 212°F; residual contamination (estimated at 750 gal) and an unsteamed area ("cold spot") remained
Accelerated Removal & Validation (ARV) Project	Continuous operation to remove residual contamination; additional electrical heating	Over 1000 gal of gasoline removed Improved understanding of electrical heating process developed
	Test of process modifications such as altering injection/extraction locations and air sparging	Sparging tests demonstrated value of modeling and use of tracer gases to better understand subsurface gas flow
	Installation of fiber-optic transmission system to allow for simultaneous electrical heating and process monitoring	Fiber-optics successfully installed

PERFORMANCE continued

Treatment Performance

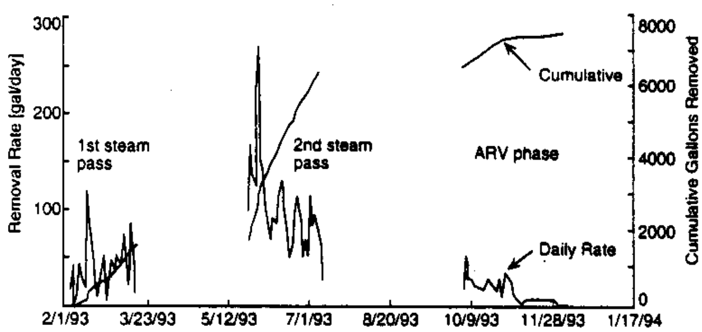
Reductions in Plume Concentrations

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



- No spreading observed; contamination drawn to extraction wells.
- Continued operation during the ARV phase 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 ground water during DUS. At one ground water monitoring well in the treatment zone, concentrations of C6 to C12 hydrocarbons had been below 30 ppm since 1987, but during DUS these concentrations rose to nearly 150 ppm before dropping to levels below those found before DUS.

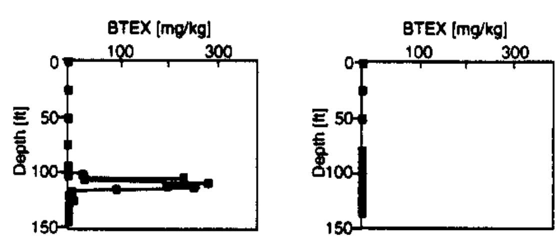
Contaminant Mass Removal



- During the DUS 1st steam pass, 74% of approximately 1700 gallons removed was collected by the vapor stream GAC unit. An additional 17% condensed in the vapor stream and the remaining 9% was dissolved in ground water.
- During the 2nd steam pass, 77% of the 4900 gallons removed was burned by the internal combustion engines, 21% was condensed, and 1% was dissolved.

Plume Containment

- The GSA was an ideal spot for demonstration of DUS because of its low ground water velocities, which kept contamination confined to a relatively small area. The plots at right illustrate that BTEX concentrations in soils at the periphery of the treatment zone declined during the demonstration. This phenomenon was determined to be indicative of the DUS process limiting further migration of contamination.



Before DUS at a typical well at the edge of the treatment zone

After 2nd steam pass of DUS at the same well

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Operational Performance

Aboveground Treatment Plan Performance

- The majority of contaminants removed from the subsurface was in the vapor phase.
- Surface treatment consisted of (1) a UV/peroxide unit to treat ground water and condensed vapors during both phases of the demonstration, (2) a GAC unit to treat vapors removed during phase I, and (3) an ICE unit to treat the vapors removed during phase II.
- The volume of contaminated vapors removed from the subsurface was initially underestimated. Thus the GAC unit selected for offgas treatment was undersized. It was replaced by an ICE unit during phase II. The ICE unit could also have been larger but nevertheless performed successfully. Dilution of air was necessary since the hydrocarbon concentrations were above the explosive limit.
- Destruction efficiencies of the UV peroxide liquid treatment unit during the last half of the first 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 UV peroxide unit after the first steam pass.

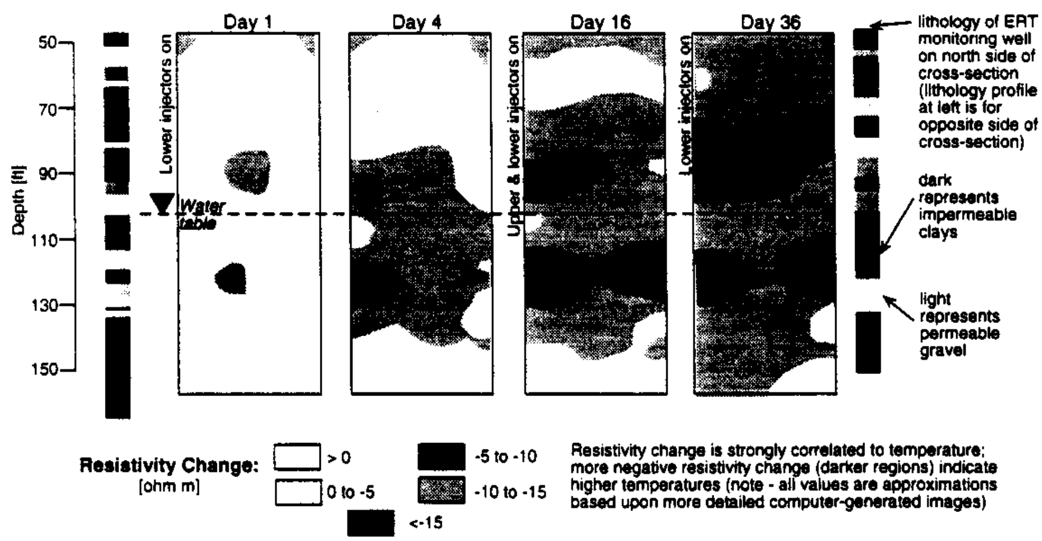
* *GAC = granular activated carbon; ICE = internal combustion engine*

In Situ Heating Performance

- A total of 100,000 yd^3 of soil were heated at least to 200°F (boiling point at applied vacuum).
- The growth of the hot zone was monitored by ERT and a network of temperature probes and tiltmeters.
- A variety of data was used to prepare multiple representations of heating effects:

Electrical Resistance Tomography Imaging

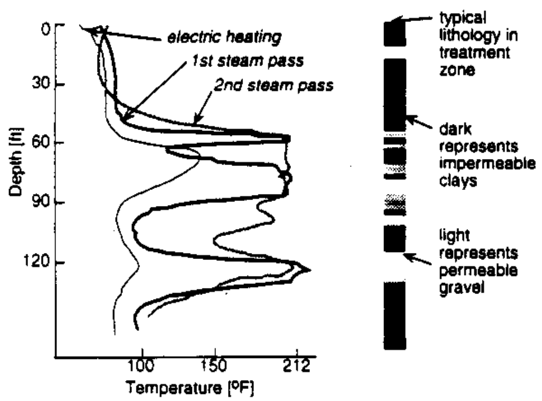
Below are images illustrating resistivity change over time between two monitoring wells approximately 50 ft apart in the central part of the treatment zone.



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

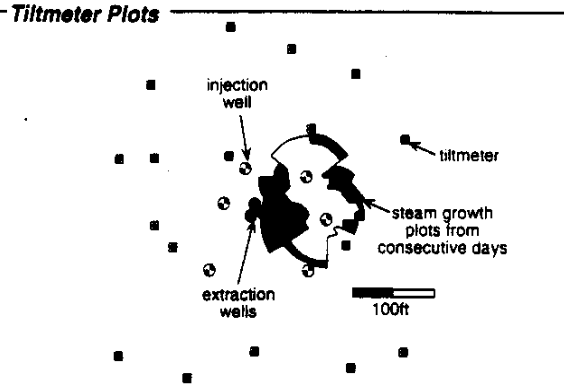
In Situ Heating Performance (continued)

Temperature Profiles Along Individual Wells



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

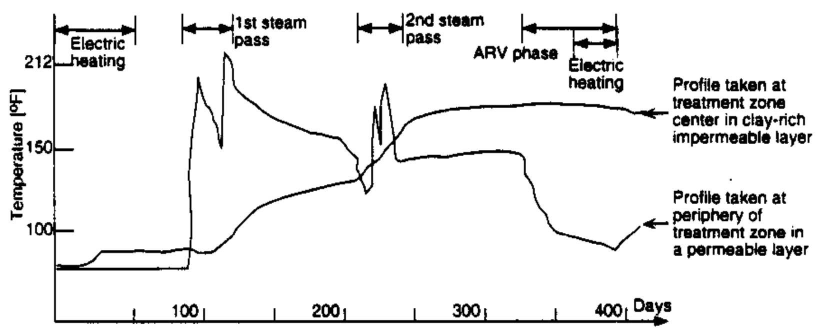
Tiltmeter Plots



- Tiltmeter data allow generation of vector-based representations of steam front growth on a given day from two injection wells.
- Data are useful for tracking any steam heading outside the treatment zone.

