Case Study Abstract

In Situ Air Stripping of Contaminated Groundwater at U.S. Department of Energy, Savannah River Site Aiken, South Carolina

Site Name: U.S. Department of Energy (DOE), Savannah River Site M Area, Process Sewer/Integrated Demonstration Site **Location:** Aiken, South Carolina	**Contaminants:** Chlorinated Aliphatics - Trichloroethene (TCE), Tetrachloroethene (PCE), 1,1,1-Trichloroethane (TCA) - Concentrations of volatile organic compounds (VOCs) in groundwater reported as high as 1800 µg/L - Groundwater TCE concentrations over 48 ppm - Groundwater contains 260,000-450,000 pounds of dissolved organic solvents in concentrations greater than 0.01 ppm, estimated to be 75% TCE - Soil TCE concentrations over 10,000 µg/L (1991) - Dense nonaqueous phase liquids (DNAPLs) are present in groundwater	**Period of Operation:** July 1990 to September 1993 **Cleanup Type:** Field Demonstration
Technical Information: Brian Looney, Principal Investigator, Westinghouse Savannah River Company (WSRC), (803) 725-3692 Carol A. Eddy Dilek, WSRC (803) 725-2418 Kurt Gerdes, DOE EM-50, (301) 903-7289 Dawn Kaback, Colorado Center for Environmental Management, (303) 297-0180, ext. 111 **SIC Code:** 9711 (National Security) 3355 (Aluminum forming) 3471 (Metal finishing)	**Technology:** In Situ Air Stripping - 7 horizontal wells installed; only 2 wells used in field demonstration - Demonstration wells: 1 installed in saturated zone; 1 installed in vadose zone; targeted contaminated sands - Air injected through lower horizontal well, below the water table - Demonstration focused on supplementing pump and treat efforts - Demonstration did not include offgas treatment	**Cleanup Authority:** RCRA Corrective Action and State: South Carolina Dept. of Health and Environmental Control, Air Quality Control, and Underground Injection Control **Licensing Information:** Caroline Teelon Tech Transfer Office, WSRC P.O. Box 616, Building 77341A Aiken, SC 29803 (803) 725-5540
Waste Source: Surface Impoundment	**Type/Quantity of Media Treated:** Groundwater and Soil - Area of VOC-contaminated groundwater has an approximate thickness of 150 feet and covers about 1,200 acres - Aquifer units characterized to 180 feet below ground surface (9 separate units), showing complex hydrogeology and discontinuous sand and clay layers	
Purpose/Significance of Application: Field demonstration of in situ air stripping using horizontal wells to supplement groundwater pump and treat technology.		

Case Study Abstract

In Situ Air Stripping of Contaminated Groundwater at U.S. Department of Energy, Savannah River Site Aiken, South Carolina (Continued)

Regulatory Requirements/Cleanup Goals:
- RCRA permit for M Area includes the following Groundwater Protection Standards: TCE 5 ppb, PCE 5 ppb, and TCA 200 ppb
- Demonstrations permitted by the South Carolina Department of Health and Environmental Control (SCDHEC) Air Quality Control (AQC) and Underground Injection Control (UIC)

Results:
- Substantial changes in groundwater VOC concentrations measured during demonstration
- Increased microbial numbers and metabolic activity exhibited during air injection period
- 139 day demonstration (July-December 1990) removed nearly 16,000 pounds of VOCs
- Vacuum extraction removed an estimated 109 lbs VOC/day while air injection resulted in an additional 20 lbs/day VOC removal

Cost Factors:
- Costs for conducting field demonstration not provided

Cost study for in situ air stripping provided the following projected costs:
- Total equipment costs - $253,525 (including design and engineering, well installation, air injection and extraction system, piping, and electrical)
- Site costs - $5,000 (setup and level area)
- Total Annual Labor Costs - $62,620 (including mobilization/demobilization, monitoring, and maintenance)
- Total Annual Consumable Costs $157,761 (including carbon recharge, fuel, and chemical additives)

Description:
At the U.S. Department of Energy Savannah River Site, aluminum forming and metal finishing operations have been performed within the "M" area. An estimated 3.5 million pounds of solvents were discharged from these operations between 1958 and 1985, with over 2 million pounds sent to an unlined settling basin. Groundwater contamination beneath the settling basin was discovered in 1981. A pump and treat program has been ongoing since 1985 for removal of VOCs from the groundwater.

A field demonstration using in situ air stripping with horizontal wells in the M Area was conducted from July 1990 to September 1993. The demonstration was part of a program at Savannah River to investigate the use of several technologies to enhance the pump and treat system. In the air stripping demonstration, air was injected into a lower horizontal well in the saturated zone and extracted through the horizontal well in the vadose zone. The demonstration did not include treatment of offgases. The in situ air stripping process increased VOC removal over conventional vacuum extraction from 109 pounds per day to 129 pounds per day. Nearly 16,000 pounds of VOCs were removed during the 139 day demonstration period.

A cost analysis performed as part of this demonstration showed that in situ air stripping would reduce costs by 40% over a conventional pump and treat with soil vapor extraction system. Installation costs for horizontal wells is greater than for vertical wells. At depths greater than 40 to 50 ft, horizontal well installation costs are approximately $200/ft; at less than 40 to 50 ft, costs are as low as $50/ft. Several implementation concerns were identified for installing horizontal wells at Savannah River.

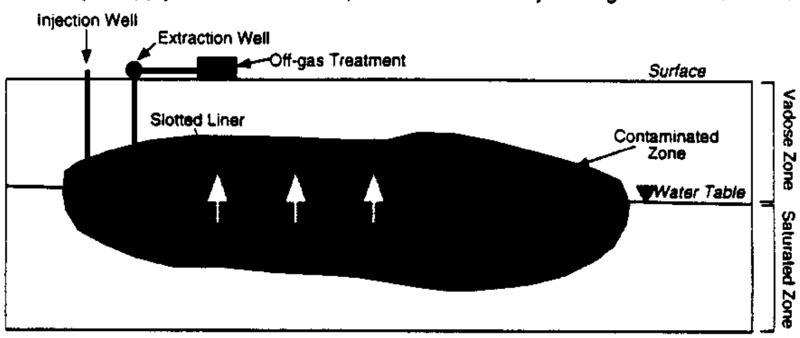
SECTION 1
SUMMARY

Technology Description

In Situ Air Stripping (ISAS) technology was developed to remediate soils and ground water contaminated with volatile organic compounds (VOCs) both above and below the water table. ISAS employs horizontal wells to inject (sparge) air into the ground water and vacuum extract VOCs from vadose zone soils. The innovation is creation of a system that combines two somewhat innovative technologies, air sparging and horizontal wells, with a baseline technology, soil vapor extraction, to produce a more efficient in situ remediation system.

- The horizontal wells provide a more effective access to the subsurface contamination
- The air sparging process eliminates the need for surface ground water treatment systems and treats the subsurface in situ, directly attacking the problem of subsurface contaminant retention.

The types of sites most likely to apply ISAS will contain permeable, relatively homogeneous sediments contaminated with VOCs.



(figure modified from Reference 6)

Technology Status

A full-scale demonstration was conducted as part of the Savannah River Integrated Demonstration VOCs in Nonarid Soils and Ground Water at:
U.S. Department of Energy
Savannah River Site
M Area Process Sewer/Integrated Demonstration Site
Aiken, South Carolina
July to December 1990

The demonstration site was located at one of the source areas within the one-square mile VOC ground water plume. Prior to application of ISAS, 1,1,2-trichloroethylene (TCE) and tetrachloroethylene (PCE) concentrations in ground water ranged from 500 to 1800 ug/L and 85 to 184 ug/L, respectively. TCE and PCE concentrations in sediments ranged from 1.26 to 16.32 mg/kg and 0.03 to 8.75 mg/kg, respectively. The site is underlain by a thick section of relatively permeable sands with thin lenses of clayey sediments. Appendix A describes the site in detail.

Key results included:

- Removal of nearly 16,000 lbs VOCs over a 139-day period. The daily removal rate from the upper horizontal well was equal to the eleven-well pump and treat system operating to contain the central portion of the plume that surrounds the demonstration site.
- Final TCE and PCE concentrations in ground water ranging from 10 to 1031 ug/L and 3 to 124 ug/L respectively. Final concentrations in sediments ranged from 0.67 to 6.29 mg/kg and 0.44 to 1.05 mg/kg, respectively.
- Completion of a cost-benefit analysis performed by Los Alamos National Laboratory showed that ISAS could reduce costs 40% over a baseline pump-and-treat/soil vapor extraction system.

The ISAS process is patented by the Department of Energy and has been licensed to eight commercial vendors with eleven additional license applications under review. Licenses are available through the Westinghouse Savannah River Company (WSRC). ISAS has been implemented at commercial sites in Minnesota, Missouri, North Carolina and New York. Many other sites plan to implement the technology in the next year.