Time Versus Temperature Plot

- Impermeable layers maintained temperature increases.
- Permeable layers were cooled by ground water pumping especially at peripheral wells because of infiltration of ground water from outside the treatment zone.



TECHNOLOGY APPLICABILITY & ALTERNATIVES

Technology Applicability

• DUS has been successfully demonstrated to remediate fuel hydrocarbons. Laboratory tests have been successful for a variety of volatile and semivolatile compounds including diesel fuel and both light nonaqeuous phase liquids (LNAPLs) and dense nonaqueous phase liquids (DNAPLs).

• DUS is effective in the presence of free-phase and dissolved-phase contaminant liquids. It is extremely effective in the absence of liquids (vadose zone) but is usually not cost effective versus alternative technologies in these instances. It would be better applied at sites with contamination both above and below the water table.

• The minimum depth for application of DUS is approximately 5 feet. At greater depths, the steam injection pressure can be increased, producing higher efficiencies and extracting more work from each well.

• DUS becomes more cost-effective the larger the application site.

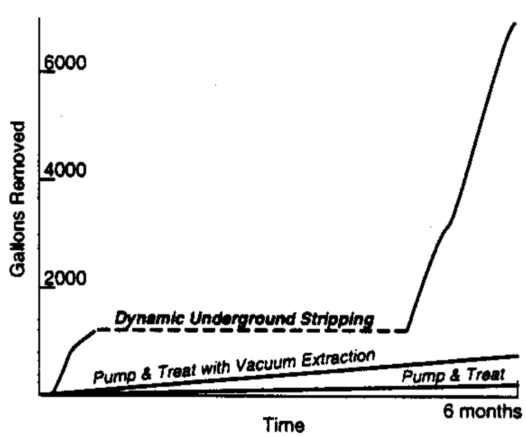
• A key competitive advantage of DUS is the speed of cleanup relative to conventional technologies. This order-of-magnitude superiority reduces overall cost, reduces risk to nearby populations and the environment, and frees land for beneficial reuse.

• DUS has a potential market at sites where conventional technologies have failed to produce acceptable results. The GSA site at LLNL is an example; soil vapor extraction had been previously applied and its performance predicted a cleanup time of greater than one hundred years.

• DUS is best suited to treat NAPLs and strongly sorbed contaminants in heterogenous or fractured formations. Unlike most competing technologies, it can directly address contamination in complexly interbedded sands and clays. Further information on the applicability of DUS is in Appendix D.

Competing Technologies

• DUS competes with conventional baseline technologies of pump-and-treat and pump-and-treat combined with soil vapor extraction. LLNL researchers estimated the effectiveness of these technologies at the GSA and compared the estimates with the results of the DUS demonstration, as shown below:



• A variety of in situ thermal treatment technologies have been either demonstrated or developed through DOE, DOD, and EPA programs. The aggregate experience with these programs enhances confidence in the fundamentals of DUS. Full-scale demonstrations of these related technologies include those shown in the table on page 9.

Competing Technologies (continued)

Technology	Developer	Basic Principle	Status/Comments
DOE			
1 Six-Phase Soil Heating	Pacific Northwest Laboratory (PNL)	Combines electrical heating with soil vapor extraction (six-phase distributes energy better)	Full-scale demonstration at DOE Savannah River as part of the VOC in Non-Arid Soils and Ground Water Integrated Demonstration in 1993; partnering/licensing discussions ongoing
2 Thermal Enhanced Vapor Extraction	Sandia National Laboratories (SNL)	Combines soil vapor extraction with powerline frequency (ohmic/electrical) and radio-frequency soil heating	Full-scale demonstration planned in 1994 at SNL chemical waste landfill in part of the Mixed Waste Landfill Integrated Demonstration; builds upon previous demonstrations at Volk Field, WI, Rocky Mountain Arsenal, CO, and Kelly AFB, TX (see EPA projects)
3 Radio Frequency Heating	KAI Technologies, Inc.	Radio frequency heating of soils combined with soil vapor extraction	Field demonstrated on VOC contaminated soils using a horizontal well at the DOE Savannah River Site as part of the VOC in Non-Arid Soils and Ground Water Integrated Demonstrationin 1993
EPA/DOD			
1 Contained Recovery of Oily Wastes (CROW ™)	Western Research Institute	Steam or hot water displacement guides contamination to extraction wells	EPA SITE field demonstration underway at the Pennsylvania Power & Light Brodhead Creek Superfund site, PA; pilot-scale demonstrations completed at a wood treatment site in Minnesota
2 HRUBOUT^R^ Process	Hrubetz Environmental Services, Inc.	Hot air injection combined with a surface exhaust collection system	EPA SITE field demonstration on JP-4 contaminated soils completed at Kelly AFB, TX, in 1993
3 In Situ Steam and Air Stripping	Novaterra, Inc. (formerly Toxic Treatments USA, Inc.)	Portable steam and air injection device (Detoxifier ™) used in soils	EPA SITE field demonstration conducted on VOC and SVOC contaminated soils at the Annex Terminal, San Pedro, CA, in 1989
4 In Situ Steam Enhanced Extraction Process	Praxis Environmental Technologies, Inc.	Steam injection/vacuum extraction (same as 5 and 7)	Field demonstrations underway at Hill AFB, UT, and McClellan AFB, CA
5 In Situ Steam Enhanced Extraction Process	Udell Technologies, Inc.	Steam injection/vacuum extraction (same as 4 and 7)	Field demonstrations underway at Naval Air Stations Lemoore and Alameda in California; Udell technologies no longer in existence
6 Radio Frequency Heating	Illinois Institute of Technology Research Institute/Halliburton NUS	Radio frequency heating of soils combined with soil vapor extraction	EPA SITE field demonstration completed at Kelly AFB, TX, in 1993; earlier demonstrations occurred at Rocky Mountain Arsenal, CO, and Volk Field, WI; demonstration cofunded by DOE
7 Steam Enhanced Recovery System	Hughes Environmental Systems, Inc.	Steam injection/vacuum extraction (same as 4 and 5)	EPA SITE field demonstration completed at the Rainbow Disposal Site in Huntington Beach, CA, from 1991 to 1993; Hughes no longer offering technology

Further information on these full-scale applications is available in references 16 (DOE programs) and 5 (DOD/EPA programs). In addition EPA's Vendor Information System for Innovative Treatment Technologies (VISITT) electronic database lists additional suppliers of equipment and services related to in situ thermally enhanced recovery of contaminants. These include:

- Bio-Electrics, Inc., Kansas City, MO
- EM&C Engineering Associates, Costa Mesa, CA
- SIVE Services, Dixon, CA
- Thermatrix, Inc., San Jose, CA

SECTION 5
COST

Cost Estimate for Future Applications

LLNL researchers have developed projected costs for applying DUS to other sites based upon demonstration results (actual costs for demonstration at LLNL are presented in Appendix E). An estimate was prepared for remediating a shallow (less than 50 ft in depth) chlorinated solvent spill. The proposed implementation approach involved successive application of DUS to 10,000 yd^3 cells by relocating equipment to various locations at the site. Key results of the cost estimate were as follows:

- Cleanup of the entire site (an estimated volume of 20,000 to 40,000 yd^3) would cost approximately \$28/yd^3.
- A pilot treatability study using full-scale equipment would cost \$37/yd^3. Economics improve as the area to be remediated increases; LLNL researchers believe that larger sites could be engineered to cost \$11-15/yd^3.
- The total cost for DUS implementation was estimated to be less than the first-year cost of constructing and operating a conventional groundwater pump-and-treat facility.

The following table details the equipment and labor costs associated with the treatability demonstration, full-scale operation for the first two 10,000 yd^3 treatment cells, and subsequent pairs of 10,000 yd^3 treatment cells.

	Treatability Demonstration			*Full-Scale Remediation*	
Equipment Costs	*Per Site Non-Reusable*	*Per Site Monthy Rental*	*Per Site Reusable*	*Incremental Cost for Next Two Treatment Cells*	*Average Cost for Additional Pairs of Treatment Cells*
Steam Equipment					
Boiler rental		$15,000		$15,000	$15,000
Boiler manifold			$2,000		
Steamhose (200 ft)			$2500		
2 ea wellhead fittings			$4,000		
6-in black pipe (wells)	$600			$300	$150
Compressor for pumps and boiler control		?	$15,000		
2 ea 6-in x 20 ft stainless steel (ss) well screens	$2,400		?	$1,200	$600
Surface coolings/confinement barriers.		$5,000			
Extraction Well Equipment					
8 ea downhole pumps		$50,000			
8 ea 6 in x 20 ft SS screens	$9,500		?	$3,200	$3,200
6-in black pipe	$1,200			$400	$400
Wellhead fittings and Instrumentation			$16,000		
ERT/Monitoring Equipment					
2-in fiberglass pipe (40 ft/well)	$6,300			$400	$400
2-in fittings for fiberglass pipe	$4,000			$267	$267
Electrical wire and electrodes	$3,990			$266	$266
Computer equipment			$15,000		
Thermocouple wire	$4,000				
Thermocouple monitoring system			$4,000		
Surface Treatment Equipment					
Air stripper (water treatment)			?		
Vacuum pump for extraction wells			$15,000		
Fiberglass extraction piping			$3,000		
4-in fiberglass pipe fittings			$5,000		
Cyclone cylinder			?		
Condenser			?		
Cooling tower			?		
Product/water separater			?		
25,000 gal treated water storage tanks		$3,000			
Storage tanks for separated product		$1,000			
Incidental Surface Equipment					
Forklift rental ($2000/month)		$2,000		$2,000	$200
Crane rental ($100/day)		$500		$500	$500
Barricades, fencing, etc.		$1,000		$1,000	$800
Miscellaneous small equipment		$5,000		$1,000	$500

Cost Estimate for Future Applications (continued)

	Treatability Demonstraton	*Full-Scale Remediation*	
Equipment Costs (continued)	*Total Costs*	*Incremental Cost for Next Two Treatment Cells*	*Average Cost for Additional Pairs of Treatment Cells*
Replacement costs for consumable equipment		$8,580	$17,160
Non-reusable equipment total (demonstation only)	$31,790		
Reusable equipment total (demonstration only)	$171,600		
Shipping (10% of equipment costs)	$20,089		
Total rental costs for 6 months onsite	$135,000		
Equipment contingency (15% of equipment costs)	$33,884		
Procurement cost-LLNL (estimated at 19.78%)	$77,609	$7,782	$6,945
Total equipment costs	***$469,972***	***$42,895***	***$46,268***
Labor Costs			
Engineering/Scientific Labor from LLNL/UC/Commercial Partners			
Planning/design/consultation (4 FTEs for 3 months)	$230,000	$23,000	$23,000
Characterization/Installation (6 FTEs for 2 months)	$230,000	$23,000	$23,000
Operation (2 FTEs for 6 mosnths)	$230,000	$23,000	$23,000
Evaluation/reporting (4 FTEs for 1 month)	$75,000	$7,500	
LLNL/UC Technical Labor			
ERT electrode preparation	$10,000	$2,000	
Pressure testing wellheads	$10,000	$2,000	
ERT installation (1 FTE for 1 month)	$10,000	$2,000	
Monitoring system operation	$40,000		
Commercial Partner Technical Labor			
Wellhead pump installation (4 FTEs for 1 month)	$40,000	$20,000	$15,000
Regulatory compliance monitoring (1/2 FTE, 6 months)	$57,500		
Health and safety monitoring (1FTE for 6 months)	$118,000		
Operation (1 FTE for 6 months)	$116,000	$57,500	$43,125
Boiler operator (1 FTE, 24 hr/day, 5 months @ $75/h)	$270,000		
Treated water disposal costs (based on LLNL rates)	?		
Analytical process chemistry	$50,000	$25,000	$12,500
Installation Expenses			
10 ea extraction/injection wells	$20,000	$10,000	$4,000
10 ea monitoring/ERT wells with chemist	$45,000	$15,000	$11,250
Treatment system hookup/lasting (4 FTEs for 1 month)	$40,000	$20,000	$20,000
Miscellaneous/Travel/Overhead			
Travel (40 person trips @ $1500/trip)	$60,000	$10,000	
Miscellaneous supplies and expenses	$20,000	$4,000	
Overhead/etc. nonwage nonprocurement at 64.89%	$51,912	$9,085	
Labor subtotal	$2,189,384	$295,978	$221,163
Labor contingency (25%)	$547,346	$73,995	$55,291
Total labor costs	***$2,737,000***	***$390,000***	***$278,000***

NOTE: All costs are preliminary approximations for work within the DOE environment (overhead, travel, and procurement charges may be less for other applications). Costs not specified in this estimate include costs for disposal of boiler blowdown (if any) and equipment for offgas treatment (see Appendix E for vapor phase equipment costs during demonstration).

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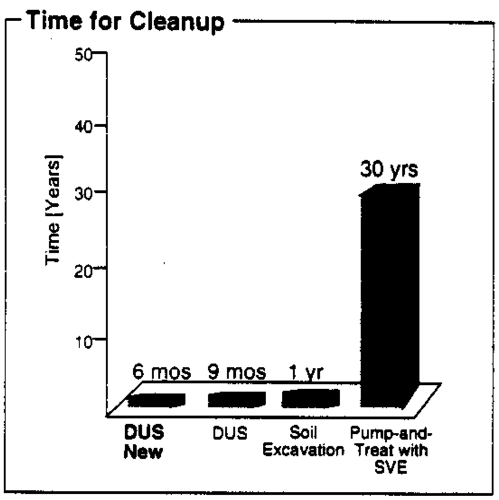
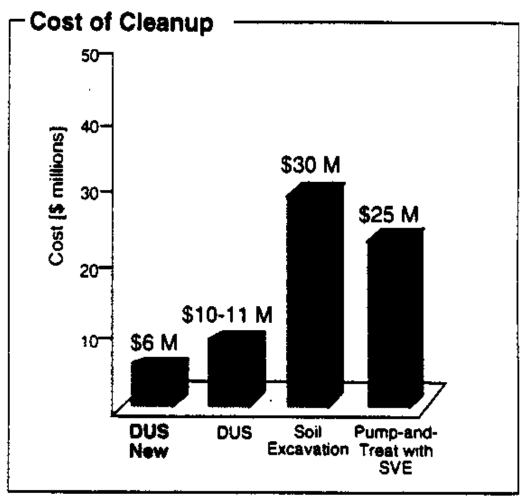
Cost Savings Versus Alternative Technologies

LLNL researchers compared DUS costs and remediation times with estimated costs and cleanup times of applying alternative technologies at the GSA:





Notes: DUS New = cost of commercial application of DUS at the GSA; assumes 40% reduction from demonstration costs due to use of lessons learned and elimination of research-oriented activities; detailed in Appendix E
DUS = cost of demonstration program for DUS
Soil Excavation includes relocation of underground utilities
SVE = soil vapor extraction

SECTION 6
REGULATORY/POLICY REQUIREMENTS & ISSUES

Regulatory Considerations

Permit requirements for future applications of DUS are expected to include:

- air permits for operation of steam generation equipment and discharge from surface treatment equipment (i.e., air stripper, GAC units, or internal combustion engine)
- liquid effluent discharge permits from aboveground treatment systems (discharge criteria are likely to be related to ground water cleanup levels)

For applications in some states, underground injection permits may be required for system application.

Permitting requirements and regulatory considerations arising from the demonstration at LLNL and relevant to future applications elsewhere are detailed below.

Water

- Ground water cleanup levels have been established for the major contaminants at the GSA:

COMPOUND	*FEDERAL MCL (ppb)*	*CALIFORNIA MCL (ppb)*	*NPDES LIMIT (ppb)*
Benzene	5	1	0.7
Toluene	1,000	-	5
Ethyl benzene	700	680	5
Xylenes (total)	10,000	1,750	5
Total VOCs	-	-	5

NOTE: MCL = Maximum Contaminant Level; NPDES = National Pollutant Discharge Elimination System

- Remediation will continue until in situ soil concentrations are deemed not to adversely impact groundwater. Those levels are determined through monitoring and modeling efforts as well by using the criteria listed above.

6

Air

- 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 instead of requiring LLNL to purchase an emission allotment of 2,200 lbs (1.6 lbs/hr) of NOx.