Contacts

Technical

Brian Looney, Principal Investigator, Westinghouse Savannah River Company (WSRC), (803) 725-3692

Carol A. Eddy Dilek, Characterization, WSRC, (803) 725-2418

Dawn Kaback, Horizontal Drilling, Colorado Center for Environmental Management, (303) 297-0180, ext. 111

Management

Kurt Gerdes, DOE EM-50, DOE Integrated Demonstration Program Manager, (301)903-7289

Jim Wright, DOE Plumes Focus Area Implementation Team Manager, (803) 725-5608

Licensing Information

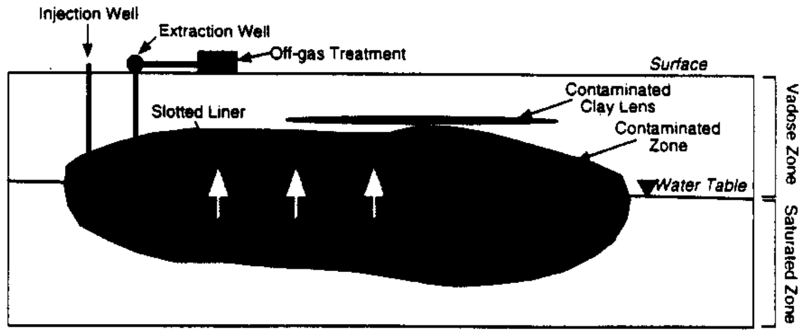
Caroline Teelon, Technology Transfer Office, WSRC, (803) 725-5540

SECTION 2

TECHNOLOGY DESCRIPTION

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, but not used for the demonstration described.

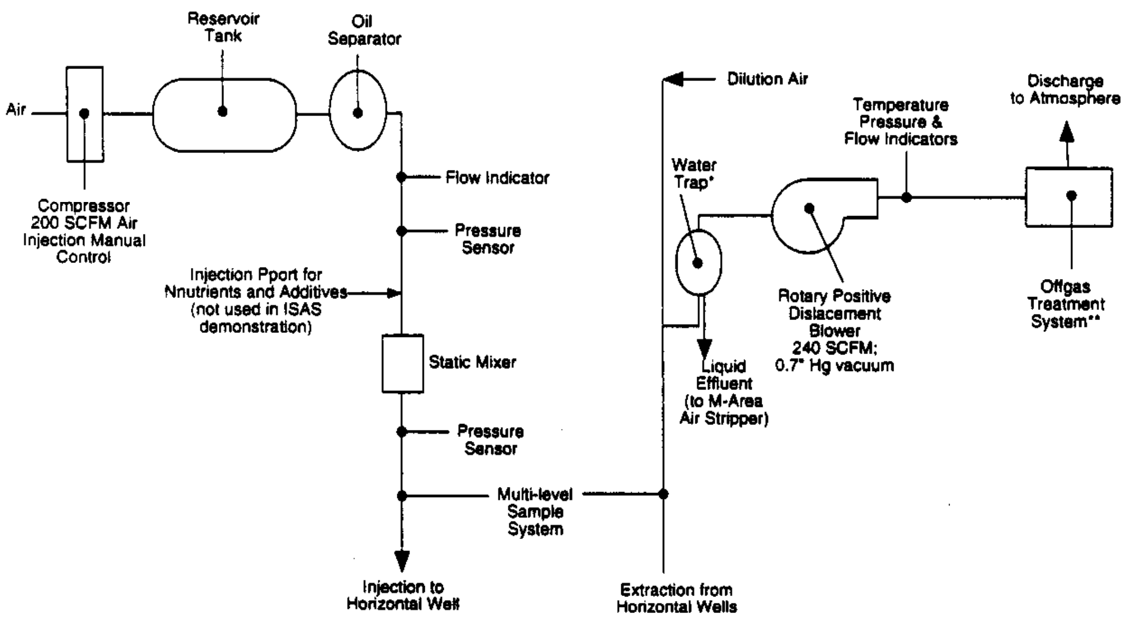


(figure modified from Reference 6)

Appendix B provides detailed information about the horizontal well installations and the monitoring wells installed.

Aboveground Systems

Air Injection ***Extraction & Offgas Treatment***



Notes:

* 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.

** Demonstration released VOCs directly to the atmosphere. Offgas treatment may be required for long-term remediation.

2

SECTION 3

PERFORMANCE

Demonstration Plan

Performance of the technology has been assessed using information from the full-scale demonstration at SRS. Major elements of the demonstration included:

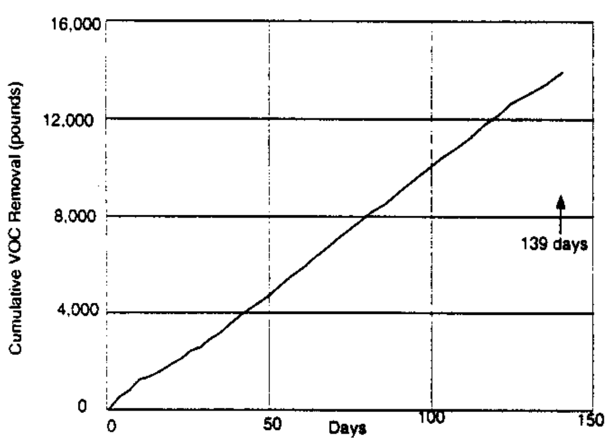
- initial vacuum extraction of vadose zone gases;
- addition of air sparging (simultaneous air injection into the saturated zone and extraction from the vadose zone) at low, medium, and high air injection rates;
- evaluation of temperature effects through heating of injected air;
- assessment of subsurface microbial activity; and
- assessment of the behavior of injected air through a 24-hour inert tracer (helium) test.

Key system parameters are explained on page 6. Appendix C describes the demonstration schedule, sampling and analysis to support performance monitoring, and the overall A/M Area cleanup program.

3

Treatment Performance

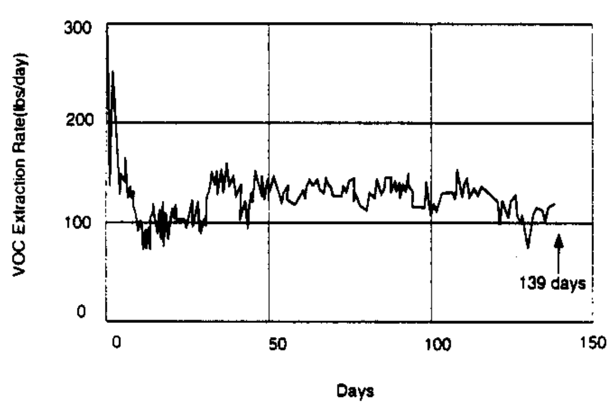
Amount of VOCs Removed



- Nearly 16,000 lbs of VOCs removed during the 139-day demonstration.
- 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 11)

In Situ Air Stripping VOC Extraction Rates

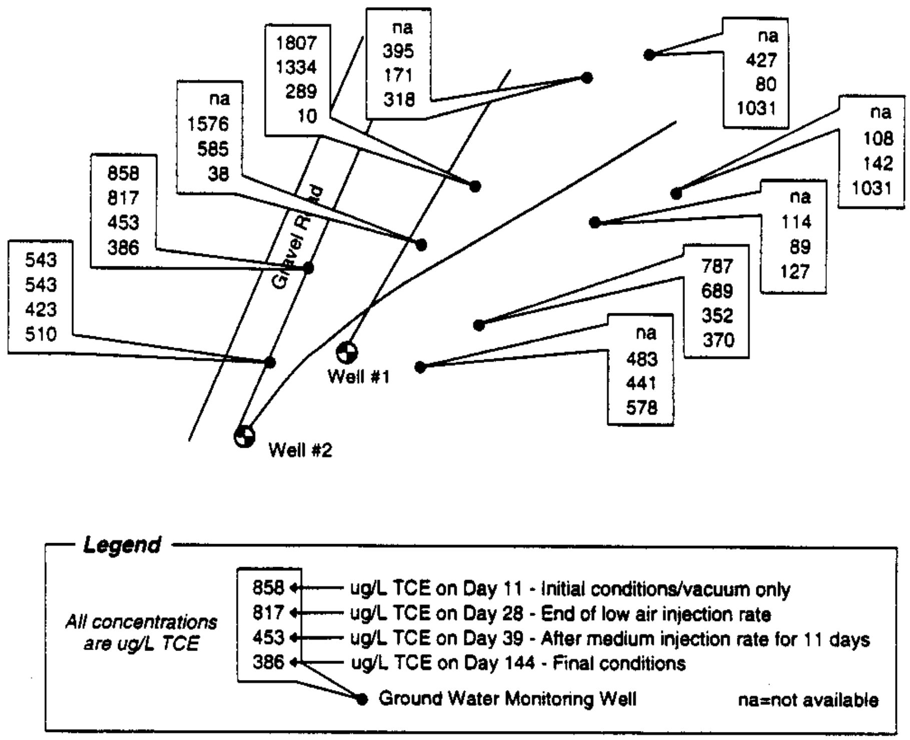


- Contaminant removal rate ranged between 100 and 140 lbs/day over most of the 139 days.
- Vacuum extraction removed an estimated 109 lbs/day (day s 1-16 and 113-139) while air injection removed an additional 20 lbs/day (days 16-113).