- The BAAQMD issued permits for the following:

DISCHARGE	*COMPOUND*	*SAMPLING FREQUENCY*	*DISCHARGE LIMIT*
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 lbs/day

- The LLNL DUS demonstration project incurred one violation from the BAAQMD because of higher than anticipated concentrations of VOCs in extracted vapor streams exceeding the capacity of surface treatment systems.

Regulatory Considerations (continued)

Other Considerations

- Waste forms generated by DUS include the air and liquid discharges (effluent limitations listed above) as well as spent activated carbon. The carbon can be either regenerated or landfilled and poses no unusual regulatory or permitting burden.
- As dictated in the LLNL sitewide Record of Decision and Remedial Implementation Plan, project milestones for site cleanup specify dates for designing and starting various treatment facilities to satisfy overall objectives of protecting human health and the environment in the shortest time possible. DUS represents the most rapid alternative identified during feasibility studies for achieving these objectives.
- No anticipated regulatory developments are expected to change the ability of DUS to comply with relevant requirements. Use of the technology at sites other than LLNL is not expected to be conducted under more stringent requirements. In some cases, permitting of airborne discharges may be easier.

Safety, Risks, Benefits, and Community Reaction

Worker Safety

- Operational Safety Procedures were developed to address DUS-specific safety issues not covered by existing LLNL procedures. Areas of concern included hazards posed by the steam generating equipment, electrical hazards from the large currents utilized, proper handling of pressurized steam injection wells, and hazards posed by implementation of ERT.
- Although large amounts of contaminants are more quickly extracted from the ground with DUS than with conventional technologies, safety measures for handling extracted liquid and vapor streams are similar to those for the conventional technologies. One exception, however, is that in some instances the contaminant concentrations of extracted vapors exceeded the upper explosive limits for the mixture.
- Level D personnel protection was used during installation and operation of DUS.

Community Safety

- Although DUS involves handling extracted vapor and liquid streams with higher concentrations of contaminants than conventional technologies, the dramatically increased speed of cleanup reduces long-term risks to nearby populations.
- DUS employs real-time monitoring controls, which greatly reduces the likelihood of accidents or offsite migration of contaminants.

Environmental Impacts

- DUS speeds cleanup relative to conventional technologies freeing land for beneficial reuse. Contaminants are either destroyed or are concentrated, transferred to other media, and disposed of offsite depending upon the configuration of surface treatment equipment.

Socioeconomic Impacts and Community Perception

- Unlike some other long-term remedial alternatives, DUS will require a staff only for a limited period of time. Selection of DUS can reduce the amount of time an environmental restoration work force is needed at some installations.
- DUS has received positive support from the general public at the LLNL Community Work Group Meetings. The basic principles of the technology have been readily understood by both technical and nontechnical audiences.

SECTION 7
LESSONS LEARNED

Design Issues

• The DUS demonstration made use of an existing groundwater treatment facility designed to treat gasoline and low levels of chlorinated solvents for the design life of 30 years. The facility utilized oil/water separation, UV/H_2O_2, 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. Sufficient steam must be injected to counter the cooling effects of inflow of ground water into the treatment zone.

• Aboveground treatment systems must be sized to handle anticipated peak extraction rates and the expected distribution of VOCs in extracted vapor and liquid streams. During demonstration, the majority of extracted VOCs were in the vapor stream. Initially, the vapor treatment system was undersized to handle this stream.

• Aboveground treatment systems must be located so as not to interfere with access to the subsurface treatment zone. This is necessary to avoid situations in which additional injection, extraction, heating, or monitoring wells need to be installed in a spot occupied by surface equipment.

Implementation Considerations

• Effective removal of contaminants from the subsurface requires repeated creation of the steam zone by successive phases of steam injection and continuous vacuum extraction. The pressure changes created by this oscillatory approach distill contaminants from pore spaces in both saturated and unsaturated sediments.

• Operational difficulties encountered included biofouling from microorganisms destroyed by steaming, scaling and deposits on sensors, and clogging from fines brought to the surface. Maintenance plans must address these situations in future applications by scheduling for routine cleaning of equipment.

• Extraction rates can vary greatly depending upon the amount of steam injected, the total vacuum applied, and cycle times.

• Permitting of air discharges from both aboveground treatment units and equipment used to supply steam energy is an issue requiring early attention.

• DUS is a labor intensive process requiring significant field expertise to implement.

• 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/Needs for Future Development

• Data on long-term routine operating experience with DUS are not yet available but are needed to better plan future applications.

• Treated soils can remain at elevated temperatures for months and even years after cleanup. This could impact site reuse plans. Soil venting can greatly accelerate the cooling process.

• Future development needs currently identified for DUS include demonstrating the process for removing chlorinated solvents including DNAPLs, mixed wastes, and sites with fractured subsurface media, automating monitoring techniques, and further refining system design and operating techniques.

Technology Limitations/Needs for Future Development (continued)

- DUS is effective in th·· presence of free-phase and dissolved-phase contaminant liquids. It is extremely effective in the absence of liquio. (vadose zone), but is usually not cost effective versus alternative technologies in these instances.
- DUS is not applicable at depths less than five feet. At greater depths, the steam injection pressure can be increased which produces higher efficiences and extracts more work from each well. (More information on technology applicability is located in Section 4 and Appendix D.)

Technology Selection Considerations

- DUS was effective at quickly removing concentrated free-product contaminants, including materials sorbed to saturated sediments, without mobilizing contaminants outside the treatment zone.
- Steam injection is effective at heating permeable zones, and repeated steam passes, when combined with electric heating, can heat adjacent impermeable areas.
- Electrical heating is effective on clay zones; however, power requirements increase when extracting hot fluids from the treatment zone.
- Future applications of DUS will be designed to focus on mobile/temporary aboveground treatment and steam injection systems that can treat plumes on a cell by cell basis.
- DUS is compatible with long-term efforts to bioremediate residual contamination following steam injection. After application of DUS at LLNL, viable microbial populations continued to degrade gasoline at the site at temperatures above 158°F. Although microbial populations present after application of DUS were different from those present before treatment; the treatment zone was not sterilized.
- 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-and-treat systems or excavation of contaminated areas. Further reductions in DUS cost are anticipated as experience is gained that will optimize subsequent applications.

APPENDIX A

DEMONSTRATION SITE CHARACTERISTICS

A

Site History/Background

- 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 source areas of contamination.

- Between 1952 and 1979, based upon inventory records, as much as 17,000 gallons of leaded gasoline was released from underground storage tanks (USTs) beneath a gasoline filling station in an area now designated the GSA. The GSA occupies an approximately 1.25-acre level area at the southern edge of LLNL and is the site of the DUS application.

- 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 Laboratories. The climate is semiarid with annual precipitation of around 14 inches/year.

- 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-and-treat system using UV/H_2O_2 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 (mixture of m, o, and p-xylenes), and
- 1,2-dichloroethane.

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

Property at STP*	Units	B	T	E	X
Empirical Formula	-	C_6H_6	$C_6H_5C_2H_5$	$C_6H_5CH_3$	$C_6H_4(CH_3)_{2m}$
Density	g/cm^3	0.87	0.87	0.87	~0.87
Vapor Pressure	mmHg	75	29	7	10
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*

Nature and Extent of Contamination

- The volume of FHC as gasoline before any remediation efforts was estimated based on soil and ground water 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 ground water. Mass volume estimates made immediately before application of DUS identified approximately 6,500 gal of gasoline within the treatment zone.

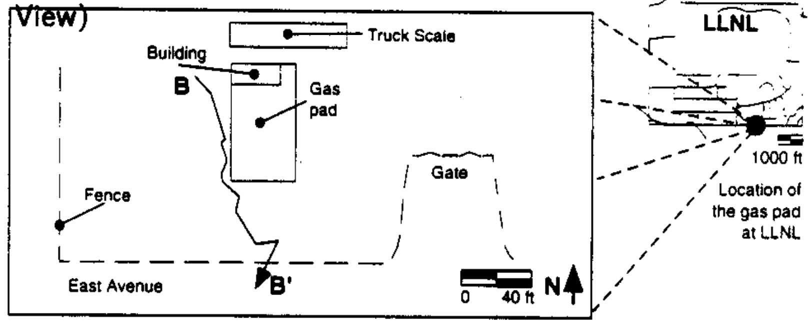
- High concentrations of gasoline in saturated sediments indicated the likelihood of free phase gasoline. The free phase was trapped within low-permeability sediments below a ground water table that has risen 10 to 30 ft since the time of the main portion of the release (1979) because of the cessation of agricultural pumping.

- 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 MCL is now 0.5 ppb] are found within 300 ft. FHCs were not found below a depth of 150 ft.

Contaminant Locations and Hydrogeologic Profiles

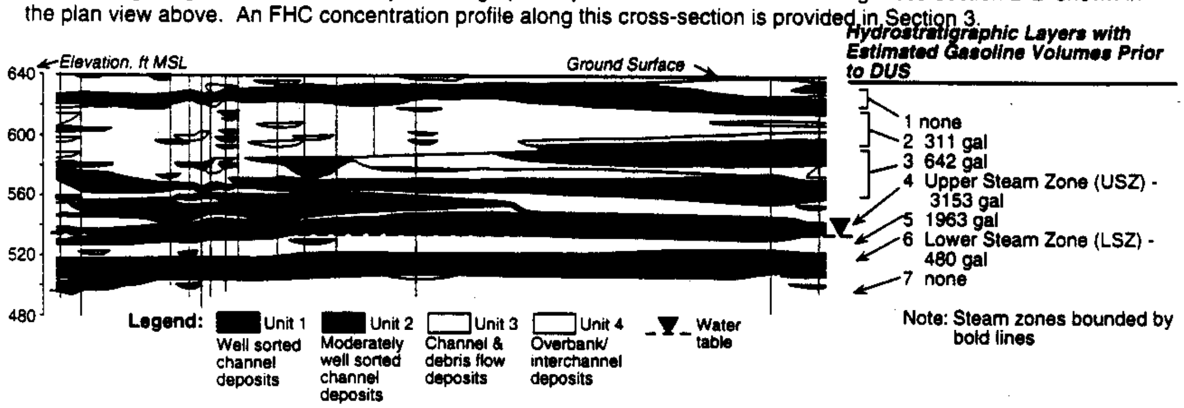
The GSA has been extensively studied since 1984. Over 70 subsurface borings and monitoring wells revealing the area's geologic, physical, and chemical characteristics have been completed. Short- and long-term drawdown, injection, and extraction tests were conducted to assess hydraulic properties. Pneumatic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

Site Layout (Plan View)



Cross-Sectional View

Four hydrogeologic units and seven hydrostratigraphic layers have been identified along cross-section B-B' shown in the plan view above. An FHC concentration profile along this cross-section is provided in Section 3.



Hydrogeologic Unit Characterization

#	Hydraulic Conductivity Range [gpd/ft2]	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

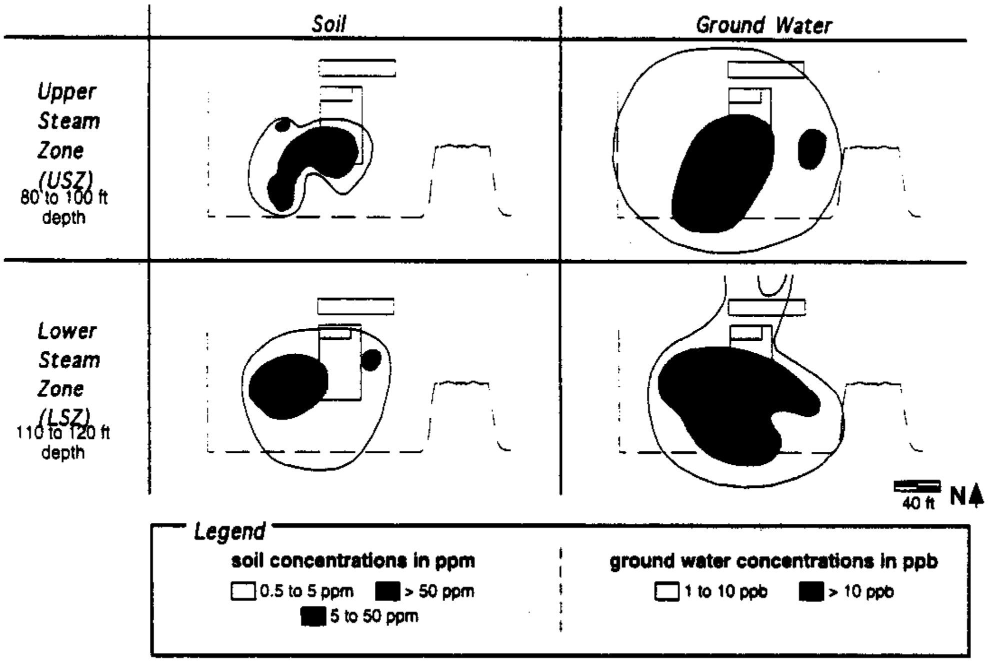
1 5-15-ft-thick interval of coarse-grained high-permeability sandy gravels and gravelly sands
2 30-ft-thick, laterally continuous interval of clayey silts to silty clays
3 very heterogeneous zone of elongated lenses of channel sands and gravels interbedded with intervals of silty clays and clayey silts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

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

- The site is underlain by several hundred feet of complexly interbedded alluvial and lacustrine sediments.
- Depth to ground water in the GSA is approximately 100 to 120 ft.
- Regional ground water 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 restricts downward migration of contaminants.

Contaminant Locations and Hydrogeologic Profiles (continued)

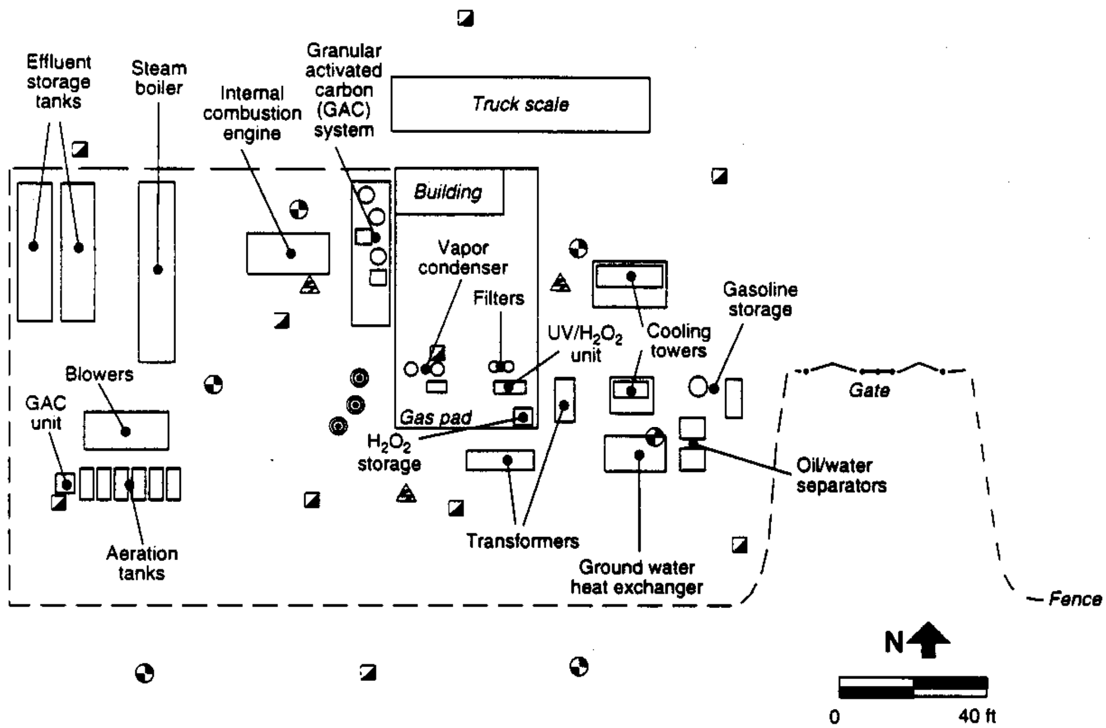
Areal Extent of Benzene Contamination (before application of DUS)



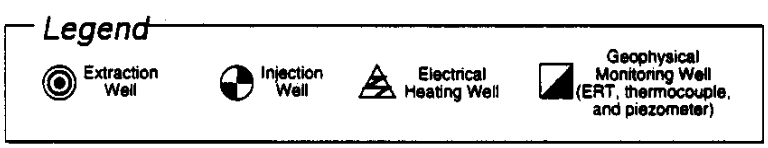
APPENDIX B
TECHNOLOGY DESCRIPTION DETAIL

B

System Configuration



NOTE: 21 tiltmeters (not shown) were also utilized. Additional subsurface borings and ground water monitoring wells are present from initial and ongoing characterization activities.