(figure modified from Reference 11)

Treatment Performance (continued)

Pre- and Post-Demonstration Ground Water Data: TCE Concentrations



- Similar reductions in PCE concentrations were observed: initial concentrations of 85 mg/L to 184 mg/L were lowered to 3 mg/L to 124 mg/L.

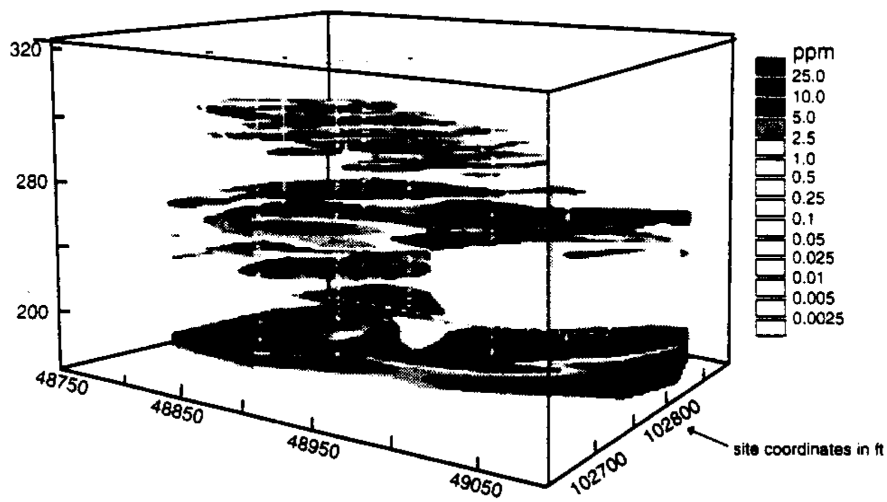
- Two hypotheses are being examined to explain increases in VOC concentrations near the far ends of the horizontal wells:
  1) upward migration of contaminants caused by the injection of air below the monitoring well screen, and
  2) slight pressurization of the vadose zone between the water table and a zone of clays resulting in downward migration from the water table to the depth of the screen being measured.

3

Treatment Performance (continued)

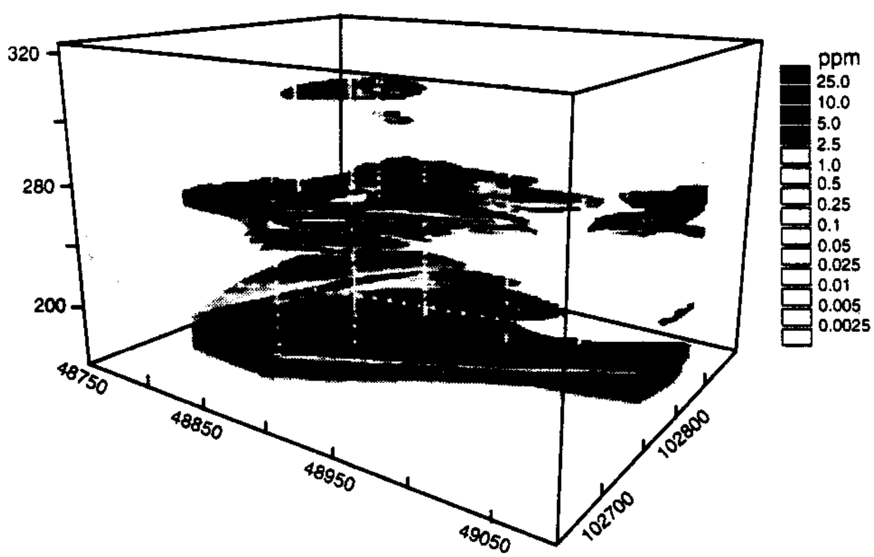
Pre- and Post-Demonstration Sediment Data

TCE concentrations in sediments before ISAS



The sediment data are known to underestimate the VOCs at the demonstration site, but can be used to develop a sense of relative amounts of contamination removed during the demonstration.

TCE concentrations in sediments after ISAS



Comparison of the pretest and post-test results suggest that 57% of the solvents were removed from the modeled volume during the five-month long demonstration.

Key System Parameters

Vacuum Applied

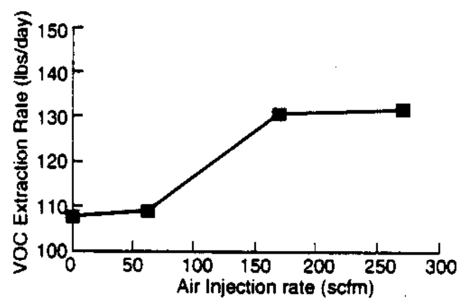
- Vacuum extraction from Well #2 in the vadose zone ranged from 550 to 600 scfm at 10 to 11 in of Hg.

Temperature Effects

- Heating of injected air up to 147°F had no measurable effect on system performance or on the temperature of extracted gas, which was relatively constant at 60°F.

Injection Pressure Effects

- Air injection was varied at low (65 scfm), medium (170 scfm), and high (270 scfm) rates during the demonstration.
- The effects of increasing injection pressure did not produce a linear increase in extracted VOCs as shown. Operating at lower flow rates may offer substantial cost savings without a major impact on performance.

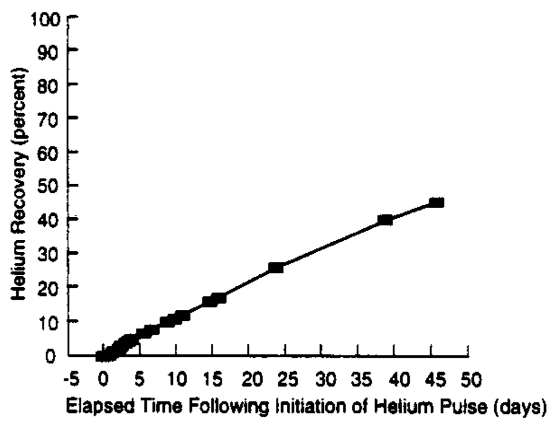


Microbial Activity

- Air injection significantly increased the biomass of microbes and their metabolic activity (2 to 3 orders of magnitude), especially at those wells where the greatest stripping effect was seen.
- Post-demonstration sediment data indicate that almost all contaminants in sediment in the vadose zone were removed primarily by microbial activity during later phases of demontration.

Results of Helium Tracer Test

- Helium was injected into the saturated zone horizontal well (Well #1) over a 24-hour period to determine:
  - the extent injected air was reaching extraction wells and
  - the extent injected air was escaping through monitoring wells.
- Results confirmed significant "communication" between injection and extraction wells with approximately 45% of injected helium recovered over nearly a 7-week period as shown at right. Injected air appeared to disperse throughout subsurface heterogeneities
- Losses through monitoring wells were estimated at less than 5% of the total injected air flow.



Zones of Influence

- The vacuum well in the vadose zone created a zone of influence estimated at greater than 200 ft based upon pressure measurements.
- Electrical resistance tomography (ERT), electromagnetic tomography (EMT) and seismic tomography were used to map a sparge zone of influence in the saturated zone approximately 40 to 60 ft wide (20 to 30 ft on either side of Well #1).

SECTION 4

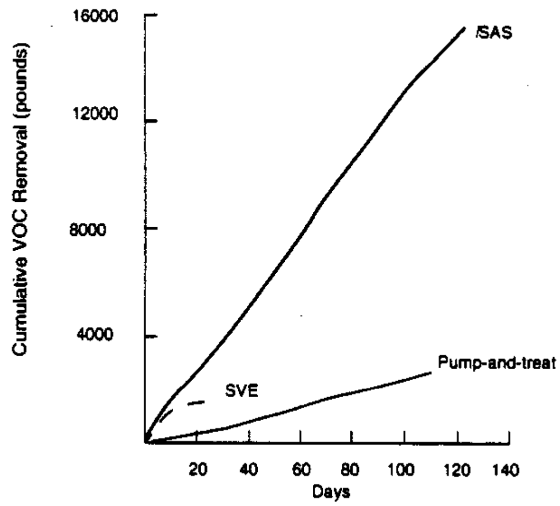
TECHNOLOGY APPLICABILITY & ALTERNATIVES

Technology Applicability

- ISAS has been demonstrated to remediate soils, sediments and groundwater contaminated with VOCs both above and below the water table.
- The geometry of horizontal well treatment conforms to typical subsurface contaminated zones, which are often relatively thin but laterally extensive areas.
- Quantitative modeling and bench- and pilot-scale work indicate that ISAS would be effective at removing light nonaqueous phase liquids (LNAPLs). It is not suitable for dense nonaqueous phase liquids (DNAPLs).
- ISAS is not well suited for sites with highly stratified soils with low permeability layers, fractured rock or clay geologies. ISAS does not effectively remediate large dilute plumes but would be useful near source areas.
- Similar to pump-and-treat, ISAS may not be able to reach drinking water standards (without enhancements such as addition of nutrients to promote biodegradation).
- Commercialization and intellectual property information is included in Appendix D.