Operational Requirements

- Typical staffing requirements for future applications of DUS, at sites of size similar to that of LLNL, are anticipated to include:

  one project engineer,
  one or two geophysicists to handle ERT and temperature monitoring and data interpretation,
  four certified boiler operators (one operator needed 24 hours/day),
  four effluent treatment technicians/sampling technicians (one technician needed 24 hours/day),
  one chemical data analyst, and
  one electrician available for periodic maintenance.

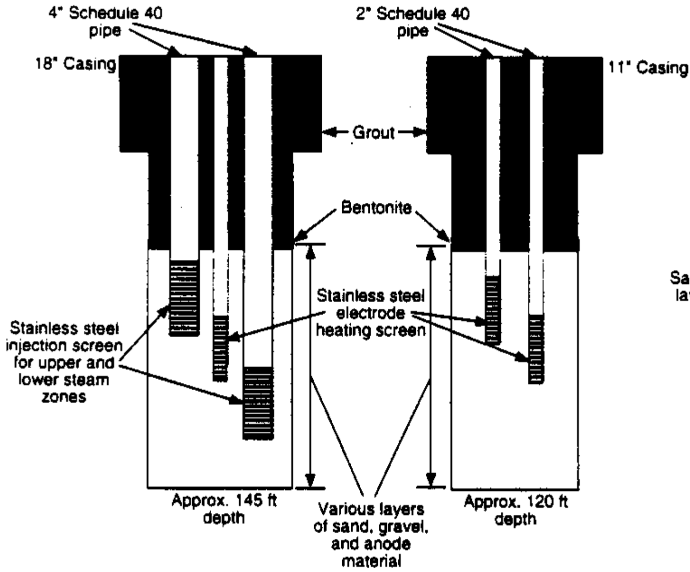
- DUS consumes significant quantities of electricity, water, and, for some applications, natural gas. These requirements can be handled via hookups to existing facilities or can be stored or generated onsite for more remote applications.

B

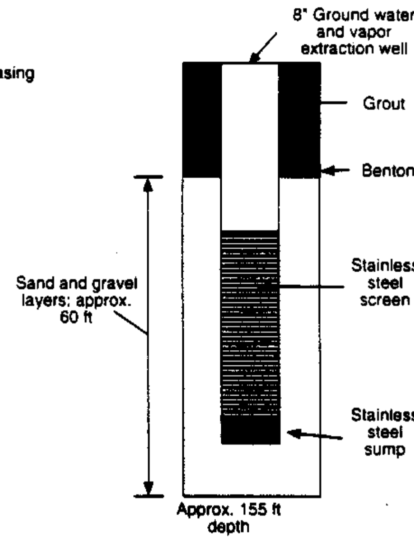
Well Close-Ups

Thermal Enhancement

Steam Injection/ Electrical Heating | *Electrical Heating*

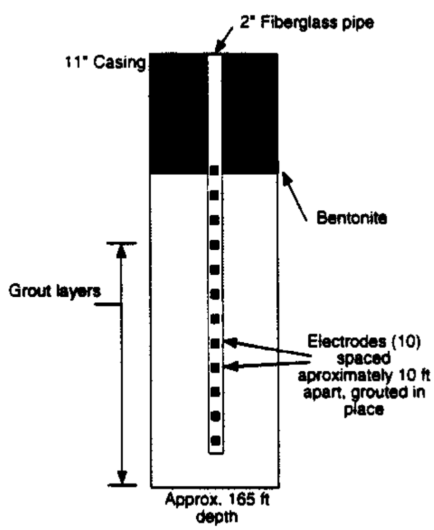


Extraction

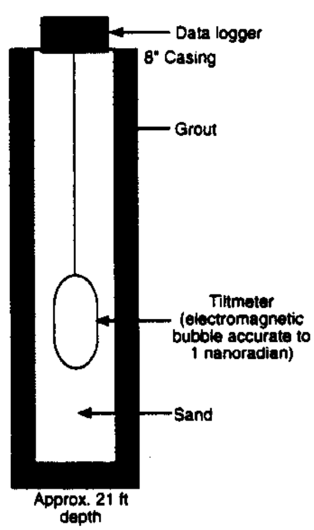


Monitoring

Geophysical Monitoring



Tiltmeter

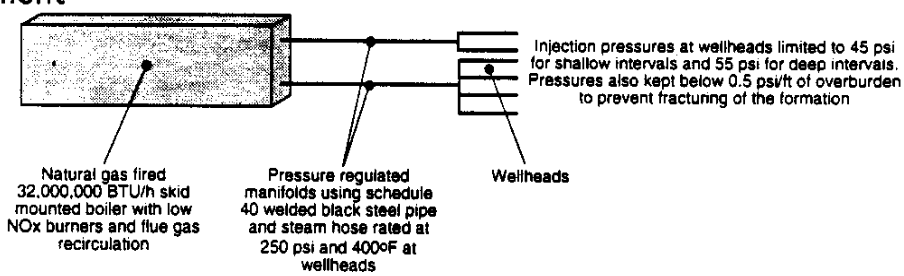


Thermocouples (not shown) are present in the monitoring, steam injection, and electric heating wells

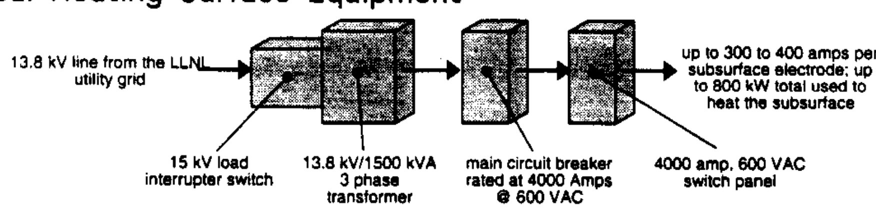
All drawings not to scale

Surface System Schematics

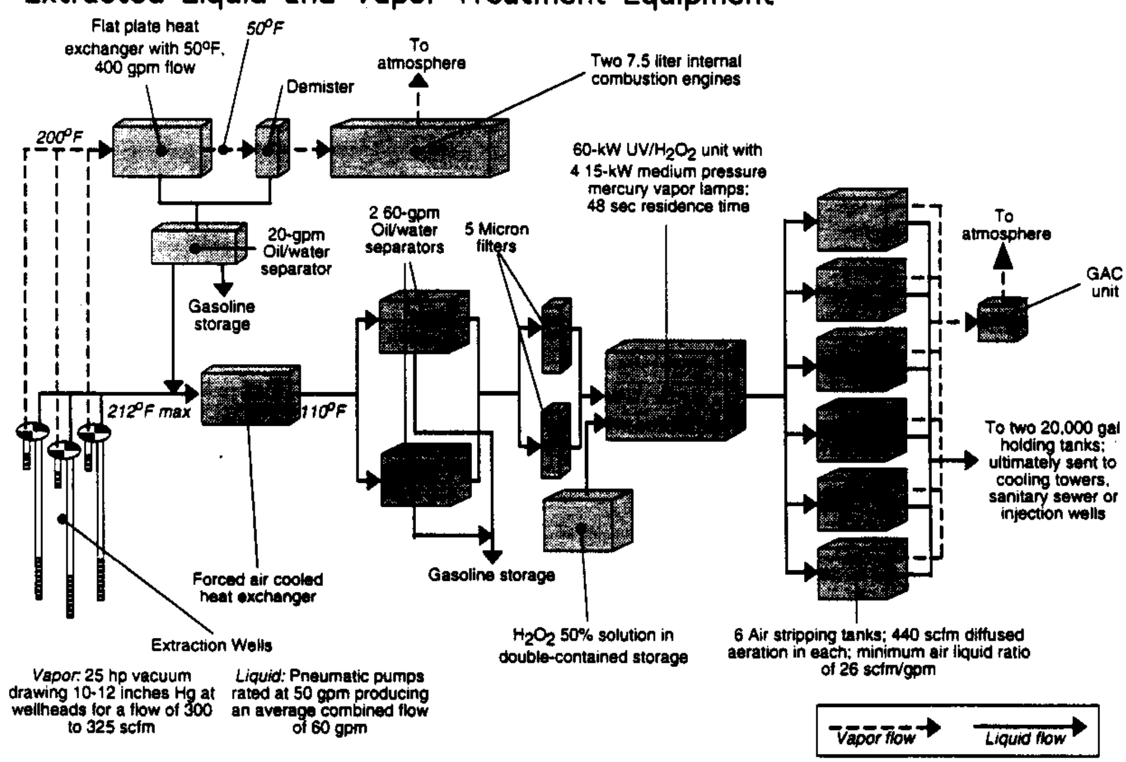
Steam Injection Surface Equipment



Electrical Heating Surface Equipment

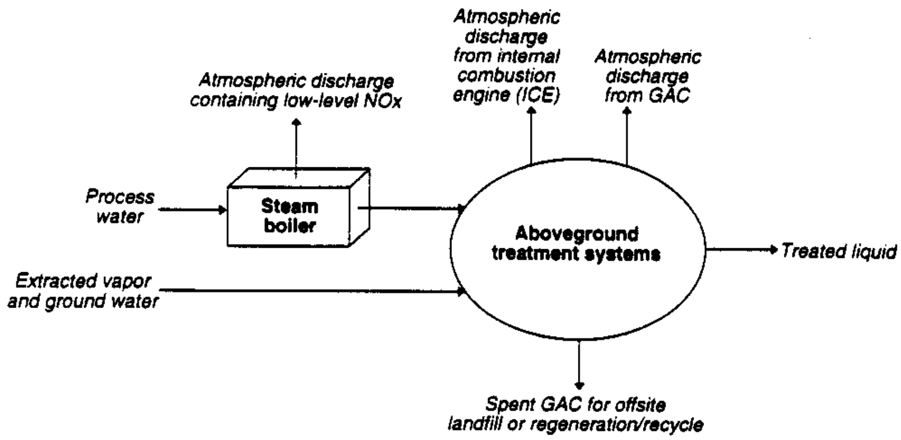


Extracted Liquid and Vapor Treatment Equipment



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

Waste Generation/Process Influents and Effluents



APPENDIX C

PERFORMANCE DETAIL

Operational Performance

Maintainability and Reliability

- A significant percentage of the field activities occurred in a shakedown mode where various processes were debugged and optimized. In addition, distinct demonstration phases used different equipment configurations; therefore, long-term routine maintenance and reliability data are 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.

Operational Simplicity

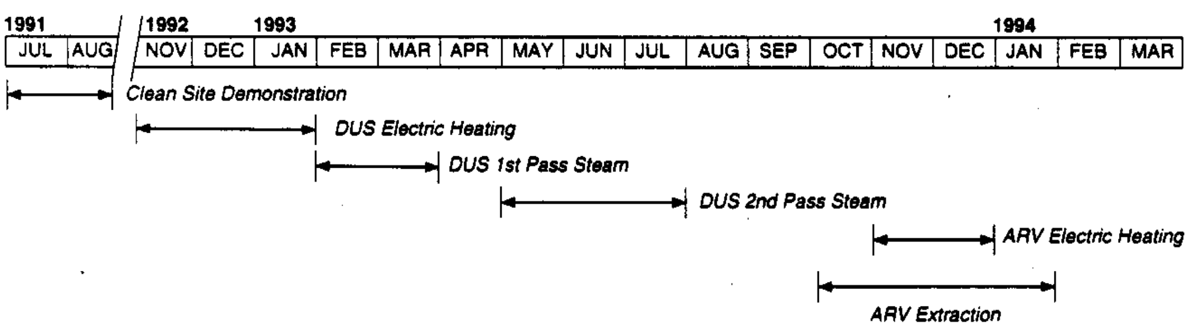
- DUS requires real-time in-the-field expertise to interpret monitoring data and appropriately adjust injection and extraction flow rates. Staffing requirements are presented on page B1.

- Routine implementation practices have not yet been developed for all aspects of DUS. Future development efforts will include consideration of automating certain process monitoring activities.

C

Schedule

Major Phases of the Demonstration Program



Performance Validation

- The EPA Superfund Innovative Technology Evaluation (SITE) program installed two soil borings for analysis of post-treatment conditions during the DUS demonstration. The results corroborated the data on pre- and post-treatment soil conditions developed by LLNL researchers.

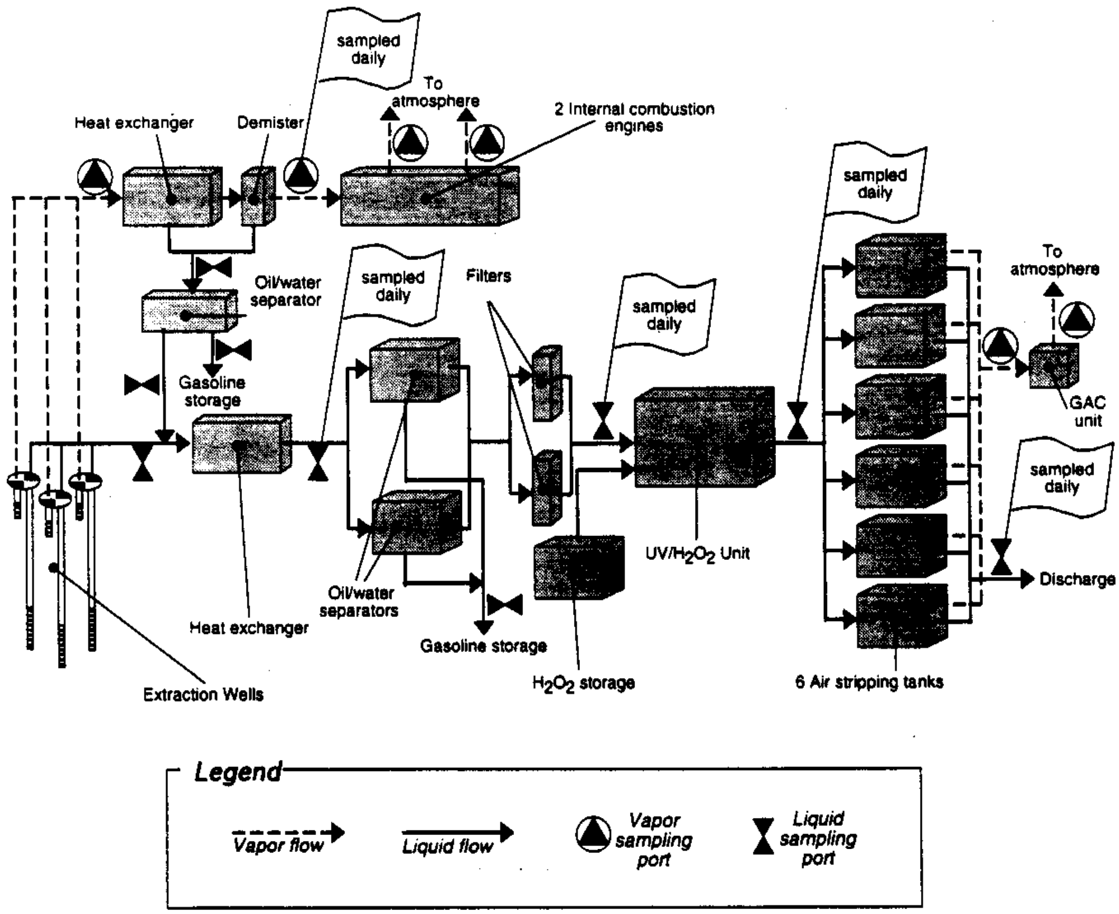
- Although DUS has not been applied at any other sites, the principle of in situ thermal treatment has been demonstrated and validated through other DOE, DOD and EPA sponsored projects which are discussed in Section 4.

Sampling, Analytical, and QA/QC Issues

Sampling and Analysis Objectives

- Obtain concentrations for calculating daily contaminant removal from vapor and liquid streams.
- Characterize the contamination removed.
- Measure destruction efficiencies of the surface treatment systems for regulatory compliance.
- Compare results with on-line monitoring instrumentation.

Sampling Locations/Procedures



- Aqueous samples were collected in 40-ml volatile organic analysis (VOA) vials after three line volumes passed through each port unsampled.
- Free product samples were collected from the megators and placed into 40-ml VOA vials.
- All liquid phase samples were cooled to 4°C until analysis.
- Evacuated 500-ml stainless steel spheres of Tedlar bags were plumbed in-line with sampling ports for collection of vapor samples.