Competing Technologies

- ISAS competes with conventional baseline technologies of pump-and-treat and pump-and-treat combined with soil vapor extraction (SVE). Numerous other thermal, physical/chemical, and biological technologies are also either available or under development to treat VOC-contaminated soils and ground water either in situ or aboveground.
- The effectiveness of ISAS was compared with performance data from application of pump-and-treat and SVE at SRS (Reference 9) as shown as right. Extrapolation of these data was the basis of the Los Alamos cost analysis discussed in Section 5.
- Vertical well air sparging and in well recirculation technologies have been implemented at a number of sites across the US and Europe.



Technology Maturity

- Air sparging with vertical wells is a relatively established technology offered by dozens of vendors. Variations of the technique have been implemented at hundreds of sites.
- ISAS using horizontal wells is currently being applied at an airport in New York and at industrial sites in North Carolina, Minnesota, and Missouri. The technology is also being implemented full-scale at SRS at two locations.
- A market survey on horizontal environmental wells was completed in 1993 (Reference 7). Key results of that study included:
  - Since 1987, over one hundred horizontal environmental wells have been installed in the U.S.
  - 25% have been used for ground water extraction, 25% for soil vapor extraction, and 50% for other purposes, including air injection, bioventing, and petroleum recovery.
  - 80% of the horizontal wells have been installed at vertical depths of 25 ft or less.
  - The rate of horizontal well installations has increased significantly in the last 2 years possibly because of more widespread recognition of advantages and improvements in drilling techniques, which have made installation more cost effective. A cursory update of the 1993 survey has shown that between July 1993 and December 1994 more than fifty horizontal environmental wells were installed.

SECTION 5

COST

Introduction

A cost study (Reference 9) was conducted by researchers from Los Alamos National Laboratory that compared in situ air stripping with horizontal wells against the conventional cleanup technologies of combined pump and treat and soil vapor extraction. Detailed capital and operating costs taken from the study for the ISAS application are presented below. Cost breakdown analyses and comparative assessments of ISAS cost versus those of conventional technologies are included in the sections that follow. Critical assumptions relevant to the quality of the cost data are included within each section.

Capital and Operating Costs

The Los Alamos study presented these costs as representative of the actual costs of demonstration (with the exception of offgas treatment as indicated below under "Notes"):

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 (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**

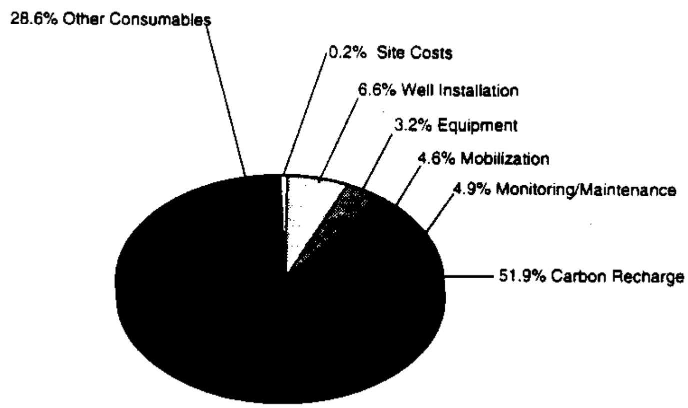
Notes:

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. Demonstration did not include offgas treatment.

Cost Breakdown Analysis

• The Los Alamos study developed a breakdown of ISAS costs per pound of VOC removed during the 139 day demonstration period by annualizing capital costs over an estimated 10-year equipment life. Carbon adsorption was included for offgas treatment. However, more cost-effective offgas treatment systems might be applicable and could reduce annual costs substantially.



Cost/Lb of VOC Removed

Equipment	$1.51
Site	$0.31
Labor	$3.91
Consumables	$9.86
Total	$15.59

Cost Considerations for Future Applications

Cost Sensitivities

• Horizontal well installation costs are quite variable, depending upon depth of installation, site geology, site specific institutional requirements, well design, well materials, etc.

- ▶ At depths greater than 40 to 50 ft, river crossing techniques are normally used at costs of approximately $200/ft.
- ▶ At depths less than 40 to 50 ft, the utility industry compaction or smaller river crossing rigs can be used at costs as low as $50/ft.

• Horizontal well installation costs have steadily decreased in recent years due to technical improvements and increased experience of drilling companies.

Horizontal Well Costs Versus Vertical Well Costs

• Promotional literature from horizontal well service providers show that, depending upon plume geometry and site characteristics, one horizontal well can replace five to fifty vertical wells. One hypothetical project cost comparison (Reference 5) illustrated that one horizontal well could accomplish the same containment/remediation objectives as ten vertical wells at a cost savings of nearly 80%. The higher individual capital cost of a horizontal well was offset in this case by the large number of vertical wells replaced and their larger associated costs for surface equipment, operations and maintenance.

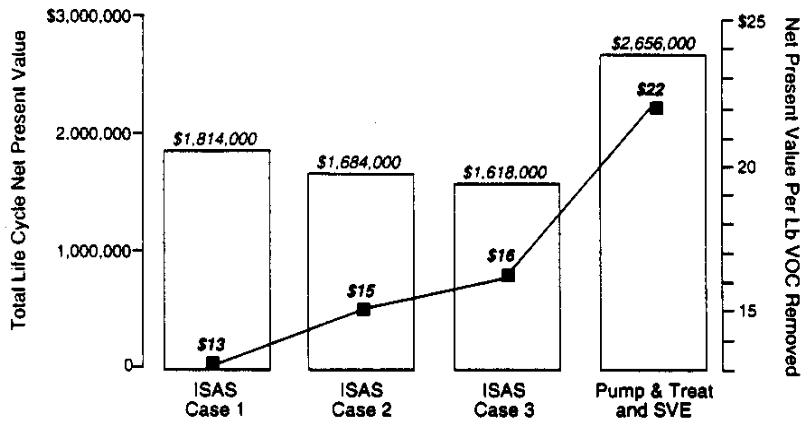
• A horizontal well case study at a Department of Defense site predicted one horizontal well to replace 80 vertical wells.

5

Cost Considerations for Future Applications (continued)

Cost Savings Versus Alternative Technologies

The Los Alamos study evaluated the demonstrated cost of ISAS versus the combined cost of pump-and-treat with soil vapor extraction. The cost and removal rates of the ISAS system were extrapolated from data from the demonstration and compared to data from the in place baseline technology at SRS. All systems were normalized to remediate equivalent zones of contamination. ISAS Cases 1, 2 and 3 represent different assumed VOC extraction rates over 5 years of operation. The VOC extraction rates assumed are detailed in the table at the bottom of the page. Costs over a 5 year life cycle were:



The costs above are based in part upon the following VOC removal data and assumptions. Unless noted, all values are in lbs of VOC extracted/day.

		ISAS Case 1	ISAS Case 2	ISAS Case 3	Pump-and-Treat and SVE	
Actual VOC Removal Data*		← 16,000 lbs over 139 days →			Pump-and-Treat: 2700 lbs over 114 days	SVE: 7480 lbs over 21 days
Assumed Projected VOC Removal Data**	Year 1	115	86	57	23	80
	Year 2	86	57	57	17	60
	Year 3	57	57	57	11	40
	Year 4	57	57	57	11	40
	Year 5	57	57	57	11	40

* VOC extraction rates taken from the results of short-term application at SRS

** Projected VOC extraction rates for five years of operation. ISAS Cases 1, 2 and 3 represent increasingly conservative estimates of ISAS performance over longer periods.

5

SECTION 6

REGULATORY/POLICY REQUIREMENTS & ISSUES

Regulatory Considerations

• Permit requirements for the demonstration conducted in 1990 were controlled by the South Carolina Department of Health and Environmental Control (SCDHEC) and included an Air Quality Control (AQC) permit waiver and an Underground Injection Control (UIC) permit issued by the South Carolina Board of Drinking Water Protection.

• Permit requirements for future applications of ISAS are expected to include an air permit for discharge of treated vapor extracted from the subsurface. For applications in some states, underground injection permits may be required for air injection. Some federal projects may also require a National Environmental Policy Act (NEPA) review.

• Groundwater Protection Standards (GWPS) have been established as part of a RCRA permit for the M-Area. The GWPS' are based upon EPA Maximum Contaminant Levels (MCLs). Specific goals for contaminants of greater concern are:

Compound	Concentration [ppb]
TCE	5
PCE	5
TCA	200

• For application of ISAS as a remedial activity at the M-Area HWMF, the RCRA Part B Permit must be reviewed to determine if a permit modification is necessary. Offgas treatment is expected to be required for full-scale remediation at SRS.

• The ISAS system experienced no regulatory compliance problems during demonstration at SRS nor are any future regulatory changes anticipated to pose compliance obstacles. ISAS has been subsequently approved by regulators for use at additional sites both at SRS and in other states, including New York, Minnesota, Missouri, and North Carolina.

Safety, Risks, Benefits, & Community Reaction

Worker Safety

• Health and safety issues for the installation and operation of ISAS are essentially equivalent to those for conventional technologies of pump-and-treat or soil vapor extraction.

• Level D personnel protection was used during installation and operation of the ISAS system.

Community Safety

• ISAS with offgas treatment does not produce any routine release of contaminants.

• No unusual or significant safety concerns are associated with the transport of equipment, samples, waste, or other materials associated with ISAS.

Environmental Impacts

• ISAS systems require relatively little space, and use of directional drilling minimizes clearing and other activities that would be needed to install a comparable vertical well network.

• Visual impacts are minor, but operation of the vacuum blower and compressor create moderate noise in the immediate vicinity.

Socioeconomic Impacts and Community Perception

• ISAS has a minimal economic or labor force impact.

• The general public has limited familiarity with ISAS: however, the technology received positive support on public visitation days at Savannah River. ISAS can be explained to the public with ease similar to that of pump-and-treat technologies.

SECTION 7

LESSONS LEARNED

Design Issues

- The bundle-tube pressure sensors installed along horizontal wells 1 and 2 to measure injection/extraction efficiency are inexpensive and recommended for future applications.
- The filter pack on all the horizontal wells is made up of natural formation solids, principally because of collapse around the borehole. This may diminish well efficiencies. Well design must be tailored to the ultimate use of the well. Prepacked screen should only be used if necessary because it adds significantly to the cost.
- A horizontal well removes water from the vadose zone that can collect in the well, reducing its effective length. Wells must be designed to channel water away from low areas.
- Careful alignment of the injection and extraction wells is probably not necessary because the zone of influence of the extraction well is far greater than that of the injection well and because subsurface heterogeneities strongly influence air flow.
- The system must be designed carefully to minimize the potential for plume spreading during injection

Implementation Considerations

- Increasing injection flow rates did not result in linear increases in mass removal; operating at lower flow rates may save on operating costs with only a modest impact on performance.
- Cycling operations may offer substantial cost savings for only a marginal performance penalty.
- Air sparging efficiency is affected by injection pressure, flow rates, permeability, and subsurface heterogeneities.
- The injection of heated air is unlikely to result in increased VOC removal based upon the results of field tests.
- Horizontal drilling methods must be tailored to specific site conditions with special considerations for the type of drilling fluid, drilling bit, drilling methodology, casing installation, etc.

Technology Limitations/Needs for Future Development

- Clay layers, because of their low permeability, are troublesome. Heterogeneities in the subsurface, caused by either stratigraphy or fractures, can create preferential air flow pathways, resulting in less effective contact and remediation.
- By inducing water flow, ISAS can accelerate lateral migration of contaminants in certain geologic settings. If clay layers or other geologic features constrict vertical flow, it may be necessary to use ISAS in conjunction with a pump-and-treat system for hydraulic control.
- Long-term performance data from several years of operation are required to assess the need for design improvements and to better quantify life-cycle costs.
- Simplified design and monitoring methods are required to facilitate implementation of ISAS.
- Determination of the most effective enhancements to the technology, such as addition of nutrients to promote biodegradation, presents opportunities to significantly improve performance. Follow-on work, not discussed in this analysis, involving methane injection to bioremediate the site has already produced positive results.
- More experience with environmental horizontal drilling under a variety of subsurface conditions will ensure better well installations at reduced costs.

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 well profile and contaminant plume geometry, borehole access to areas beneath existing facilities, and drilling along facility boundaries to control plume migration. However, each site must be assessed for the utility of horizontal wells.

- Successful ISAS requires good contact between injected air and contaminated soils and ground water. 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 is more effective in coarse-grained soil.

- For ISAS to be effective, the contaminants of concern must be strippable, that is mobile in and between all phases. Most light hydrocarbons and chlorinated solvents satisfy these conditions.

- Horizontal wells may provide for better contact with linearly shaped plumes. ISAS may be more effective with relatively thin plumes of contaminants.

APPENDIX A

DEMONSTRATION SITE CHARACTERISTICS

A

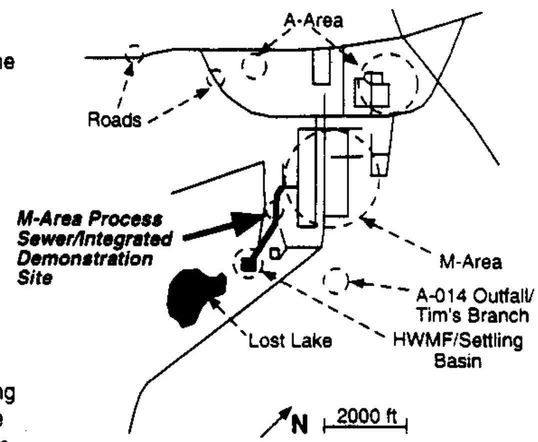
Site History/Background

• 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 by-products now managed as 266 waste management units located throughout the 300 mile^2 facility.

• The A and M Areas at Savannah River have been the site of administrative buildings and manufacturing operations, respectively. The A/M-Area is approximately one mile inward from the northeast boundary of the 300 mile^2 Savannah River Site. Adjacent to the site boundary are rural and farming communities. Specific manufacturing operations within the M-Area included aluminum forming and metal finishing.

• The M-Area operations resulted in the release of process wastewater containing an estimated 3.5 million lbs of solvents. From 1958 to 1985, 2.2 million lbs were 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 were discharged from Outfall A-014 to Tim's Branch, a nearby stream, primarily during the years 1954 to 1982.

Site Layout



• Discovery of contamination adjacent to the settling basin in 1981 initiated a site assessment effort eventually involving approximately 250 monitoring wells over a broad area. A pilot ground water remediation system began operation in February 1983. Full-scale ground water treatment began in September 1985.

• High levels of residual solvent are found in the soil and ground water near the original discharge locations. Technologies to augment the pump-and-treat efforts, for example soil vapor extraction, ISAS, and bioremediation, have been tested and are being added to the permitted corrective action.

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	-	$ClCH=CCl_2$	$Cl_2C=CCl_2$	CH_3CCl_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 ^oC*

Nature and 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 ground water in concentrations greater than 10 ppb is between 260,000 and 450,000 lbs 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 ground water has an approximate thickness of 150 feet, covers about 1200 acres, and contains contaminant concentrations greater than 50,000 ug/L.

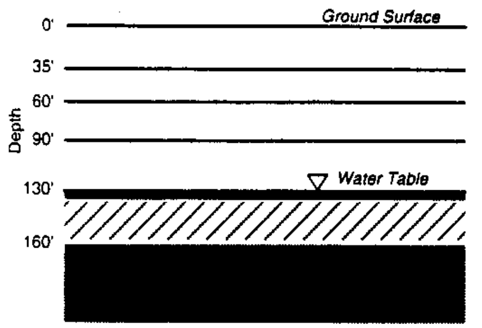
• DNAPLs found in 1991 present challenges for long-term remediation efforts.

• 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 Hydrogeologic Profiles

Simplified schematic diagrams show general hydrologic features of the A/M Area at SRS.

Vadose Zone and Upper Aquifer Characteristics



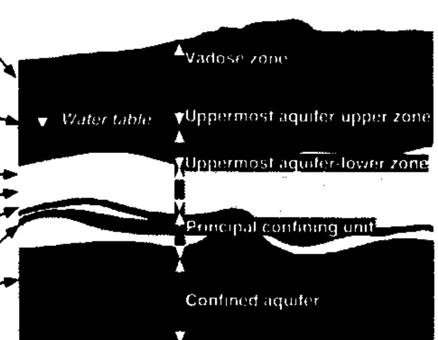
(figure modified from Reference 12)

Legend
- Water Table
- Unsaturated Zone
- Semiconfined Aquifer
- Confined Aquifer

- 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.
- The 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 ft/year.
- Radial flow outward from a groundwater plateau under most of the A/M-Area exists. Flow is approximately 15 to 100 ft/year.

Hydrogeologic Units

Aquifer Unit	Description	Thickness
Vadose Zone	Poorly sorted mix of sand, cobbles, silt and clay	~57 ft
	Moderate to well-sorted, fine to medium sand containing some pebbles; 13% silt and clay	0-97 ft
	Moderately to well-sorted medium sand; 18% silt and clay	30-55 ft
Water Table Unit	Moderate to well-sorted fine sand with some calcaneous zones; 25% silt and clay; 14% silt and clay beds	16-34 ft
Lost Lake Aquifer — Upper	Well-sorted fine to medium sand; 16% silt and clay; 7% silt and clay beds.	14-60 ft
	Discontinuous clay beds containing 70% silt & clay	
Lost Lake Aquifer — Lower	Moderate to well-sorted medium sand; 17% silt and clay; 7% silt and clay beds	4-44 ft
Crouch Branch Confining Unit	Clay, clayey silt, and poorly sorted fine to coarse, clayey sand; 62% silt and 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 and clay beds; an important production zone for water supply wells in the M-Area	152-180 ft

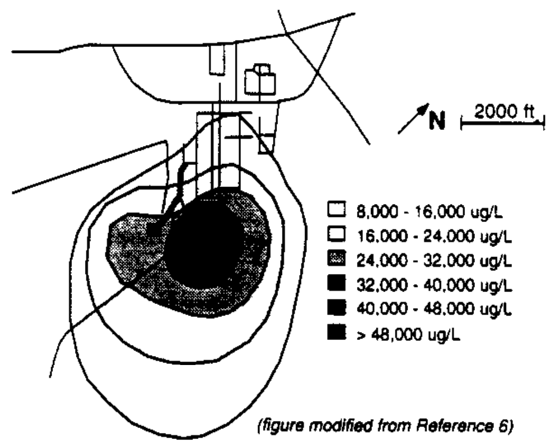


Contaminant Locations and Hydrogeologic Profiles (continued)

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, ground water monitoring wells, and a variety of other investigative techniques have established a well-documented VOC plume in both the vadose and saturated zones.