Sampling, Analytical, and QA/QC Issues (continued)

Analytical Methods

- Aqueous samples were analyzed onsite according to EPA methods 601/602 and 8015 [total petroleum hydrocarbons (TPH)].
- Sudan IV was used as a petroleum indicator to visually determine the presence of gasoline in aqueous samples. These experiments were conducted on surplus sample volumes subsequent to gas chromatography (GC) analysis
- GC/mass spectroscopy (GC/MS) analyses of recovered free product were performed offsite to determine composition changes with time.
- Vapor samples were analyzed onsite in accordance with EPA method T014.
- Results of onsite analyses were available within 24 hours of sampling to implement necessary changes in extraction rates and treatment facility operations.

Equipment

- TPH analyses were performed using an autosampler and purge-and-trap concentrator coupled to a Hewlett Packard (HP) 5890 Series II GC equipped with a flame ionization detector.
- EPA 601/602 and T014 analyses were performed using an HP 5890 Series II GC outfitted with an autosampler, photoionization detector, electrolytic conductivity detector, purge and tap concentrator, and low dead volume injector port.
- An HP Chemstation, an automated GC systems control and data acquisition workstation was used to gather, process, and archive GC data.

QA/QC Issues

Liquid Phase

- Quality control limits were set for surrogate recoveries, field spike recoveries, and precision and accuracy.
- The Internal Standard method was used for data calculation and reporting.
- Limits of detection were set using American Chemical Society recommendations.
- Three-point calculation checks were run daily.
- Instrument calibration was performed at least quarterly or as needed (determined by daily checks).
- Method blanks were run every 3 to 4 unknown samples.

Vapor Phase

- Quality control limits were set for precision and limits of detection. Vapor samples were not spiked; therefore, accuracy was not calculated.
- Stainless steel spheres were cleaned, pressure-checked, and analyzed for EPA 601/602 compounds before use.
- Two-point calibration checks were run daily.
- Instrument calibration was performed quarterly or as needed (determined by daily checks).

Intellectual Property Rights (continued)

Existing/Pending Patents

- Twelve patent applications have been filed for different processes and designs.
- To date, two patents have been issued:

  - Patent 5,018,576 "Process for In Situ Decontamination of Subsurface Soil and Groundwater," K.S. Udell, N. Sitar, J.R. Hunt, and L.D. Stewart assignors to The Regents of the University of California and

  - Patent 5,325,918, "Optimal Joule Heating of the Subsurface," J. Berryman and W.D Daily, assignors to the United States of America as represented by the DOE.

Licensing Information

- DUS technology is commercially available through UC Berkeley/LLNL, who are currently negotiating nonexclusive licenses with several government and private parties (see Contacts section below for further information).

- LLNL has received hundreds of inquiries from site owners concerning the potential applicability of DUS to their sites. This level of interest combined with the attention focused upon other in situ thermal treatment technologies attests to the broad market for DUS. Specific commercialization activities already initiated by LLNL include:
  - performing a feasibility and cost analysis to remediate a chlorinated solvent-contaminated site at the DOE Pinellas facility,
  - the design of a system to remediate shallow underground hydrocarbons at a U.S. Navy facility in California,
  - the conceptual design to remediate a large shallow fuel-contaminated U.S. Army Corps of Engineer managed site in Alaska, and
  - other private sector projects.

These efforts are part of LLNL efforts to transfer DUS know-how to new licensees of the technology.

APPENDIX E
COST DETAIL

Demonstration Costs

- DUS costs were obtained from a variety of sources at LLNL. The costs of demonstration were 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 second steam pass (which is most representative of operating costs for future applications).

- 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. **Resultant total savings would be approximately $4,000,000 or a 40% reduction versus demonstration costs.**

Overall Program Costs

Construction through 1st Steam Pass	$7.240M
2nd Steam Pass	2.200M
ARV Phase	1.000M
Total	$10.440M

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

Identified Cost Components

The following program elements were taken from planning documents.

Project Management

Management	$225,000
Analysis and report writing	335,000
Safety plan writing and review	70,000
Permitting	65,000
Equipment design	200,000
	$895,000

Process Monitoring

Design	$50,000
ERT and thermal	270,000
Tiltmeter	70,000
Hydraulic testing	55,000
	$445,000

Characterization and 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
Sampling during experiment	25,000
	$455,000

E

Demonstration Costs (continued)

Identified Cost Components (continued)

The following capital cost items include overlaps with the program cost elements shown previously:

Subsurface Wells

Note: Costs do not include design and installation labor

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

Electrical Heating Surface Equipment

Note: Costs do 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	63,000
	$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	79,000
	$395,000

Extracted Ground Water and Vapor Surface Treatment Systems - Treatment Facility F

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

Piping and power	$1,512,000
Process equipment	400,000
Vapor modifications for DUS	160,000
Discharge pipeline	87,000
Activation	80,000
Other direct costs	291,000
	$2,530,000

Operating Costs

Utility Consumption

Boiler natural gas (3.8E10 ft^3 @ $0.39/100,000 ft^3)	$149,000	$1.50/$yd^3$ treated
Boiler water (3.6E6 gal @ $1.25/100 ft^3)	$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 and 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 and Engineers	*Technicians*	*External Analysis*	*Materials*	*TOTALS*
Phase 1: Planning	44	-	-	-	44
Phase 2: Maintenance and 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 and 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 and Technology Transfer	400	-	-	-	400
Phase 6: Dismantling (conservative estimate)					181
Contingencies					228
				Grand Total	***$1,871***

Cost Considerations for Future Applications

Cost Savings for Commercial Applications

• 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 or a 40% reduction versus demonstration costs

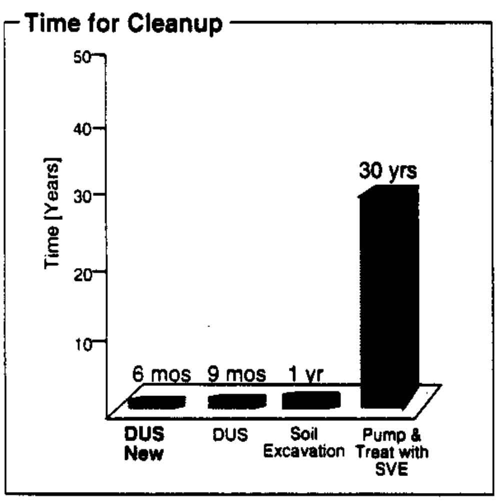
Cost Estimates Completed for Additional Applications

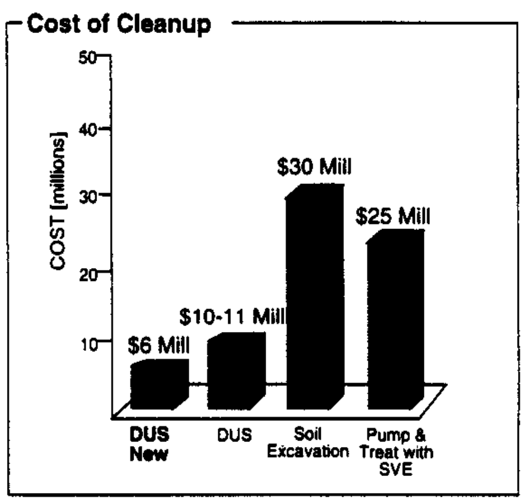
• LLNL researchers prepared a cost estimate for applying DUS to a shallow chlorinated solvent spill at the DOE Pinellas facility. Key results of that cost estimate were:

- average cleanup costs of approximately $65/yd3 which was based upon a fixed cost of approximately $1.5 M and a variable cost of $20/yd^3 indicated the increased cost-effectiveness of the technology at larger sites
- a total cost for DUS implementation was estimated as less that the first year cost of constructing and operating a conventional groundwater pump and treat facility

Cost Savings Versus Alternative Technologies

DUS costs and remediation times were compared, by LLNL researchers, to estimated costs and cleanup times of applying alternative technologies at the GSA:





Notes: DUS New = cost of commercial application of DUS at the GSA as outlined at top of page
DUS = cost of demonstration program for DUS
Soil Excavation includes relocation of underground utilities
SVE = soil vapor extraction

E

APPENDIX F
REFERENCES

Major References for Each Section

Demonstration Site Characteristics:	Source (from list below) 1 and 17
Technology Description:	Source 1, 4, 6, 7, 8, 9, 10 and 11
Performance:	Source 1, 2, 4, 6, 7, 8, 9, 10, 11, 13, 14,15 and 18
Cost:	Source 1, 3 and 18
Regulatory/Policy Issues:	Source 1, 6, 8, 9, 14 and 15
Lessons Learned:	Source 1, 2, 6, 7, 8, 9, 10, 11, 13, 14, 15, and 18
Commercialization:	Source 1, 5, 8, 12 and 16

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