TCE Ground Water Plume (Top View)

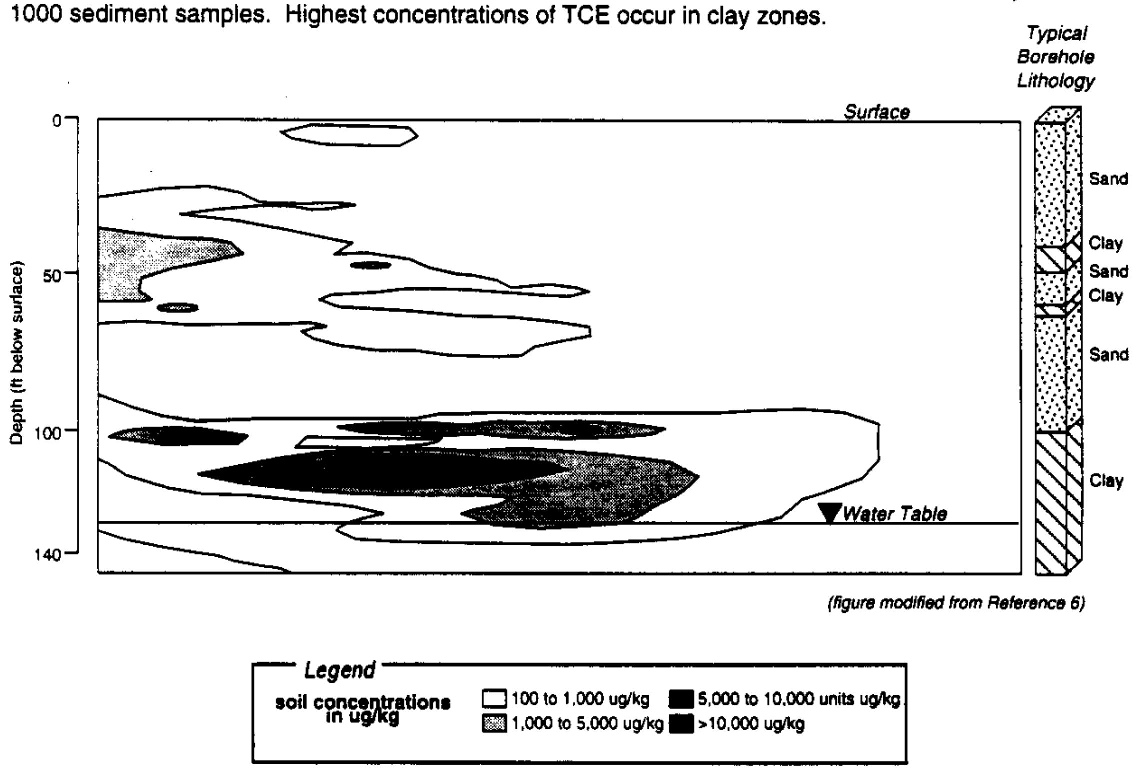
Data from 15 feet below water table in the third quarter of 1990.



(figure modified from Reference 6)

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. Highest concentrations of TCE occur in clay zones.



(figure modified from Reference 6)

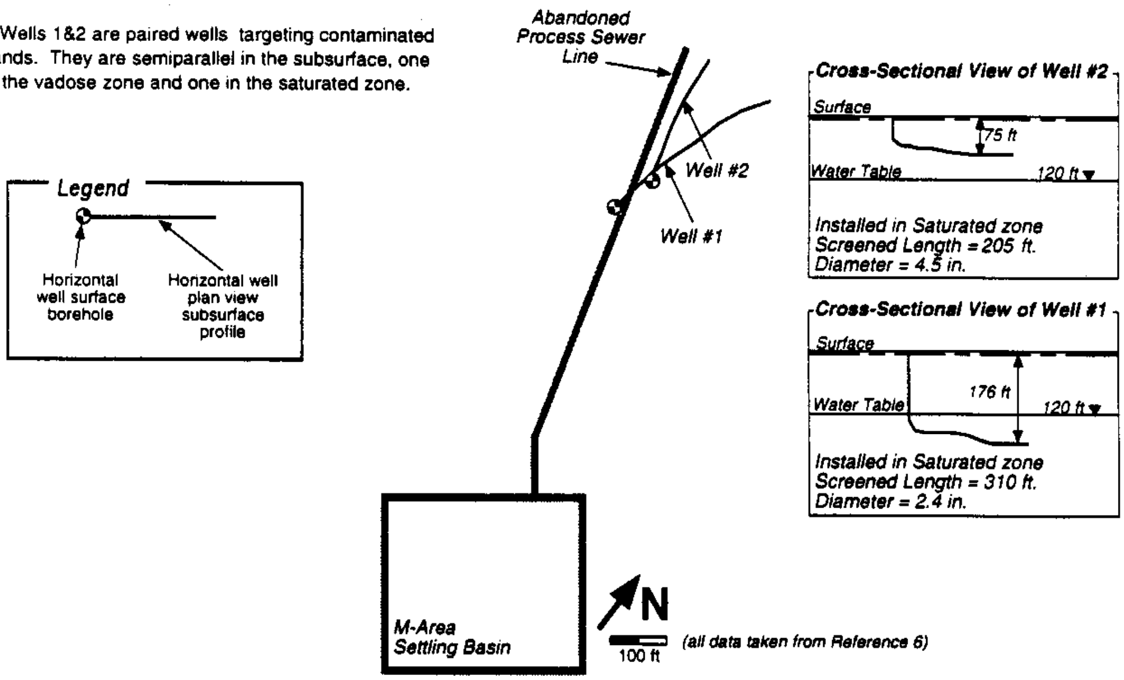
APPENDIX B

TECHNOLOGY DESCRIPTION DETAIL

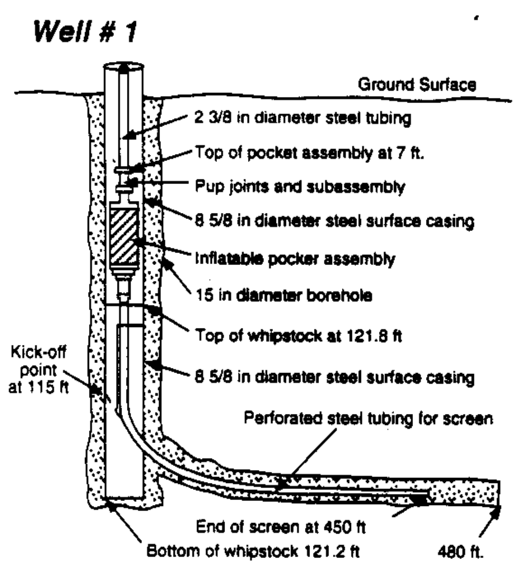
B

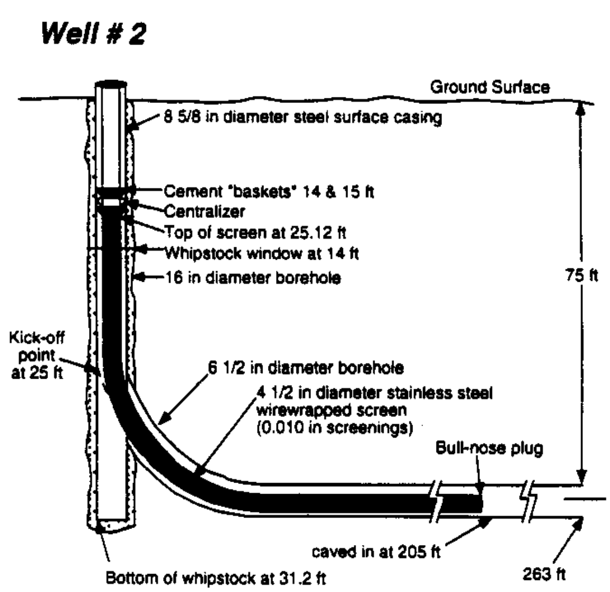
System Configuration

- Wells 1&2 are paired wells targeting contaminated sands. They are semiparallel in the subsurface, one in the vadose zone and one in the saturated zone.



Horizontal Well Close-Ups





Horizontal Well Installation Techniques

The techniques used to directionally drill and install a horizontal well depend on the location and purpose of the well. Petroleum industry technology was used to install wells 1 and 2 at the Savannah River Site; however, this technology is no longer used. Current installation techniques include the following:

1. **Pipeline/Utility River Crossing System-** Based on a mud rotary system used to drive a downhole drill assembly, including a drilling tool, a hydraulic spud jet with a 2-degree bend to provide directional drilling or a downhole motor depending on the lithology to be drilled.

2. **Utility Industry Compaction System** -Down hole drill assembly consists of a wedge-shaped drilling tool and a flexible subassembly attached to the drill string. The borehole is advanced by compaction, forcing cuttings into the borehole wall. Reduced volumes of water are introduced to cool the drill bit; no cirdulation of drilling flulid is accomplished.

3. **Hybrid Petroleum Industry/Utility Industry Technology** - Modified mud rotary system with bottom hole assembly comprised of a survey tool, steerable downhole motor, and expandable-wing drill bit. Drilling fluids are used. Curve is drilled and pipe is installed in curve before horizontal is drilled. Only one company provides this type of drilling system.

Operational Requirements

- Design and management of ISAS systems require expertise in environmental, chemical, mechanical, and civil engineering as well as hydrogeology and environmental regulations. Operation of multiple systems of the scale implemented at the Savannah River Site can be performed by a 1/3 full-time equivalent technician. Larger systems or extensive monitoring activities would require additional staff.

Monitoring Systems

Ground Water Monitoring Well Clusters

- Ten boringswere completed as 4-in monitoring well clusters in the locations shown on the following page.
- One well from each cluster was screened in the water table at elevations ranging from 216 to 244 ft.
- The second well in the cluster was screened in the underlying semiconfined aquifer at elevations ranging from 204 to 214 ft.

Vadose Zone Piezometer Clusters

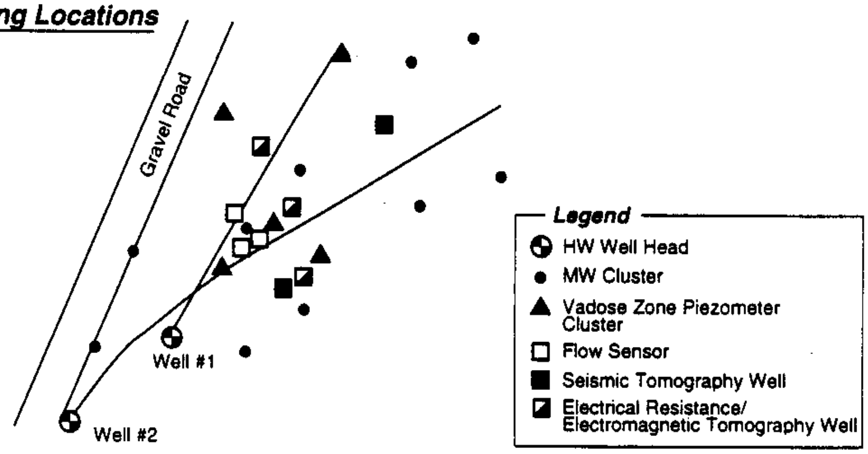
- Five borings were cored in order to install piezometer clusters in the vadose zone.
- Three piezometer tubes having lengths of approximately 52 ft, 77 ft and 100 ft were installed into each borehole.

Geophysical Monitoring

- Eight borings were completed for geophysical monitoring.
- Seismic tomography was performed in two borings. This technique was used to map subsurface structure and to monitor the extent of the air-stripping process.
- ERT and EMT were performed in three borings. ERT and EMT map the behavior of subsurface fluids as they change in response to natural or remedial processes.
- Several single-point flow sensors were placed between the injection and extraction wells (just below the water table) to measure ground water flow in the area most affected by the ISAS process.

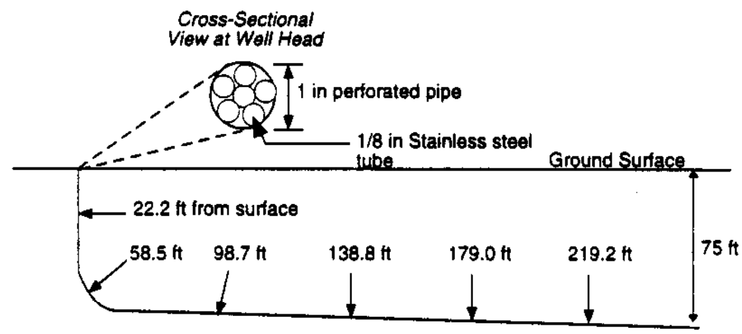
Monitoring Systems (continued)

Sampling/Monitoring Locations



Bundle Tubes

Each horizontal well was filled with a bundle of six tubes encased in a perforated pipe or well screen. Each tube terminated at a discrete distance from the surface for sampling or monitoring at different locations along the well bore.



B

APPENDIX C

PERFORMANCE DETAIL

Operational Performance

Maintainability and Reliability

- No functional problems encountered during demonstration; system was operational approximately 90% of all available time.
- Operational performance over long periods (years) not yet available.

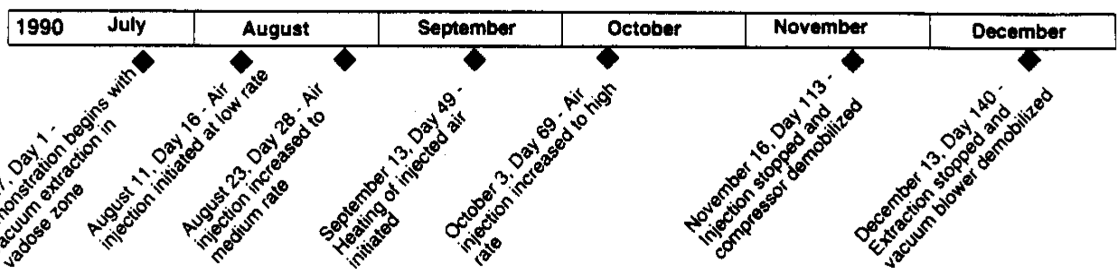
Operational Simplicity

- Monitoring performance of ISAS is more difficult than monitoring performance of baseline pump-and-treat technology; however, systems can be operated and maintained in the field typically by less than 1 full-time equivalent technician. Staffing requirements are detailed in Appendix B.

C

Demonstration Schedule

Major Milestones of the Demonstration Program



Sampling, Monitoring, Analysis, and QA/QC Issues

Objectives

- Gather baseline information and fully characterize site
- Evaluate removal efficiencies with time
- Identify and evaluate zones of influence

Baseline Characterization

- Baseline characterization was performed before the demonstration to gather information on the geology, geochemistry, hydrology, and microbiology of the site. The distribution of contaminants in soils and sediments in the unsaturated zone and ground water was emphasized. These data were compared with data on soil collected during and after the demonstration to evaluate the effectiveness of ISAS.
- Continuous cores were collected from monitoring well and vadose zone boreholes. Sediments for VOC analysis were collected at 5-ft intervals and at major lithology changes. Samples for microbiological characterization were collected every 10 ft.
- Water samples were collected and analyzed for VOC content and microbial characteristics from monitoring well clusters and at discrete depths adjacent to monitoring well clusters.
- Geologic cross-sections were prepared using gamma ray, sp, resistivity density, and neutron geophysical logs and core logs.

Sampling, Monitoring, Analysis and QA/QC Issues (continued)

Sampling & Monitoring

	Location(s)	Frequency	Technique
Pressure Monitoring	vadose zone piezometers	3 X daily	measured at surface using magnehelic or slack-tube macrometer
	injection well		measured at wellhead using pressure gauge
Vacuum Monitoring	extraction well	3 X daily	measured at wellhead using vacuum gauge
	extraction well bundle tubes	weekly	measured at surface
Temperature Monitoring	vadose zone piezometers	3 X daily	measured at surface using temperature gauge
	injection well	3 X daily	same as above
	extraction well	3 X daily	same as above
Vapor Sampling	vadose zone piezometers	weekly	sampled through a septum on the vacuum side of a vacuum pump using gas-tight syringes
	extraction well	3 X daily	same as above
	bundle tube	weekly	same as above
Ground Water Sampling	monitoring well clusters	weekly	sampled using documented Savannah River Site (SRS) well sampling protocols
Microbiological Sampling	monitoring well clusters	biweekly	sampled using documented SRS well sampling protocols
Helium Tracer Test	all exit points	once	sampled using 500-ml disposable syringes and transferred to 30-ml preevacuated serum vials

Analytical Methods and Equipment

- Vapor grab samples were analyzed in the field using both a Photo Vac field gas chromatograph (GC) and a GC fitted with flame ionization and electron capture detectors. Analysis was performed immediately after collection.
- Bulk water parameters, including temperature, pH, dissolved oxygen, conductivity, and oxidation reduction potential, were measured using a Hydrolab.
- VOC analysis of water and sediment samples was performed onsite using an improved quantitative headspace method developed by Westinghouse Savannah River Company. Analyses were performed on an HP-5890 GC fitted with an electron capture detector and headspace sampler.
- Helium tracer samples were analyzed using a helium mass spectrometer modified to sample serum vials at a constant rate.

QA/QC Issues

- Vapor samples were analyzed immediately after collection and GC analysis of soil and water samples were completed less than 3 weeks after collection.
- Duplicate analysis was performed for nearly every water and sediment sample collected.
- Approximately 161 samples were analyzed offsite using standard EPA methods to corroborate onsite testing which used the improved quantitative headspace method described earlier. Cross-comparison showed that the quantitative headspace analysis generated equivalent to superior data.
- GC calibration checks were run daily using samples spiked with standard solutions.

Performance Validation

- Samples analyzed onsite by nonstandard EPA methods were sent offsite for confirmatory analysis using EPA methods. Results from these analyses confirmed the findings of Savannah River efforts.
- The effectiveness of horizontal wells for environmental cleanup has been demonstrated by their use in vapor extraction and ground water/free product recovery systems which are also discussed in Appendix D.

APPENDIX D

COMMERCIALIZATION/INTELLECTUAL PROPERTY

Marketplace Opportunities

- A key competitive advantage of ISAS is the use of horizontal wells. Horizontal wells can be used to:
  - remediate beneath buildings and other obstacles to avoid interference with aboveground activities,
  - remediate linear sources of contamination such as beneath pipelines,
  - prevent further migration of contamination along site boundaries, and
  - provide improved access to the subsurface especially for remedial enhancement processes such as bioremediation.
- Additional advantages of ISAS/horizontal well technology include:
  - reduction in the numbers of wells required and their associated pumps and surface equipment, and
  - elimination of contaminated ground water as a secondary waste stream as a result of the in situ treatment.
- The success of the ISAS demonstration has led to plans for reimplementation at the same site as well as application at other locations at SRS.
- ISAS has a potential market at sites where conventional technologies have failed to produce acceptable results. An application at an airport in New York is one example where a pump-and-treat system had been previously applied.
- WSRC has received hundreds of inquiries from private industrial site owners (especially oil companies) as well as from consultants and regulators. This response has led to the creation of a WSRC Industrial Assistance Program. Specific activities of this program have included:
  - input to feasibility studies to determine potential applicability of ISAS,
  - aid in determining design criteria for surface and subsurface equipment,
  - technical assistance to equipment vendors and manufacturers, and
  - participation in the regulatory negotiating and permit approval process.

D

Intellectual Property

Primary Sponsor

U.S. Department of Energy, Office of Environmental Management, Office of Technology Development

Existing/Pending Patents

Several parties, including national laboratories, technology developers, and consultants, participated in the development and implementation of the ISAS system. These participants are listed on page 26.

- Patent 4,832,122, "In Situ Remediation System and Method for Contaminated Groundwater," J.C. Corey, B.B. Looney, and D.S. Kaback, assignors to the U.S. as represented by the U.S. DOE.
- Patent 5,186,255, "Flow Monitoring and Control System for Injection Wells," J.C. Corey, assignor to the U.S. as represented by the U.S. DOE.
- Patent 5,263,795, "In Situ Remediation System for Groundwater and Soils," J.C. Corey, D.S. Kaback, and B.B. Looney, assignors to the U.S. as represented by the U.S. DOE.

- Related patents include:
  - Patent 4,660,639, "Removal of Volatile Contaminants from the Vadose Zone of Contaminated Ground," M.J. Visser and J.D. Malot assignors to the Upjohn Company. WSRC paid a one-time license fee to the assignee for the use of the process with horizontal wells.
  - Patent 5,006,250, "Pulsing of Electron Donor and Electron Acceptor for Enhanced Biotransformation of Chemicals," P.V. Roberts, G.D. Hopkins, L. Semprini, P.L. McCarty, and D.M. McKay, assignors to the Board of Trustees of the Leland Stanford Junior University.

- There are no pending patents for ISAS.

Intellectual Property (continued)

Licensing Information

- ISAS is commercially available through the WSRC Technology Transfer Office
- To date, 19 licenses have been applied for and 8 licenses have been granted.

Collaborators

ISAS Demonstration Participants

CDM Federal Programs Corporation
Conoco, Inc.
Eastman Christensen Company
Environmental Monitoring and Testing
Graves Well Drilling
Los Alamos National Laboratory
Lawrence Berkeley Laboratory
Lawrence Livermore National Laboratory
Martin Marietta Energy Systems, Inc., HAZWRAP
Sandia National Laboratories
Sirrine Environmental
South Carolina Department of Health and Environmental Control
Terra Vac, Inc.
University of California at Berkeley
University of South Carolina
U.S. EPA

APPENDIX E

REFERENCES

Major Refernces for Each Section

Technology Description	Sources (from list below) 1 and 6
Performance	Sources 1, 3, and 6
Technology Applicability and Alternatives	Sources 1, 3, and 4
Cost:	Sources 5 and 11
Regulatory/Policy Requirements and Issues	Sources 1, 3, 4, 6, 11, and 12
Lessons Learned:	Sources 2, 4, and 5
Demonstration Site Characteristics	Sources 6, 8, 15, and 17
Technology Description Detail	Sources 1, 6, 14, 15, and 16
Performance Detail	Sources 1, 3, 4, and 6
Commercialization/Intellectual Property	Sources 1, 3, 4, and 7

Chronological List of Refernces and Additional Sources

1. Personal communications with Brian Looney, Westinghouse Savannah River Company, November 1994 - January 1995.

2. Personal communications with C.A. Eddy Dilek, Westinghouse Savannah River Company, April 1994.

3. Looney, B.B., C.A. Eddy Dilek, D.S. Kaback, T.C. Hazen, and J.C. Correy, *In Situ Air Stripping Using Horizontal Wells: A Technology Summary Report (U)*, Westinghouse Savannah River Company, Working draft, 1994

4. Battelle Pacific Northwest Laboratories, PROTECH Technology Information Profile for In Situ Air Stripping, PROTECH database, 1994.

5. The Hazardous Waste Consultant, *Horizontal Wells Prove Effective for Remediating Groundwater and Soil,"* July/August, 1994.

6. *Turnover Plan for the Integrated Demonstration Project for Cleanup of Contaminants in Soils and Groundwater at Non-Arid Sites, SRS*, Science Applications International Corporation, September 7, 1993.

7. Wilson, D.D., and D.S. Kaback, *Industry Survey for Horizontal Wells,* Westinghouse Savannah River Company, July 1993

8. C.A. Eddy Dilek, et al., *Post Test Evaluation of the Geology, Geochemistry, Microbiology, and Hydrogeology of the In Situ Air Stripping Demonstration Site at the Savannah River Site,"* WSRC-TR-93-369 Rev 0, Westinghouse Savannah River Company, July 1993.

9. A.L. Ramirez, and W.D. Daily, "Electrical Resistance Tomography During Gas Injection at the Savannah River Site", UCRL-JC-114126 preprint, Lawrence Livermore National Laboratory, May 1993

10. B.B. Looney, C.A. Eddy, and W.R. Sims, "Evaluation of Headspace Method for Volatile Constituents in Soils and Sediments", Proceedings of the National Symposium on Measuring and Interpreting VOCs in Soils: State of the Art in Research Needs, 1993.

E

Chronological List of References and Additional Sources (continued)

11. J.D. Schroeder, et al., *In Situ Air Stripping: Cost Effectiveness of a Remediation Technology Field Tested at the Savannah River Integrated Demonstration Site*, Los Alamos National Laboratory, June 1992.

12. G.J. Elbring, *Crosshole Shear-Wave Seismic Monitoring of an In Situ Air Stripping Waste Remediation Process*, SAND91-2742, Sandia National Laboratories, February 1992.

13. *Cleanup of VOCs in Non-Arid Soils - The Savannah River Integrated Demonstration*, WSRC-MS-91-290, Rev. 1, U.S. DOE, 1991.

14. Looney, B.B., T.C. Hazen, D.S. Kaback, and C.A. Eddy, *Full Scale Field Test of the In Situ Air Stripping Process at the Savannah River Integrated Demonstration Test Site* (U), WSRC-RD-91-22, Westinghouse Savannah River Company, June 29, 1991.

15. Eddy, C.A., B.B. Looney, J.M. Dougherty, T.C. Hazen, and D.S. Kaback, *Characterization of the Geology, Geochemistry, Hydrology and Microbiology of the In-Situ Air Stripping Demonstration Site at the Savannah River Site"* (U), Westinghouse Savannah River Company, WSRC-RD-91-21, May 1, 1991.

16. D.S. Kaback, B.B. Looney, J.C. Corey, and M.L. Wright, Well Completion Report on Installation of Horizontal Wells for In Situ Remediation Tests (U), Westinghouse Savannah River Company, WSRC-RP-89-784, August 1989.

13. *Preliminary Technical Data Summary M-Area Groundwater Cleanup Facility*, Savannah River Laboratory, E.I. DuPont deNemours, October 1982.

This summary was prepared by:

CKY Incorporated Environmental Services
140 E. Division Rd. Suite C-3
Oak Ridge, Tennessee, 37830
Contact: Kenneth Shepard (615) 483-4376

in conjunction with:

Stone & Webster Environmental Technology & Services
245 Summer Street
Boston, MA 02210
Contact: Bruno Brodfeld (617) 589-2767

Assistance was provided by the
WESTINGHOUSE SAVANNAH RIVER COMPANY
which supplied key information and reviewed report drafts.
Final editing and production was provided by the
Colorado Center for Environmental Management
999 18th Street Suite 2750
Denver CO 80202
Contact: Dawn Kaback (303) 297-0180

for:

HAZWRAP

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

950R-7400-001-009